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Nikola Tesla

From Colorado Springs to Long Island



Research Notes

Colorado Springs 1899-1900

New York 1900-1901

Nikola Tesla

From Colorado Springs to Long Island



Nikola Tesla
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to Long Island**

Research Notes

Colorado Springs 1899-1900

New York 1900-1901

Fig.





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The background of the cover is a dark, high-contrast image of a handwritten electrical circuit diagram on aged, textured paper. The diagram features several rectangular components, likely representing coils or capacitors, connected by thin lines. There are also some wavy lines and a small circular component. The paper has a mottled appearance with some visible wear and tear. In the top left corner, there is handwritten text in cursive that reads "induction alternator" and "1891-1892". In the bottom right corner, the number "12" is handwritten.

Prologue
The Road to the New Edition of Tesla's
Research Notes from Colorado Springs
and New York 1899-1901

Vladimir Jelenković

Because of the enormous significance of Tesla's contributions to modern civilization, and the need to preserve and promote heritage of universal value, in 2003 UNESCO included Tesla's archives, as a segment of the movable documentary heritage of humanity, in the Register "Memory of the World". This is the highest form of protection of cultural property and, for that reason, in September 2006, the development strategy of the Nikola Tesla Museum, especially in its segment based on the use of the latest information technologies, was to start a large and significant project of digitalization of the complete archive materials from the personal legacy of Nikola Tesla, kept in his museum in Belgrade. In this manner, the Museum is fulfilling its two main basic obligations – to preserve Tesla's archives in the best possible manner, and to also allow the largest possible number of people to use these archives, and thus become a member of the special community, which is incessantly, and tirelessly, working on the project "Preserving and Sharing Memory".

Owing to the support of information technologies, allowing far more efficient and more analytical insights into the most significant segments of Tesla's archives, precious and as yet unpublished notes from Tesla have been rediscovered and included in this new and amended edition of his previously published research notes, which the Nikola Tesla Museum is publishing in its edition *Monographic Works*, under the title "From Colorado Springs to Long Island".

The Road to the New Edition

The beginning of the road to this edition, more than 30 years long, stretches back to the time of the first large publishing projects of the Nikola Tesla Museum. Many years of great efforts by a large number of associates gathered around the director, and one of the founders of the Museum, Professor Veljko Korać, led in 1976, on the 120th anniversary of Tesla's birth, to the first publication of the Research Notes from Colorado Springs. Work on this very important edition, and the translation of Tesla's research notes, was principally carried out by Vojin Popović, long-standing Professor of the Belgrade Faculty of Electro Technology, Honorary Doctor of Belgrade University, and a great expert and promoter of the work of Nikola Tesla.

Unlike the previous Museum editions (*Nikola Tesla: Lectures, Patents, Articles*, Nikola Tesla Museum, Belgrade, 1956, and *Tribute to Nikola Tesla, Presented in Letters, Articles, Documents*, Nikola Tesla Museum, Belgrade, 1961), Tesla's Research Notes was the first work translated into Serbian. Since these writings by Tesla have never been published before, and the expert and general public was expecting to discover some of the long hidden secrets of the great inventor in these texts, the book generated great attention and the Serbian edition was sold out in a very short time. The edition in English (*Nikola Tesla: Colorado Springs Notes 1899-1900*, Nolit, Belgrade, 1978) was prepared over the next two years and published in 1978. Immediately after the publication of Tesla's notes, this unique publishing enterprise by the Museum and the foreword and comments by Professor Aleksandar Marinčić were highly praised by the greatest scientific authorities from around the world.

The next edition in Serbian of Tesla's notes appeared in 1996. On the occasion of the 140th anniversary of Tesla's birth, the Belgrade Institute for Schoolbooks and Teaching Aids (Zavod za udžbenike i nastavna sredstva, Beograd) published Nikola Tesla's Colorado Springs Notes with a new introduction and additions to the commentaries and reference literature by the editor-in-chief, Academician Aleksandar Marinčić.

Tesla kept his diary regularly, almost daily, during the eight months of his stay in the laboratory built on the slopes of the Pikes Peak Mountain, the farthest east of the big peaks in the Rocky Mountain chain. He came to Colorado Springs on May 18, 1899, with the intention to, as he himself stated, "to construct a generator of high-frequency currents of high-power, to develop method of individualization and mutual insulation of energy transmitted, and to determine the laws of transmission of currents through the Earth and the atmosphere."

He left his research notes, taken between June 1 that year and January 7, 1900, containing diverse measured values and calculations, numerous diagrams, observations or comments pertaining to daily experiments and the use of new configurations of instruments, working equipment and their arrangements.

Full Insight into Tesla's Research Preceding the Long Island Project

The book "From Colorado Springs to Long Island" presents the entire edition of "Colorado Springs Notes 1899-1900", with the significant addition of never before published notes that Tesla wrote in New York after his return from Colorado Springs, and before he moved to the new laboratory on Long Island.

Encouraged by the results obtained in Colorado, Tesla started thinking about the construction of a large transmitter that would allow not just for reception of radio and telegraph signals around the world, but would also provide energy for high-power devices. At the end of 1900, he found a financier for the project of his life, and at the beginning of 1901 he signed an agreement with John Pierpont Morgan, one of the key figures of the business and finance world, whose decisions crucially influenced the development of the economy, and especially the electrification and industrialization of the US.

During the same time period, immediately before and several months after the signing of the agreement with J. P. Morgan, Tesla continued to organize his notes from Colorado Springs. Moreover, in his New York laboratory, he performed some additional research and experiments to establish the influence of the arrangement of coils in the oscillation circuit on inductivity and their resonance tuning, worked on new devices and the development of his theory of wireless energy transmission, in preparation for a huge undertaking – the construction of the world communication system on Long Island, which would be based on his enormous high-voltage sparking transmitter from Colorado Springs.

Exactly these "new" notes, written almost exclusively on the notepaper of the New York Waldorf-Astoria Hotel during 1900 and 1901, together with the previous writings from Colorado Springs, form a new, complete unit, giving a more comprehensive insight into everything that preceded Tesla's, regrettably never completed, life project.

The processing of new materials demanded special effort, experience, and huge knowledge of the whole work of Nikola Tesla. Therefore, the Museum owes special thanks to Milan Ćirić PhD, long-term scientific associate of the Nuclear Research Institute "Vinča" in Belgrade, who expertly performed the very difficult task of reading Tesla's manuscripts, and, as a great expert on this specific material, translated all the New York notes into Serbian. Another great expert on Tesla's work, academician Aleksandar Marinčić, accompanied all the new notes with precious scientific and expert commentaries and explanations, as he did for the previous editions of "Colorado Springs Notes 1899-1900". At the same time, Professor Marinčić also took upon himself the responsibility of analyzing all the drawings of

electrical circuits, various sketches and diagrams, and transferring them to electronic form, which allows every researcher to precisely and easily understand Tesla's experiments and the results he obtained.

In the digital processing of old and new writings, the processing of original photographic plates and positive photographs, the introduction of various calculations, tables and formulas, a significant contribution to the realization of this significant edition of Tesla's notes was also given by the associate of the Nikola Tesla Museum, Ivana Zorić, as well as the graphic designer, Olivera Sinadinović, who, in the final processing of this extremely difficult material, gave a special character to the graphic design and layout of this book with her simple, elegant solutions.

Further Challenges

In 1902, Tesla continued his research performed in New York in his laboratory on Houston Street, in the new Wardenclyffe laboratory on Long Island. It is there that he began the research that would demonstrate his boundless creative spirit and visionary mind, when he envisioned the technical innovations that would be realized only at the end of the 20th and the beginning of the 21st century. At the same time, the three years of work on Long Island were the source of great disappointment. The end of Morgan's financial support, certainly also influenced by Marconi's successful demonstration of transatlantic communication, led to Tesla's abandonment of further work on the Long Island station, and his significant shift towards other research, especially in the field of machine engineering. Over the next twenty years, Tesla would, based on his new and completely original transfer of energy by friction from and to the fluid, realize new constructions of working circuitry for his bladeless turbo-machines – pumps, turbines, blowers, compressors, and similar devices.

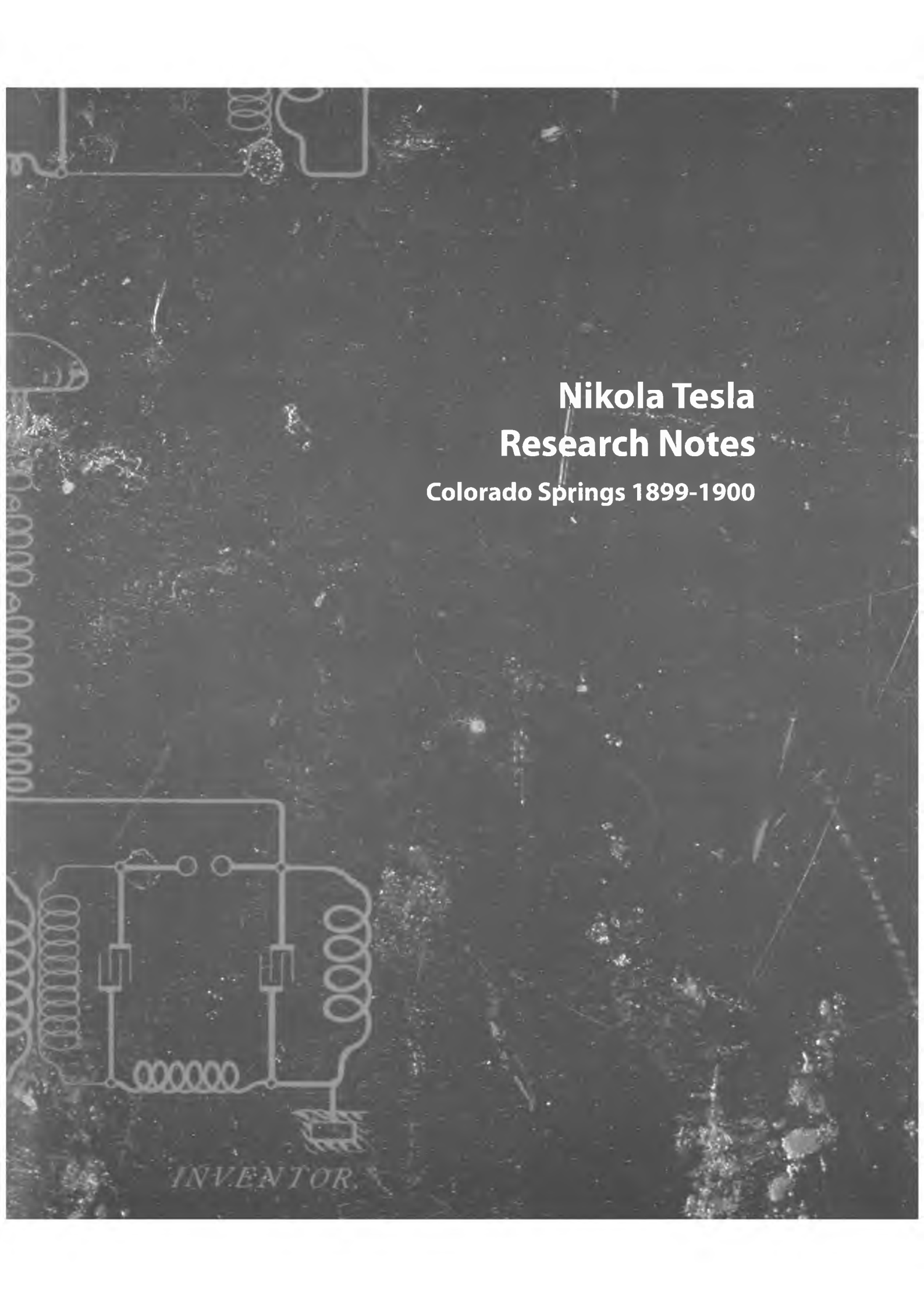
Based on the fact that key segments of archive materials have been digitalized, primarily the original photographs and documents covering Tesla's research and personal correspondence, the Nikola Tesla Museum has significantly intensified its publishing activity, and, between 2006 and the publication of this edition, has published 22 publications within its six newly established editions. In this manner, over less than two years, numerous documents covering Tesla's life and work have been made available to the widest domestic and world public, by being published in Serbian and English.

New information technology resources allow the possibility of continuing the processing and presentation of the materials from the period covered by this edition, by publishing all documents related to Tesla's research on Long Island, as well as those from the later decades of his work, primarily from the field of machine engineering. These insufficiently processed and researched fields represent a great challenge for the associates of the Nikola Tesla Museum, and will certainly be a fresh and precious inspiration for future researchers – to further investigate the work of the ingenious inventor, expecting new and exciting discoveries still hidden in his huge body of work.



Vladimir Jelenković

Director of the Nikola Tesla Museum



Nikola Tesla

Research Notes

Colorado Springs 1899-1900

INVENTOR.

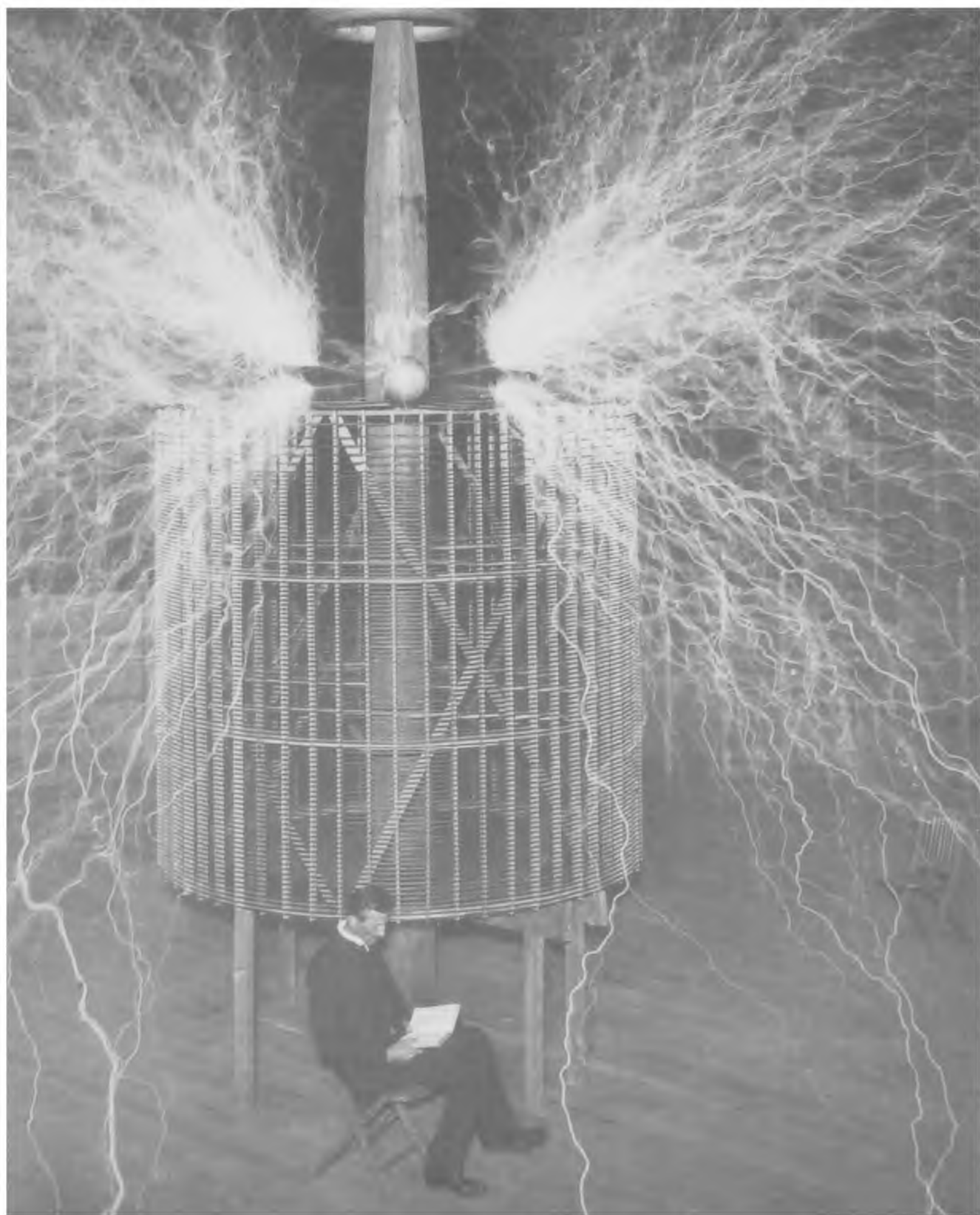
Patented June 23, 18

Fig. 1

Introduction

Aleksandar Marinčić





In the year 1898 culminated the creative impulse of Nikola Tesla in high frequency currents research. Since his first steps, actually the steps of the world pioneer in that field and his initial ideas of 1890, Tesla created, thanks to his highly intensive work, masterpieces unsurpassed, in some instances, till to date. Neither had the loss of his laboratory in the Fifth Avenue in 1895 prevented him for long to pursue his creative zeal; although the loss was enormous, he soon continued in a new laboratory in Houston street in New York and with no less vigor went on with his discoveries of new principles and ever more sophisticated appliances operated on those principles. He used this laboratory until June 1902 when he moved his laboratory operations to Wardenclyffe, Long Island.

Tesla's polyphase system of alternate currents resolved the problem of cost effective transmission and utilization of electrical energy. When he started experimenting with high frequency currents, Tesla almost immediately foresaw great possibilities of those currents in wireless transmission of "energy or signals". Starting from the idea conceived between 1891 and 1893, he progressed at such a pace that in 1897 he applied for two patents covering the system of transmission and apparatus for transmission of electrical energy without wires. Somewhat earlier, at the celebration of the commissioning of the hydropower plant at Niagara, at the time when the world was getting used to the polyphase system, which enabled transmission of electrical energy at a distance, for the first time in history, Tesla said: "Progress in this field (i.e. transmission of energy, rev. obs.) gives me hope that I will live to see the realization of my dearest dream: namely transmission of energy from a station to station without the use of any sort of wire."

True to his principle to prove his ideas by experiments, Tesla constructed powerful generators of high frequency currents in his laboratories and investigated them using the system and apparatuses for wireless transmission of energy. A photo of the original Tesla's slide was found among the documents treasured in the Nikola Tesla Museum in Belgrade, confirming that the experiment described in his patent "System for Transmission of Electrical Energy"⁽¹³⁾ was actually performed and moreover in the presence of the Chief Inspector of the Patent Office. To double check the methods of wireless transmission of energy "via conduction through earth and atmospheric layers" on a global scale, Tesla needed higher voltages and larger space (in his laboratory in Houston street he produced voltages between 2 and 4 MV, with high frequency transformer with a coil of 244 cm in diameter); that is why he started looking for a location of new laboratory by the end of 1898. By mid 1899 he had finally chosen a plateau at the altitude of some 2000 meters near Colorado Springs, where he had a wooden shed built, large enough to accommodate a high frequency transformer with a coil 15 m in diameter.

The arrival of Nikola Tesla to Colorado Springs was publicized by Evening Telegraph, a local newspaper, on May 17, 1899, entitled *Nikola Tesla will "wire" to France*. The subtitle informed the readership that "the genius of electricity arrived to the city at noon to investigate the problems of wireless telegraphy and the role of upper layers of atmosphere". In a statement on his arrival to *Alta Vista* Hotel he told a journalist that "he intended to send messages from Pike's Peak to Paris". He installed an office in the hotel where he expected two assistants to join him with many versatile appliances. Tesla was welcomed by his old friend Leonard Curtis, of the law firm *Hall, Preston & Babbitt*, who earlier used to work as a

lawyer with *Kerr, Curtis and Page* firm for Tesla, while in New York. Tesla was represented by the Curtis New York firm in every important patent litigation at the time.

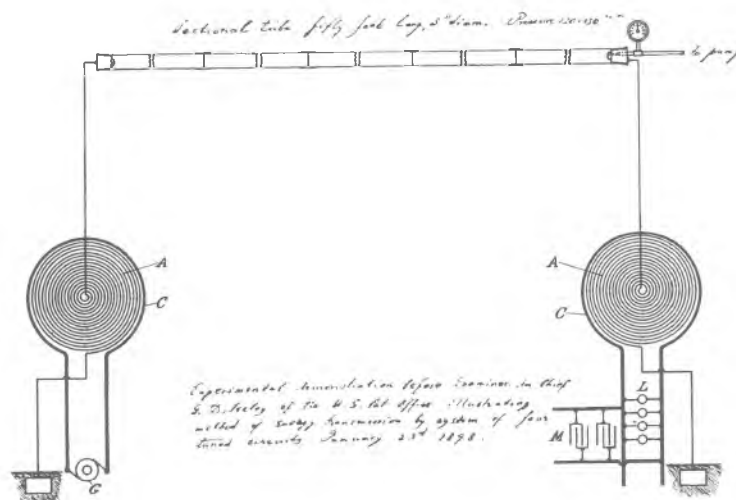


Fig. 1k. Diagram of an apparatus demonstrating transmission of Electric Power through Rarefied Gas (original Tesla's slide at the Nikola Tesla Museum, Belgrade).

Evening Telegraph of Colorado Springs again reported about Nikola Tesla's work on June 2, 1899 in a brief article *Tesla's Station Ready*. In the meantime Tesla completed the wooden shed, approximately 50 by 60 feet, some 18 feet high with two windows and a large door. It seems that Tesla himself was the main "architect", and being confident that storm would not damage his shed, he prompted the reporter's comment in the following words: "Mr. Tesla is a great scientist, but a poor architect." It is the fact, however, that storms have never interfered with Tesla's work and the shed itself withstood for five years more after his departure.

By end July Tesla was already performing various experiments in total secrecy, allowing access to the laboratory to no one except his assistants. He told the reporter of Evening Telegraph that "he would not work with wireless telegraphy, because he had already worked a lot on it". He experimented mainly by night, because of the availability of electrical energy supplied by *The City Electric Company*. Evening Telegraph published again on October 7, an interview with Tesla revealing that he elaborated a new procedure in telegraphy, which unlike any other (including the Marconi's system) would not be prone to interference and tapping. The new way of operating telegraphy was described on Jun 27, 1899 in his Notes. An interesting piece of information disclosed to the reporter "that he would advance a system enabling transmission of 1500-2000 words per minute" he never mentioned in his Notes. Asked about Marconi's experiment, Tesla said: "I have no time to occupy myself with that issue but I am happy that there is interest in it. You should understand that there is nothing new in what Marconi is doing. His experiments are interesting and this is it. I am satisfied that his experiments are successful, reportedly, but the system and all its elements, which I had described earlier, have one fatal defect - they can not be used if strong induction instruments are operated within the radius of 200 miles from the source. Under such conditions any exchange of messages is impossible."

On October 30, 1903 Tesla's laboratory in Colorado Springs was still there, according to the reports in Colorado Springs Gazette on the occasion of his intention to visit the city. The same Gazette wrote on April 6, 1904 that Tesla was sued to pay electricity bill for the period from Jun 1, 1903 till March 31, 1904, while the bill for water consumption had also been sent out. On July 2, 1904 Colorado Springs Gazette published a piece of news that Tesla's experimental station was sold for the value of wooden structure. The instruments were stored away so that Tesla could take them over. The structure was sold to a C. E. Maddocks. So, Tesla's laboratory in Colorado Springs ceased to exist five years later.

According to Engineering Mechanics of Philadelphia Tesla came to Colorado Springs on May 18, 1899 to intensively research in wireless telegraphy and the properties of high atmospheric layers. In his article *The transmission of electric energy without wires* in 1904⁽¹⁾ " Tesla wrote that he came to Colorado Springs with the following purpose:

1. To construct a generator of high frequency currents of high power;
2. To develop method of individualization and mutual insulation of energy transmitted;
3. To determine the laws of transmission of currents through the earth and atmosphere.

Before he came to Colorado Springs, Tesla had spent some 10 years working in the field of high frequency currents. Back from Pittsburgh in 1889, where he was a consultant of Westinghouse Company for a while, he elaborated his polyphase system. Tesla started the construction of an alternator for alternate currents of higher frequencies than those used in power generation, transmission and utilization. In 1890 he submitted two patent applications⁽²⁾ covering two types of alternators for currents over 10 kHz. One of these patents was linked to "soundless" arc lighting, but that was only the beginning of a new application of alternate currents soon named "Tesla's currents". In the history of technique Tesla's alternators have a prominent place and have been used as prototypes for the alternators that some quarter of a century later served to feed radio stations of high power and even later on for induction heating.⁽²⁴⁾

At the very beginning of his research in the field of high frequency currents, Tesla discovered their specific physiological effects and pointed to their possible application in medicine. He was fervently working on utilization of high frequency currents for generation of electric lighting by means of rarefied gas tubes of various forms and structures. In the course of 1891 he published the results of his research in magazine⁽³⁾, patents⁽¹⁵⁾ and in his renowned lecture before the American Institute of Electrical Engineers at the Colombia college.⁽⁴⁾ The lecture to eminent experts in electrical engineering resulted in many a recognition and he soon became famous throughout the world. His impressive experiments also contributed to success. Among others Tesla demonstrated luminescence of gas in the tubes with rarefied gas unconnected by wire to any source of electricity. It was the first experiment ever of wireless transmission of energy and conception of an idea to which Tesla devoted much of his life. Strong electrical field, in which a tube with rarefied gas becomes bright, was produced between plates of condenser connected to the secondary of high frequency transformer. The primary of the transformer was connected through the condenser to the generator of alternate current of *high frequencies*. The entire system performed best when the conditions of resonance were established in the primary and in the secondary of the transformer. Tesla applied resonant transformer also to spark-gap oscillator and so made a device for easy and efficient generation of high frequency currents from direct current or alternative current of low frequency. Spark-gap oscillator played an extraordinary role in the development of the technique of alternate currents of high frequency. It was an appliance that, only a couple of years later, occupied almost every laboratory of physics under the name of "Tesla's coil".⁽²⁰⁾

Chronologically, Tesla's oscillator of high frequency currents with spark-gap and transformer without iron core appeared for the first time in his patent № 454 622 of Jun 23, 1891 (submitted on April 25, 1891) under the name: "System of Electrical Lighting". The oscillator converted low frequency currents into the currents "of high frequency and very high voltage" and served to supply single-terminal lamps (figure 2k). In the oscillator circuit there is a network transformer *PS* supplying high voltage for charging a condenser. When the voltage on the condenser reaches break-down voltage of air gap – sparker *a*, condenser *C* is suddenly discharging via the primary of high frequency transformer *P*. The oscillating circuit *CP* is closed by means of the spark and oscillations occur. The phenomenon of discharge from a condenser in this case is different than the discharge from a condenser through coil with resistance studied by Henry* and which had been known in Tesla's era. In Tesla's oscillator the energy of high frequency oscillations from the primary coil progressively pass on the secondary coil. In the secondary circuit distributed capacitance and inductance form a resonant circuit. Depending on the spark duration energy oscillate between the primary and secondary resonant circuits. Upon passage of

* Henry observed something unusual in 1842, when an iron needle was magnetized by the

energy from the primary to the secondary circuit, the rest of the energy reverses to the primary circuit and again to the secondary etc., until the energy is spent on losses to such a measure that sparks in the primary circuit extinguishes. Then a new cycle of supply of condenser C from the source G via network transformer is started. A theoretical analysis of Tesla's oscillator was provided by Oberbeck⁽²⁹⁾ in 1895. Some major results of this theory, enabling more clear understanding of the process in Tesla's high frequency oscillator, are given in Appendix I.

In his lecture at the Institute of Electrical Engineers of England in February 1892, repeated again in London and then in Paris,⁽⁵⁾ Tesla gave a series of new data on his spark-gap oscillators and further investigation in high frequency currents.

No. 454,622.

Patented June 23, 1891

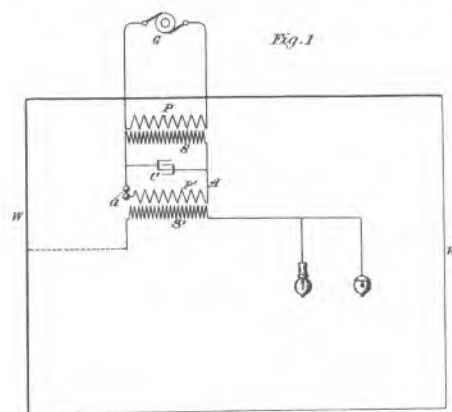


Fig. 2k. System of Electrical Lighting – Tesla's spark-gap oscillator

Among others Tesla described in great detail the structure of one type of high frequency transformer without iron core and pointed to the fact that the secondary voltage can not be approximated on the basis of ratio between turns of the primary and the secondary. Tesla devoted full attention also to the spark-gap and provided several construction proposals (some of which were later attributed to others⁽²⁴⁾). In describing the apparatuses by means of which he performed his experiments during the above mentioned lecture, he suggested more ways for quick extinction of spark by means of a strong magnetic field of compressed air, of serially connected spark-gaps and ordinary or serially connected spark-gaps with rotating wheel.

The lecture described how capacitance in the primary and the secondary circuits of high frequency transformer should be adjusted to reach the maximum effect, which according to Tesla "received insufficient attention in the past". Tesla experimentally confirmed that the secondary voltage can be increased by adding capacitance to the extent where it "compensates" the inductivity of the secondary (resonant transformer). He demonstrated several lamps with one electrode connected to the secondary, described the famous tube with brush discharge and expressed his view that it may probably find its application in wireless telegraphy. At one point he mentioned that high frequency currents pass easily through somewhat rarefied gas and hinted that it could be utilized to charge motors and lamps at a considerable distance from the source. A significant role in such a transmission system would be played by high frequency resonant transformer.

The diagram presented in figure 3k dates back to the early period of Tesla's work with high frequency currents. This one was reproduced from the original Tesla's slide, found in the archives of the Nikola Tesla Museum, dating back to 1891-1892. According to the title written by Tesla, the diagram is "An Illustration of Various Modes of Use of High Frequency Alternator in the First Experiments

current discharged from the Leyden jar. Helmholtz explained later the phenomenon and concluded that electricity probably passes from one to another condenser plate until balance establishes. Mathematical formula of the problem of discharges from Leyden jar through the coil with losses was published by Lord Kelvin in 1853. Commenting the result he found out that the discharge from Leyden jar will be oscillating by

$\frac{1}{LC} > \left(\frac{R}{2L}\right)^2$ (L , C and R stand for inductance, capacitance and resistance of the circuit, respectively) with frequency determined by

$$\omega = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$$

In case of circuits with small losses a simplified formula may be used $\omega = \sqrt{1/LC}$, known under the name of Thomson form and often found in the notes. Experimental testing of oscillating nature of a spark in condenser discharges was first performed by Feddersen in 1858 by means of a rotating mirror. Detailed discussion of the matter may be found in Fleming's book.⁽²²⁾

Performed in the Laboratory in Grand street in 1891-1892". Only some of those connections were published in literature. Consequently, this is an important document shading light on an especially fruitful but insufficiently known period of Tesla's accomplishments. It becomes clear, for instance, from these drawings that Tesla introduced at an early stage the high frequency transformer in the open circuit of an antenna. The connection, like that in figure 3k under 4 is found later in two patents from 1897^(13,14) covering Tesla's apparatus and the system for wireless transmission of electric energy (Tesla's spark-gap oscillator is mentioned in these patents as an alternative to high frequency generator).

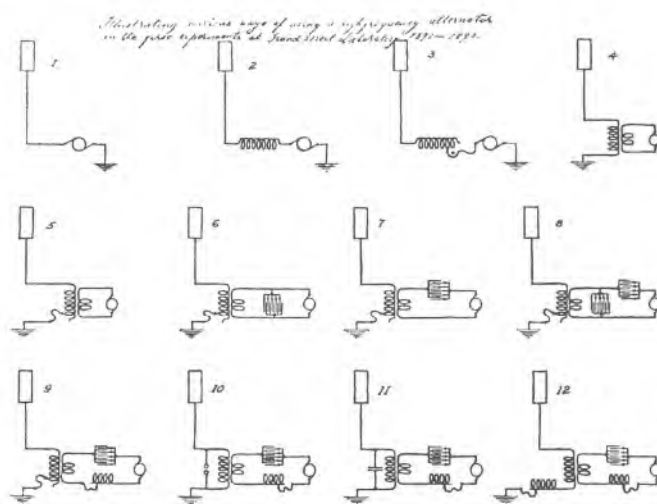


Fig. 3k. Diagram of Connections of Alternator to the System Antenna-Earth (original Tesla's slide)

In February 1893 Tesla held the third lecture on the topic of high frequency currents in the Franklin Institute in Philadelphia.⁽⁶⁾ He repeated the same lecture in March 1893 before the National Society for Electrical Lighting in Saint Louis. The most important part of the lecture was the system "for transmission of signals, or probably even power through any distance without the use of wire". What Tesla described then has often been quoted as a basic blueprint of radio technique, because it contained the principles and ideas of elementary importance. These are: the principle of adjustment of resonance for the sake of increasing sensitivity and selectivity of reception; induction coupling between the driving and operating circuits; antenna system where antenna acts as a capacitive load. Tesla has also correctly observed the significance of proper selection of frequency of high frequency currents and advantages of sustained currents in achieving transmission of signals through great distances.

In the period between 1893 to 1898 Tesla applied and was awarded for seven American patents covering the entire high frequency oscillators⁽²⁵⁾, one covering high frequency transformer⁽²⁶⁾ and eight covering various types of spark-gap rotating interrupters.⁽²⁷⁾ Tesla offered a summarized survey in a later article⁽²⁸⁾ on his work with his high frequency oscillators, stating that during eight years of work, since 1891, he had produced no less than 50 types of those oscillators capable of operating at direct or alternate currents of low frequency.

In parallel with his work on improvements of high frequency oscillators, Tesla ardently investigated the fields of application of high frequency currents. Well known are his works concerning the advancement of appliances for generation of X-rays, he described in a series of articles between 1896 and 1897⁽⁷⁾ and in his lecture in the New York Academy of Sciences.⁽¹⁷⁾ Tesla spoke of the applications of high frequency oscillators during his lecture in the American Electro Therapeutic Association in Buffalo in September 1898.⁽¹⁸⁾ Also noteworthy is his patent of the same year entitled: "Method of and apparatus for controlling mechanism of moving vessels or vehicles".⁽⁵⁹⁾ That patent contains the fundamentals of telemechanics - a branch that developed many decades after Tesla opened it.

* For the history of radio technique of special importance is the second of the two patents, protecting the apparatus for wireless transmission of energy, known as "System of Four Adjusted Circuits to Resonance". That patent was a subject of a long court dispute launched by Marconi Co. vs United States, adjudged in 1943 in favor of Tesla annulling Marconi's American patent No. 763 772 registered in 1904, because "it contained nothing new compared to the patents of Lodge, Tesla and Stone."⁽⁶⁵⁾

** Scientific knowledge of radiation and propagation of electromagnetic waves was rather scarce at the end of eighties of 19 century. After the publication of Hertz's research⁽²³⁾ in 1888, which provided evidence for Maxwell's theory of dynamics of electromagnetic field, published in 1865⁽⁶⁰⁾, the belief was growing that electromagnetic waves behave similarly as light waves and move in a straight line. Such an approach led to pessimistic conclusions about the reach of radio stations, soon discarded by experiments performed with the system antenna-earth according to Tesla's scheme from 1893.⁽⁶⁾ Tesla was reluctant as usually to the approach that there was one way only in which "electrical vibrations" propagate without wires - that is in a straight line, because he was convinced

On September 2, 1897 Tesla applied for the patent № 650 343 which was later divided* and patented under Nos. 645 576 of March 20, 1900⁽¹³⁾ and 649 621 of May 15, 1900.⁽¹⁴⁾ Unlike the rest of researchers in radio technique, who worked with damped high frequency currents and at very high frequencies,⁽⁴³⁾ Tesla investigated the field of lower frequencies of continuous high frequency currents. And while the others were developing mainly Hertz apparatus with spark-gap oscillator in antenna circuit (Lodge, Righi, Marconi and others) and advanced the receiver by introducing sensitive coherer (Branly, Lodge, Popov, Marconi and others), Tesla implemented in practice his idea of 1892-1893. How far he succeeded in testing his ideas about wireless transmission of electrical energy before his arrival to Colorado Springs it is possible to judge from his patent № 645 576 and the diagram in figure 1k.

In his elaboration of the idea of wireless transmission of energy on a global scale, Tesla started from the awareness that gas under small pressure is an excellent conductor of high-frequency currents. Under high voltages, the pressure at which gas becomes a good conductor is higher, so according to Tesla it was unnecessary to raise the metal conductor some 15 miles up (altitude), because good conductive atmospheric layers could be reached with considerably lower elevation of the conductor (antenna, in fact). *"Briefly, my invention (quotation from patent 645 576), based on those discoveries, comprises generation of electrical voltage at one place of such a character and size that it causes flow of current through high layer of air between the place of the source and a distant place where energy should be received and used."* Figure 1k proves that Tesla experimented with transmission of energy through rarefied gas in front of an employee of the US Patent Office. The patent shows that the pressure in the tube ranged between 120 and 150 mm Hg. At such a pressure, with adjusted circuits, efficient transmission of energy was achieved under the voltage between 2 and 4 million volts at the antenna of the transmitter. In his patent application Tesla requested protection of a similar method, provided that Earth would serve as the second conductor.**

Tesla stayed for almost a year in Colorado Springs. One can learn something about his work and results at the time from the articles published in the magazines *American Inventor* and *Western Electrician*. It was said, for instance, that Tesla intended to transmit electrical signals to Paris in 1900, without wires. In November 1899 it was written that Tesla progressed well in sophistication of his system for wireless transmission and that the messages he sent could not be interfered. In February 1900 it was reported that Tesla returned to New York.

An exhaustive description of the research, in the period from Jun 1, 1899 to January 7, 1900, is found in the diary of his work, which Tesla kept hand writing daily. Contrary to many other notes in the archives of the Nikola Tesla Museum in Belgrade, the notes from Colorado Springs were permanently written and nicely arranged. Since it was no writing for publication, Tesla kept it most probably to record the results of his investigation. Possibly, it was done for precaution in case of destruction of his laboratory, which could have easily happen due to performance of dangerous experiments with strong electrical discharges. Some parts of the diary were sent by Tesla to the US Patent Office, evidenced by the fact that some pages were stamped on the reverse. Some days Tesla wrote nothing, but at the beginning of respective month he usually stated the reasons why.

According to his notes, Tesla devoted most of his time to the transmitter, namely generator of high frequency currents of great power (some 56%), then to weak signals receivers (around 21%), measurement of capacitance of the vertical monopole antenna (some 16%) and to other different studies and explorations (about 6%). He designed a structure of a big high frequency oscillator with three oscillating circuits, obtaining voltages of the magnitude of 10 million volts. He tested various variants of receivers with one or two coherers with special circuits with bias for increasing sensitivity.⁽⁸⁶⁾ He performed measurements of electromagnetic radiation of electrical discharges in nature, elaborated measurement techniques in radio technique, considered constructions of modulator, of antennas supplied in parallel, and so on. He also explained his theory of development of fire balls which he claimed to have made artificially.

Tesla presented parts of his accomplishments from Colorado Springs in his patents and articles. In the period between June 1899 and July 1900 Tesla submitted applications for 7 patents and published an extensive article: *The Problem of Increasing Human Energy*.⁽⁴¹⁾

A few days before he left for Colorado Springs, Tesla called a photographer who shot a series of photos of the exterior and interior of the laboratory. He described 63 photographs in total, the most of which showed his big transformer in operation with a large number of streamers and sparks snapping from "the additional" coil. He probably enjoyed the sight of those powerful discharges accompanied by thunders and sparks some tens of meters long. At that time Tesla's coil-oscillator was already well known and used in various ways but Tesla was still ahead in research of super high voltages with his mammoth transformer. When he ended his work in Colorado Springs, he published some of the photographs in several articles which arouse a flood of enthusiasm and admiration, similar to those following his lectures in America, England and France in the period 1891-1893. The great German scientist Slaby wrote, having seen Tesla's photographs, that experimental appliances of other researchers are but toys compared to Tesla's.

The description of photographs contained in his diary was accompanied by detailed descriptions of oscillator operations. The photos themselves were professionally done and convincingly illustrative of the dimensions of experiments. Tesla resorted to the double exposure in their production. First the apparatus in operation was shot and then the next shot was done with flesh light, non operative apparatus and a man sitting. He claimed to have seen bright spots on some photos -fire balls and gave a description of how they were produced. Studies and generation of ball lightning was no objective of Tesla's investigation in Colorado Springs but these were special experiments, "interesting from scientific point of view"⁽⁶⁸⁾, according to Tesla's words, dealt with when he had time.

Tesla used some parts of his diary in drafting patent specifications which he submitted in the period between 1899 and 1902. Tesla practiced permanent keeping of notes which probably served as reminder for writing documents at the time when he published his inventions.

The diary contains some interesting descriptions of nature, most often around his laboratory and some unusual meteorological phenomena, but everything was concerned with the past or future explorations.

Immediately after cessation of works in Colorado Springs Tesla wrote a big article *The Problem of Increasing Human Energy*⁽⁴¹⁾ revealing a series of results arrived at in Colorado Springs. In 1902 he described in his statement in the court⁽⁶⁸⁾ how he wrote that article in the following words: "The Century insisted that I should write the article I promised, but it demanded all my strength. I knew the article was going to be historical, because for the first time I presented the results far beyond anything I or any one else in the world have ever done."

Tesla's article proved to be a great sensation and was reprinted more than once, widely quoted, too. The style of the article was quite different to that of the diary.

His works of Colorado Springs were again written of in 1904.⁽¹⁾ Some interesting data about it were located in Tesla's replies to the officials of the American Patent Office in 1902, concerning patent rights of Tesla and Fessenden.⁽⁶⁸⁾ That document contains the statements by Tesla's assistant Fritz Lowenstein and Tesla's secretary George Scherff. Tesla temporarily employed Lowenstein in April 1899 in New York and invited him to Colorado Springs in May the same year, where he stayed to work with Tesla till late September, when due to family reasons he had to return to Germany. Tesla was satisfied with his work and invited him to come back, which he did in February 1902.

After a triumphant return from Colorado Springs in New York on January 11, 1900, Tesla did not stop his research into the radio field. In that period, after returning from Colorado Springs and before beginning to work in a new Wardenclyffe laboratory some time in 1902, Tesla continued to work on radio transmitters and receivers following the work he had done in Colorado Springs. In the Nikola Tesla Museum in Belgrade, under a separate section in the Archives several notes have been found and they are presented in this new edition of Nikola Tesla Notes 1899-1900. They precede the Notes written some times later in the Wardenclyffe laboratory⁽⁸¹⁾.

In this period Marconi came to New York in January 1900 seeking investors and planning on lecturing on his progress in wireless. According to one of Tesla's recent biographer, Michael Pupin as

that Earth is a good conductor through which electrical energy could be transmitted. He had a premonition about certain role of high, conductive atmospheric layers in the "global" system of electrical energy transmission without wires. Interestingly enough that view on radio wave transmission was considered as something special at the beginning⁽¹⁶⁾ but then almost forgotten until lately. In the fifties of XX century the works of Schumann, Bremmer, Budden, Wait, Galeys⁽³⁴⁾ and others treated the propagation of electromagnetic waves of extremely low frequencies (6 to 30 Hz) and very low frequencies (3 to 30 kHz) in the way quite similar to the basic Tesla's postulates.

intermediary introduced Marconi to Tesla at the New York Science Club. After Tesla's explanations of the function of his transmitter for transmission of power to great distances using Tesla's earth currents and not Hertzian waves Marconi said that it was impossible⁽⁸²⁾. However, using Tesla's apparatus with four tuned circuits he succeeded nearly two years later to transmit three-dot telegraph signals across the Atlantic Ocean from Poldhu in Cornwall, England to St. Jones, Newfoundland.

Between 1900 and the first half in 1901 Tesla was looking for a new financial support for the practical application of his discoveries in radio. Finally, on March 1, 1901, Nikola Tesla officially signed the contract with Morgan. He was now able to begin construction of his laboratory and tower in Wardencllyffe on Long Island, sixty-five miles from New York City. No announcement was made about the Tesla Company explaining the details of Morgan-Tesla relationship. In fact, it was a simple business partnership although Tesla had told O'Neill, his first biographer, that the financier provided the funds in the capacity as a philanthropist⁽⁸²⁾.

In the first two months after signing the contract with Morgan, suddenly on May 10, 1901 the stock market crashed. The collapse of the stock market occurred because of the bitter rivalry between Morgan and Ned Harriman. The collapse created heavy financial burden on Tesla which caused increase on construction cost, wages, needed equipments and machines.

Tesla's ultimate plan was to construct a "World Telegraphy Center" with a laboratory, wireless transmitter, and production facilities for making oscillators, receivers etc. With Morgan he negotiated the first step to build a laboratory and a simple tower for reporting yacht races, signaling ocean steamers, and sending Morse-coded messages to England. Later he modified his plans in order to fulfill more ambitious plans of wireless energy transmission not only for minute amounts of energy but for a higher energy level transmission at any distance around the World.

For a new site Tesla selected a place near New York in Long Island and it was announced in the press on August 1901 that "Inventor Nikola Tesla has purchased a 200-acre tract at Wardencllyffe on the Sound, nine miles east of Port Jefferson for the establishment of a wireless telegraphy plant. The land and improvements will cost \$150,000."⁽⁸³⁾

Throughout the late spring and summer Tesla visited regularly Wardencllyffe, and at night he returned to the city. In July 1901 Tesla and architect Stanford White resumed talks about the construction of antenna tower. Initial Tesla's intention to build six-hundred-foot-high tower had to be modified. After construction it was 187 feet. Tesla also constructed a well beneath the tower to a depth of 120 feet.

Occasionally Tesla made notes – scarcely in 1900 and 1901, because he was preoccupied with finance problems and the design of new laboratory which he intended to make with most advanced equipment for his World Telegraphic Center. We learn from his notes made later that he intended to confirm his ideas about the resonance of Earth, of which he wrote in his patent submitted in 1900.⁽⁴²⁾ The experiments he wanted to perform seem not to have been repeated till the sixties of XX century, when it was experimentally proven that Earth is resonant at about 8,14 and 20 Hz.⁽³⁴⁾ Tesla anticipated the resonance at 6, 18 and 30 Hz. Being preoccupied with that great idea, he slowed down the works on transoceanic radio station, but when Marconi succeeded in transmitting the signal over the Atlantic in December 1901 with a more simple apparatus, Tesla had to admit to his financier Morgan that his aim was not to transmit weak signals only but bigger power for various applications. Commenting upon Tesla's undertaking, one of the greatest experts of the world in that field Wait⁽²¹⁾ wrote among others: "From historical point of view, it is important to state that the genius Nikola Tesla conceived the world communication system based on his huge, high voltage, spark-gap transmitter, located in Colorado Springs in 1899. Several years later he built a big facility on Long Island from which he intended to send messages to the Cornwall in England. Moreover, he planned to use modified version of the system for distribution of power to any point on Earth. Unfortunately, his sponsor, J. Pierpont Morgan stopped his support at that point, probably in consequence of Marconi's successful demonstration of transatlantic communication with much cheaper apparatus. In spite of it, Tesla's experiments bear close resemblance to the later development of communications at extremely low frequencies.

Tesla proposed that the Earth itself could be set into a resonant mode at frequencies of the order of 10 Hz. He indicated that energy was reflected from its antipode to his transmitter in Colorado Springs in such a way that standing waves were established."

In his letter to Morgan⁽⁶⁹⁾ in early 1902 Tesla explained that what he was exploring could be summarized in three "distinct projects: 1) *transmission of small amounts of energy and excitement of weak effects, hardly measurable by sensitive devices*; 2) *transmission of significant amounts of energy eliminating the need for sensitive devices and enabling safe operation of any appliance which requires small power*; and 3) *transmission of power in the amounts on industrial scale*. Completion of the present stage of my work shall mark the first step." For experiments in transmission of high power he anticipated construction of a facility at Niagara for generation of voltage of the magnitude of 100 million volts.

However, Tesla failed to secure the necessary financial support and after three strenuous years and attempts to complete the station on Long Island, he gave up his plans and turned to other fields of exploration. On several occasions he wrote articles about his great ideas on wireless transmission of electrical energy and remained convinced as long as he lived that one day it would turn into reality. Today, when we have proof of Earth's resonance, known as Schumann resonance⁽³⁴⁾ and when we know that waves of very low frequencies travel in space of earth-ionosphere with strikingly small attenuation, so small that standing waves are established⁽⁹³⁾, we can see that Tesla rightfully claimed that the mechanism of electromagnetic propagation in "his system" differs from that in Hertz's system using directed radiation. It is understandable that Tesla could not know exactly to which frequencies could wave movement be treated as guided waves in a thin shell between the earth and ionosphere, because he had probably never been capable of performing the experiments which he had brilliantly planned and described as early as in 1893 in his lecture in Saint Louis.⁽⁶⁾ The wheels of justice grind slowly and after many years of almost complete oblivion of Tesla's attainment in the development of radio, his name triumphantly reappeared in the works dealing with propagation of electromagnetic waves of very low frequencies and resonance of Earth.^(21, 54, 62, 74, 76, 94) In Jackson's book⁽⁵⁴⁾ it was written that "this prominent genius clearly described Earth as a resonant circuit (he did not know of ionosphere), estimated the lowest resonance at 6 Hz (close to 6.6 Hz for ideally conductive sphere) and described the ways and means for generation and detection of those waves. I am grateful to W. L. Fitch for this fantastic element of history."

The diary of Nikola Tesla from Colorado Springs is an important historical document of the period when Tesla reached the peak of his creative powers. It makes it possible to penetrate into Tesla's creative imagination, unfolding of ideas and sway of his experimental spirit. For Tesla, the experimental proof of his idea was crucial but he at the same time aspired at achieving concord between experimental and calculated values. He used simplified mathematical models for his calculations of the explored systems. Similar approach to the calculation of telegraphic radio stations are met in later literature.⁽⁶¹⁾

Those who want to acquire deeper knowledge of Tesla's work will find the diary of Colorado Springs a source offering better understanding of already known documents and identification of numerous papers kept in the Nikola Tesla Museum in Belgrade, often undated or without description.

Preparation of the manuscript for print took quite some time and effort to present the material in a form essentially authentic to the original but easier to explore. The text was not changed in case of minor mathematical errors, either, or incorrectly applied units of energy and power, with the exception of some major errors of consequence for the conclusions inferred. Commentaries to Tesla's text were provided at the end of the Notes with explanations and survey of his earlier works and those of other researchers. Commentaries relied on extensive literature and records kept in the Nikola Tesla Museum in Belgrade.

Academician Aleksandar Marinčić

Senders { one impulse } for one telephone
 { several impulses } impulse

form of { static action } form of
 Energy { current } energy
 Senders { Rays { light } affecting
 { Roentgen's rays } receive
 { magnetic field }
 { sound } "

Colorado Springs Notes

June 1-30, 1899

Instructions { static machines
 to be used { induction coil
 { Oscillator { magnetic lens and
 { two terminals
 Batteries
 Dynamos High frequency, full
 Condensers { Rheostat in circuit
 { Oscillator

To this to be added two applications filed with Curtis and some other patent matters chiefly foreign.

arrangement of circuit

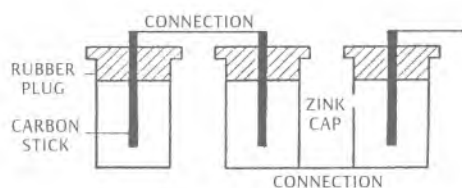
upon the capacity of the container
 system as before and contained
 of 846 hours to 10 in a round or down in
 can again used. The gaskets are in the
 separate covers 24 feet long each. The reading
 follows

Spacing total	in distance in spacing from previous + cover	Length of material in space to be covered of material	Calculating space on the side of cover
23 ft. = 210 ft. MF	$7' + \text{Cover}$	45 feet	$3\frac{3}{4}$
MF	$6\frac{3}{4} + "$	36 "	4
	$5\frac{3}{4} + "$	27 "	3
	$5\frac{3}{16} + "$	18 "	$3\frac{1}{4}$
	$7\frac{3}{4} + "$	9 "	$3\frac{1}{2}$
	$3\frac{5}{8} + "$	0 "	$3\frac{1}{2}$

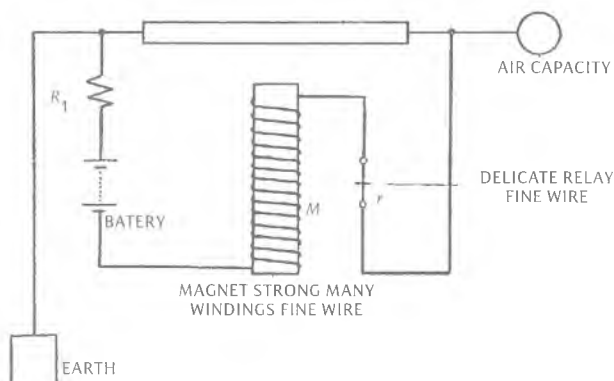
In repeated statement, the best addition
 in the length of the coil produces
 by a given effect. But a certain small loss

June 1, 1899

The following seems to be the best plan for constructing small batteries of very high e.m.f. required for exciting vacuum tube to be used as receiver in telegraphy: As the current for exciting the tube need be only very small the battery can furnish a minute current. From previous experiments about $\frac{1}{20,000}$ amp. is amply sufficient. Approximate dimensions of box $\frac{1}{4}$ cu. foot. The price will not be prohibitory. Tin caps, plugs and carbons will be readily obtainable.



The connection of the receiver is to be as in experiments in New York: If necessary the resistance R_1 will be used to strain the tube exactly just to point of breaking down. It is very important as in all sensitive devices so far used that the dielectric is strained *exactly* to the breaking point. The magnet M is to have a resistance nearly equal to the internal resistance of the battery, so as to get best output. The relay will suit as it is with 1000 ohms resistance. The magnet must be strong to blow out tube when lighted. This device should be *very sensitive* and should break down by very minute currents propagated through the earth from a similarly connected oscillator.



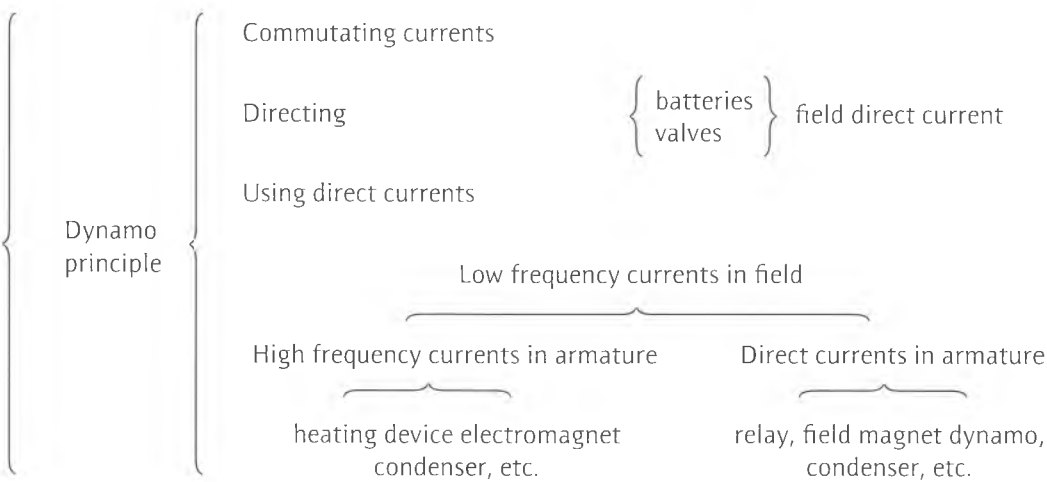
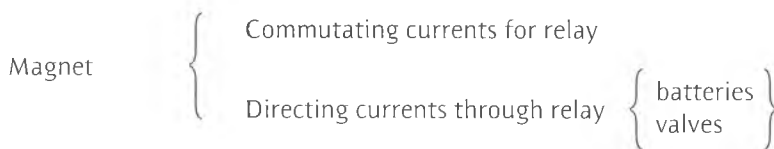
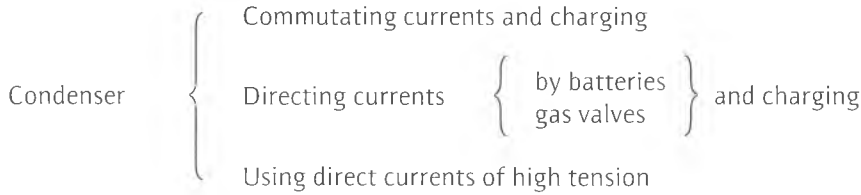
Colorado Springs

June 2, 1899

Signalling Valuable Uses of Condenser Methods	{	Telegraphy	{	Ships Land Cables (this very much so, but powerful apparatus required).		
		Protection		{ Ships Icebergs		} Collisions
Research	{	Animal Plant	{	Electricity	{	
		Terrestrial Disturbances		Magnetism Static Atmosph. Earth currents Solar influence etc..		Electricity
		Locating on deposits		Magnetic Non-magnetic by reflection		
		In connection with Roentgen rays, other rays and dark rays of the sun. Most important.				
Measurements etc.	{	Resist., current., e.m.f. etc. Intensities, light, heat etc.	{	Power current integrators of all kinds		
		Meters				

Various modifications of a principle consisting in accumulating energy of feeble impulses received from a distance and utilizing magnified effect for operating a receiving device. Several modes of carrying out the same, generally considered:

Resonance —



Colorado Springs June 4. 1899.

Telephony in those cities.
General observations.



General aberrations

[illegible]

form of { Static action
Energy { Current "
Rays { Light "
Sunder { Heat "
Röntgen r.t.c.
Magnetic act.
Sound "

Form of Energy affecting receiver

- Electric
- Two current attraction repulsion
- Magnetic
- Cathode rays
- Heat
- Light
- Cathodic mechanical action
- Reflection by mech. displacement.

Instruments
to be used

- Static machine
- Induction coil
- Oscillator { single terminal
two terminals
- Batteries
- Dynamos (high frequency) { all.
direct
- Condensers { Rheostat & mach.
oscillator

Receiving
Instruments,
suited for
the various
transmitting
instruments

} to be worked
out.

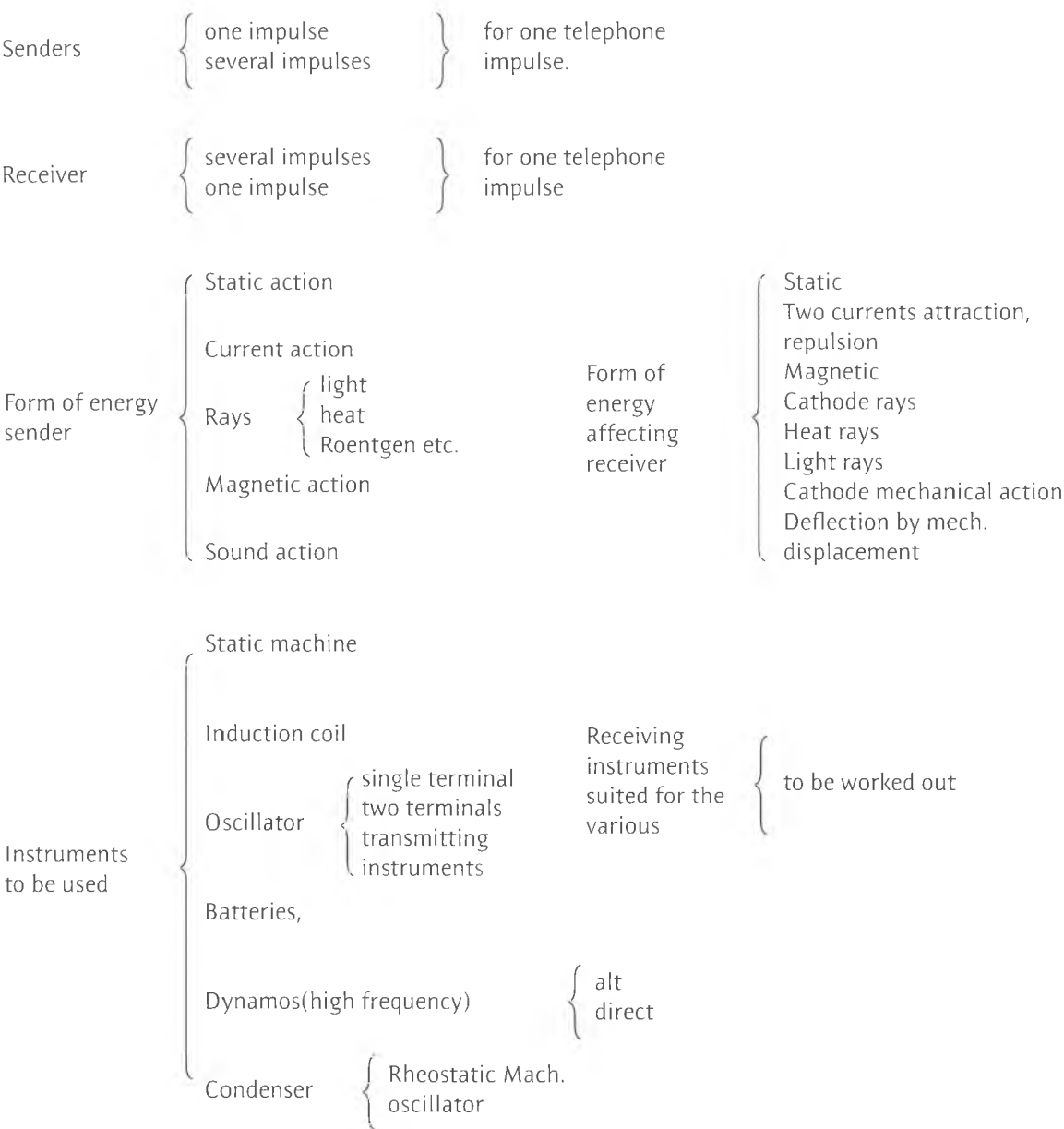
Arrangements of a rail c. l. c. to be worked out

Colorado Springs

June 4, 1899

Telephony without wires.

General observations:



Arrangements of circuit etc. to be worked out.

Colorado Springs

June 5, 1899

Induction method; results with apparatus to be used calculated from

$$M = \frac{p^2 s^4 W_p V_i^2}{32^2 D^6 S^2} \quad (\text{This formula is very problematical})$$

M = Power in secondary or receiving circuit

p = $2\pi n$, estimated 40,000 = 4×10^4

s = length of side of square circuit = 1200 = 12×10^2 cm.

W_p = power spent in primary = 4×10^{10} ergs assumed.

V_i = total volume of wire in both circuits = 25×10^3 cu.cm.

D = distance from center to center of circuits (horizontal)

S = specific resistance of wires = 1.7×10^3

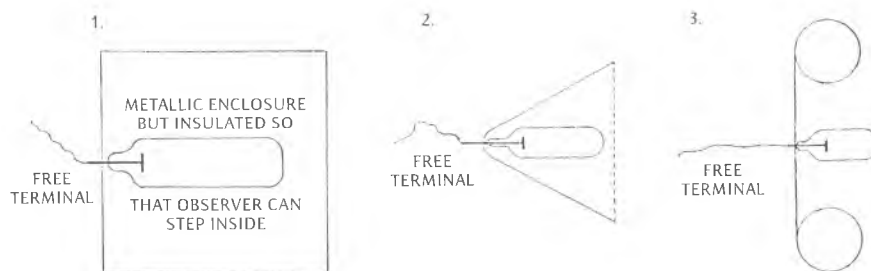
Taking M to be the minimum 0.3 ergs to affect relay, it is found that with above circuits and under such conditions about 1 mile communications should be possible. With circuits 1000 meters square, about 30 miles. From this, the inferiority of the induction method would appear immense as compared with disturbed charge of ground and air method.

Colorado Springs

June 6, 1899

Arrangements with single terminal tube for production of powerful rays

There being practically no limit to the power of an oscillator, it is now the problem to work out a tube so that it can stand any desired pressure. The tubes worked with in New York were made either with aluminium caps or without same, but in both cases a limit was found so that but a small fraction of the obtainable e.m.f. was available. If of glass, the bottom would break through owing to streamers, and if an aluminium cap were employed there would be sparking to the cap. Immersion in oil is inconvenient, likewise other expedients of this kind. The best results will probably be obtained in the end by static screening of the vulnerable parts of the tube. This idea was experimented upon in a number of ways. It is now proposed to test the arrangements indicated below:



In each case there would be an insulated body of capacity so arranged that the streamers can not manifest themselves. The capacity would be such as to bring about maximum rise of e.m.f. on the free terminal.

Colorado Springs

June 7, 1899

37

Approximate estimate of a primary turn to be used in experimental station.

$$L = \pi \left[4A \left(\log_e \frac{8A}{a} - 2 \right) + 2a \left(\log_e \frac{8A}{a} - \frac{5}{4} \right) - \frac{a^2}{16A} \left(2 \log_e \frac{8A}{a} + 19 \right) \right]$$

Here A radius of circle = 25 feet = 300 inch = $300 \times 2.54 = 762$ cm.

$$a = \text{cable } \frac{13''}{32} = \frac{13}{32} \times 2.54 = 1.03 \text{ cm.}$$

$$\frac{8A}{a} = 5919 \quad \log_e \frac{8A}{a} = 3.772248 \times 2.3 = 8.6762$$

$$4A = 3048 \quad 2a = 2.06 \quad a^2 = 1.061 \quad 16A = 12,192$$

$$L_s = \pi \left[3048 \times (8.6762 - 2) + 2.06 \times (8.6762 - 1.25) - \frac{1.061}{12,192} \times (17.3524 + 19) \right]$$

last term being negligible, we have

$$L_s = 3.1416 \times (3048 \times 6.6762 + 2.06 \times 7.4262) =$$

$$= 3.1416 \times (20,349.06 + 15.3) = 3.1416 \times 20,364.36 =$$

$$L_s = 63,976.67 \text{ cm.}$$

or approx: 63,900 cm.

Two turns in series should be approx. 255,600 cm.

Approximate estimate of inductance of primary loop used in experimental oscillator on vertical frame in New York

Diameter of loop = 8 feet = 244 cm.

This gives A = 122 cm diam. of cable = $\frac{13''}{16}$

$$a = \frac{13''}{32} \times 2.54 = 1 \text{ cm. nearly}$$

$$\frac{8A}{a} = 976 \quad \log_e \frac{8A}{a} = 2.98945 \times 2.3 = 6.875735$$

$$a^2 = 1 \quad 4A = 488 \quad 16A = 1952$$

$$L = \pi \left[4A \left(\log_e \frac{8A}{a} - 2 \right) + 2a \left(\log_e \frac{8A}{a} - \frac{5}{4} \right) - \frac{a^2}{16A} \left(2 \log_e \frac{8A}{a} + 19 \right) \right]$$

$$= \pi \left(488 \times 4.875735 + 2 \times 5.62735 - \frac{1}{1952} \times 32.75 \right) =$$

$$= \pi (2379.3600 + 11.2515 - \text{small fraction})$$

$$= \pi \times 2390.6115 = 3.1416 \times 2390.6115 \quad L = 7210.345 \text{ cm.}$$

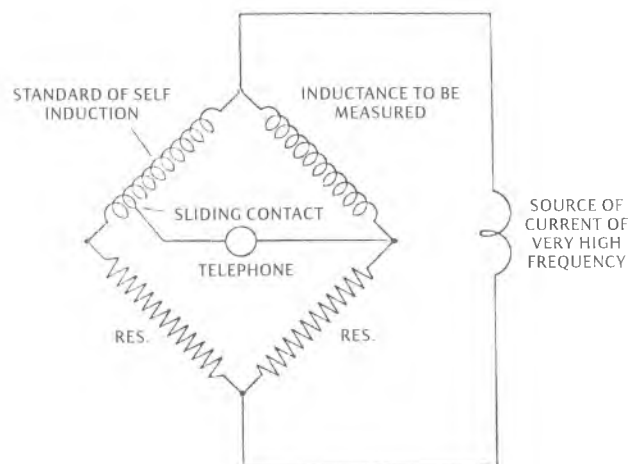
this is a trifle more with ends close enough 8,000 cm.

Colorado Springs

June 8, 1899

Method and apparatus for determining self-inductances, also capacities, particularly suitable for determining small inductances

Since resistance can be neglected when the frequency of the currents is high the inductances can be easily compared in the following way: A standard of self-induction is provided with a sliding contact so that any number of turns can be inserted. Two resistances, suitable for the source of high frequency current and the inductance to be measured, are connected in the manner of a bridge. The two opposite points, one movable, are connected through a telephone. When no sound is heard then we have the two inductances – that is, the one to be measured, and that part of the standard which corresponds to equilibrium or silence in the telephone – practically equal if the quantities are suitably chosen. By determining inductances capacities may from these be easily measured. It is possible that the high frequency source might be dispensed with and a very *sudden* discharge of a condenser passed through instead. The auxiliary resistance should be so determined that the resistances in the two parts through which the current divides are equal or nearly so.



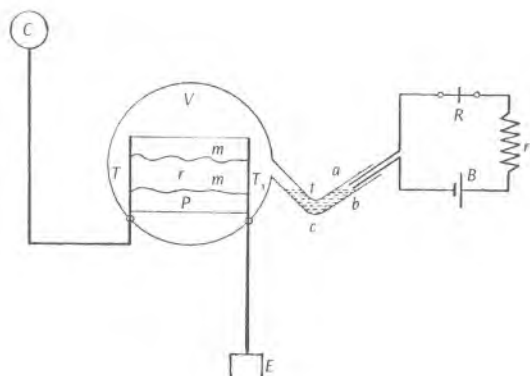
Colorado Springs

June 9, 1899

Consider the practicability of using a column of air or other gas as detector of disturbances from a distance. This would be on the principle of the Ries thermometer as experimented with in New York. The arrangement of apparatus is illustrated in the diagram below. There is a reservoir V , preferably of polished surface, made in the manner of mirrors to reflect rays to center. In this reservoir is placed a resistance r of *minute mass*. This resistance may be conveniently obtained by connecting with pencil marks m two terminals T and T_1 , holding a glass plate P . The *mass must* be minute so that the smallest amount of current would raise the temperature of the marks or conductors and thus heat the air in the reservoir which, expanding, would drive a minute column of liquid c contained in tube t towards contacts a b . The liquid should be very light and need not be highly conducting, barely enough to allow the relay R to be worked by battery B when contact between a and b is established. The resistance r_1 may be

used to regulate battery strength. The terminals T T_1 I would preferably connect in the manner I generally resort to, that is, one to the ground and the other to a body of some surface and elevated. Suppose air is used, we would want 0.1696 Ca per °C per gramme. It will be now easy to calculate how much the air can be expanded per erg of energy supplied.

(to work out)



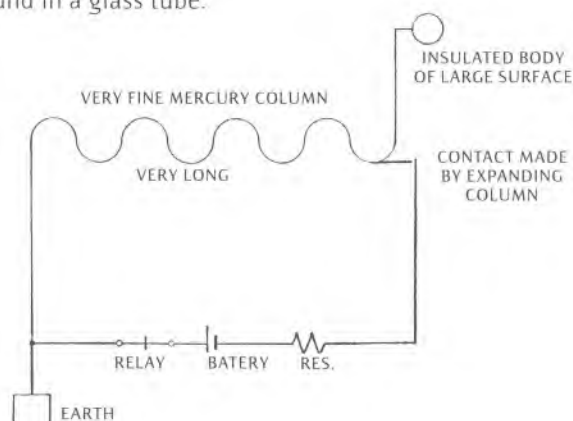
Colorado Springs

June 10, 1899

Suppose a *very fine* mercury column were prepared of resistance R , length L and connected to a ground and an elevated insulated conductor in the manner illustrated in diagram.

Then if a current I be passed through it the energy lost in the column and converted into heat will be RI^2 watts. The current is, of course, minute and we could scarcely calculate on more than 1 erg in telegraphy being transmitted to a great distance from the transmitting station; the question is what can be done with that little amount of energy.

If the mercury be raised to a temperature t degrees above normal it will expand for each degree 0.00018 of its length hence its length will be $L + Lt \times 0.00018 = L(1 + 0.00018t)$. This value is a little greater than would actually be found in a glass tube.



Suppose the tube were $\frac{1}{10}$ mm. diam. and 10 meters long; its resistance would be approx. 1000 ohm. Then $Rl^2 = 1000l^2 = \frac{1}{10^7}$, taking one erg as energy supplied, gives $l^2 = \frac{1}{10^{10}}$, $l = \frac{1}{10^5}$ amp. The column in the tube would expand for one degree $0.00018 \times 10 = 0.0018$ meters or 0.18 cm or 1.8 mm.

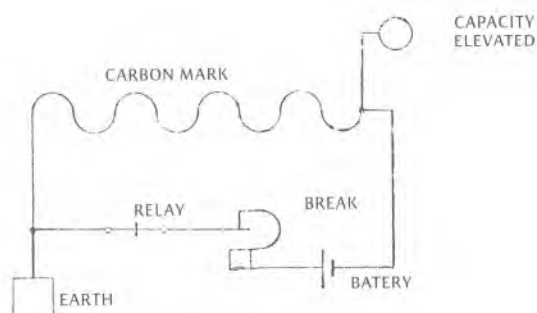
The volume of the column would be $0.01 \times 10,000 = 100$ cu.mm. or 0.1 cu.cm. Now this would weigh $0.1 \times 13.6 = 1.36$ gramme. The mass of this would be $\frac{0.00136}{9.81}$. Now to raise water 1° C we want 41,600,000 ergs per gramme. Specific heat of mercury being 0.0319 we would want $41,600,000 \times \frac{320}{10,000} = 41,600 \times 32 = \text{about } 1,330,000$ ergs.

This shows that on the above assumptions, indication of disturbances by mercury column would be hardly practicable unless the column could be made *much thinner*.

Colorado Springs

June 11, 1899

The following method and apparatus for detecting feeble disturbances transmitted through a medium seem to be particularly adapted for telegraphy. The idea was followed up in New York but results were not satisfactory. Now the experiments are to be resumed with apparatus as illustrated below.



The general idea is to provide a path for the passage of a current such that it will diminish in resistance when the current passes and also such that it will be of as minute a mass as possible. The specific heat of the material forming the path for the current should also be as small as possible. The best way I have so far found is to make a mark of the required thickness with a carbonstick so as to connect two terminals through a conductor of high resistance so deposited. This conductor I preferably connect with one end to the earth and with the other to an elevated object of a large surface. The conductor is further connected in circuit with relays and batteries in any way suitable, as for instance in the arrangement here shown. Now when a feeble impulse passes it reduces the resistance of the carbon and more of the battery current can pass through and so on until the relay is brought into action. The relay then, in any way suitable, breaks the current of the battery and a normal regime is established. The relay itself may be utilized to break the current or an auxiliary magnet may be employed as illustrated. The carbon mark may be connected in the manner of a *bridge* to increase sensitiveness.

This to be followed up.

Colorado Springs

June 12, 1899

A convenient way of obtaining a conductor (rather a poor one) of small mass, such as will be instantly evaporated or disintegrated by a battery current, and one which is also automatically renewed in a simple manner, is the following:

Two terminals are fastened to an insulating plate, preferably of glass, and provision is made once for a film of poorly conducting substance to be deposited on the plate thus bridging the terminals and establishing sufficient contact between them to allow a current to pass.

The best manner to carry this idea out seems to be the following:

In a small bottle, having a stopper with two terminals, is placed a quantity of iodine and the bottle is by any suitable means kept at a temperature such that the haloid is deposited in an exceedingly fine film causing a leak of the battery current through a relay. A stronger current may then be passed by establishing a suitable connection with the relay and the film of iodine may thus be destroyed and the terminals again insulated, this process being repeated in as rapid succession as may be desired. This film may be used in the detection of feeble impulses as in telegraphy through media, in which case it is connected to ground and capacity.

Colorado Springs

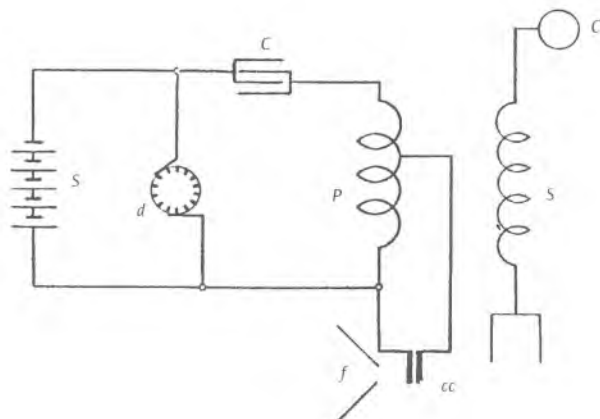
June 13, 1899

Arrangements of transmitting apparatus for telephony at a distance without wires

The most difficult part in the practical solution of a problem of this kind of telephony is to control a powerful apparatus by feeble impulses such as are produceable by the human voice.

One of the best ways is to use carbon contacts as in the microphone, but when powerful currents either of great volume or high e.m.f. are used, as they must be in such cases, the problem offers great difficulties.

A solution which I have before described is offered in the following scheme, illustrated diagrammatically below.



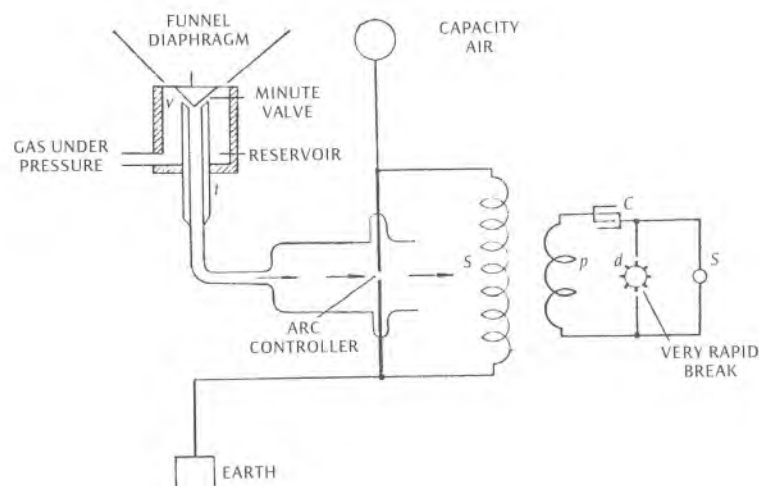
S is a source of preferably direct current as a powerful battery or dynamo, C a condenser which is connected with a primary p and break d as usual in an oscillator. The break d is such that at the number of breaks resonance is obtained.

A secondary s is provided which is connected to the ground and an insulated body of capacity and elevated as shown, and normally the adjustment is such that the secondary with its capacity and self-induction is in resonance with the primary p . From the latter a shunt is made by two contacts c c preferably of carbon. Normally these carbons touch loosely but by speaking upon funnel f they are harmonically pressed together and the primary current is diverted thus destroying the resonance and greatly diminishing effect in the secondary rhythmically with the undulations of the voice. In this manner very minute variations in the contact resistance are made to produce great variations in the intensity of the waves sent out. The breaks at d must be much above undulations of the voice.

Colorado Springs

June 14, 1899

The following arrangement, considered before in a general way, seems to be particularly suitable for telephony at a distance without wires and for such purposes where it is necessary to effect control of a powerful apparatus by feeble impulses such as those produced by a human voice.



The idea is to use an ordinary oscillator, preferably one operated from a source of direct currents with a break (mercury or simply an air gap) which is much higher in frequency than the vibrations of the voice. At any rate, there will be an arc, whether in the primary of the secondary which will be blown out, or the resistance of which will be enormously increased, rhythmically with the vibrations impressed by voice or otherwise, as the case may be. The control of the arc is effected by a jet of air or other gas issuing under pressure from an orifice the opening of which is controlled in some convenient way by the vibrations. An arrangement of such apparatus is illustrated in the diagram below, the arc controlled thus being in the secondary. The source of direct currents S charges a condenser C and the discharges of the same (a very great number) through a break d and primary p energize a secondary s with the usual connection in telegraphy as I have introduced. The air or gas under pressure is controlled by a diaphragm and valve v . The outlet pipe t can be screwed up as close to the diaphragm as is necessary for the best result. In this or a modified way a powerful apparatus may be controlled by very feeble undulations, as those of the human voice.

Colorado Springs

June 15, 1899

First experiments in the station were made today. The e.m.f. of the supply transformer was 200 volts only. The break on the disk, which was driven by a Crocker Wheeler motor, varied from 800–1200 per second. ω was found to be 800 approximately.

Under these conditions the secondary from the New York high tension transformer could only charge from 3–4 jars and it was impossible to obtain more than a harmonic of the vibration of the secondary system of the oscillator, which required many more jars.

The secondary was wound on a conical framework, there being 14 turns of an average length of 130 feet each, that is approximately.

The primary was formed by one turn of cable, used in New York laboratory for the same purpose, consisting of 37 wires № 9 covered with rubber and bredding. The details of construction are to be described later.

Note: Sparks went over the lightning arresters instead of going to the ground. This made it necessary to change the connection to the ground, separating that of the secondary of the oscillator from the ground of the arresters. By connecting the secondary to a water pipe, and leaving the ground of the arrester as before, the sparks ceased. This indicates a bad ground on the arresters. The *latter work exceedingly well*. The ground connection was made by driving in a gas pipe about 12 feet deep and gammoning coke around it. This is the usual way as here practised.

The power taken in these first experiments was small, $\frac{1}{2}$ – $\frac{3}{4}$ H. P. only. The spark on the secondary was 5" long but *very thick and noisy*; indicates considerable capacity in the secondary. The variation of the length of the spark in the break did not produce much change. The weather was very stormy, hail, lightning.

Colorado Springs

June 16, 1899

Experiments were continued today. A new ground connection was made by digging a hole 12 feet deep and placing a plate of copper 20" × 20" on the bottom and spreading coke over it again, as customary. Water was kept constantly flowing upon the ground to moisten it and improve the connection but in spite of this the connection was still bad and to a remarkable degree. It is plain that the rocky formation and dryness is responsible and I think that the many cases of damage done by lightning here are partially to be attributed to poor earth connections. By keeping the water constantly running the resistance was finally reduced to 14 ohms between the earth plate and the water main. By connecting the earth plate and water main again, the lower end of the secondary being connected to the latter, sparks would again fly over the arresters. When the water main was disconnected they again ceased.

The action of the waves spreading through the ground was tested by a form of sensitive device later to be described and it was found that there was a strong vibration passing through the ground in and around the laboratory. The device was purposely unresponsive, to get an idea by comparison with former experiences in this direction. It did not respond when placed close to the oscillator, but unconnected to ground or capacity, but responded 200 feet from the shop when connected to the ground with one terminal. It responded also all along a water main, as far as it reached, although it was connected to the ground fairly well. The action on the device was still strong when there were no sparks from the secondary terminal. This is a good indication for the investigation of waves, stationary in the ground. It

was concluded the earth resistance was still too great. Possibly the ground affects the primary and the secondary, more than assumed, by the formation of induced currents.

To be investigated.

Colorado Springs

June 17, 1899

Measurements of resistance between ground wire and water main showed the surprising fact that it was 2960 ohms, and even after half an hour watering it still was 2400 ohms, but then by continued watering it began to fall rapidly. Evidently the soil lets the water run through easily and being extremely dry as a rule it is very difficult to make a good ground connection. This may prove troublesome. The water will have to be kept flowing continuously. The high resistance explains the difficulty, from a few days before, of getting the proper vibration of the secondary. The first good ground was evidently at the point where the water main feeding the laboratory connected to the big main underground and this was several hundreds of feet away. This introduced additional length in the secondary wire which became thus too long for the quarter of the wave as calculated. The nearest connection to earth was as measured about 260 feet away and even this one was doubtful.

Measurement of inductances primary, secondary and mutual induction.

Readings for two primary turns in series showed:

$$I=34, \quad E=7, \quad R=0.015, \quad \omega=716, \quad I=\frac{E}{\sqrt{R^2 + \omega^2 L^2}}$$

Neglecting R^2 we have $\omega L_p = 0.206$ and $L_p = 287,000$ cm approx.

For secondary 14 turns on conical frame average length of turn 130 feet.

$$E=57.7 \quad \frac{E}{I}=4.57 \quad \omega^2 L^2 = 16.49 \quad L_s = \frac{4}{716} = 0.0056 \text{ henry approx.}$$

$$I=12.65$$

$$\omega=716 \quad \left(\frac{E}{I}\right)^2 = 20.98 \quad \omega L = 4 \text{ approx. or } L_s = 5,600,000 \text{ cm. approx.}$$

$$R=2.12 \quad R^2=4.49$$

Coefficient of mutual induction, 2 primary turns in series:

$$M = \frac{E_p}{\omega I_s} = \frac{6 \times 10^9}{716 \times 10.7} = 783,300 \text{ cm.} \quad \begin{array}{l} E_p = 6 \\ I_s = 10.7 \\ \omega = 716 \end{array}$$

This will reduce L . Reduction estimated from

$$L - \frac{M^2}{N} = L \left(1 - \frac{M^2}{NL} \right) = L \times 0.64$$

Colorado Springs

June 18, 1899

Experiments were continued with the oscillator showing that proper vibration does not take place, evidently owing to some cause which is still to be explained. To see whether the trouble is due to poor induction from the primary, a coil-wound on a drum of about 30" diam, 10" long, 500 turns approx. of No.26 wire, used in some experiments in New York – was connected to the free end of the secondary and with this coil a great rise was obtained, streamers about 12" long being obtained on the last free turn even with a small excitation of secondary. The trouble seems to be due to internal capacity. The total length of a quarter wave with coil was about 2400 feet, which agrees fairly with the calculation from the vibration of the primary circuit. The experiments with the coil show strikingly the advantage of an *extra coil*, as I call it, already noticed in experiments in New York; that is, a coil practically not inductively connected but merely used to raise the impressed electromotive force.

Measurements of inductance of the secondary as used: 12 turns on tapering frame 1 ¼" apart from center to center showed:

Current through secondary	E.m.f. on terminals	ω
10.9	74 V	710

from this $L' =$ was found=9,500,000 cm.

Readings for mutual induction:

	E.m.f. on primary (one turn)	ω
10.9	4.75	710

gave $M' = \frac{E}{\omega I} = 0.00062H$ or 620,000 cm.

Compared with the first winding (14 turns far apart) the second winding was better because of both higher self-induction and greater mutual induction coefficient.

Measurement of capacity of condenser in sections:

The condenser was compared today with ½ mfd. standard by wirebridge and telephone receiver, according to the Maxwell method. There are 80 sections in the condenser, 40 on each side, which can be connected by plugs as desired.

They are: $1+2_1 + 2_2 + 5 + 10 + 10 + 20 + 30 = 80$

The measurements made by Mr. L. today gave 0.153 mfd per unit.

This to be verified.

Colorado Springs

June 19, 1899

Sensitive automatic device for receiving circuits in telegraphy through the natural media, purposes of tuning, etc. The device in simple form is illustrated in the diagram below.

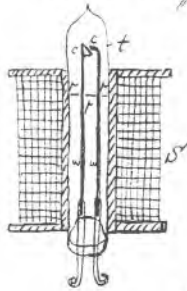
In a small glass tube t are fixed two thin wires $w w$ of soft iron or steel carrying contact points of platinum $c c$ on the top. A spool S wound with wire surrounds tube t . The contact points are shaped so that the wires can deviate considerably without the separation becoming too great. When the current passes through coil S the wires $w w$ are separated and the distance between the contact points, $c c$ increased. The tube is moderately exhausted. The dielectric between the points is strained, as in sensitive powders,

Colorado Springs, Colo. 19. 1898.



Sensitive automatic device for receiving currents in telegraphy through the wireless method, purpose of tuning c.c.

The device in a simple form is illustrated in diagram below. In a small glass tube t are two thin wires ww of soft iron or steel carrying contact points of platinum cc on the top. A spiral s wound with wire surrounds tube t . The contact points



are shaped so that the wires can draw aside readily without the separation becoming too great.

When the current passes through coil s the wires ww are separated and the distance between

the contact points cc increases. The tube is moderately exhausted. The distance between the points is increased

is a sensitive powder very near to the point of breaking down by means of a battery and when the disturbance reaches the ground the distance given by under the increased strain and the battery current passes through coil s separating the terminals and now breaking the battery current. It is supposed

in this instance that the contact points cc and coil s are connected in series with the battery but the connection may be made

in many other ways for the purpose of securing the same result.

That is of automatically interrupting the current after the signal has been received. The contact points must be very close together and

protected. Stops $p p p$ are provided to limit the movement of the

wires ww and prevent vibration upon each action. An additional

coil may be placed upon s for the purpose of adjusting the wires to

the point will be at the required minute distance from each other

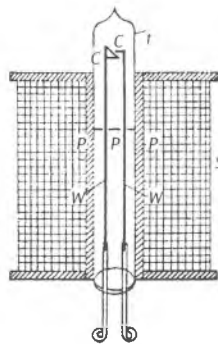
which is easily effected by graduating the strength of the current passing

through the additional coil and an independent relay may be connected in the circuit

is any convenient way for registering the signals. The degree of vacuum may also be made adjustable

In the first device coil s had 24 layers, 94 mm per layer = 2256 turns, 4-21 wire Res. 14.7 ohms.

very nearly to the point of breaking down by means of a battery and when the disturbance reaches the circuit the dielectric gives way under the increased strain and the battery current passes through coil S separating the terminals and now breaking the battery current. It is supposed in this instance that the contact points *c c* and coil S are connected in series with the battery, but the connection may be made in many other ways for the purpose of securing the same result – that is of automatically interrupting the current after the signal has been received. The contact points must be very close together and pointed. Stops *p p p* are provided to limit the movement of the wires *w w* and prevent vibration upon each action. An additional coil may be placed upon S for the purpose of adjusting the wires so the points will be at the required minute distance from each other, which is easily effected by graduating the strength of the current passing through the additional coil and an independent relay may be connected in the circuits in any convenient way for registering the signals. The degree of vacuum may also be made adjustable. In the first device coil S had 24 layers, 94 turns per layer=2256 turns, № 21 wire, res. 14.7 ohms.



Colorado Springs

June 20, 1899

Approximate estimate of some particulars of apparatus

With new jars the capacity will be about 0.174 mfd. that is with two sets of condensers in series as usual. Assume 20,000 volts on the supply transformer, the energy per impulse will be

$$\frac{4 \times 10^8 \times 0.174}{2 \times 10^6} = 34.8 \text{ watts estimated roughly.}$$

Suppose 1600 discharges through the primary per second, the condensers will deliver $34.8 \times 1600 = 55,680$ watts or a little over 74 H.P. With ten thousand volts they would still deliver $\frac{74}{4} = 18.5$ H.P. Now the vibration of the primary will be approximately:

$$T = \frac{2\pi}{10^3} \sqrt{\frac{7 \times 10^4}{10^9} \times 0.174} = \frac{2\pi}{10^5} \sqrt{0.7 \times 0.174} = \frac{2.2}{10^5} \text{ or } \frac{22}{10^6}$$

This gives $n=45,500$ per sec. about. This vibration supposes only one primary turn.

The wave length calculated from this is about 4 miles or 21,120 feet and $\frac{\lambda}{4} = 5,280$ feet. As each turn has, on the average, 130 feet we shall want to make up the lengths of a quarter wave $\frac{5280}{130} = 40$

turns about. Or, if two primaries are used in series, the capacity remaining as before, the wave length will be doubled and 80 turns will be needed. Let it then be assumed that 80 turns are used, the self-induction of the secondary will be not far from 165×10^6 cm. The period of the secondary will then be:

$$T_1 = \frac{2\pi}{10^3} \sqrt{\frac{165 \times 10^6}{10^9} \times \frac{38}{9 \times 10^5}}$$

assuming no internal capacity or that it is overcome by suitable construction and only a ball of 30" diam. or approximately 38 cm. radius on the free terminal of the secondary. We have then

$$T_1 = \frac{164}{10^7} \text{ and } N=61,000 \text{ approx.}$$

But this vibration will not be in harmony with the primary vibration. To effect this the self-induction of the secondary can be estimated. We have namely:

$$T = \frac{1}{45,500} = \frac{2\pi}{1000} \sqrt{\frac{38}{9 \times 10^5} L_s},$$

where L_s is the self-induction of the secondary required.

From this $L_s = \frac{10}{32}$ henry or $L_s = 312,500,000$ cm. Suppose the wire wound on the same spool or frame and the length to remain as before, the turns necessary can be estimated from $\frac{165 \times 10^6}{312 \times 10^6} = \frac{6400}{N^2}$, from which follows $N^2 = 12,102$ and $N = 110$ turns.

In addition to the wire already on hand this would cost about \$ 250 but with 80 turns only \$ 100 will be necessary. To keep the vibration of the secondary the same, the capacity on the free terminal will have to be increased. The capacity necessary will be C and we have:

$$\frac{1}{45,000} = \frac{2\pi}{1000} \sqrt{\frac{165 \times 10^6}{10^9} C} \text{ from which follows } C=67.3 \text{ cm.}$$

A ball of this size is not to be had. If we employ a disc we have $\frac{2r}{\pi} = 67.3$, $r=56$ cm. A disc could scarcely be employed except with small pressures, there would be too much leakage.

All these estimates assume, of course, that the distributed capacity of the secondary is overcome in some way or other as by condensers in series, for instance. It is quite certain that the vibration of the secondary will be much slower.

Colorado Springs

June 21, 1899

Considerations of the various particulars of apparatus to be used, continued

The present supply transformers can furnish 26 H.P.

Assume this energy consumption, that is, $26 \times 750 = 19,500$ watts and 1600 breaks or charges of the condensers per second. This gives per each break $\frac{19,500}{1600} = 12$ watts roughly. Let us further suppose that an excess of power is supplied so that the secondary receives clear 12 watts per each discharge of the primary. This means to say that the capacity on the end of the secondary will be charged 1600 times per second to a potential p . If C be the capacity on the free end we have $12 = \frac{p^2}{2} C$ from which $p^2 = \frac{24}{C}$.

Assume C to be a sphere 38 cm. radius we have

$$\frac{24}{38} = p^2 = \frac{9 \times 10^{11} \times 24}{38 \times 9 \times 10^{11}}, \text{ from this}$$

$$p = 3 \times 10^5 \sqrt{\frac{240}{38}} = 3 \times 10^5 \sqrt{6.32} = 3 \times 10^5 \times 2.51 = 753,000 \text{ volts}$$

Approximate estimate of primary voltage necessary for above output.

To get e.m.f. lowest value it would be necessary to connect condensers in multiple, both sets. This would give a capacity of $0.174 \times 4 = 0.696$ mfd. Calling p_1 the primary e.m.f. necessary for this output, we have

$$\frac{0.696 \times p_1^2}{2 \times 10^6} = 12.$$

From this $p_1^2 = \frac{10^9}{29}$ and $p_1 = 6000$ volts approx. (26 H.P. expenditure, 1600 breaks per sec.)

With this e.m.f. assume 4 ohms res. of arc, the initial current would be 1500 amp. through the primary. From these assumptions the loss in the primary may be computed.

Colorado Springs

June 22, 1899

Wire for the new secondary ordered from Habirshaw № 10 B. & S. rubber covered; all in all about 11,000 feet needed (more nearly 10,500 feet). This will do for 80 turns of an average length of 131 feet each.

№ 10 am. gauge 5.26 mm. square or $\frac{5.26}{645}$ sq.inch

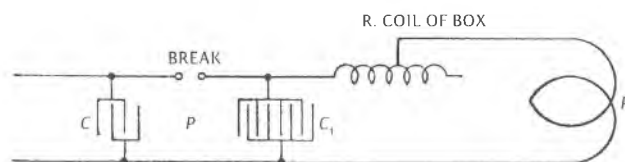
100 feet will have: $\frac{5.26}{645} \times 1200 = 9.8$ cu.inches.

The weight of this, taking 5.13 ounces per cu.inch will be

$$\frac{5.13}{16} \times 9.8 = 3.14 \text{ lbs.}$$

Accordingly, 11,000 feet will weigh 345.4 lbs. This will give still less copper in the secondary than there is in the two primary turns. With secondary wire double we shall have 40 turns and with four wires (for quick vibration) 20 turns. The weight of copper should be equal and some of the № 10 cord may be used on the first low turns.

Some arrangements were tried aiming chiefly at prolonging the vibration in the primary after each break. One of these was as illustrated in the diagram below:



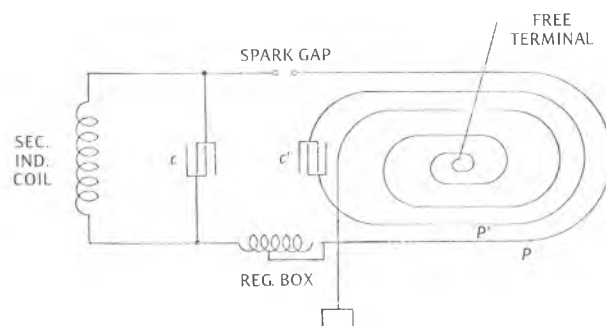
The condenser C_1 was placed in shunt to the primary P . Since there was no spark gap in this circuit and the magnifying factor was very large, the resistance being minute, the vibration continued

much longer after each break as would be the case with the ordinary connection. A very curious feature was the *sharpness* of tuning. This seems to be due to the fact that there are two circuits or two separate vibrations which must accord exactly. The sparks were strong on terminals of the secondary always when $C=aC_1$, a being a whole number (no fraction), and particularly when $a=2$ or 4 .

This arrangement was carried out in New York on one of the later type oscillators and similar results were observed.

In this form there was a loss in circuit p since this part did not act upon the secondary in inductive relation to P . A modification consisted in including in circuit p one or more turns of the primary P or independent turns which acted inductively upon the secondary.

An arrangement intended for the same purpose was also tried. It consisted of providing two primaries, one independent of the break and merely shunted by a condenser, as illustrated.



This plan was also experimented with in New York and it was found that it is good when the break number is *very small*. When the break is very rapid there is not much difference. In making the adjustments $C'P'$ was first tuned to the vibration of CP , then the secondary was adjusted.

This to be followed up.

Colorado Springs

June 23, 1899

Approximate self-induction of Regulating box brought from New York to be used in primary.

Dimensions: diam. of drum 12" = 30.48 cm.

Length of drum 18" = 45.72 "

Number of turns = 24

Area inclosed by one loop $\frac{\pi}{4}d^2 = 730$ cm. sq. From this

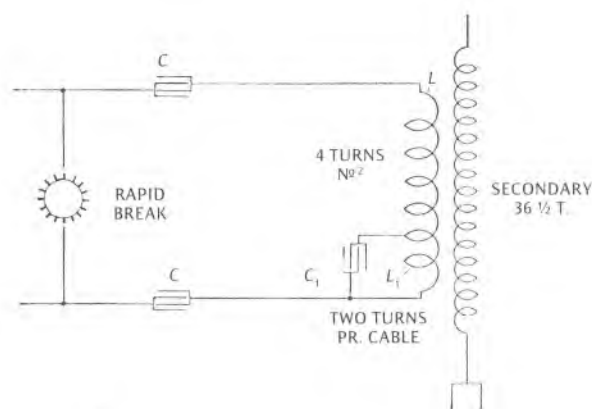
$$L = \frac{4\pi N^2 S}{l} = \frac{12.57 \times 576 \times 730}{45.72} \text{ cm} = 0.275 \times 576 \times 730 = 115,600 \text{ cm.}$$

From this for approximate estimates we may take $\frac{115,600}{24} = 4800$ cm per turn. This will be too much, as turns are far apart and thick. After Langevin's formula $L_s = \frac{L^2}{l}$. Here L total length of wire is $30.5 \times 3.1416 \times 24 = 2300$ cm approx.

This would give value $L' = \frac{2300^2}{45.72} = \frac{5,290,000}{45.72}$

$L' = 115,700 \text{ cm.}$, remarkably close.

Experiments with oscillator secondary 36 ½ turns were continued. Many modified arrangements with auxiliary condensers – one of which is illustrated in the sketch below – were tried. All these chiefly aimed at prolonging the vibrations in the primary after each break and also at effecting sharper tuning of the circuits. In using auxiliary condensers in this way circuits are obtained containing no spark gap in which the damping factor was extremely small and the magnifying factor very great.



In this arrangement the relation $\frac{C}{2}L = C_1L_1$

had to be attained for the best result. Or $L_1 = \frac{L}{4}$ $C_1 = 4 \times \frac{C}{2}$

Resonance was obtained with 15 jars on each side, 6 turns primary. With 4 turns primary there would have been necessary $15 \times \frac{36}{16} = 34$ jars or thereabouts. On thick cable about 68 jars, (for reference)

Note: Several rates of vibration were tried with such arrangements. Remarkable was the sharp tuning in some of them, one turn of the regulating coil being sufficient to entirely destroy the effect or to produce a great maximum rise of pressure. The jars broke down frequently, owing to sudden rise, as the handle of the regulating coil was turned.

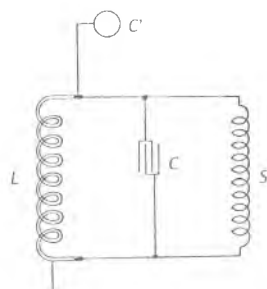
Colorado Springs

June 24, 1899

The following plan of producing a conducting path of extremely low resistance suitable for resonating circuits and other uses offers the possibility of attaining results which can not be reached otherwise. It is based on my observation that by passing through a rarefied gas a discharge of sufficient intensity, preferably one of high frequency, the resistance of the gas may be so diminished that it falls far below that of the best conductors. So through just a bulb of highly rarefied gas an immense amount of energy may be passed and currents of a maximum strength such that they can not traverse a copper wire, owing to its resistance and impedance, may be made to traverse the rarefied gas. The plan now is to constitute a circuit composed of a rarefied gas column, heated by auxiliary means to a very high incandescence so as to offer an inconceivably small resistance to the passage of the current and use this

column for the purpose to which it is suited. To illustrate the use of this idea in telegraphy, for instance the dia-gram below is shown in which S is a source of oscillating currents of preferably high frequency, C a condenser in shunt to same, L a coiled glass tube containing the rarefied gas which is kept at a high degree of excitation. The conductor L is connected, as in my system, to earth and a capacity preferably elevated. Through this path the currents of a distant transmitter are made to pass which are of the same frequency and cause a great rise of the e.m.f. on the terminals of conductor L , which may then be utilised to affect a receiving instrument in many ways.

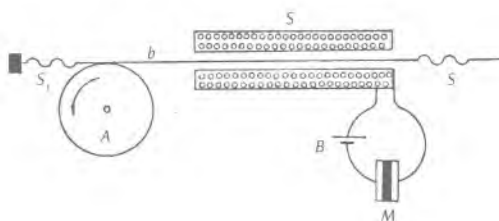
(To follow up).



Colorado Springs

June 25, 1899

The following plan seems to be well adapted for magnifying minute variations such as are produced by the action of a microphone, for example. Suppose that on a rotating or, generally speaking, moving surface of iron (polished or smooth) there is arranged a brush of soft iron, steel or at least having a surface of such magnetic materials whatever they be then there will be a certain amount of friction developed on the contact surfaces between the brush and moving surface and the brush will be dragged in the direction of movement of the surface. A spring may be used to pull the brush back against the friction and to maintain it in a position of delicate equilibrium. Let now the brush or surface be but slightly magnetized, then the friction between the magnetic surfaces will be enormously increased and the brush will be pulled forward with great force. A small variation in the magnetization of the surface will thus make great changes in the force exerted upon the brush, and the movements of the latter may be utilised for any purpose, as for instance in loud speaking telephones, or in perfecting a "wireless telephone" or such purposes. A simple form of apparatus is illustrated below:

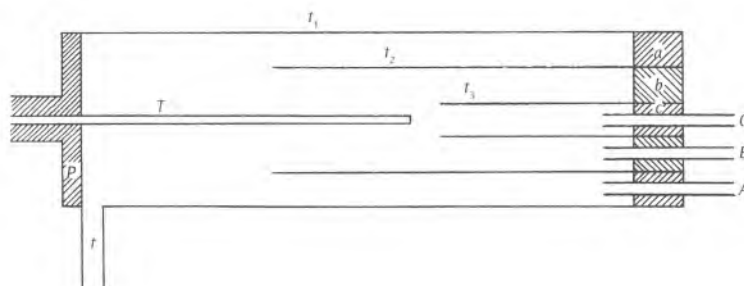


A is a rapidly rotating cylinder with a polished iron surface, if not all of iron; b is a small bar or brush bearing upon the cylinder and also of soft iron. This light plate or bar is held in a balanced position by differential spring s_1 , so as to bear lightly on the cylinder A . S is a solenoid energized through battery B in series with a microphone M . By speaking upon the latter the bar b will be vibrated back and forth and the movements of the bar may control any other apparatus, for instance a valve or other microphone.

Colorado Springs

June 26, 1899

In following up an old idea of separating gaseous mixtures by the application to them of an excessively high electromotive force, the following apparatus is to be adopted with a new oscillator.



Note: in this apparatus it will be preferable to use a form of oscillator with mercury break supplied from a source of direct current, so that the force on T will be mostly unidirectional. Any other generator developing the necessary e.m.f. should, however, accomplish the same result.

Three tubes t_1 , t_2 , t_3 (assuming only three will be needed) are slipped one into the other, being held apart by insulating plugs a , b , c . In these plugs are fastened outlet tubes A , B , C to lead the several separated gases away to reservoirs into which they may be compressed. It is therefore to be understood that there is the desired degree of suction on the outlet pipes, or else the mixture is forced under desired pressure through a tube t serving to let in the mixture. The high tension terminal T is led in through an insulating plug P fastened into the largest tube t_1 . The particles of the gas coming in contact with the active terminal are thrown away with great force and are projected at different distances according to their size and weight, hydrogen farther than most others. The latter element, if it be present, will therefore pass through tube A , that is mostly, the heavier and larger molecules through the other tubes. By repassing the gases drawn off through the apparatus again, any degree of purification or separation is obtained.

Colorado Springs

June 27, 1899

Arrangements of apparatus in telegraphy through the natural media aiming at exclusion of manager, in accordance with method experimented with in New York

This is not quite so good as the method used with condenser of commutating individual impulses, but great safety can be secured nevertheless. The idea was to provide more than one synchronized circuit and to make the receiver dependent in its operation on more than one such circuit. Experiments have shown that a great degree of safety is reached with two circuits. I think with three it is almost impossible to disturb the receiver when the vibrations have no common harmonics very near to the fundamental tones. Several arrangements experimented with are illustrated below. These are to be followed up.

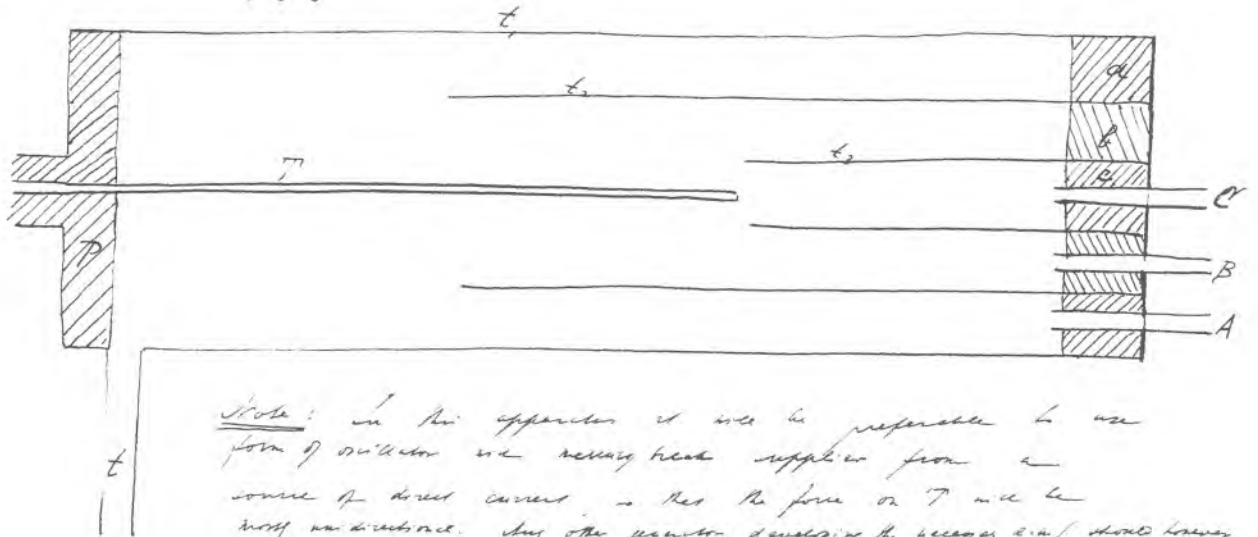
Figs. 1., 2. and 3. illustrate some arrangements of apparatus on the sending station by means of which two vibrations of different pitch are obtained. A greater number is omitted for the sake of simplicity. In case 1. are provided two sending circuits which should be some distance apart and which are energized alternately by discharging condensers of suitable capacity through the corresponding

Colorado Springs June 26. 1899.



am following up the idea of separating gaseous mixtures by the application to them of an exceedingly high electromotive force following apparatus is to be adopted with new oscillator.

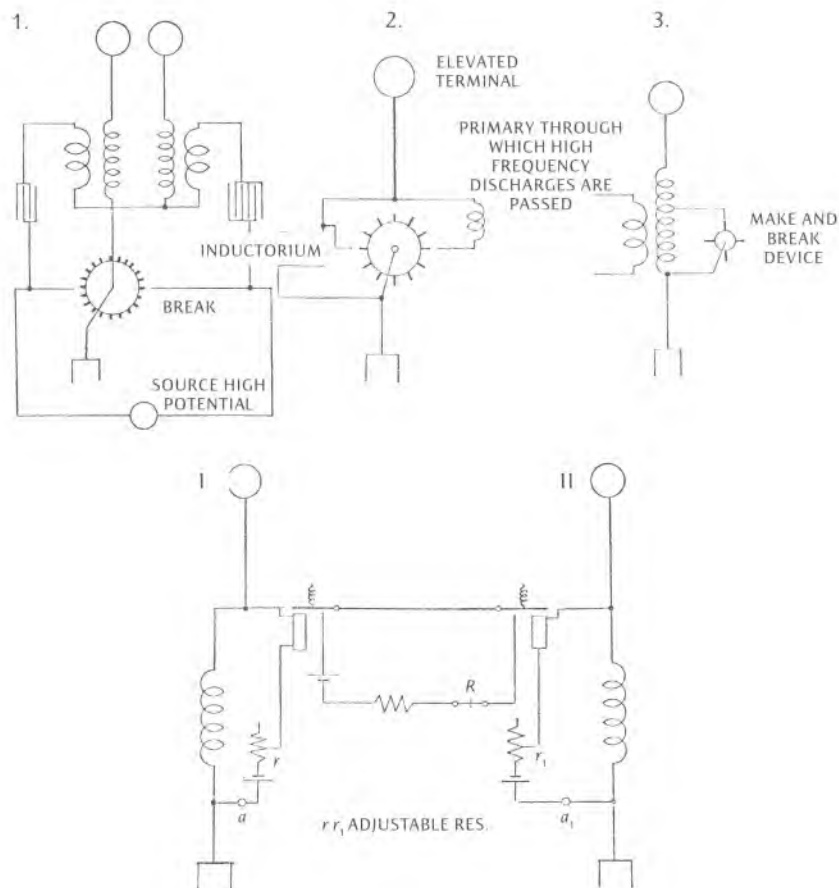
Three tubes (assuming only three are needed) are disposed one



Note: In this apparatus it will be preferable to use form of oscillator we recently made supplied from a source of direct current so that the force on T will be very unidirectional. Any other generator developing the necessary e.m.f. should, however, accomplish same result.

into the other, being held apart by insulating plugs a, b, c. In these plugs are fastened outlet tubes A B C to lead the several separate gases away to receivers into which they may be compressed. It is therefore to be understood that there is the desired degree of suction on the outlet pipes, or else the mixture is forced under desired pressure through a tube & serving to set in the mixture. The high tension terminal T is led in through an insulating plug P fastened into the larger tube t1. The particles of the gas coming in contact with the electric terminals are thrown away with great force and are projected at different distances according to their size and weight, hydrogen farther than most others. To better illustrate, if it be present with therefore pass through tube t1, that is mostly, the heavier and larger molecules through the other tubes. By repeating again through the apparatus the gases drawn off any degree of purification or separation is obtained.

primaries. In Figures 2. and 3. one sending circuit is arranged so that its period is altered by inserting some inductance as in 2., or by short-circuiting a part of the circuit periodically, by means of an automatic device. It is not necessary to use such a device; however, arrangements of this kind will be later illustrated. On the receiving station two synchronized circuits responding to the vibrations – each to one – of the sender. The receiver R responds only when both circuits I and II affect sensitive devices aa_1 . The diagrams are self-explanatory.



Colorado Springs

June 28, 1899

Approximate estimate of the secondary with 20 turns on tapering frame, before referred to, from data of the secondary with 36 turns on the same frame. In the latter the wires 3 notches apart, in the former 7 notches

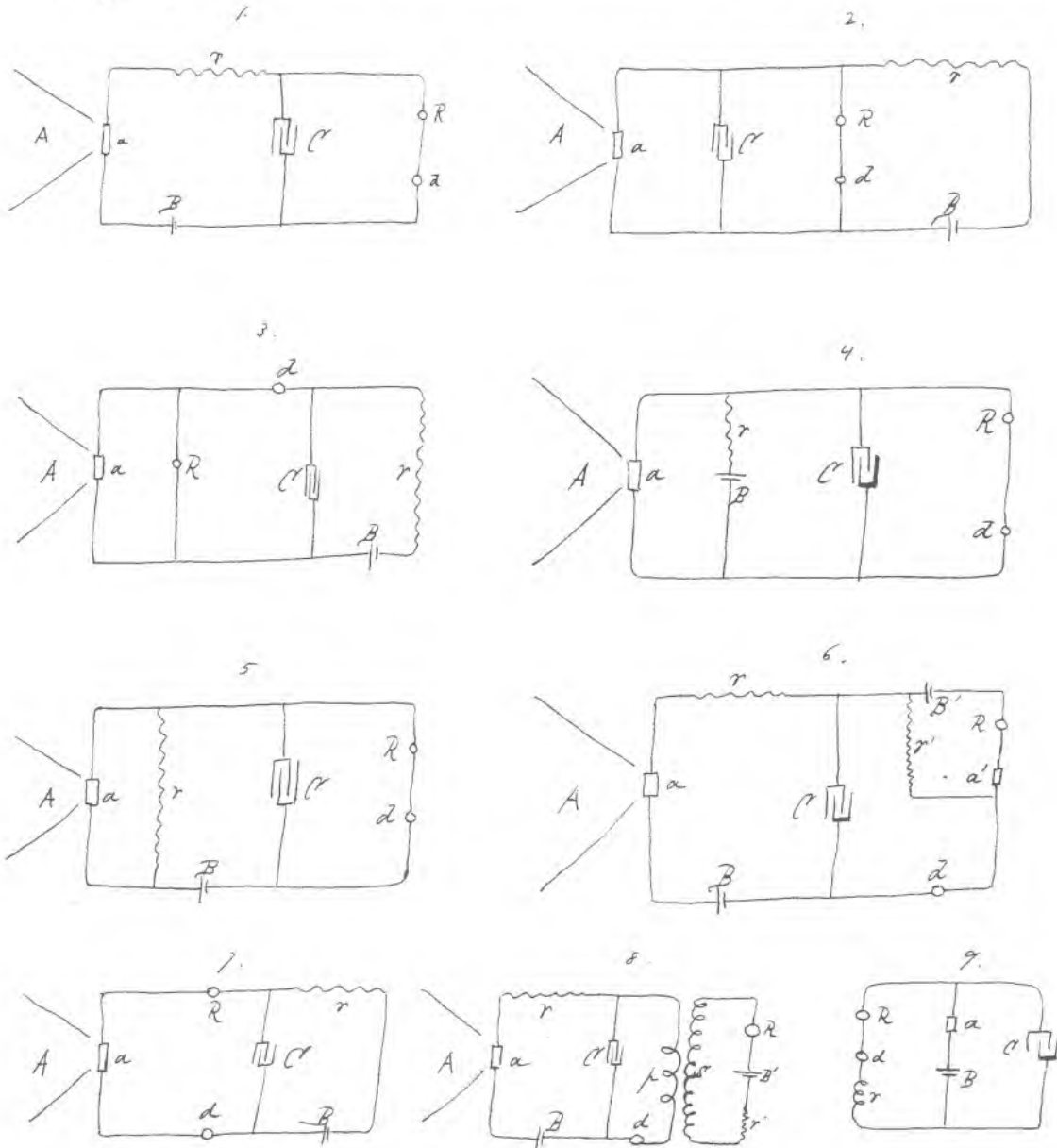
Roughly, the capacity of the secondary with 20 turns will be, if C be that of the secondary with 36 turns:

$$C_1 = \frac{20}{36} \times \frac{3}{7} C = \frac{60}{252} C = \frac{20}{84} C = \frac{10}{42} C = \frac{5}{21} C$$

Colorado Springs June 29, 1898



Arrangements of apparatus experimental to the
charging and condenser method. (This for further applic.)



and the self-induction L_1 of the secondary with 20 turns compared with L – that of the secondary with 36 turns, will be

$$L_1 = \left(\frac{20}{36}\right)^2 \times \frac{36 \times 3}{20 \times 7} L = \left(\frac{5}{9}\right)^2 \times \frac{27}{35} L = \frac{675}{2835} L \quad \text{Now } L = 383 \times 10^5 \\ C = 1200 \text{ cm.}$$

Therefore $C_1 = \frac{5}{21} \times 1200 = 290 \text{ cm}$ and $L_1 = \frac{383 \times 675 \times 10^5}{2835} = 9 \times 10^6 \text{ cm.}$ From this

$T = \frac{2\pi}{10^3} \sqrt{\frac{290}{9 \times 10^5} \times \frac{9 \times 10^6}{10^9}} = \frac{107}{10^7}$ approx as period of sec system (roughly) and $n = \frac{10^7}{107} = 93,458$ per sec. Now the length of wire for 20 turns, about 139 feet per turn, will be 139×20 feet. This gives $\lambda = 11,120$ feet or $\frac{\lambda}{4} = 2780$ feet and this would correspond to $n = 90,000$ approx.

Adding a ball of 38 cm. capacity would give a total capacity

$$290 + 38 = 328 \quad \sqrt{328} = 18.11 \quad \sqrt{290} = 17 \text{ approx.}$$

hence by adding a ball the secondary vibration will be reduced by a ratio of: $\frac{17}{18.11}$ or it will be $\frac{17}{18.11} \times 93,460 = 88,000$ approx. This would be too quick a vibration to best suit the apparatus as then we would have only 4 jars on each side of the primary.

With the additional coil of 1500 cm. capacity added in series with secondary on free terminal, the capacity would be $1500 + 290 = 1790$, that is about 6 times as much as before. The vibration will then be slower $\sqrt{6} = 2.5$ approx. times slower, about 37,400 per sec. This better suited.

Colorado Springs

June 29, 1899

The first good trial of a new wound secondary with 36 turns was made today. The wire was No 10 cord, the turns being wound in every third groove. The distance of wires is approx. $1\frac{7}{8}$ ".

Vibration under the conditions of the first experiments: Approximate self-induction of secondary about $5 \times 10^7 \text{ cm.}$ Additional coil connected to free end of secondary, the coil having 240 turns, spool 6 feet long, 2 feet diam. Estimated self-induction of coil roughly 10^7 cm.

$$A = 2900 \text{ sq.cm.} \quad l = \frac{2900 \times 240^2 \times 4\pi}{183} = \frac{576 \times 29 \times 10^4 \times 12.57}{183} =$$

$$N = 240 \text{ turns} \quad = 1140 \times 10^4 = 114 \times 10^5, \text{ for rough approximation } = 10^7$$

$$l = 183 \text{ cm.}$$

The wave length should be (ignoring capacity):

$$4 \times [5280 \text{ (sec)} + 1440 \text{ (spool)}] = 4 \times 6720 = 26,880 \text{ feet or about 5 miles.}$$

To give this wave length the primary vibration should actually be $187,000 : 5 = 37,400$ per sec. (same number before found).

The capacity C_p in primary to be found:

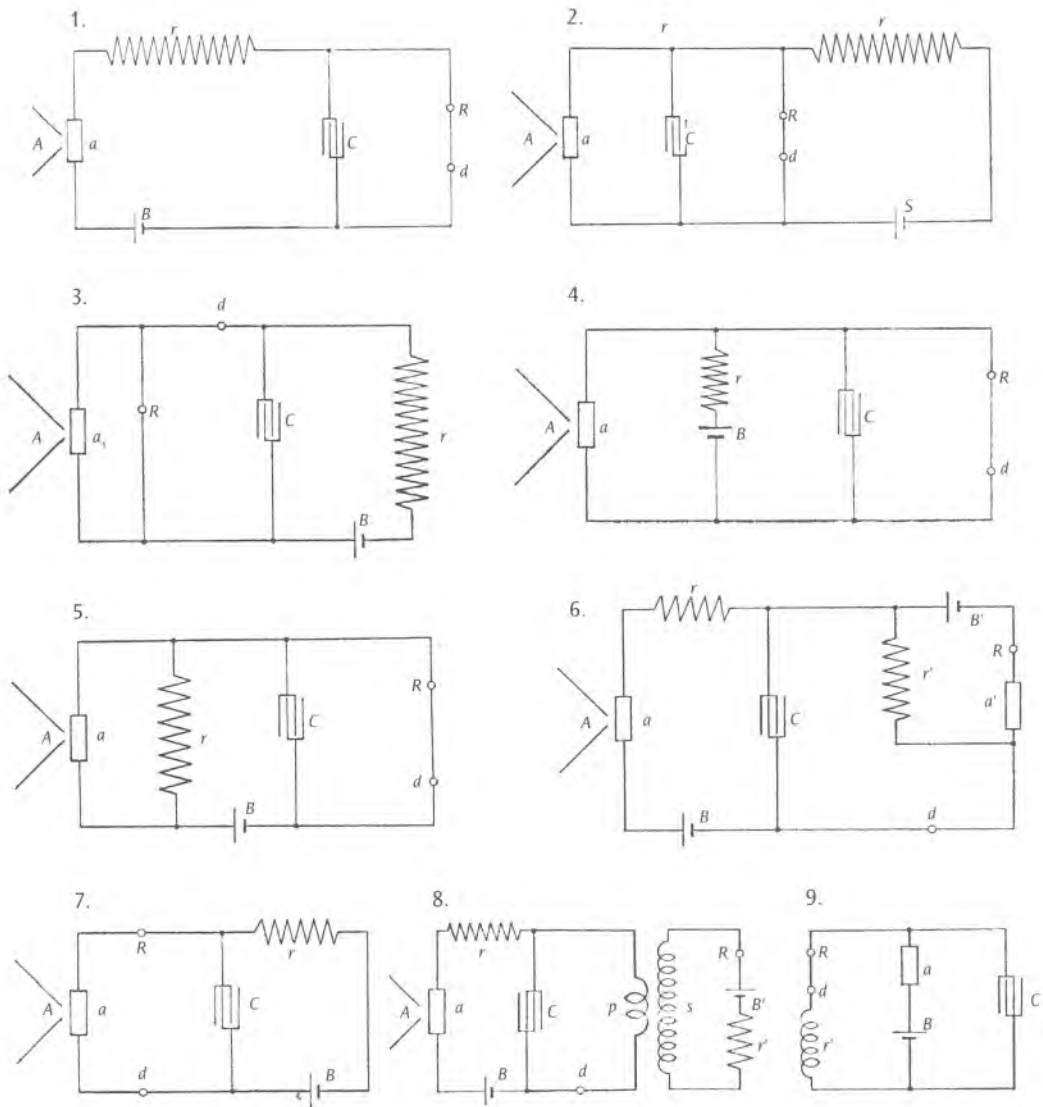
$$\frac{1}{37,400} = \frac{2\pi}{1000} \sqrt{LC_p} = \frac{2\pi}{10^3} \sqrt{\frac{7 \times 10^4 \times C_p}{10^9}} = \frac{2\pi}{10^3} \sqrt{\frac{7 \times C_p}{10^5}}$$

$$\frac{1}{374} = \frac{2\pi}{10^3} \times 0.84 \sqrt{C_p}, \sqrt{C_p} = \frac{10^3}{2\pi \times 0.84 \times 374} = \frac{1000}{1975} \text{ or } 0.5 \text{ approx.}$$

$$C_p = 0.7 \text{ mfd.}$$

This would require $\frac{0.7}{0.003}$ jars=233 jars with two primary turns in multiple and $\frac{233}{4}$ or about 58 jars total with two primaries in series. As so many jars were not available evidently only a higher vibration was obtainable. This explains why first results unsatisfactory.

Arrangements of apparatus experimented with in carrying out condenser method. (This for Curtis application)



June 30, 1899

Simple formulas to be used in rough estimates of the quantities frequently wanted

In formula $T = \frac{2\pi}{10^3} \sqrt{LC}$, L is in henry but usually is wanted in cm. We may therefore use

$$T_1 = \frac{2\pi}{10^3 \times 10^4 \sqrt{10}} \sqrt{LC} \text{ or approx. when } L \text{ is in cm.}$$

$$T_1 = \frac{2}{10^7} \sqrt{LC} \text{ } C \text{ in mfd.} \dots\dots\dots 1)$$

$$\text{From } L = \frac{T_1^2 \times 10^{14}}{4C} \text{ we have}$$

$$C = \frac{T_1^2 \times 10^{14}}{4L} \dots\dots\dots 2)$$

Introducing jars for C we have $C = n \times 0.003$

$$\text{therefore } n = \frac{T_1^2 \times 10^{17}}{12L} \dots\dots\dots 3)$$

Introducing again λ in miles in place of T_1

$$T_1 \text{ being } = \frac{\lambda}{187,000} \text{ we have:}$$

$$\lambda = \frac{374}{10^4} \sqrt{LC} \text{ or, since usually } \frac{\lambda}{4} \text{ is needed}$$

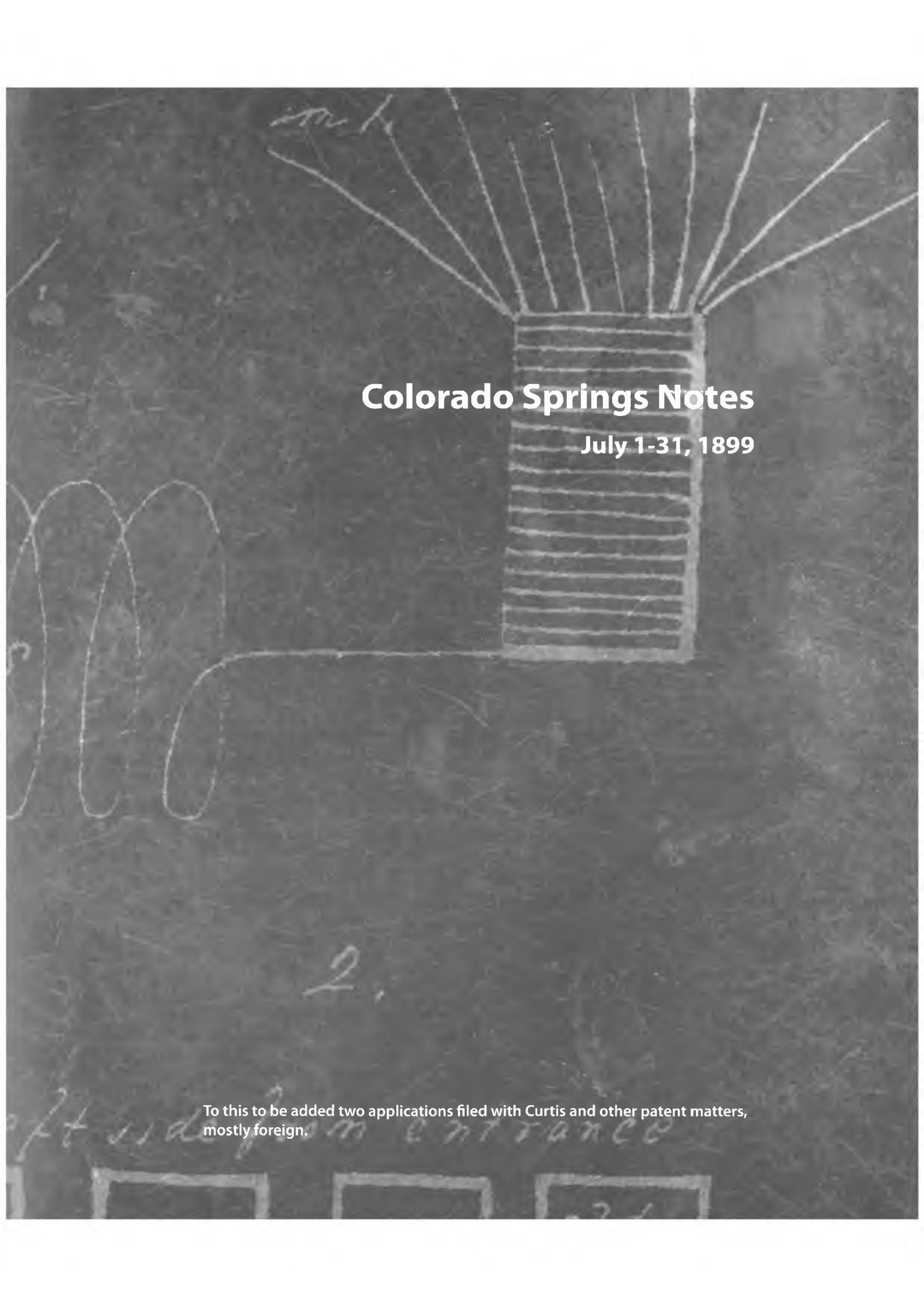
$$\frac{\lambda}{4} = \frac{93.5}{10^4} \sqrt{LC} \dots\dots\dots 4)$$

Observations made in experiments with oscillators, 36 ½ turns and additional coil:

The additional coil is, as observed in the New York apparatus, an excellent means of obtaining excessive electromotive force. But it is peculiar that to properly develop the independent vibration of such a coil its momentum should be very great with respect to the impressed vibration. When such a relation exists the free vibration asserts itself easily and prominently. But when the impressed vibration is very large and the coil's own momentum small, the free vibration can not assert itself readily. It is exactly as in mechanics. A pendulum with great momentum relative to the impressed momentum swings rigorously through its own period but when impressed momentum is very large relatively it is hampered, for then the impressed dominates more or less. This I look upon as distinct from the magnifying factor which depends on $\frac{pL}{R}$.

It was evident that in such excitation of the additional coil there should be, for the best result, three vibrations falling together: that of the coil, that of the secondary and that of the combined system. In view of the above it is of advantage to place inductance between the secondary and additional coil to free the latter, when impressed vibration is too powerful to allow the intended vibration of the coil to take place readily.

From experiments it further appeared as though it would be of advantage to have some self-induction in the primary spark gap. This is to be ascertained. The use of condensers in series with the supply secondary is sometimes of advantage but little so when the vibration of the secondary is in resonance with the primary. Then there is less short circuiting of the secondary of the supply transformer and sparks are loud and sharp.



Colorado Springs Notes

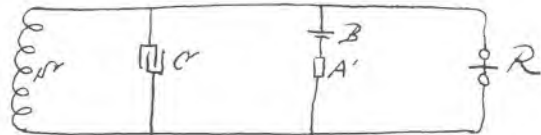
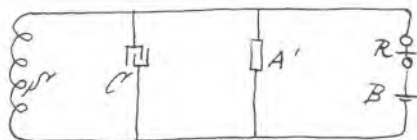
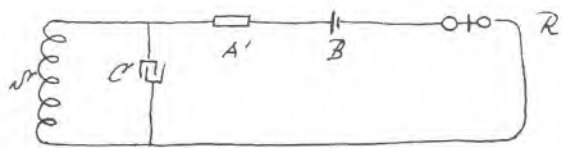
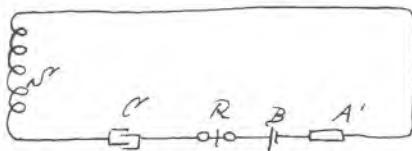
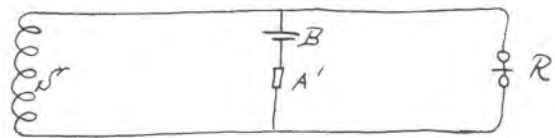
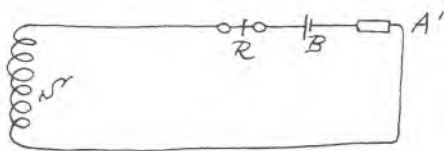
July 1-31, 1899

2.
To this to be added two applications filed with Curtis and other patent matters,
mostly foreign.

Collected Groups July 1, 1899.



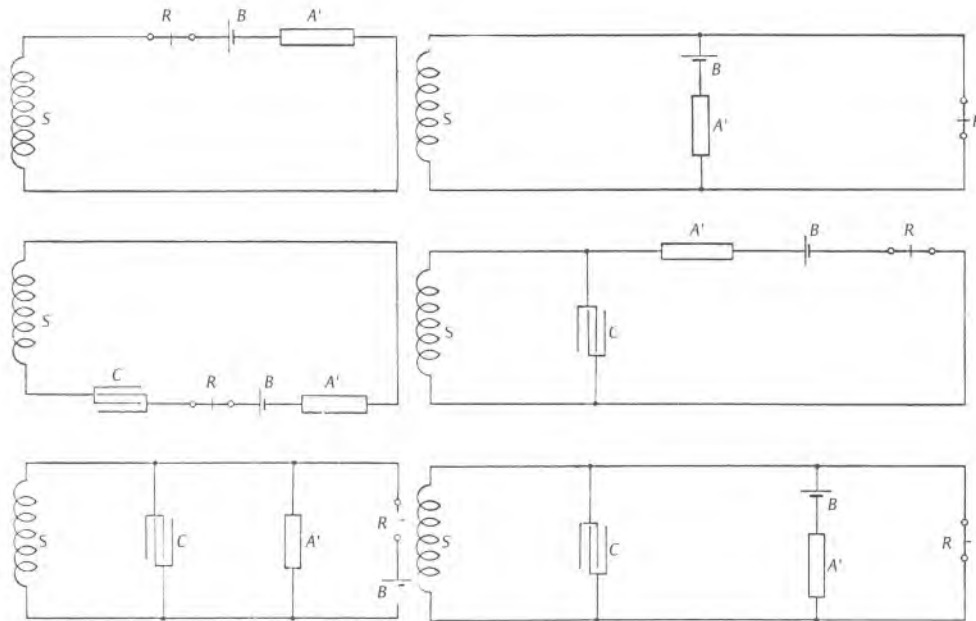
Various ways of connecting apparatus when applying condenser method of magnifying effects. The charging or discharge of condenser is controlled by the effects transmitted through the medium and the condenser discharges are passed through the primary of the oscillatory transformer. The diagrams below show various arrangements with the instruments in the secondary of the transformer.



In these arrangements the primary is not shown. The same is assumed to be connected in the circuit in any way but so that the charging or discharging of the condenser is controlled by a sensitive device affected by the feeble effects which are to be magnified. In the above diagrams S is the secondary of oscillatory transformer, B battery to strain sensitive device in secondary, A' sensitive device, R fine relay (magnetic), C condenser in secondary. The primary circuit which is not shown includes: a sensitive device, battery, condenser and induced break device. This method with two sensitive devices very good.

July 1, 1899

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July 2, 1899

Considerations regarding best conditions of working apparatus in experimental station particularly with reference to stationary waves in the ground which will be investigated

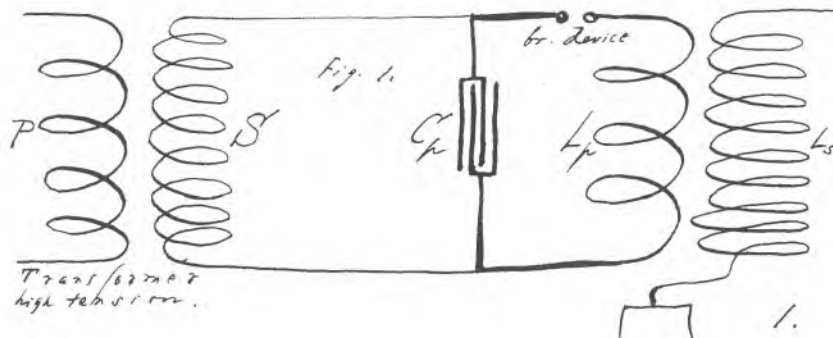
First assumption on which to base calculations of other elements is made by deciding on the wave length of the disturbances. This in well designed apparatus determines $\frac{\lambda}{4}$ or length of secondary wound up. The self-induction of the wire is also given by deciding on the dimensions and form of coil hence L_s and λ are given. For the best working of the secondary we should have the capacity on end or free terminal just counteracting the self-induction of the secondary. This will be the case when $C_s = \frac{L_s}{R_s^2 + p^2 L_s^2}$.

Colorado Springs July 2. 1899

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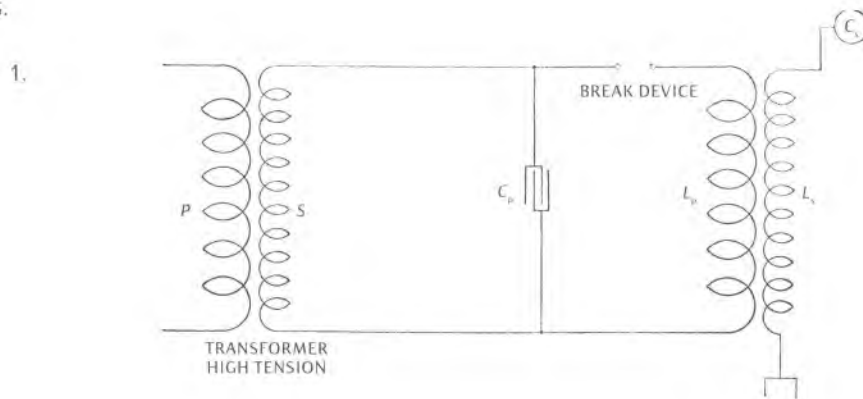
First assumption is that to have calculations of other elements is made by deciding on the wavelength of the disturbance. Then we will design apparatus determines $\frac{\lambda}{4}$ or length of secondary wound up. The self-inductance of the wire is also given by deciding on the dimensions and form of coil hence L_s and λ are given. For the best working of the secondary we should have the capacity at end or free terminal just counteracting the self-inductance of the secondary. This will be the case when $C_s = \frac{L_s}{R_s^2 + \mu^2 L_s^2}$. Since the resistance should be negligible we have $C_s = \frac{1}{\mu^2 L_s}$. Now μ is given by assuming λ hence from above equation C_s is given. Furthermore, to get best results the same relation between μL_p and C_p must also be preserved so that $C_p = \frac{1}{\mu^2 L_p}$ C_p and L_p being the capacity and inductance of primary. From these considerations follow a relation between C_s, C_p, L_s, L_p . Hence, $C_s = \frac{1}{\mu^2 L_s}$ and as $\mu^2 = \frac{1}{C_p L_p}$ we have $C_s = \frac{1}{L_s \cdot \frac{1}{C_p L_p}} = \frac{C_p L_p}{L_s}$ or otherwise expressed $L_s C_s = L_p C_p \dots \dots \dots I.$



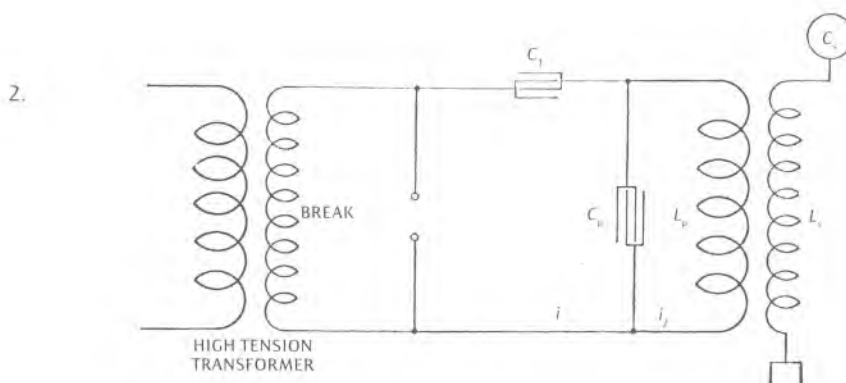
③ This applies to a simple case as the one here illustrated which was one of the earliest arrangements.

Since the resistance should be negligible we have $C_s = \frac{1}{p^2 L_s}$. Now p is given by assuming λ . Hence from above equation C_s is given. Furthermore, to get best results the same relation between p , L_p and C_p must also be preserved so that $C_p = \frac{1}{p^2 L_p}$, C_p and L_p being the capacity and inductance of primary. From these considerations follows a relation between C_s , C_p , L_s , L_p . Namely, $C_s = \frac{1}{p^2 L_s}$ and as $p^2 = \frac{1}{L_p C_p}$ we have $C_s = \frac{1}{L_s \frac{1}{L_p C_p}} = \frac{L_p C_p}{L_s}$ or otherwise expressed, $L_s C_s = L_p C_p$ I.

This applies to a simple case, as the one here illustrated which was one of the earliest arrangements.



The scheme of connections illustrated in Fig. 1. has the disadvantage that the primary discharge current passes through the break hence, the resistance of the latter being large, the oscillations are quickly damped and there is besides a large current through the break which makes good operation of the latter difficult. To prolong oscillation in primary and increase economy one of the schemes before considered may be resorted to. One of these is illustrated in Fig. 2. which follows: in this arrangement the currents through the break device are much smaller and the oscillations started by the operation of break in circuit $L_p C_p$ continue much longer. We can now determine the magnitude of currents i , i_2 .



Capacity $C_p = \frac{L_p}{R_p^2 + p^2 L_p^2}$ from foregoing or approximately $C_p = \frac{1}{p^2 L_p}$ as before, neglecting resistance.

We have then $\frac{i_2}{i} = \sqrt{\frac{R_p^2 + p^2 L_p^2}{R_p^2}}$ or, since the first term is negligible in numerator, we have $\frac{i_2}{i} = \frac{p L_p}{R_p}$ or

$i_2 = i \frac{pL_p}{R_p}$. From this relation it is evident that, other difficulties or disadvantages not considering the arrangement as illustrated in Fig. 2. should be superior to that in Fig. 1. It secures two chief advantages: 1) less current through the break and more through the primary and 2) longer and better oscillation in circuit including primary because it is easy to constitute such a system without break with an extremely small resistance or frictional waste.

Fig. 3. illustrates an arrangement similar to that shown in Fig. 2. but with a condenser in each branch. The same considerations made in regard to Fig. 2. hold good for this and in both cases, if there is to be resonance and best conditions attained, the circuit including the break should have the same period and be in phase with primary circuit $L_p C_p$ and secondary $L_s C_s$. Referring to Fig. 2. as the simpler, this is the case when the relation between C_1 and self-induction in this circuit is such that they annul each other at that frequency.

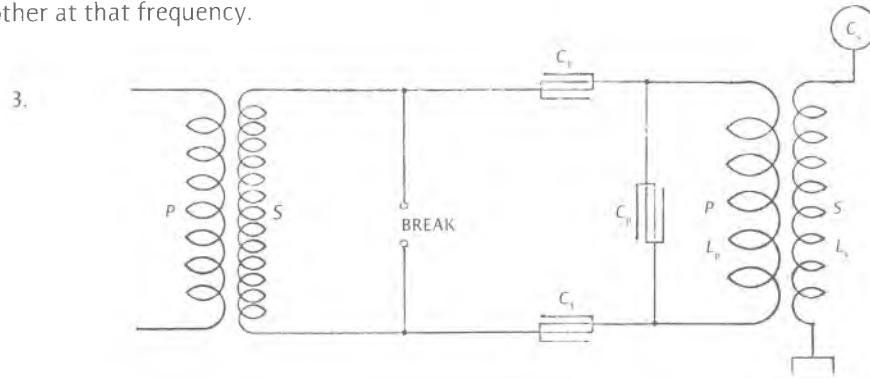


Fig. 4 – a further modification shows the system with inductance L_1 in circuit. To satisfy above conditions we must have

$$C_1 = \frac{L_1}{R_1^2 + p^2 L_1^2}$$

R_1 being the resistance including the arc. Since in most cases, even with the arc included, R_1 will be negligible against pL_1 , we have again

$$C_1 = \frac{1}{p^2 L_1}$$

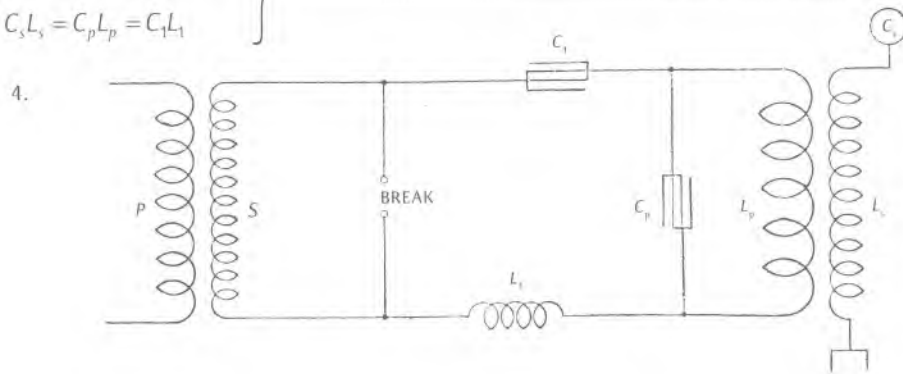
From all the above considerations we get a general relation between the constants of all the three circuits which is expressed by:

$$\frac{1}{C_s L_s} = \frac{1}{C_p L_p} = \frac{1}{C_1 L_1}$$

or

$$C_s L_s = C_p L_p = C_1 L_1$$

} II.



We have seen from the preceding that of the quantities considered p was given by arbitrary selection of the wave length, L_s necessarily by the wire and design of secondary and, lastly, C_s as following from the two preceding quantities. One more quantity is, however, given by practical considerations and that is C_1 . Namely, this capacity C_1 must be sufficient to take up the entire energy of the transformer, if all things are rightly proportioned. Now let P' be the e.m.f. on the secondary of the supply transformer, then there will be stored each time in condenser C_1 a quantity of energy $\frac{P'^2 C_1}{2}$ and if this value be taken for the average energy stored each time and if, furthermore, the frequency of the make and break be p_1 that is $p_1 = 4\pi n$, n being number of charges per second, or

$$n = \frac{p_1}{4\pi}, \text{ then } \frac{P'^2 C_1}{2} \cdot \frac{p_1}{4\pi} = M \text{ or } C_1 = \frac{8\pi M}{P'^2 p_1}$$

M is here the total power of the transformer expended and expressed in watts, P' the pressure of secondary (average as defined) and p_1 as before stated the frequency of the break. The quantity C_1 thus being given in each case, these remain still to be determined: L_p , L_1 and C_p .

Now it is evident that when the relation between p_1 , L_p and C_p exists, which is here implied, the current passes through the system as if there would be no inductance, hence insofar as the circuit including the break, C_1 and L_1 is concerned the system $L_p C_p$ will comport itself as if it consisted of a short wire of inappreciable resistance, the primary being generally made of stout short conductor – therefore, in estimating the quantities of the circuit C_1 , L_1 by the compound system $L_p C_p$ may be neglected since it will have little influence upon the period under the conditions assumed, and we may then put $C_1 = \frac{1}{p^2 L_1}$ when resistances are, as always before, negligible.

Since C_1 is known we can determine L_1 because

$$L_1 = \frac{1}{p^2 C_1} = \frac{1}{p^2 \frac{8\pi M}{P'^2 p_1}} = \frac{P'^2 p_1}{8\pi M p^2}$$

Presently then all the quantities are known for determining the constants of circuit $L_p C_p$ from the two equations:

$$\left. \begin{array}{l} L_p C_p = L_s C_s \\ L_p C_p = L_1 C_1 \end{array} \right\} \dots\dots\dots \text{III.}$$

Colorado Springs

July 3, 1899

In experiments with the secondary as last described, fairly good resonance was obtained with 15 jars on each side of the primary. A length of wire No 10–170 feet – was covered with intense streamers. The capacity – total – was $7.5 \times 0.003 = 0.0225$ mfd. L_p was approximately estimated $36 \times 7 \times 10^4$ cm. (six

primary turns in series). From this $T = \frac{4.836}{10^5}$ as calculated. This gives $n = \frac{1}{T} = 20,700$ per sec. approx.

With this vibration λ was nearly 9 miles or $\frac{\lambda}{4} = 2.25$ miles. Actually, there was only one mile of secondary wire but owing to the large capacity (distributed) in the secondary the vibration was much slower than should be inferred from the length of wire. We may estimate the ideal capacity, which associated

with the inductance of the secondary would give a vibration of the above frequency. Since there was resonance we have:

$$T = \frac{4.836}{10^5} = \frac{2\pi}{10^3} \sqrt{\frac{5 \times 10^7}{10^9} C_s}$$

Taking the inductance of the secondary as being 5×10^7 cm. and from this

$$C_s = \frac{23.34}{20,000} = \text{roughly } \frac{1}{1000} \text{ mfd. more exactly } 0.0012 \text{ mfd. or } 1080 \text{ cm.}$$

But we may approximately estimate capacity in another way taking the wires in pairs as a condenser. This would give $C_s = \frac{A}{4\pi d} \times 40$, there being 40 pairs since there are 40 turns wire. Now A =surface of half wire: 131 feet, about 4000 cm. long; half circumference about 0.4 cm. gives $A = 1600$ cm. sq. The distance of wires d was=5 cm. From this: $C_s = 40 \times \frac{1600}{4\pi \times 5} = 1040 \text{ cm approx.}$ (probably accidentally close.)

Last night the 50,000 volts transformer brought from New York broke down. This happened upon connecting to the lower end of the secondary a condenser composed of two adjustable brass plates of 20" diam., one being connected to the ground, the other to the secondary. The plates were about 5" apart. The experiment was repeated with the transformer after repairing it and all was found in good order.

Experiments were now continued with the secondary of 40 turns wire No 10 just one mile long. In connection with this secondary a coil was used wound on a drum 2 feet in diam. and 6 feet long, with wire No 10 (cord), there being 260 turns. Approx. estimate of capacity after a previous similar estimate: 6 feet=6×12=72"=72×2.54= 183 cm. Half circumference of wire 0.4 cm. Area= 183×0.4=74 sq.cm. (about)= a , distance of wires about 1 cm.= d . This would give roughly the capacity $C_1 = \frac{a}{4\pi d} = \frac{74}{4\pi}$ for one

pair of wires; there being 260 pairs, total capacity would be according to this $\frac{260 \times 74}{4\pi} = 1532 \text{ cm.} = C_1$ (for coil). Now, the capacity in the secondary was previously found 1080 cm. Hence the total capacity of the system would be 1080+1532=2612 cm. = C' . This, of course, gives only an idea and the determination in this manner is far from being exact. Consider what the period would be with the capacity and secondary and coil together as a whole. Since the coil will have only about 12,000,000 cm. the inductance of the secondary will be the chief governing factor. Taking this at 5×10^7 cm. we would have a total inductance $5 \times 10^7 \times 12 \times 10^6$ or $(50 + 12) \times 10^6 = 62 \times 10^6$ cm. This would give

$$T = \frac{2\pi}{10^3} \sqrt{\frac{62 \times 10^6}{10^9} \times \frac{2612}{9 \times 10^5}} = \frac{2\pi}{3 \times 10^7} \sqrt{164,944} = \frac{2\pi \times 406}{3 \times 10^7} = \frac{2549.68}{3 \times 10^7} = \frac{849.9}{10^7} \text{ or } \frac{850}{10^7} = \frac{85}{10^6}$$

and $n = 11,800$ roughly. To this the primary to be adjusted for first approximate trials. Now the primary has six turns. Since one turn is approx. 7×10^4 cm. we may put:

$$\frac{85}{10^6} = T = \frac{2\pi}{10^3} \sqrt{\frac{36 \times 7 \times 10^4}{10^9} C_p}$$

From this a rough idea of the capacity in primary may be gained. We get $C_p = 0.0717$ mfd. roughly. Taking capacity of one jar=0.003 mfd. we would want total $\frac{0.0717}{0.003} = 24$ jars approx. or 48 jars on each side of primary. This vibration would be impracticable under the present conditions as the transformer could not charge this number of jars. Although for *stationary waves* in ground it would be desirable to use such a low frequency the vibration will have to be quickened. An octave would require only 12 jars on each side. This was tried and results were good although the octave vibration had only $\frac{1}{4}$ of the en-

ergy as the fundamental would have had. To get the true vibration we shall want at least 8 *turns* in the primary with present transformer to keep the capacity in the primary 36 within the limits given by the output of transformer. This would then give $48 \times \frac{36}{64} = 27$ jars on each side. While this might do, still for best conditions not more than 16 jars should be used on each side of primary. This just taxes the transformer to full capacity within safe limits.

Conclusion: *Used about 10 turns in the primary.*

Colorado Springs

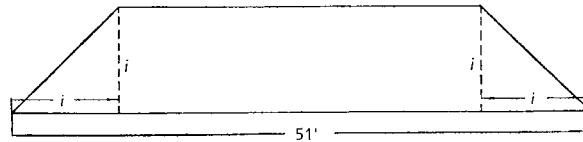
July 4, 1899

Observations made last night. They were such as not to be easily forgotten, for more than one reason. First of all a magnificent sight was afforded by the extraordinary display of lightning, no less than 10–12 thousand discharges being witnessed inside of two hours. The flushing was almost continuous and even later in the night when the storm had abated 15–20 discharges per minute were witnessed. Some of the discharges were of a wonderful brilliancy and showed often 10 or twice as many branches. They also appeared frequently thicker on the *bottom* than on top. Can this be so? Perhaps it was only due to the fact that the portion close to the ground was nearer to the observer. The storm began to be perceptible at a distance as it grew dark and continuously increased. An instrument (rotating “coherer”) was connected to ground and a plate above ground, as in my plan of telegraphy, and a condenser was used to magnify the effects transmitted through the ground. This method of magnifying secures much better results and will be described in detail in many modifications. I used it in investigating properties of Lenard and Roentgen rays with excellent results. The relay was not adjusted very sensitively but it began to play, nevertheless, when the storm was still at a distance of about 80–100 miles, that is judging the distance from the velocity of sound. As the storm got nearer the adjustment had to be rendered less and less sensitive until the limit of the strength of the spring was reached, but even then it played at every discharge. An ordinary bell was connected to earth and elevated terminal and often it also responded. A small spark gap was bridged by a bright spark when the lightning occurred in the neighbourhood. By holding the hands across the gap a shock was felt indicating the strength of the current passing between the ground and the insulated plate. As the storm receded the most interesting and valuable observation was made. It happened this way: the instrument was again adjusted so as to be more sensitive and to respond readily to every discharge which was seen or heard. It did so for a while, when it stopped. It was thought that the lightning was now too far and it may have been about 50 miles away. All of a sudden the instrument began again to play, continuously increasing in strength, although the storm was moving away rapidly. After some time, the indications again ceased but half an hour later the instrument began to record again. When it once more ceased the adjustment was rendered more delicate, in fact very considerably so, still the instrument failed to respond, but half an hour or so it again began to play and now the spring was tightened on the relay very much and still it indicated the discharges. By this time the storm had moved away far out of sight. By readjusting the instrument and setting it again so as to be very sensitive, after some time it again began to play periodically. The storm was now at a distance greater than 200 miles at least. Later in the evening repeatedly the instrument played and ceased to play in intervals nearly of half an hour although most of the horizon was clear by that time.

This was a wonderful and most interesting experience from the scientific point of view. It showed clearly the existence of *stationary waves*, for how could the observations be otherwise explained? How can these waves be stationary unless reflected and where can they be reflected from unless from the

point where they started? It would be difficult to believe that they were reflected from the opposite point of the Earth's surface, though it may be possible. But I rather think they are reflected from the point of the cloud where the conducting path began; in this case the point where the lightning struck the ground would be a nodal point. It is now certain that they can be produced with an oscillator

(This is of immense importance)



Measurement of inductance of oscillator secondary 36 ½ turns on tapering frame repeatedly referred to. The approximate dimensions and form of same are indicated in the sketch. On the base it was about 51 feet and the sides were inclined at an angle of 45°. The sides were formed of light lattice work notched for the reception of the wires. The first turn of the secondary began some distance from the ground so that the average turn was smaller than it ought to have been, judging from dimensions, that is nearly 145 feet. Nevertheless more wire was actually coiled up owing to the fact that there was some loss in the corners, and the wire not being perfectly straight added still further to the length so that 6 coils of wire were rolled up, their lengths being: 1000+1000+1005+1002+762+546=5315 feet total, № 10 B. & S. wire. Deducting ends left gave very nearly 5280 feet or a mile =1610 meters approx. The wire was wound on by the help of a stand rolled on the floor and supporting the reel. The resistance of the wire was 5.55 ohms. The readings were as follows:

motor ω	E	I
2115	212	6.2
2100	211	6.16
2120	211	6.16

from this average values were $\left. \begin{array}{l} I = 6.17 \\ E = 211.33 \\ \omega = 883.42 \end{array} \right\}$

$$\frac{E}{I} = 34.25 \quad \left(\frac{E}{I}\right)^2 = 1173 \quad R^2 = 30.8 \quad L = \frac{\sqrt{\left(\frac{E}{I}\right)^2 - R^2}}{\omega}$$

gives $L = 3826 \times 10^4$ cm. or 0.03826 henry.

With 40 turns placed at same distance we may take approximate inductance to be about 42×10^6 cm. Note: It was before assumed 5×10^7 but the turns were a trifle closer.

Readings were taken today with the synchronous 8 pole motor to ascertain co as closely as possible for future measurements with following results:

Time	Speed generator (10 pole)	Speed motor	Speed reduced
5.35	1700	2155	1724
5.40	1700	2165	1732
5.50	1730	2160	1728
6.10	1710	2150	1720
6.20	1705	2170	1736
6.25	1717	2150	1720

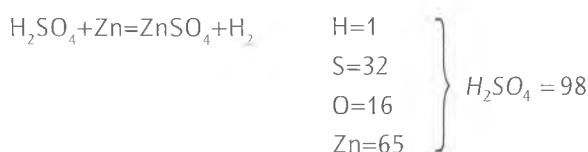
Speed of generator on station was taken by Mr. L. and on motor in exp. station by myself. The readings on generator were more liable to be underestimated. General results show that high values obtained on generator agree well with values obtained on motor. The latter *can* go a little faster without load. This I have observed with such motors before. The reason for this may be found in the fact that the generator fluctuates about a certain average value, a greater momentum is impacted to the motor when the speed of the generator is *above* than when *below* that value. This will result in the motor making a few more revolutions than would strictly follow from the average value. Or, the counter-electromotive force is out of phase giving higher e.m.f. on motor than on generator, thus changing amount of positive or negative slip. Taking average from three evidently best readings we get on generator 1719, on motor 1722 which agrees fairly. Accordingly, *with this generator* ω will be generally $2\pi \times 29 \times 5 = 911$ or, for ordinary estimates $\omega = 900$.

Colorado Springs

July 5, 1899

From older notes:

Consider generation of hydrogen for balloons in the ordinary way:



From this:

$98(\text{H}_2\text{SO}_4) + 65(\text{Zn}) = 2\text{H}$ in lbs. Now weight of hydrogen 0.00561 lbs. per cubic foot, for filling 10 ft balloon we would want $523 \times \frac{2}{3} = 350$ cu. feet hydrogen, namely capacity of 10 foot balloon would be 523 feet but it ought to be filled only to about $\frac{2}{3}$. This quantity of hydrogen will weigh about $350 \times 0.00561 = 1.96$ lbs.

Result: We want $\left. \begin{array}{l} 100 \text{ lbs } \text{H}_2\text{SO}_4 \\ 65 \text{ ,, } \text{Zn} \end{array} \right\}$ to fill balloon of only 10 feet diam

Now consider and compare process which some years ago occurred to me and which consists in decomposing a hydrocarbon as by an electric current heating a wire to incandescence. To get a rough idea take, for instance, a hydrocarbon of the general composition C_2H_4 (not to speak of combinations richer still in hydrogen). In such a combination we have for the quantity of hydrogen contained in it an extremely small weight. For instance, from $\left\{ \begin{array}{l} \text{C}=12 \\ \text{H}=1 \end{array} \right\}$ 28 units of weight total we get 4 units of weight hydrogen, much more than possible in former method. In case therefore a very small weight is essentially required this method *is most excellent*. Now as to electrolytic generation: 1 amp.-hour gives 37.3 milligram of hydrogen, 1000 amp.-hours $\frac{37,300 \times 2.2}{10^6}$ lbs., 0.00561 lbs per cu. foot gives 1.2 cu. feet per 1000 amp.-hours! Ridiculously small!

Colorado Springs

July 6, 1899

On a previous occasion the capacity of a coil was estimated by considering it as a series of parallel conductors and in this manner a tolerably close estimate was obtained. Applying this to the secondary of 40 turns we would have:

$$C = \frac{0.01206}{\log \frac{d}{r}} \text{ from a practical formula } \left\{ \begin{array}{l} d = \text{distance between} \\ r = \text{diameter of} \end{array} \right\} \text{wires}$$

This gives C in microfarad per 1 km., according to the authority. Here the length of wire total is 5280 feet roughly or $5280 \times 12 \times 2.54 = 160,934$ cm. Taken as a pair of conductors this would give length $\frac{160,934}{2} = 80,467$ cm.

$$\text{Now } \frac{d}{r} = \frac{4.23}{0.127} = \frac{4230}{127} = 33.3 \quad d = \frac{10''}{6} = 4.23 \text{ cm.}$$

$$\log \frac{d}{r} = 1.522444 \quad r = \frac{0.1''}{2} = 0.127 \text{ cm.}$$

from these data we would have per 1 km. in microfarad

$$C_1 = \frac{0.01206}{1.522444} = 0.00792 \text{ mfd. per km.}$$

Now the length of the pair of parallel wires as supposed would be 80,467 cm. or 0.80467 km. or for the secondary the capacity would be $C = 0.80467 \times C_1 \times 2$, double since both sides must be counted, or $C = 0.00792 \times 2 \times 0.80467 = 0.01584 \times 0.80467 = 0.012746$ mfd. or $9 \times 10^5 \times 0.012746 = 1274.6 \times 9 = 11,471.4$ cm. Evidently this is not applicable, the capacity could be at the utmost 3000–4000 cm. judging from the vibration of the secondary.

Colorado Springs

July 7, 1899

General conclusions arrived at after all these and previous experiences with electrical oscillators of this kind

It is important as a rule and sometimes imperative to overcome distributed capacity. In large machines it also becomes necessary to overcome the too great self-induction since it prevents obtaining a very high frequency which is generally of great advantage. The high e.m.f. being for the chief purposes aimed at – that is power transmission and transmission of intelligible messages to any point of the globe – essentially necessary, it is important to ascertain the best manner to obtain it. As has been already stated this result may be reached in two ways radically different – either by a high ratio of transformation or by resonant rise. For power transmission it seems that ultimately the former method must prevail, but where a small amount of energy is needed the latter method is unquestionably the better and simpler of the two. By placing the secondary in a very close inductive relation to the primary, the self-induction is diminished so that the self-induction in a highly economical machine of this kind would not seem to be an impediment in the way of obtaining a very high frequency, at least not one

which could not be more or less overcome by scientific design of the machine. But the distributed capacity is a troublesome element in such a machine and all the more so as the e.m.f. increases. When the pressure reaches a few million volts almost all the energy is taken in charging the condenser or capacity distributed along the wire. The difficulty becomes greater still when it is realized that in an economical machine the turns must be close together, which increases the drawbacks resulting from the distributed capacity. Now one way of reducing the internal capacity is to place between the turns, and *in series* with them, condensers of proper capacity, but this is not always practicable. This will be *later considered* more in detail. By such means the full rise of pressure on the terminal or terminals of the secondary may be obtained, which is impossible with distributed capacity of any magnitude. Very often only a small rise at the terminals can be obtained as all the charge remains "inside". Now as to obtaining the required pressure by a resonant rise there are again two ways: either to place a secondary in *loose* connection to a primary thereby enabling the free vibration of the secondary to assert itself, or using a secondary in *intimate* connection with the primary and then raising the pressure by an additional coil – extra coil – or inductance *not in inductive relation* to the primary. The latter method I have found preferable when a very high e.m.f. is desired. More particularly for purposes of telegraphy to any point of the globe which is one of the objects, I conclude that: 1) ratio of transformation should be as large as practicable with reference to the preceding; 2) magnifying factor of coil as large as possible; 3) minimum internal capacity; 4) high self-induction in coil for *sharp tuning*. Experiences up to present indicate flat spiral form of coil in sections as best suitable.

Rough estimate of period of vibration to be adopted with Westinghouse transformer 40,000 – 60,000 volts.

Required: that only one turn of primary be used because of 1) high ratio of transformation to be attained and 2) facility of regulation with the Regulating coil brought from New York. Now the total output of W.E. Transformer will be, say, 50 H.P. (though the machine may be strained to many times that output). From this follows the number of jars which it will be possible to use. We have

$50 \times 750 = \frac{1}{2} 60,000^2 \times 300 \times C$, assuming now 150 cycles per second, a little more than is likely to be the case. From this follows $C = \frac{75 \times 10^3}{36 \times 10^8 \times 3 \times 10^2} = \frac{75}{36 \times 3 \times 10^7}$ farad or in centimeters we would

have the capacity of condenser which the transformer will be able to charge without considering resonant conditions or other causes which may enable the transformer to charge many more jars

$C = \frac{9 \times 75 \times 10^{11}}{108 \times 10^7} = \frac{9 \times 75 \times 10^4}{108} = C = 62,500$ cm. total. Now taking the capacity of one jar as 0.003 mfd.

or 2700 cm. this would give only $\frac{62,500}{2700} = \frac{625}{27} = 23$ jars total, or in two series 46 jars on each side of

primary. The capacity of new jars will be probably 0.0025 and a correspondingly greater number may be taken. With 40,000 volts we would be able to take $\frac{36}{16} \times 23 =$ nearly 52 jars *total* or 104 on each side.

Assuming 60,000 volts and say 48 of new jars on each side this would give capacity in the primary most suitable to the transformer $24 \times 0.0025 = 0.06$ mfd. and the inductance of the primary being say 7×10^4

cm. The period T would be $\frac{2\pi}{10^3} \sqrt{\frac{7 \times 10^4}{10^9} \times 0.06} = \frac{12.874}{10^6}$ and $n = 77,660$ per second.

Colorado Springs

July 8, 1899

Further conclusions relative to the best working conditions and constructional features of such oscillators derived from observations made in these and previous experiments

Beginning with the primary, the capacity should, as stated before, be best adapted to the generator which supplies the energy. This consideration is, however, of great importance only when the oscillator is a large machine and the object is to utilize the energy supplied from the source in the most economical manner. This is the case particularly when the oscillator is designed to take up the *entire output* of the generator, as may be in the present instance. But generally, when the oscillator is on a supply circuit distributing light and power the choice of capacity is unrestricted by such considerations. In most cases the advantages secured by using a very high frequency are so pronounced that the primary circuit will have to be designed with this feature in view. The resistance of the primary circuit should be in any event as small as it is practicable to make it. I also think that generally, the inductance should be as small as practicable for that frequency which is supposed to be arbitrarily selected beforehand. When, however, the break number is comparatively small, that is, much smaller than the number of free vibrations, it is of great advantage to have the inductance great in order to give a greater momentum to the circuit and to thus enable it to vibrate longer after each break. But if the break number is of a frequency comparable with that of the free vibrations, the inductance should be as small as possible for however small it be, the circuit will generally vibrate long enough. One more reason why the inductance should not be large in such a case is that, in the primary, it is unnecessary to raise the pressure by making $\frac{pL}{R}$ very large. Necessarily this factor *will* be large in a well designed circuit, but should be so

chiefly owing to an extremely small resistance and not owing to a high self-induction. By making the inductance smaller a greater capacity may be used and this will give a greater output, a feature which is sometimes of importance. Of course, as the capacity becomes large the difficulties in the make and break device increase, but with a properly designed mercury break these difficulties are in large measure overcome. I conclude from the above facts that the best way to construct a primary in such a machine is to use thin sheet of copper or at any rate a stranded cable. I have settled upon using copper sheet in the smaller machines since long ago, this giving the best result. By using sheet a very small inductance is obtained and *more length* of conductor can be wound on for same frequency, at the same time the opportunity for radiation is excellent and the construction is simple and cheap. For the same section sheets heat *much less* than cable and the difference in this respect is so marked that I have been tempted to believe that there is a special reason for it, not yet satisfactorily explained. The *actual length* of the primary conductor, relative to that length which is obtained by dividing the velocity of light by $2n$, n being the number of vibrations of the primary per second – is of little importance since the primary is generally but a very small fraction of that length, but I believe to have observed that it is preferable, in a slight degree, to make the conductor of such a length that, if l be this length and n the frequency, $2Knl$ should $= v$, the velocity of light, and K should be a *whole* number and not a *fraction*. At least this seems to hold good in circuits made very long, expressly for the purpose of ascertaining whether there is truth in this idea which was arrived at by considering the ideal conditions of such a vibrating circuit. In this abstract case l should be rigorously equal to that *half wave* length which is obtained by computation from the velocity of light. In practice it is invariably observed that l is smaller and K is not as it should be $= 1$ but is often a large number, this simply following from the fact that the velocity of propagation in a circuit with considerable inductance and capacity is generally much smaller than that of light and often considerably smaller. It is to be stated that for a number of reasons it is of advantage, whatever be the actual length of the primary conductor, to arrange it so that it is *symmetrical* with respect to the condenser and the make-and-break device, one of the chief objects being to secure the maximum difference of potential on the terminals of the condenser. This consideration leads to the adoption of at

least *two condensers* in series, the primary generally joining the outer coatings while the inner ones are bridged by the break device.

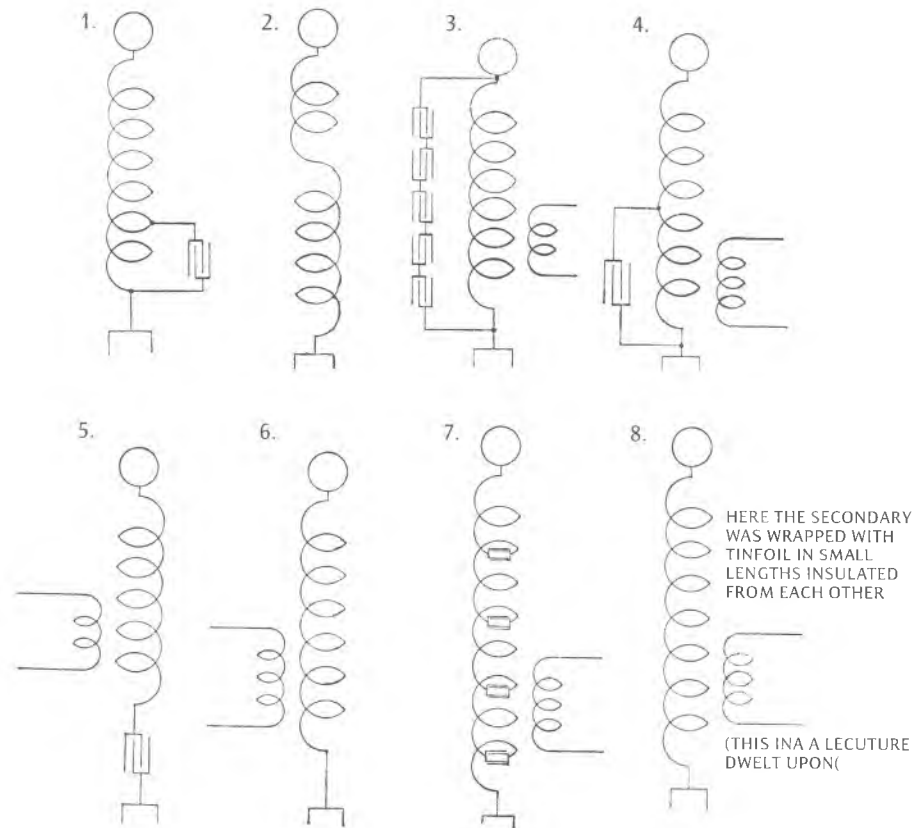
Coming now to the secondary quite different considerations apply. First, we must decide whether the secondary high electromotive force is to be obtained exclusively or entirely by transformation as in the commercial transformers with iron core, or not. In the first case obviously similar rules of economic design as followed in ordinary transformers will have to be respected. The secondary will have to be placed in the closest possible inductive relation to the primary and this will give an economical machine and one of relatively high frequency, since the inductances of the circuits by mutual reaction will be considerably reduced. But it is at once seen, that in a machine as here chiefly considered for the purposes followed from the outset, the connection between the primary and secondary can never be as close as in ordinary transformers, and the connection must be all the less intimate as the pressure on the secondary is increased since the wires must necessarily be placed at a greater distance from each other. From this it follows that in such a machine the free vibration of the secondary can never be quite ignored even if the electromotive force is not extraordinarily high. Now directly as the free vibration of the secondary becomes an important element to consider in the design, the careful adjustment be-

comes obviously imperative. It goes without saying that $\frac{pL}{R}$ should be as large as possible in all cases where resonant rise is one of the objects. But here is where we find in practice, and particularly in a large machine, difficulties not easily overcome. Both the inductance and capacity grow rapidly as turns are added, so much so that very soon it is found the secondary period becomes longer than that of the primary. The chief drawback is, as has been already pointed out, the distributed capacity but also the inductance though in a lesser degree. While the inductance in a certain sense has a great redeeming feature and is *necessary*, yet it stands in the way of obtaining a very high frequency in a large machine. To get a high electromotive force we must have many turns or turns of great length and this means great inductance and this again entails the drawbacks of *slow vibration*. Thus, in a large machine we encounter those difficulties which meet us in the design of too large a bridge, for instance, difficulties which are based on the very properties of matter and seemingly insuperable. Make a wire rope of twice the section and it will not be able to carry a longer piece of its own, since the weight is increased in the same proportion as the section and the strain per unit of the latter remains the same. Fortunately for us in electrical machinery, of this kind at least, this limit is immensely remote owing to the wonderful properties of this agent. Still the difficulties encountered on account of the capacity and inductance, and equally on account of the insulation are such as will require great deal of persistent effort to be effectively done away with in these oscillators, if the results aimed at are to be achieved in a thoroughly practical manner. Much attention will be devoted to this part of the problem in perfecting the machines which are necessary for the successful carrying out of the projects of transmitting power as well as effecting communication with any point irrespective of distance. But the machines for these two purposes will necessarily differ in design, since in one case – the first – a great amount of energy is imperative, while in the other only a high electromotive force and immense rate of *momentary energy delivery is required*. The two most promising lines of development are evidently these two: either to obtain the necessary electromotive force in a secondary alone, or in an extra inductance, not affected inductively by the primary or even by the secondary but merely excited by the latter, the rise of pressure being due to a great magnifying factor. The latter method has been found to be by far the best when a high e.m.f. but not a great amount of energy is required and there is scarcely any limit to the maximum pressure so producible. But it does not seem to me as though this method should be applied in power transmission contemplated, but this will be decided in the future.

Recognizing in the distributed capacity the chief drawback, I have since long thought on ways of overcoming it and the best seems to be so far, to make the secondary in sections of the determined length and to join them all in series through condensers of the proper capacity. By this means the greatest possible length of conductor may be utilized by a given frequency and placed in good inductive con-

nection with the primary. Theoretically it is possible to entirely do away with the effect of distributed capacity in this manner and to use an excessively large inductance and consequently a large magnifying factor as well as magnifying transformation ratio. The wave length in such a theoretical case will be then exactly that which follows from the velocity of propagation of light.

Various arrangements experimented with for the purpose of studying effect of diminished inductance of secondary.



In Diagram 1. one part of the secondary was used as primary, this part being shunted by the primary condenser; in 2. a few turns of the secondary, those remote from the primary, were wound opposite; in 3. a series of condensers capable of standing the entire pressure of the secondary were used to shunt the same; in 4. a larger part of secondary inductance was counteracted by a condenser; in 5. the entire secondary inductance was counteracted by a condenser; in 6. the inductance of the secondary was reduced by placing the turns far apart; in 7. inductance was counteracted by a series of condensers inserted between the turns and also distributed capacity was reduced and in 8. (not shown) static screening was resorted to.

To ascertain to what extent the distributed capacity of secondary wire № 10 was responsible for the small spark length obtained on the free terminal and to further study this capacity effect, wire № 31 is to be wound on the secondary frame. For these experiments the present transformer brought from New York is to be used – which can charge just about 16 jars, as now operated, on each side of the primary, this giving primary capacity = 8 jars or $8 \times 0.003 = 0.024$ mfd. Since L with connections (1 primary turn) is $L = \frac{7 \times 10^4}{10^9} = \frac{7}{10^5}$ henry, the period of the system to be adopted for new experimental coil of this wire will be:

$$T = \frac{2\pi}{10^3} \sqrt{\frac{7}{10^5} \times \frac{24}{1000}} = \frac{2\pi}{10^7} \sqrt{168} \quad \sqrt{168} = 12.9$$

$$\text{or } T (\text{approx.}) = \frac{6,28 \times 13}{10^7} = \frac{82}{10^7} \quad \begin{array}{l} 68:2 \\ 2400:24 \\ 159 \end{array}$$

This would give $n = 10,000,000 : 82 = 122,000$ per second.

$$\begin{array}{c} 180 \\ 160 \end{array}$$

From this again we get $\lambda = 186 : 122 = 1.524$ miles, or length of secondary roughly $= \frac{\lambda}{4} = 0.38$ miles or wire length = 2000 feet approx. When two primary turns in 4 series are to be used we shall have $\frac{\lambda}{4}$ or length of wire = 4000 feet.

This to follow up.

The effects of distributed capacity in some experiments with the secondaries constituted of wire № 10 (or cord) were so striking that it seemed worth while to carry on some investigations with very thin wire and consequently very small capacity in the secondary. It was decided to use wire № 31 in these experiments. The diameter of this wire was only $\frac{1}{11.4}$ of that of wire or cord № 10 hence the capacity of the new secondary, assuming all other things to remain the same, would be only $\frac{1}{11.4}$ of the

capacity of the old secondary. The capacity of the new coil would be, however, reduced or increased in proportion to the length of the new wire relatively to the old and would be furthermore regulated by the distance of the turns. It was resolved to adopt 122,000 per second (see note before) in the primary as compared with 21,000 per second with the old secondary which was obtained with 15 jars on each side of the primary. For this vibration (122,000) the length of the new secondary should be about 2000 feet, this being the length of a quarter wave. Calling now the distance between the turns of the new coil d , its

capacity as compared with that of old secondary of a length of 5280 feet would be: $C_1 = \frac{1}{11.4} \times \frac{20}{53} \times \frac{d}{d_1} C$, C being capacity of old secondary and d_1 the distance of turns in same. We may call $\frac{d}{d_1} = D$ a number

which will modify the capacity according to the distance of the turns, and we then have the capacity of the new coil $C_1 = \frac{1}{11.4} \times \frac{20}{53} \times DC$. Now L being the inductance of old coil and L_1 that of the new, we have, disregarding effect of the smaller diameter of wire for the present, $L_1 = \left(\frac{14}{36}\right)^2 DL$ for the inductance will evidently be changed in accordance with the same number D . This relation follows from the fact

that 2000 feet of new secondary with 143 feet average length of turn give $\frac{2000}{143} = 14$ turns or nearly so, and there were 36 turns in old secondary, the length being preserved the same in both coils. From this it follows that the new system will vibrate with a period $T=?$ which will be $\sqrt{\left(\frac{14}{36}\right)^2 \frac{20}{53 \times 11.4}} D^2$ times the period of the old system, or $\frac{14}{36} D \sqrt{\frac{1}{30}}$ or $0.07D$ times. From this we may calculate D .

The old primary system was 21,000 per second, the new 122,000 per second, hence we have $0.07D \times 21,000 = 122,000$ or $D=83$. This means to say that without any additional capacity on the free terminal the turns would have to be put at a distance only $\frac{1}{83}$ that of the former secondary. This would not be realizable because the sparks would pass between the turns. Capacity must be, therefore, added on the free terminal. Calling this capacity c and the old C , the total capacity on the new coil would be $C' = \frac{20DC}{11.4 \times 53} + c$ and the inductance would be $L'_1 = L_1 = \left(\frac{14}{36}\right)^2 DL$. Hence, for estimating D and c we have the equation:

$$\frac{1}{122 \times 10^3} = \frac{2\pi}{10^3} \sqrt{\left(\frac{14}{36}\right)^2 D \frac{38 \times 10^6}{10^9} \left(\frac{20 \times 1200D}{11.4 \times 53} + c\right) \frac{1}{9 \times 10^5}} \quad \left\{ \begin{array}{l} L=38 \times 10^6 \\ C=1200 \end{array} \right\} \quad \text{old coil}$$

$$\frac{1}{122 \times 2\pi} = \frac{14}{36 \times 3 \times 10^4} \sqrt{D(40D + c)} \quad \text{or} \quad \frac{108 \times 10^4}{3416\pi} = \sqrt{D(40D + c)}$$

Taking here now $D=1$ we get approx: $\frac{11,664 \times 10^7}{1166 \times 10^4} = 10,000 = (40 + c)$ or $c \approx$ roughly 10,000 cm. for same distance of wires in new coil as in old.

It was of interest to determine the period of the combined primary and secondary system of the experimental oscillator and the following method was adopted. A coil wound with thin wire, turns separated by a string to reduce distributed capacity, was placed at a distance of a few feet from the vibrating system and so that it was about equally affected by the primary and secondary. One end of the coil was connected to earth and the other end was left free. An idea was already obtained beforehand as to the frequency which was likely to be found but more wire was wound on the coil to enable the adjustment to be effected by taking off turns. Turns were then taken from the lower end of the coil until a maximum of spark length from free terminal was obtained. The coil then gave a spark 5" long. This took place when there were 1140 feet of wire on the coil, this length being found by measurement of resistance

$$\left\{ \begin{array}{l} \text{res. of coil } 38.4 \text{ ohms} \\ \text{res. of 12 feet } 0.405 \text{ ohms} \end{array} \right.$$

Neglecting the capacity of the coil this length should be $= \frac{\lambda}{4}$ or the quarter of a wave length. Of course, it was less but it was surmised that it would not be very much less. The total length of wave was then $\lambda=4560$ feet. From this would follow

$$n = \frac{186,000 \times 5280}{4560} = 215,317 \text{ per second.}$$

Now the capacity in the primary circuit was ten new jars on each side, this making a five jars total or $5 \times 0.0025 = 0.0125$ mfd. Or $\frac{125}{10^4}$ mfd. From this the period of the system ought to have been

$$T = \frac{2\pi}{10^3} \sqrt{\frac{125}{10^4} L \left(1 - \frac{M^2}{NL}\right)}$$

N = inductance of secondary
 L = inductance of primary
 M = mutual inductance

But on a previous occasion $1 - \frac{M^2}{NL}$ was found to be nearly 0.6 so that $T = \frac{2\pi}{10^3} \sqrt{\frac{125}{10^4} \times 0.6 \times L}$.

Taking now $L = 7 \times 10^4$ cm. or $\frac{7}{10^5}$ henry we have

$$T = \frac{2\pi}{10^3} \sqrt{\frac{125}{10^4} \times \frac{6}{10} \times \frac{7}{10^5}} = \frac{2\pi}{10^8} \sqrt{42 \times 125} = \frac{2\pi}{10^8} \sqrt{5250} = \frac{72.46 \times 2\pi}{10^8} = \frac{455}{10^8} \text{ approx.}$$

and from this would follow $n_1 = \frac{10^8}{455} = 219,800$ per second. This is fairly close within the limits of ordinary errors of measurement and observation.

On the bases of above estimate of n , we may also determine the inductance of primary cables or cable as modified by the influence of the secondary since we have the equation

$$\frac{1}{215,370} = \frac{2\pi}{10^3} \sqrt{\frac{125}{10^4} L'} \text{ which gives } L' = \left(\frac{10^4}{21,537 \times 2\pi} \right)^2 \times \frac{1}{125} = \frac{10^8}{185,537 \times 10^5} \times \frac{1}{125}$$

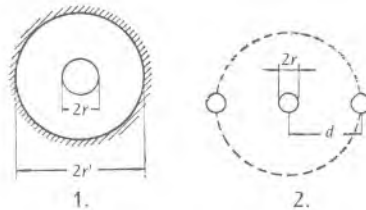
$$L' = \frac{10^8}{2319 \times 10^4 \times 10^5} = \frac{1}{23,190} \text{ henry or } \frac{10^9}{23,190} = \frac{10^8}{2319} = 43,120 \text{ cm.}$$

This is not far from the truth since

$$7 \times 10^4 \times 0.6 = 70,000 \times 0.6 = 42,000 \text{ cm.}$$

Estimate of capacity of a large coil (secondary) by Lord Kelvin's formula for concentric cable, to see how far it is applicable to a coil. Kelvin gives $C = \frac{KS}{4\pi r \log \frac{r'}{r}}$. Here S is the surface of inner copper

conductor, r' radius of inside hole of conductor outside of cable, r radius of copper conductor inside (Diag. 1.). Assuming now a cable wound up having n turns at a distance d , each turn may be considered as having a conductor on either side at distance d . If we draw a circle of radius d around the conductor and imagine the inner surface conducting, we have the capacity of such a system according to above formula. Now in the case of a coil of this ideal surface we utilize only a small part which is approximately, when d is very large compared to r , $\frac{2r\pi}{2\pi d} = \frac{r}{d}$.



Now if there are n turns there will be $(n-1)$ such systems as illustrated in Diagram 2. Taking air as insulation and neglecting the effect of the small thickness of other dielectric, we would then have the total capacity: $C_1 = \frac{S_1}{4\pi r \log \frac{d}{r}} (n-1) \frac{r}{d}$. Now $S_1 = 2\pi r l$, l being the length of one turn. The values calculated

out in this particular case of a secondary of 37 turns (36 $\frac{1}{2}$ + connecting wires = approx. 37 turns) are as follows:

$n=37$; $S_1 = 3600$ sq.cm.; $r=0.125$ cm.; $d=4.2$ cm.; $K=1$; $l=143$ feet $= 4360$ cm.; $\frac{d}{r} = 33.5$, $\log \frac{d}{r} = 1.525045$

Substituting these values we have:

$$C_1 = \frac{3600 \times 36}{4\pi \times 1.525 \times 4.2} = \frac{9 \times 3600}{\pi \times 1.525 \times 4.2} = \frac{32,400}{3.1416 \times 1.525 \times 4.2} = \frac{32,400}{4.791 \times 4.2} = \frac{32,400}{20.12}$$

$$C_1 = \text{approximately} = \frac{32,400}{20} = 1620 \text{ cm.}$$

This is not far from the value found. It shows that an approximate estimate may be made in this manner.

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The following consideration conveys an idea of the drawbacks of distributed capacity in the secondary. Suppose the total capacity of 12 such large turns would be 1200 cm. as may be frequently the case, or 100 cm. per one turn and now let us ask to what potential this condenser may be charged – assuming further the energy to be carried away for the performance of work – by expending 1 H.P.

In this case we would have $\frac{1000P^2}{9 \times 10^{11} \times 2} 2n = 750$ watts. Here P is the potential, n the number of vibrations per second.

In our case n may be 20,000 and then we may put

$$750 = 40,000 \times \frac{1000P^2}{9 \times 10^{11} \times 2} = \frac{2P^2}{9 \times 10^4} \text{ or } P^2 = \frac{9 \times 10^4 \times 750}{2} = 9 \times 10^4 \times 375 = 3375 \times 10^4 \text{ or}$$

$$P = 100\sqrt{3375} = \text{nearly } 5800 \text{ volts.}$$

This shows that by only charging the internal capacity to the insignificant pressure of 5800 volts we would have to expend 1 H.P. Of course, normally the power is small although the capacity is charged up to a much higher potential, but the consideration shows why with a large distributed capacity a very high pressure can not be obtained on the free terminal. All the electrical movement set up in the coil is taken up to fill the condenser and little appears on the free end. This drawback increases, of course, with the frequency and still more with the e.m.f.

In accordance with the preceding, an experimental coil of № 31 wire (№ 30 not being on hand) was wound on the secondary frame. In the first experiment 14 ½ turns were coiled up. The results were disappointing and for some time mystifying. The induced e.m.f. ought to have been 14 ½ times the primary less 40% of total as before stated, but it did not seem so. Finally it was recognized that, as the capacity of the new secondary was very small, the free vibration of the coil was very high hence no good result could be obtained. The capacity in the primary was now reduced until to all evidence resonance was obtained, but the results were much inferior to what might have been expected, probably because

$\frac{pL}{R}$ was small owing to large resistance. One of the reasons was, however, that the capacity in the primary was too small to allow a considerable amount of energy to be transmitted upon the secondary. To better the conditions, one of the balls of 30" diam. was connected to the free terminal; this allowed a greater number of jars in the primary to be used but the capacity of 38.1 cm. was by far too small to secure the best condition of working. The resonating condition in secondary was secured with approximately 7 jars on each side of the primary and when the ball was connected with about 14 jars.

The capacity of the secondary was estimated to be 40 cm. and the inductance approx 15×10^6 cm = $\frac{15}{10^3}$ henry.

Note: In these estimates I consider not the actual distributed capacity, but an ideal capacity associated with the coil.

This gave period of secondary roughly:

$$T = \frac{2\pi}{10^3} \sqrt{\frac{15}{10^3} \times \frac{40}{9 \times 10^5}} = \frac{2\pi}{10^7} \sqrt{\frac{600}{9}} = \frac{20\pi}{3 \times 10^7} \sqrt{6} = \frac{2\pi}{3 \times 10^6} \times 2.45 = \frac{4.9 \times \pi}{3 \times 10^6} = \frac{15.4}{3 \times 10^6}$$

or about $\frac{1}{195 \times 10^3} = T$.

From this $n = 195,000$ per second. This vibration was far above that of the primary circuit working under favorable conditions, that is with the full number of jars. As the thin secondary did not yield any satisfactory results a coil was now associated with it. It was one used in some experiments before, having 260 turns of cord No 10 (okonite) wound on a drum 2 feet in diam. and 6 feet long. The total length of wire was 1560 feet and the capacity of the coil (as above) 1530 cm. This coil was connected to the free terminal of the secondary and the free end of the coil was placed vertically on the top of the same and in the prolongation of its axis. Fairly good resonant rise was obtained on the free end, the streamers being $2\frac{1}{2}$ –3 feet long. The primary circuit had 9 jars on each side, this giving $4.5 \times 0.003 = 0.0135$ mfd. primary capacity and as the inductance of the primary was $\frac{7 \times 10^4}{10^9}$ H the period of the primary was about $\frac{2\pi}{10^6}$ and $n = 160,000$ per second. According to this $\frac{\lambda}{4}$ should have been about $\frac{1.16}{4}$ miles or 1531 feet. Assuming the coil and the secondary of $14\frac{1}{2}$ turns vibrated together as one, λ would have been $4(2000 + 1560) = 4 \times 3560$ feet and $\frac{\lambda}{4} = 3560$ feet. But the experiment disproved this and showed clearly that the coil vibrated *alone*, the secondary merely exciting it, since the $\frac{\lambda}{4}$ on primary bases was 1531 feet, while the spool had 1560 feet, very nearly the same. For best results secondary should have been tuned to the same period as that of the coil. *Conclusion of experiments with thin wires* was: results must be inferior as free vibration is important.

In using wire No 30 in the experiments proposed instead of wire No 10 in the present secondary, we shall have to consider the following: the largest number of jars would be 154 on each side of the primary and with *one primary turn* which it is advantageous to use on account of facility of adjustment. We would have, as before found,

$$n = 43,500 \text{ approx.} \quad \left. \begin{array}{l} \text{Thus } C_p \\ L_p \end{array} \right\} \text{ primary capacity and inductance are fixed.}$$

The wave length will be:

$$\frac{186,000}{43,500} = 4.2 \text{ miles of } \frac{\lambda}{4} = 1 \text{ mile roughly.}$$

Now No 30 wire has diam. 0.01 }
 Now No 30 wire has diam. 0.1 } Suppose the same number of turns as before, wound on the secondary frame and placed at twice the distance, the distributed capacity will be not far from $\frac{1}{2} \times \frac{1}{10}$ or $\frac{1}{20}$ of that of the old secondary. The inductance of the new coil – neglecting effect of small diameter of No 30 wire – will be one half of the old, hence the new system will vibrate $\sqrt{20 \times 2} = \sqrt{40} = 6.3$ times

quicker than the old secondary system. Since the old system vibrated 21,000 per sec. the new will vibrate 6.3 times that or 132,000 times per second, this number being $=n$. We should now, for the best suitable conditions, make the new system vibrate only about $\frac{1}{3}$ that number since this would be approximately the vibration of the primary system, as above stated. Now taking the capacity of the old secondary 1200 cm., that of the new would be only $\frac{1200}{20} = 60$ cm.; we would have, therefore, to bring the pitch down to make the capacity 9 times as large or $9 \times 60 = 540$ cm. or we would have to put about 480 cm. on the free terminal of the new coil.

Further consideration in using a new secondary of No 30 wire. The length of 1 mile of this wire will have a resistance on the basis of 9.7 feet per ohm from tables $\frac{5280}{9.7} = 544$ ohms approx. To get a rough idea of how the coil might work suppose that on the primary there would be 40,000 volts and that there were 36 turns of secondary, then there would be theoretically an e.m.f. on the terminals of secondary $40,000 \times 36 = 1,440,000$ volts and, deducting with reference to mutual inductance 40%, we would have $1,444,000 \times 0.6 = 864,000$ volts impressed or induced e.m.f. Suppose now we had a capacity of 480 cm. on the free terminal as before estimated, the charge stored in this condenser would be:

Coulombs or amp. – sec } $\frac{864,000 \times 480}{9 \times 10^{11}}$ per one charge and there being
 $43,500 \times 2 = 87,000$ charges per second and taking a theoretical case we
 would have $\frac{864,000 \times 480 \times 87,000}{9 \times 10^{11}} = \frac{86 \times 87 \times 48}{9 \times 10^4} = 4$ amp. nearly. The current in the secondary would be quite large for the small section of the wire. Suppose 50 H.P., expended we may say roughly: $E_s i_s = 50 \times 750 = 37,500$ watts. With the above pressure we would have: $864,000 \times i_s = 37,500$ or $i_s = 0.043$ amp. only. In this case the energy lost per second would be $544 \times \frac{43^2}{10^6} = \frac{1849 \times 544}{10^6} = 1$ watt approx.

The loss in this case, in spite of the great amount of energy transformed, would be ridiculously small owing to the great e.m.f. despite comparatively high resistance of the secondary. But this only seems so, for 544 ohms would be extremely small resistance for such e.m.f. The theoretical case above considered is hardly realizable, it would require an immense amount of energy.

Additional coil used before in some experiments, also in trials with a secondary of No 31 wire.

Approximate inductance of coil

Data: diam. 2 feet = 24" = 61 cm. = d

$$\text{Area} = \frac{\pi}{4} d^2 = \frac{\pi}{4} \times 3721 = 2922 \text{ sq. cm.}$$

$$\text{length } 71" = 71 \times 2.54 = \text{approx. } 180 \text{ cm.}$$

$$\text{From this } L = \frac{4\pi N^2 A}{l} = 12.57 \times \frac{260^2 \times 2922}{180} \quad N = 260 \text{ turns, this gives}$$

$$L = 13,925,000 \text{ cm. approx.} = 0.0139 \text{ H}$$

Period of primary was before found $\frac{1}{16 \times 10^4}$, hence

$$\frac{1}{16 \times 10^4} = \frac{2\pi}{10^3} \sqrt{\frac{13,900,000}{10^9} C}$$

From this a rough idea of the capacity of the coil may be had, resonance being observed when the primary had $T = \frac{1}{16 \times 10^4}$ as above. From above equation we find

$$C = \frac{10}{142,336} \text{ mfd. or in cm.}$$

$$C = \frac{9 \times 10^5 \times 10}{142,336} = \frac{9 \times 10^6}{142,336} = 63.2 \text{ cm.}$$

This is a much smaller value than would be expected from previous approximate estimates. The correctness of the value found depends, among other things, chiefly on the correct determination of the period, for resonance might have been also obtained with a lower or upper harmonic, but this is not very likely to be the case as the vibration was very intense. There were approximately 5000 volts on primary turn. Resistance of coil was 1.56 ohm. From this $\omega = 2\pi \times 16 \times 10^4 = 1,004,800$ or 10^6 approx; $\omega L = 0.014 \times 10^6 = 14,000$, $\frac{\omega L}{R} = \frac{14,000}{1.56} = 8910$ as factor for magnifying e.m.f. impressed; very large.

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Some considerations on the use of "extra coils"

As has been already pointed out an excellent way of obtaining excessive electromotive forces and great spark lengths is to pass the current from a terminal of an oscillating source into such a coil, properly constructed and proportioned, and having preferably a conducting body – best a sphere – connected to the free terminal. In free air the *highest economy* is obtained with a well polished sphere, but for the greatest spark length – if this be the chief object – no capacity on the free terminal should be used, but all the wire should be carefully insulated so that streamers can not form except on the very end of the wire which as a rule should be pointed. This, however, is not always true. When the apparatus delivers a notable amount of energy the curvature of the end of wire or terminal attached to it should be such that the streamer breaks out only when the pressure at the terminal is *near the maximum*. Otherwise, very often, when a finely pointed terminal is employed the streamer begins to break out already at a time when the e.m.f. has a small value and this reduces, of course, the spark length and power of the discharge. By careful experimentation and selection of terminal the most powerful spark display is easily secured which the particular apparatus used is capable of giving. When the conditions are such that for the most powerful discharge a terminal of some, relatively small, curvature is needed, the curvature of the terminal can be beforehand calculated so that the discharge will break out at any point of the wave desired, when the e.m.f. at the terminal has reached any predetermined value. The greater the curvature of the terminal the smaller an electromotive force is required to enable the discharge to break out into the air. In fact, the curvature of the terminal may serve as an indication of the value of the e.m.f. the apparatus is developing and it is often convenient to determine the e.m.f. approximately by observing how large a sphere will just prevent the streamers from breaking out, and for such purposes I have found it useful to provide the laboratory with such metallic spheres of different sizes up to 30" diam. It is of course necessary to guard in such experiments against errors which might be caused by any modification of the constants of the vibrating circuit through the addition to the system of a body of some capacity. The latter should be such as to insure the maximum rise of the pressure. With apparatus of inadequate power the pressure may be very much diminished by the addition of capacity merely because there is not enough energy available to charge the same to the full pressure. It is a notable observation that these "extra coils" with one of the terminals free, enable the obtainment of practically *any* e.m.f. the limits being so far remote, that I would not hesitate in undertaking to produce

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For $A = \frac{\pi}{4} D^2$ $\ell = \pi (T+d)$ Hence the inductance will be

$L = \frac{4\pi \cdot \frac{\pi}{4} D^2 N^2}{\pi (T+d) 10^9} = \frac{\pi^2 D^2 N^2}{(T+d) 10^9}$ Henry. Taking these values for L and C we have with reference to above $\frac{1}{p^2} = \frac{\pi^2 D^2 N^2}{(T+d) 10^9} \cdot \frac{4 \ell D}{6 \times 9 \times 10^{10}}$ or

$p^2 = \frac{(T+d) 6 \times 9 \times 10^{20}}{\pi^2 D^3 \ell N^2 K}$. Since in the preceding the diameter of the drum is assumed from practical considerations it will be convenient to find the number of turns N . The quantities D and ℓ are of course intercorrelated since by assuming D and depending on the pressure to be obtained beforehand ℓ is practically given. The diameter of the wire will in most cases also be selected beforehand so that then merely N is to be determined to satisfy the condition of resonance for any frequency specified. Now $\ell = \pi D N$

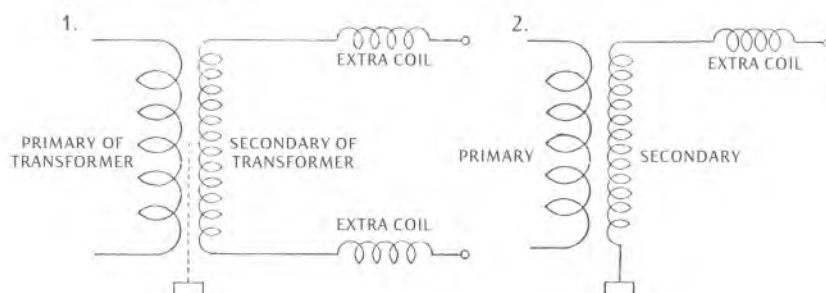
hence substituting this we have from above:

$$p^2 = \frac{(T+d) 6 \times 9 \times 10^{20}}{\pi^2 D^3 \ell N^2 K} \quad \text{or} \quad p^2 = \frac{(T+d) 6 \times 9 \times 10^{20}}{\pi^3 D^4 N^2 K} \quad \text{and from this}$$

$$\text{we get } N^2 = \frac{(T+d) 6 \times 9 \times 10^{20}}{\pi^3 D^4 p^2 K} \quad \text{or} \quad N = \frac{3 \times 10^{10} \sqrt{(T+d) 6}}{D^2 p \sqrt{\pi^3 K}} \cdot \sqrt{\ell} \quad \text{This}$$

formula may serve to give an approximate idea how many turns are to be wound on a core when the length of the wire, owing to the capacity in the excited circuit is smaller than $\frac{1}{4}$, [or respectively smaller than $\frac{1}{2}$, if the circuit is not one of the kind illustrated in diagrams above, that is one, in which the potential on one terminal is many times higher than on the other, but an ordinary circuit, in which there is a symmetrical rise and fall of pressure at both the terminals], but the equation assumes that the dielectric constant is = 1 or nearly so.

sparks of thousands of feet in length in this manner. Owing to this feature I expect that this method of raising the e.m.f. with an open coil will be recognized later as a material and beautiful advance in the art. No such pressures – even in the remotest degree, can be obtained with resonating circuits otherwise constituted with two terminals forming a closed path. It is also a fact that the highest pressure, at a free terminal, is obtained in that form of such apparatus in which one of the terminals is connected to the ground. But such “extra coils” with one terminal free may also be used with ordinary transformers and by using one such coil on each of the terminals of the transformer, practically any spark length may be reached. Of course, it is desirable that the frequency of the currents should be high, as with the common frequencies of supply circuits the lengths of the wires in the coils become too great. In the diagrams below the two typical arrangements with such an “extra coil” or coils are illustrated in which Diagram 1. illustrates their use with an ordinary transformer, which may have an iron core or not, and Diagram 2. shows typically the connection as I use it in my “single terminal” induction coil. As has been stated on a previous occasion in connection with this subject, to enable a considerable rise of pressure to take place in a circuit, the same must be tolerably free from inductive influences of other circuits. It follows from this that, although with a secondary in *loose* connection with a primary a very high pressure is obtainable, yet the pressure will never be as high as when an “extra coil” not in inductive connection with the primary is employed to raise the pressure, because the secondary always reacts upon the primary thus dampening the vibration, while the “extra coil” does not react in such a *manner*, the rise of pressure being simply due to the factor $\frac{pL}{R}$.



The object of the considerations which follow is to establish simple relations between the quantities which are known or adopted beforehand, so as to enable the experimenter to construct such coils without previous trials.

Calling E_0 the impressed e.m.f. and E the pressure measured with reference to the free terminal – that is the maximum pressure, p the product $2\pi n$ as usual, L the inductance of the “extra coil” and R its resistance, we have the known relation $E = \frac{pL}{R} E_0$. Obviously the maximum rise will take place when the period of the excited system or “extra coil” is the same as that of the oscillating system impressing the movement, for although the results obtained with a lower or upper harmonic, and particularly the former, may be sometimes so remarkable, as to be mistaken for effects of the true vibration, they are nevertheless always inferior, and I as a rule try the first upper and undertones to be sure of the result, when there exists any doubt in this respect. In ordinary practice the first element which is given will be the frequency, hence the wave length must be assumed as the first fixed quantity. But as has been already stated on another occasion, in an apparatus *designed* to give the *best result* the actual length of the wire should be that which is obtained on the basis of a velocity of propagation v equal to that of light. I have already remarked before that this is generally not true, the actual length of wire being always smaller than the theoretical length, and I propose to put together data derived from many experiments with coils wound with different wires and varying in size, from which it will be possible to always obtain, beforehand, with any particular wire, insulation and size of coil etc. the length required – by multiplying the theoretical length with a coefficient dependent on these and other particulars of this kind, dif-

ferent in special cases. Such coefficients will be certainly useful to the practitioners. The chief element determining the length of the wire is the distributed capacity and I shall presently suppose, that by proper design it is so reduced, that the length of wire is very nearly equal to the theoretical length, or the length of one quarter of the wave as computed from the velocity of light. In this case then, if l be the length of wire in the "extra coil", and X this wave length, the length of the wire will be such that $l = \frac{\lambda}{4}$. Now since $\lambda = \frac{v}{n}$, where n is the frequency and furthermore $n = \frac{p}{2\pi}$, we have $\lambda = \frac{v}{\frac{p}{2\pi}}$ or $\frac{2\pi v}{p} = \lambda$.

This is the simplest case. The period of the exciting as well as the excited system will be $T = 2\pi\sqrt{LC}$

where C is the capacity in farad } of each of the "extra coils"
and L the inductance in henry }

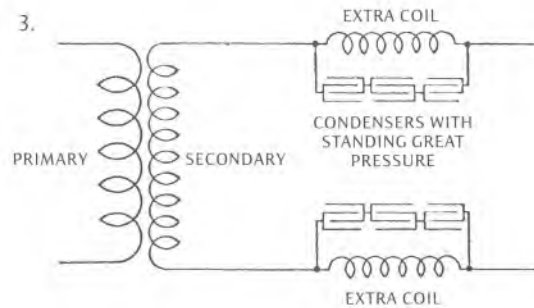
$$\text{or } n = \frac{1}{T} = \frac{1}{2\pi\sqrt{LC}} = \frac{p}{2\pi}; \text{ or } p = \frac{1}{\sqrt{LC}} \text{ or } LC = \frac{1}{p^2}.$$

This condition, as is well known, must be fulfilled, whatever be the length of the wire, to enable the maximum rise of pressure to take place, and also, p must be the same number for both systems, obviously. Now evidently in designing the apparatus, in any case, the experimenter will know approximately what e.m.f. he would wish to secure, and consequently he will have an idea how much difference of pressure he will have between the turns, and this will give him again an idea how he must place the windings most advantageously. He will furthermore recognize at once that the simplest form of such a coil, and also the cheapest, will be *one* with one single layer and, settling upon this form, he will get an approximate estimate as to the diameter of the coil to be adopted. This will, of course, depend much on the kind of wire he uses and particularly on the insulation, since the better the insulation the closer will be two points of the coil between which there will exist a certain maximum pressure. Granted now the diameter of the coil to be constructed is settled upon, it will be at once seen that, assuming turns are wound on until resonance is obtained, the inductance of the coil and the capacity of the same will vary in the like manner. If more turns are wound on the drum their number will be proportionate to the length of the coil, therefore to the length of the wire, and the inductance will be proportionate – on the one hand, to the square of the turns or respectively to the square of the length of the wire, and on the other hand, it will be inversely proportionate to the length of the coil. Inasmuch as this length is likewise proportionate to the length of the wire, the inductance, on the whole, will be proportionate to the ratio $\frac{l^2}{l}$ or to l , that is to say, the inductance of the coil, as more turns are wound on, will grow as

the length of the wire. And so will also, and obviously, the distributed capacity. And furthermore, and for the same reasons, under the conditions considered, both the capacity and the inductance of the coil will vary inversely as the distance of the turns which I shall designate r . This is clear since, as far as the inductance of the coil is concerned, the number of turns will be inversely as t , and the length of the coil *directly* as t , hence the inductance will be inversely as t ; and, as regards the distributed capacity, it will be, of course, inversely proportionate to t . Hence we can express both the unknown quantities L and C_1 (distributed capacity) in terms of l and τ . But it should be remembered that in the equation $LC = \frac{1}{p^2}$, C is capacity associated with the coil on the free terminal and not the distributed capacity.

In case, therefore, we should make the capacity on the free terminal very large in comparison with the distributed capacity of the coil, or if capacity be associated with the coil in other ways, as by *shunting* the coil with a condenser as in sketch 3. – or in any other way, but so that the distributed capacity *may* be *neglected*, then the design of the coil is much simplified, for then one of the constants, preferably C , can be adopted beforehand and the other constant calculated. It will be in such case better to adopt first a capacity, because it is easy to get an idea of what kind of condenser to use when the pressure of

the terminals of the coil is approximately known. A practical way is, sometimes, to adopt a construction before suggested, securing a negligible internal capacity, consisting of the placing of condensers in series with the turns of the coil, and then merely calculating one of the constants, assuming first a value for the other constant, whichever is the more convenient of the two. I have also found it practicable in some cases to avail myself of some methods of tuning allowing exact observations as to the rise of pressure in the excited circuit, and to tune a small number of turns first to a much higher harmonic and, after completing this adjustment, to calculate the dimensions of the coil for the fundamental vibrations from the experimental data secured. But in most cases such resources are not readily available and an approximate idea must be gained in other ways. There are a number of different considerations which, when followed out in connection with the preceding, will lead to the establishment of simple relations between the quantities primarily adopted and will enable an experimenter to construct such a coil to suit source, without previous experiment and some of these I propose to consider on other occasions. Presently I shall indicate a way which, in some cases to which the calculated data were applied, has given satisfactory results.



The ideal capacity C which should satisfy the equation $LC = \frac{1}{p^2}$ is always a function of the distributed capacity C_1 and furthermore a linear function, so that $C = K_1 C_1$ where K_1 is a constant, the value of which is to be deducted from the results of many varied experiments carried on to this end. But this capacity C_1 is, as has been found in many experiments with coils of widely different dimensions, directly proportionate to the length of wire and to the diameter of the same and furthermore to the diameter of the drum. The latter will be understood when it is considered that the greater the diameter of the drum the greater is the potential difference between the turns and, consequently, the greater is the amount of the energy stored in the coil with a given length and diameter of the wire. Finally the quantity C_1 is inversely proportionate to the distance of the turns τ . As to the dielectric constant it is only then important to consider when the turns are quite close together so that the entire space between the turns is filled with the dielectric. When the turns are far apart this constant may be taken=1. From this it follows that the capacity C interpreted as above may be expressed by the following equation: $C = K \frac{Ddl}{\tau \times 9 \times 10^{11}}$ when the dielectric constant can be neglected. Here D is the diameter of the drum, d diameter of the wire, l length of wire, τ the distance between the turns. C is the "ideal" capacity which will satisfy equation $LC = \frac{1}{p^2}$ expressed in farads. The constant K is determined by practical experiments. When the turns are very close the dielectric constant must be introduced and C will be multiplied with the latter quantity. Now the inductance of the extra coil to be constructed is $L = \frac{4\pi AN^2}{l_1 \times 10^9}$ henry. Here A =area of coil in cm. square, N =number of turns, and l_1 length of coil in cm. Now $A = \frac{\pi}{4} D^2$, $l_1 = N(\tau + d)$. Hence the inductance will be $L = \frac{4\pi \frac{\pi}{4} D^2 N^2}{N(\tau + d)10^9} = \frac{\pi^2 D^2 N}{(\tau + d)10^9}$ henry.

Taking these values for L and C we have, with reference to above, $\frac{1}{p^2} = \frac{\pi^2 D^2 N}{(\tau + d) 10^9} \times \frac{d l D}{\tau \times 9 \times 10^{11}} K$ or $p^2 = \frac{(\tau + d) \tau \times 9 \times 10^{20}}{\pi^2 D^3 d l N K}$.

Since in the preceding the diameter of the drum is assumed, from practical considerations it will be convenient to find the number of turns N . The quantities D and τ are, of course, interconnected since by assuming D and deciding on the pressure to be obtained beforehand, τ is practically given. The diameter of the wire will in most cases also be selected beforehand so that then merely N is to be determined to satisfy the condition of resonance for any frequency specified. Now $l = \pi D N$ hence substituting this we have from above:

$$p^2 = \frac{(\tau + d) \tau \times 9 \times 10^{20}}{\pi^2 D^3 d N \pi D N K} \text{ or } p^2 = \frac{(\tau + d) \tau \times 9 \times 10^{20}}{\pi^3 D^4 d N^2 K} \text{ and from this we get}$$

$$N^2 = \frac{(\tau + d) \tau \times 9 \times 10^{20}}{\pi^3 D^4 d p^2 K} \text{ or } N = \frac{3 \times 10^{10} \sqrt{(\tau + d) \tau}}{D^2 p \sqrt{\pi^3 K \cdot d}}$$

This formula may serve to give an approximate idea of how many turns are to be wound on in cases when the length of the wire, owing to the capacity in the excited circuit, is smaller than $\frac{\lambda}{4}$ (or respectively smaller than $\frac{\lambda}{2}$ if the circuit is not one of the kind illustrated in diagrams above – that is, one in which the potential on one terminal is many times higher than on the other, but an ordinary circuit, in which there is a symmetrical rise and fall of pressure at both the terminals], but the equation assumes that K , the dielectric constant, is 1 or nearly so.

From a number of experiments the value for K with wire No 10 as used in preceding experiments was found to be nearly $\frac{52}{10^6}$. Introducing this value in equation for N and reducing the constant quantities we find $N = \frac{747 \times 10^9}{D^2 p} \sqrt{\frac{\tau(\tau + d)}{d}}$.

To see how close this formula will give the value of TV in a special case take, for instance, the secondary with 40 turns experimented with before. In this particular case we have the following data: diameter of coil, average, 40 feet = 480" = 1220 cm. approx.

$$D = 1220 \text{ cm.}; \quad D^2 = 1488 \times 10^3; \quad \tau = 5 \text{ cm.}; \quad d = 0.254 \text{ cm.}$$

Resonance in secondary from previous tests took place with the primary period being $T = \frac{4,836}{10^5}$, this was also the secondary period and from this $n = 20,700$ approximately and this gives $p = 130,000$ very nearly. On the basis of these data we would have:

$$\begin{aligned} N &= \frac{747 \times 10^9}{D^2 p} \sqrt{\frac{\tau(\tau + d)}{d}} = \frac{747 \times 10^9}{1488 \times 10^3 \times 13 \times 10^4} \sqrt{\frac{5 \times 5.254}{0.254}} \\ &= \frac{747 \times 10^2}{1488 \times 13} \sqrt{103.4} = \frac{747 \times 10^2}{19,344} \times 10.16 \\ &= \frac{747 \times 1016}{19,344} = \frac{758,952}{19,344} = 39.24 \text{ turns} \end{aligned}$$

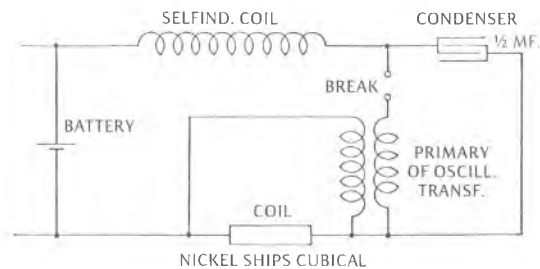
This comes indeed very close, the turns being actually 40 for the condition of resonance as experimentally shown.

This will be followed up.

Colorado Springs

July 12, 1899

Self-induction coil for condenser method in conjunction with oscillating transformer. Adapted to Thomas clockwork and condenser $\frac{1}{2}$ mfd. mica on hand (one of the two small condensers)



Capacity given $\frac{1}{2}$ mfd., break also given: wheel of clockwork breaking and making contact has 180 teeth, turns about 20 a minute. This gives breaks $\frac{180 \times 20}{60} = 60$ per second. Here at each make and break we have a wave in the condenser, and tuning may be effected either by making $n=60$ or $n=30$. Best result seemingly, from former experiments with oscillators, seems to make n = the number of breaks. We have then

$$T = \frac{2\pi}{10^3} \sqrt{L \times \frac{1}{2}}$$

$$T = \frac{1}{n} = \frac{1}{60} = \frac{2\pi}{10^3} \sqrt{L \times \frac{1}{2}}$$

$$\text{From this } L = \frac{2 \times 10^3}{144} = 2000 : 144 = 14 \text{ H}$$

$$= 560$$

This would not be realizable with a condenser of $\frac{1}{2}$ mfd. Therefore a larger condenser or quicker break necessary – will vibration always take place through the high resistance of sensitive device? $\frac{4L}{C} > R^2$ Take $L=1$ henry, we have $\frac{4}{1} > R^2$, $8 \times 10^6 > R^2$ or roughly $3000 > R$. This shows that although resistance may be very large, vibration will still take place.

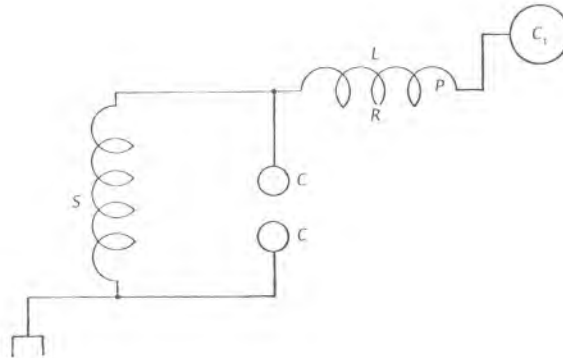
Follow up.

Colorado Springs

July 13, 1899

Considerations regarding working of oscillator without spark in secondary. This is a considerable advantage because of economy and also facility of exact synchronous adjustment. When spark used the latter difficult as capacity is changed by varying distance of terminals, also because spark establishes short circuit temporarily. In general, the process is very complicated and the tuning only partially successful. But using spark allows obtaining of great suddenness and using short wave lengths. The short-

ness of waves gives high e.m.f. and, therefore, great effect at distance. Without spark it is difficult to obtain high e.m.f. with *short waves*. Long waves on the other hand are less absorbed and allow exact tuning. Following plan seems to offer particular advantages that seemed to work well in New York oscillator.



S is the secondary of oscillator. To this is connected a coil L with capacity C_1 . The secondary is shunted by a condenser C . This condenser can be of large spheres when practicable. No spark should go over the spheres C and streamers should be prevented. Now the adjustment may be such that system $L C_1$ is any upper harmonic. In this system $\frac{Lp}{R}$ should be as large as possible. The free vibrations of $L C_1$ can be transmitted upon earth through condenser C .

Colorado Springs

July 14, 1899

Further considerations in regard to producing most effective movement without spark gap in secondary

2) A way which was experimented with in New York about a year and a half ago and worked exceedingly well and also later with boat, was to produce a very quick primary vibration and induce currents in secondary of a few turns which has one of its ends to earth and the other connected to a large capacity. Connections were as illustrated.

Fig. 1) supply direct current 220 volt. Mercury break 1600 per second. The secondary S_1 with small condenser C and spark gap d , primary P 2–3 turns.

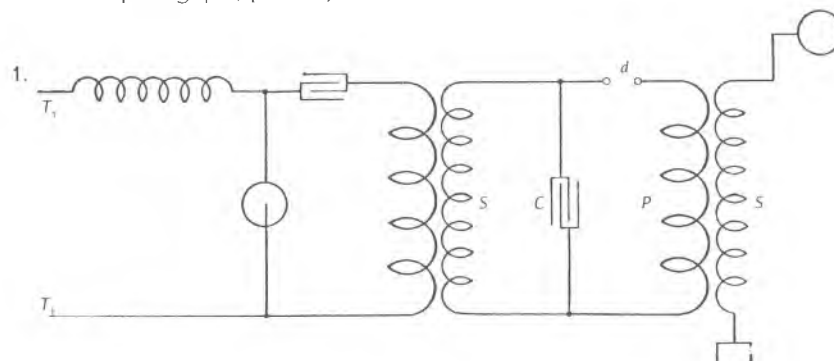
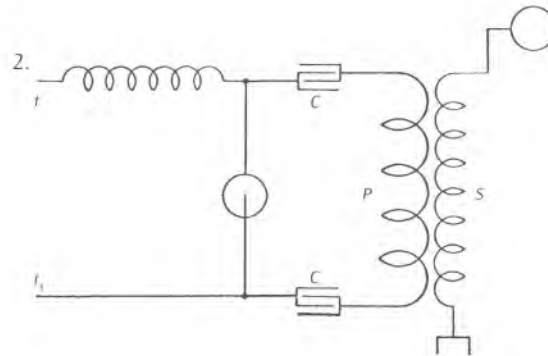
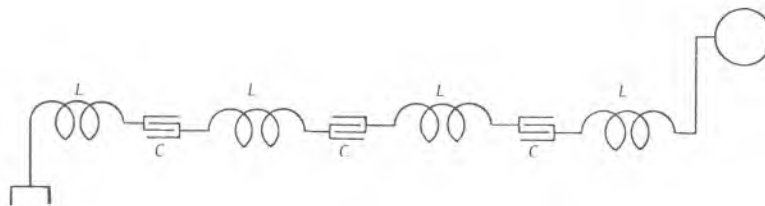


Fig. 2) supply circuit about 600 V; small condensers C , $\frac{1}{2}$ mfd. each, 1 turn primary. Both of the arrangements worked well, that illustrated in 2) more economical but waves longer.



3). Another way (and seemingly best) is to provide a secondary which consists of a number of elements comprising condenser and coil each of a high frequency of vibration and all joined in series. The primary vibration should be quick corresponding to that of each of the elements of the secondary. In this manner any e.m.f. may be secured, the secondary may be of any length yet it will vibrate quick.

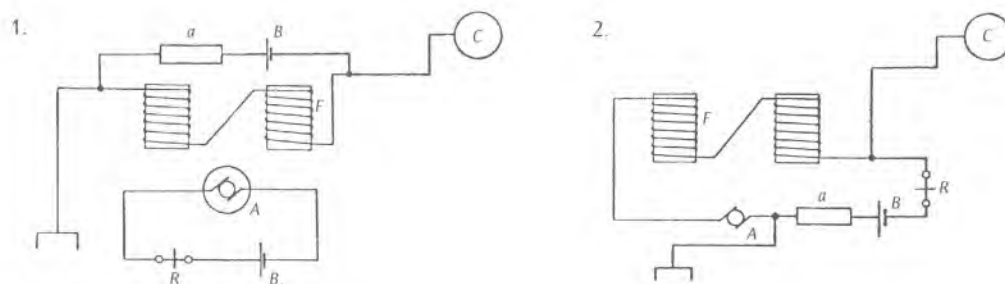


(To be followed up).

Colorado Springs

July 15, 1899

Some arrangements in telegraphy involving the Dynamo principle (first brought to Page some years ago)



Present apparatus built two years ago in New York, worked very well. Consider which the best of the following modifications: In case 1. sensitive device a with battery around field F . In armature circuit independently a receiver R and battery B_1 . The receiver may be a relay, and in addition, to insure

greater sensitiveness another sensitive device as a , may be joined in convenient manner in the armature circuit. In case 2. the armature and field circuits are joined in series and battery and receiver are in shunt to both, also sensitive device a . In both cases the sensitive device may be also in series with the field or field and armature though arrangements 1 and 2 seem preferable. In arrangement 3. a shunt dynamo is shown, the sensitive circuit being also in shunt to the terminals of the dynamo. In addition, to regulate excitation of dynamo a shunt of high self-ind. is placed around the sensitive device a . Such a shunt may also be used with good effect in Fig. 2.

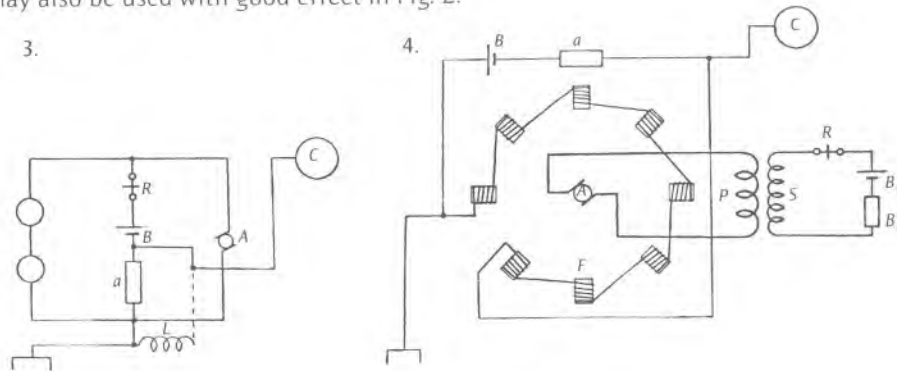
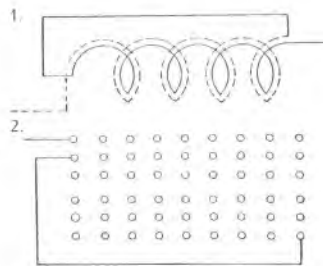


Fig. 4 illustrates one of the dispositions with an alternate and – preferably – high frequency dynamo. The letters are self-explanatory. The sensitive device a_1 may be omitted.

Colorado Springs

July 16, 1899

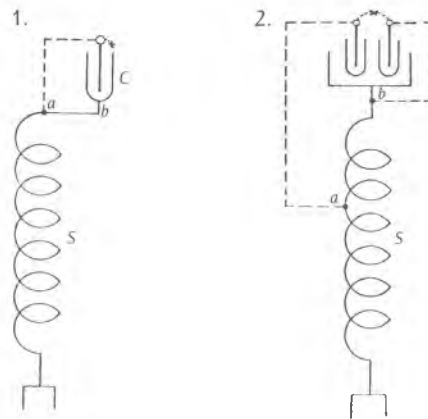
In order to produce the greatest possible movement of electricity through a region of the earth in accordance with the plan involving use of a single terminal oscillator, as here experimented with, it is desirable to obtain in some way a large capacity on the free terminal. This is connected with difficulty as spheres get to be too large with moderate tensions and when the tensions go into the millions, streamers can not be easily overcome. The streamers involve loss of pressure just as leaks would on a water pipe which is closed at one end. Large capacity is obtainable in a number of ways of which some are:



1) a coil wound for *maximum capacity* (internal). The turns are so disposed that between the adjacent turns of layers there exists a great difference of potential, as much as the insulation can stand. This is best done by following plan illustrated in Fig. 1 in which there exists between each two turns one half of the total difference of pressure which is active on the terminals of the coil. But other arrangements may be followed as, for instance, illustrated in Fig. 2, or similar dispositions may be made so that there shall be the greatest possible difference of pressure between the adjacent layers. Or the capacity may be increased by a conducting coating over the insulation of the wire, which coating may be connected suitably so to secure the maximum storage of energy in the coil;

2) A valuable way of providing capacity is to employ a vessel in which the gas is more or less rarefied. The electrodes leading in should be of wire gauze and present a large surface but throughout of small radius of curvature. Such a way of obtaining large capacity I find very good in telegraphy in connection with receivers and their circuits. Hydrogen seems to be better than other gases to employ in the rarefied vessel.

3) Capacity may be also provided by storage batteries or voltmeters or liquid condensers.



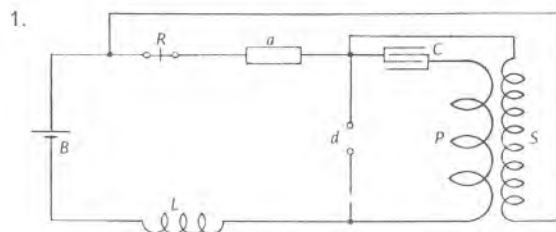
4) Another way is by local condensers arranged on end of wire near the free terminal. This is illustrated in annexed diagrams. In Fig. 1. and 2. two of the many arrangements are shown. In Fig. 1. a condenser is placed at the free end of the secondary S of the oscillator, the other end being connected to earth. One coating is directly connected to the end of the secondary, that is to b , the other coating to a point a which has a suitable difference of potential with respect to b . By the operation of the oscillator energy is stored in the condenser C , which energy must all be supplied through the secondary, thus producing a large movement in and out of the earth. A modified arrangement is shown in Diagram 2.

An arc may be maintained on the places marked x . Proper rules of tuning are observed to secure best result.

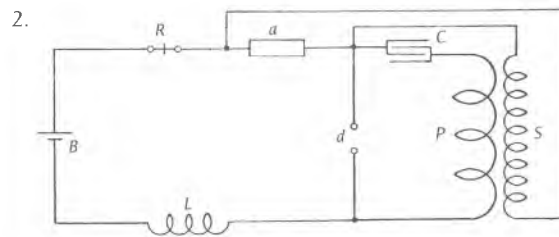
Colorado Springs

July 17, 1899

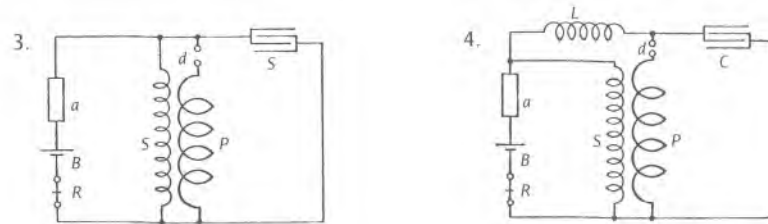
Some arrangements of apparatus experimented with. Modifications of former plans.



Here relay is placed in series with sensitive device but in secondary. In this way relay is not affected by break. The charge of condenser may be regulated by varying L or by resistances in series with L or with S .



The relay is affected by the break in this disposition but the action was good in some instances; probably secondary S was more effective in breaking through the sensitive device a .

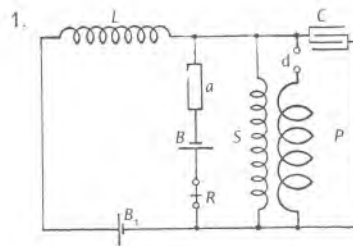


This disposition is simple and secures good results but one disadvantage has been found in the short circuit of the secondary through the condenser, which is necessarily too large for the high tension secondary since it fits the primary P . The above defect is reduced largely by the introduction of regulable self-induction L , or similarly a resistance is used instead of L . In all these dispositions of apparatus the effect upon the sensitive device is rendered accumulative.

Colorado Springs

July 18, 1899

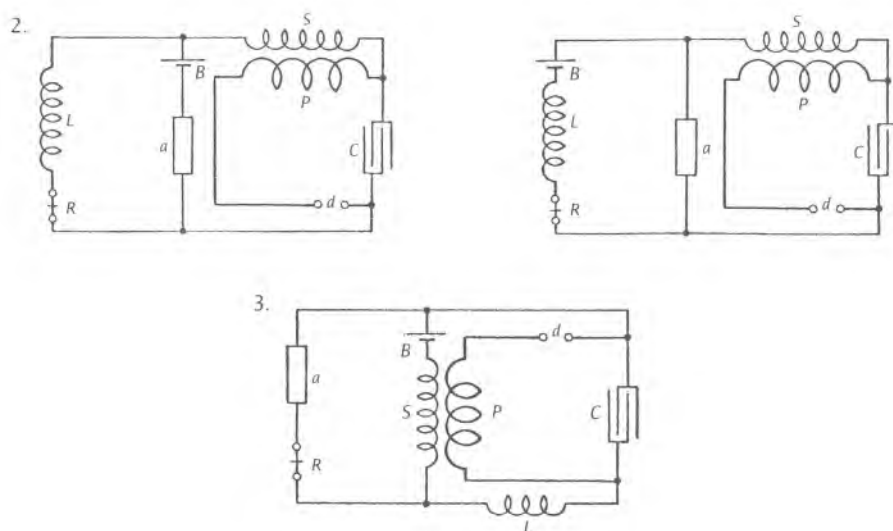
Other arrangements of apparatus experimented with



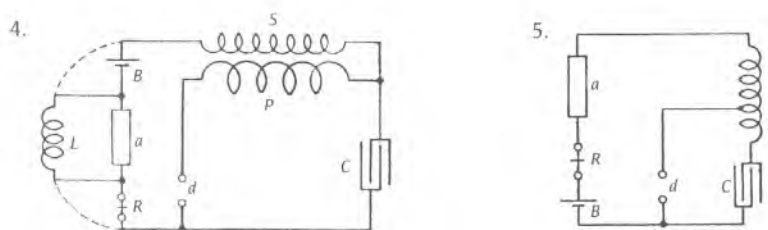
In this scheme the excitation of the condenser and therefore also of the sensitive device a was regulated by an adjustable self-induction and additional battery B_1 . The battery B can be in the same or opposite direction working through the device a . The former was apparently preferable.

Of these two connections the first was advantageous as the battery was not working except when the sensitive device was excited.

This was a plan (3) similar to one previously experimented with, only the battery B was placed so as to be able to charge the condenser.



To determine excitation of sensitive device to the point of breaking down a self-induction coil L (very high) was placed around it (4). This coil was also tried with connections changed as indicated by dotted lines.

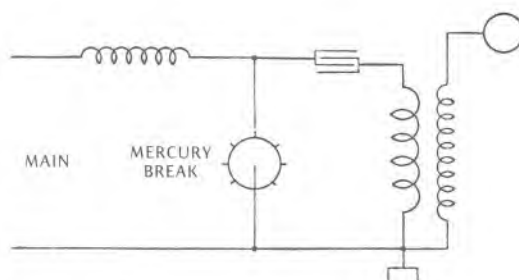


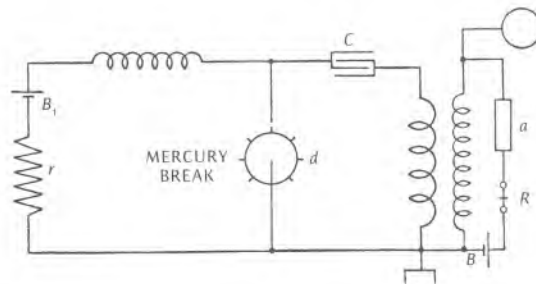
Here again (5) a part of secondary was used as primary. The arrangement worked well probably because as in some instances previously the secondary was open and the rise of pressure considerable upon a small excitation of device a . This is suitable for a device of great resistance.

Colorado Springs

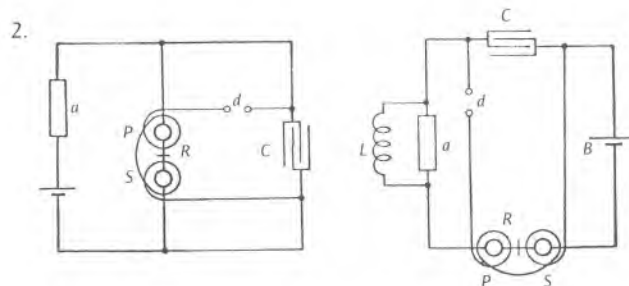
July 19, 1899

Some simple dispositions in the practical uses of apparatus as now available





The connections in the oscillator as now manufactured are as shown in first sketch. In this way the apparatus is used as a sender. The connections are now by a throw of a switch changed in such a way that all can be used in receiving the message. One of the simplest connections is shown in the following sketch. The relay R should have small self-induction. By battery B_1 the excitation of device a is regulated. For facility of adjustment a resistance r is also inserted. The switch is to be worked out in detail.



In using the method of exciting the device a by means of oscillating transformer the construction of a special apparatus may be obviated by winding the primary directly upon the relay so that the relay itself is the transformer. This is schematically indicated in the sketches in which the letters indicate the same. In the first the battery should be an open circuit, in the latter a closed circuit type.

Colorado Springs

July 20, 1899

Galvanometer from Colorado College set up on lead plate and four rubber supports

Lead plate 50 lbs. Resistance roughly 2530 ohms. The filament is very short, vibration quick, altogether not best quality but possible suitable for approximate determinations of ratios and resistance measurement etc.

1 dry cell 1.43 volt

$$i = \frac{e}{10,000 + \frac{2530 \times 100}{2630}} = \frac{1.43 \times 2630}{2630 \times 10,000 + 2530 \times 100}$$

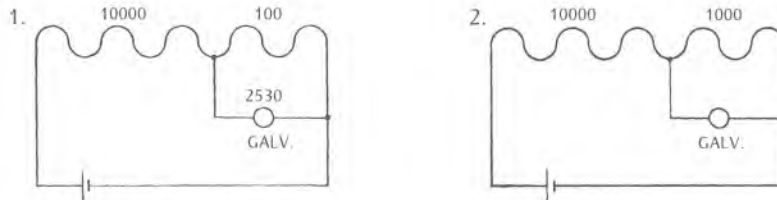
$$i = \frac{1.43 \times 263}{2,655,300} \text{ this gave 13.5 deflection.}$$

Now the current in galvanometer was

$$I = \frac{100}{2530} i \text{ or } I = \frac{10}{253} \times \frac{1.43 \times 263}{2,655,300} = \frac{376.09}{67,179,090} i$$

this gave 13.5 degrees of scale, hence K for one degree current

$$K = \frac{376.09}{67,179,090 \times 13.5} = \frac{1}{67,179,090 \times 13.5} = \frac{1}{2,411,438} \text{ approx. Will do for use intended.}$$

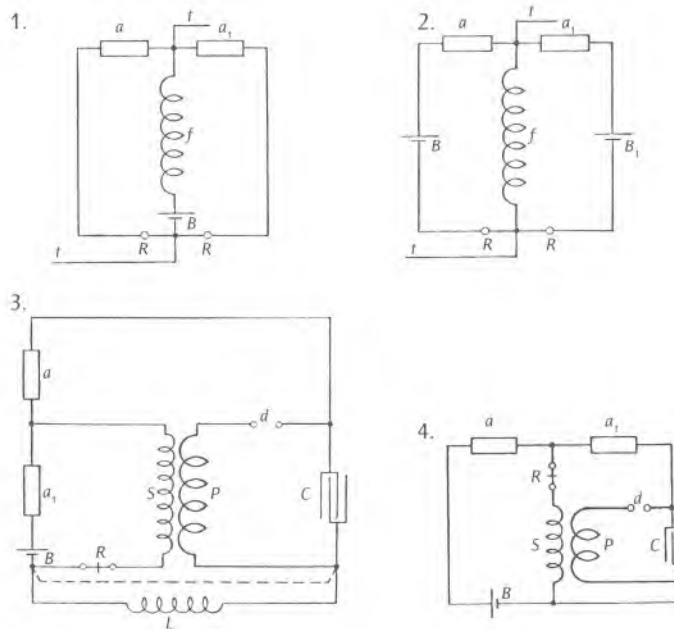


To test proportionality on scale the galvanometer was connected across 1000 ohms. This gave a deflection of 98° on scale. The currents computed were in both cases as $\frac{10,716.7}{100,961.9}$. This showed the necessity of increasing range of reading by placing scale further. For small deflections proportionality quite rigorous.

Colorado Springs

July 21, 1899

Various arrangements with two sensitive devices for the purpose of increasing efficiency of receivers in telegraphy. Also for directing currents



Two sensitive devices, disposed as indicated and so constituted that they break down or respond easier to impulses of one direction than to those of the other, allow the commutation of alternating

currents. For this purpose a device may be employed, described before, consisting of a glass tube and two metallic plugs, the glass tube being about half filled with nickel chips or fillings of other metal. In Fig. 1. it is supposed that the devices a, a_1 have this quality which may be given, for instance, by a battery in each circuit as shown in Fig. 2. In both sketches 1) and 2) a relay R, R is shown having one of its legs in one of the circuits and the other leg or coil in the second circuit. In this manner the impulses coming, for instance, from a distance as in telegraphy can be made to exercise an accumulative effect. The alternating impulses are led in through terminals tt .

Fig. 3. illustrates one of the connections of apparatus experimented with with good success. The method of excitation and magnification by means of an oscillating transformer is used and the relay and secondary were connected either as shown in the plain lines or in the modification indicated by the dotted lines. The letters have the same meaning as in previous instances. In Diagram 4. similar connections are shown, merely the self-induction coil L has been done away with and secondary S adjusted accordingly.

Figs. 5.—8. show again modified dispositions. Fig. 5.: the condenser is in the bridge and the legs of the receiver are placed one in each of the two circuits. In Fig. 6. the condenser is placed around a battery which is graduated by a resistance (not shown) so that the secondary S strains the devices a, a_1 to the point desired. Fig. 7. shows a similar plan with the secondary in shunt to one of the sensitive devices and in Fig. 8. two sensitive devices one in one and the other in the second circuit of which each contains a condenser and its own primary.

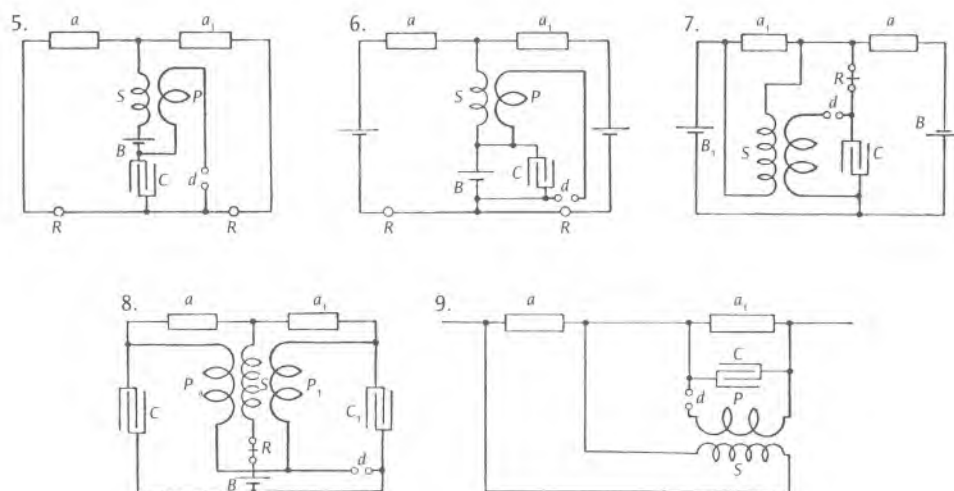


Fig. 9. shows a plan followed in numerous variations and which is capable of excellent results.

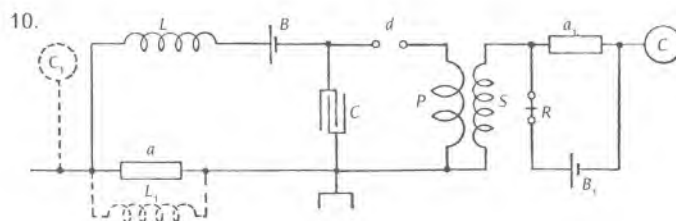
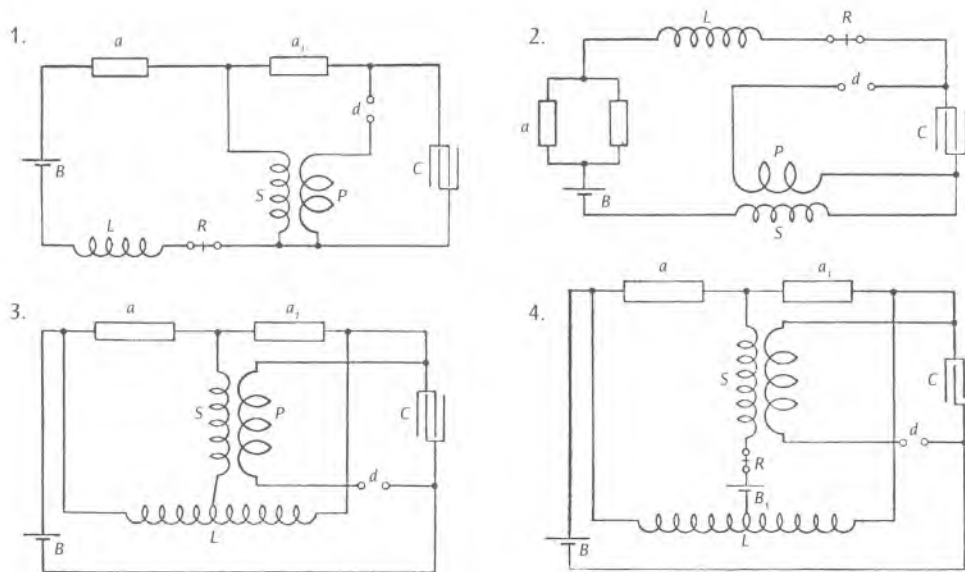


Fig. 10. again shows a form of connections which works extremely well. It is suitable for use in connection with single terminal oscillators. The capacity or elevated terminal may be at C and also at C_1 . Both cases result good.

Further modes of connecting apparatus with two sensitive devices for telegraphy and such purposes. A connection as in sketch showed quite satisfactory results. The sensitiveness was probably due to the fact that the secondary was open as in a previous instance. Several plans of working with two or more devices in multiple were experimented with. The idea was to introduce greater regularity and reduce resistance of the path through the sensitive apparatus. Some arrangements worked well, for instance the one illustrated in sketch 2. In 3. both devices a and a_1 were shunted by a high self-induction L , the inductive and ohmic resistance of which was regulated so that devices a and a_1 would break down at the slightest disturbance. The results were fair but not better than before obtained with other dispositions. The relay was placed in a number of ways, best results when it was in the secondary S .



In Diagram 4. the same mode of connection was employed, only a battery and relay were placed in the bridge. The employment of the special battery B_1 allowed some adjustments to be made not practicable in Diagram 3. Generally, battery B_1 was differentially connected with respect to battery B .

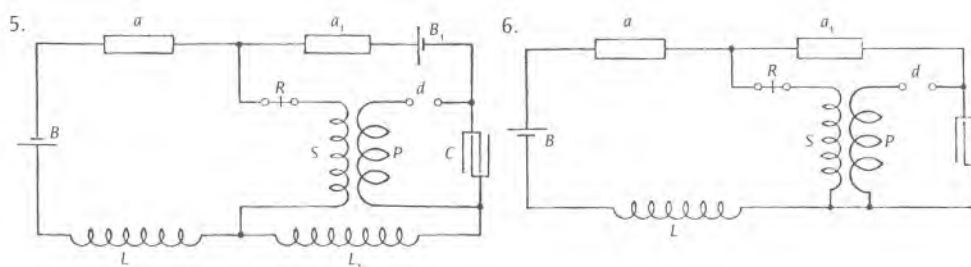
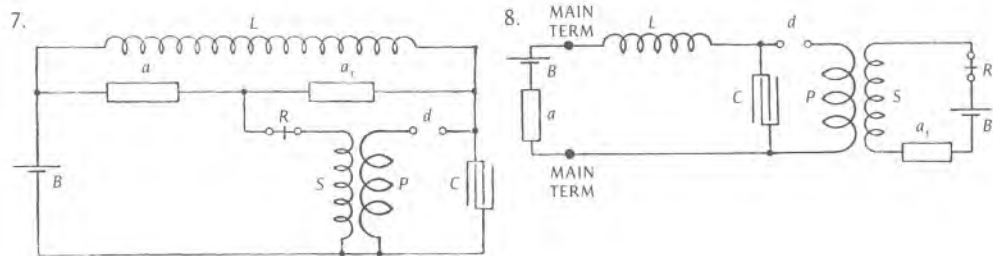


Diagram 5. again shows a form of connections slightly modified, two batteries being used in series to strain the sensitive devices a and a_1 . Results about the same.

In Diagram 6. the connections were as previously shown in Diagram 1. only the relay was placed in the secondary S . This worked *excellently*.

In Fig. 7. the same connections were retained only a high self-induction was connected around the devices and regulated so that devices were rendered very sensitive.

Fig. 8. shows an arrangement to be used in connection with present oscillator employed as sender. The switching connections are to be simplified. The oscillator with mercury break and its induction coil work *much better* than interrupters driven by clockwork and small special coils. *Important.*

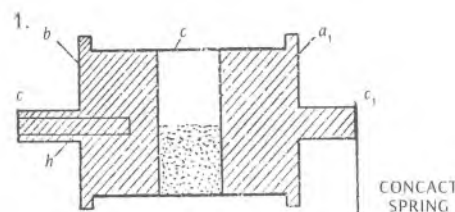


The employment of the mercury break particularly makes the apparatus efficient, probably because of perfect regularity of working which can not be secured by spring contacts or brushes. The efficiency is also in a measure due to the small resistance of primary circuit because of the large copper section and good mercury contact. It is highly important that in preceding dispositions of apparatus the break is of high frequency, the condenser large and best insulated and the conversion in coil *efficient*.

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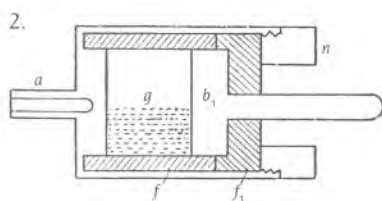
In investigating the propagation through the media, and more particularly through the ground, of the electrical disturbances produced by the experimental oscillator, as well as those caused by lightning discharge, to which work a few hours were so far devoted every day, a form of sensitive device used in some experiments in New York was adopted, as the best suitable for these purposes. This device, and the manner of preparing it, it is now necessary to describe. In one form it comprised a glass tube $\frac{3}{8}$ " inside diameter having two brass plugs fitted in its ends. The plugs had their inner surfaces highly polished and the distance between them was from $\frac{1}{8}$ "– $\frac{1}{2}$ ". The tube is illustrated in Diagram 1. in which a is the glass tube and b b_1 the plugs of metal with narrow projections C C_1 for support and contact, respectively.



The space between the plugs was filled about $\frac{1}{3}$ full with coarse chips of nickel. These chips were made by a milling tool or punch so as to be as much as possible equal in size and shape, this being of considerable importance for the good performance of the instrument. The plug b had a small reamed (tapering) hole h in the center extending to some distance into the plug so as to enable its being placed on a small arbor fitting into the hole and rotated by clockwork at a uniform rate of speed. In some cases when the working of the device was excellent the speed was 16 revolutions per minute. But often the instrument was rotated very much faster in which case it was merely necessary to increase the e.m.f. of the battery which was used to strain the device to the point of breaking down. A beautiful feature of this kind of device is that by regulating the speed its sensitiveness may be regulated at will and in this respect it is preferable to similar devices which are stationary, the contact after being established being broken by

tapping. The device acts exactly like a cell of selenium, its resistance diminishing when the disturbances reach it, being automatically increased in consequence of rotation and separation of the chips when the disturbances cease to affect the latter. The rotation of the device replaces here the property of recovery which the selenium possesses, otherwise the similarity is complete. To insure a quite satisfactory working and permanent state I prepare this form of device in the following manner:

The glass tube, plugs and the chips to be used are first thoroughly cleaned with pure absolute alcohol and dried. Next, one of the plugs, as *b*, is slipped into one end of the glass tube and the required amount of chips is put in the other, plug *b*₁ being finally inserted closing the tube *nearly* hermetically, but not quite so. Now the device is placed upon a cylinder of metal with a hole in the center, to allow the small part of one of the plugs *b* or *b*₁ to slip in, with some space between, and permit the plug to rest upon and in good contact with the upper surface of the metal cylinder which is then slowly heated, as by being placed upon an electrical stove or a plate supported above an alcohol lamp. When the lower plug is brought to the required temperature, sealing wax is run around the rim projecting for this purpose, beyond the glass tube. The metal cylinder is now allowed to cool down slowly until the sealing wax is in some degree solidified when the instrument is turned over and placed with the other plug on the cylinder and the operation of sealing the joint between glass and plug repeated. During this preparation the chips are of course at an elevated temperature and all moisture is expelled so that, when the instrument is ready, a thoroughly dry atmosphere exists within the same, this being essential for good performance.



The atmosphere is, however, at a pressure slightly below that of the surrounding air. When the device is carefully prepared it works remarkably well, and in comparative tests showed itself superior to this kind of device of the form ordinarily advocated. During a few days I carried on tests of this kind which brought out the good qualities of this kind of instrument. In one instance two of them were compared with a third device of the ordinary form in which the sensitive grains were immersed in an atmosphere considerably rarefied and contact was broken with a tapper. In all three instruments the grains of nickel were of the same size and shape. One of the terminals of each of the devices was connected to a ground wire, while the other terminals were each joined to a piece of wire extending to a small height, these pieces of wire being the same in all particulars. All the three devices were strained as far as was practicable by batteries so as to be at the point of breaking down and sensitive to a high degree. Although the pieces of wire extending into the air were only of a length of a few feet, all the instruments recorded the discharges of lightning up to about 30 miles as the storm moved away. At this point it was found necessary to set the instrument with the "tapper" so that it was still more sensitive when it responded but in an irregular manner, while the other two devices continued to record regularly up to a distance of about fifty miles when the disturbances ceased, probably owing to the cessation of the storm. I inferred from these experiments, carried on for some time with the view of selecting and adopting the best form of such a device, that when the particles of metal are rotated they are, as it were, suspended in the air and in this condition more susceptible to the influence of the disturbances than when they are kept stationary. It seems, however, that when rotated, the particles are not so liable to stick together and cause irregularity of action such as observable in the ordinary form of such a device. As to the amount of chips, if more are put in the instrument must be rotated at a higher speed or else the battery straining the dielectric must be weaker. Through this kind of instrument much stronger currents can be passed without damaging it and making it further unfit for work. Another form of such instrument particularly suitable for experimentation is illustrated in Diagram 2. It consisted of a brass plug *b* with a fibre tube

into which was fitted another brass or metal plug b_1 which was held in place by a fibre washer f_1 and metal nut n . In other devices of similar construction the space between the plugs was adjustable. This form of instrument was particularly suitable for testing the properties of sensitive grains g . Before testing the grains and the instrument as well were thoroughly dried. To get an idea of the resistance of such devices when in either state, excited or not, the resistance of many was measured under varying conditions. A fair idea is conveyed by saying that, unexcited, they measured more than 1,000,000 ohms while the resistance would sink down to 300 or even 50 ohms or still less when excited. When highly sensitive they would respond to sound waves at a considerable distance.

Experiments with oscillator 35 turns in secondary on tapering frame No 10 B. & S. wire

This is the first test of the Westinghouse transformer installed a few days ago. It was tried yesterday evening but only for a short time to merely get an idea how it will behave. The e.m.f. used was 7500 volts or less. Today a pressure of 15,000 volts on the secondary was used. Best resonating action was obtained with one primary turn and a few turns in the regulating coil. The spark gaps were as long as obtainable in the box, that is, about 7 turns of the screw on each side, possibly an inch or so. An approximate estimate places the primary inductances at 75,000 cm. or $L_p = \frac{75}{10^6} H$. The primary capacity was 88 jars in each of the sets in series. The capacity of one jar being approximately 0.0035 mfd. The total capacity C_p is 0.154 mfd. From this calculated, and neglecting as in most cases before the reaction of the secondary, we get $T = \frac{214}{10^7}$ or $n=46,730$ per second.

Observations: A spark gap being established between the free terminal of the secondary and an earthed wire, strong streamers were seen on the *latter*. This shows very rigorous action and demonstrates that the potential of the neighbouring parts of the ground must be considerably affected. *Very strong* sparks on lightning arresters as the secondary discharge is playing over the gap. This is certainly *extraordinary* as the ground is now excellent on the secondary. The arc, horizontally passing about 32" long is very powerful, thick and giving a vivid light, the noise is deafening. The arc passes sometimes on a downward course. Is it attraction or due to surgings of the air in consequence of violent explosions? When large balls 30" diam. are placed in the gap the spark length is nevertheless small. This shows the secondary can not supply the great amount of energy necessary for charging the large balls to full pressure. This may be due simply to the imperfect inductive connection with the primary or to the small amount of power now available from the supply transformers, as there are only two of them, and the Westinghouse transformer works only at $\frac{1}{4}$ of the normal pressure. This would mean roughly $\frac{1}{16}$ of its total performance. On some points of the balls small streamers are observed; must be due to roughness or points on the places. The balls will have to be gone over and all the surface polished up. It would be impossible for streamers to break out from balls of such size unless the pressure is a few millions of volts, which cannot be the case at present. A curious feature is to see the sparks deviate and follow wooden beams or planks placed nearby. I rather think this is merely due to an effect of the currents of air which are prevented from circulating freely on the side of the plank or beam. The intensity of the vibration in the primary is evidenced by sparks passing between the turns of the regulating self-induction coil in the primary. Between the beginning and end of the coil, although only a few of the turns are inserted, the sparks are sometimes 3" long. This shows a very high e.m.f. on the primary and I almost think there must be a mistake as to the pitch estimated which, judging from these sparks, would seem to be much higher. This is to be investigated closer. Experimentation shows that it is very decidedly better to adopt one turn of primary instead of two and if a lower frequency is desired rather to increase the primary capacity. With one turn the explosions are more violent and the regulation is much more convenient. In these experiments the jars do not seem to be much strained, which indicates well. At times sparks will break through inside of the secondary between the turns and to the ground. The sparks are very strong from small wires attached to the free end of the secondary more so than

from thick wires. When a coil was connected to the free secondary end the vibration could not be well established, evidently the coil was "out of tune" and by its capacity and inductance interfered with the free vibration of the secondary. The sparks went from the gap-box to the ground though the box was well insulated; there is danger of inflaming the building by this or by the secondary sparks following the wooden structure. The experiments were continued with 7500 volts as yesterday but the working was unsatisfactory. This showed finally that yesterday one of the jars in one set was bad and there was only one set acting, the other set being short circuited; that is why an e.m.f. of 7500 volts was sufficient yesterday. The Westinghouse transformer gains in e.m.f. as jars are put on, the maximum rise seems still remote, this argues well for the economy of the transformer. The incandescent lamps are all destroyed in consequence of the intense secondary vibration, the filaments being broken by electrostatic attraction towards the glass. Lamps were spoiled at a distance of 40 feet from the secondary free terminal! This action is likely to give trouble in future experiments. A curious observation is that all horses shy. It is due to sound or possibly to current action through the ground to which horses are highly sensitive either owing to greater susceptibility of the nerves or perhaps only because of the iron shoe establishing good ground connection. I am not quite certain that the secondary vibration is fundamental although for a lower or higher tone it is too powerful. The external gaps used in some trials seem to improve the action somewhat in rendering the discharges of the primary more *sudden*. If time should permit the vibration will be investigated by a rotating mirror to be prepared.

Colorado Springs

July 24, 1899

Experiments with the secondary 35 turns were continued today. In connection with the secondary an "extra coil" was used. The same was before described having 260 turns on a drum 2 feet in diam. of cord № 10. The inductance of the coil as before found was 139 approximately $\frac{139}{10^4}$ henry. The coil was connected with the lower end to the free terminal of the secondary while the upper end was left free, a few feet of wire extending into the air. Resonance, as evidenced by streamers (maximum) on free end of coil, was obtained exactly as in a previously recorded experiment with 9 jars in each set of the primary condensers, or slightly less, at any rate 8–9 jars caused the largest display of the streamers on the free end. The streamers were only three feet long as the energy from the supply circuit was limited, the intention being to first study the peculiarities and behaviour of the transformers before taking them to their full output. A simple computation showed that the resonant rise on the free end was chiefly, if not wholly, due to the rise in the coil itself, the free vibration of the secondary being comparatively of small moment. To study the harmonics the capacity in the primary circuit was doubled but the effect, as expected, was very small. Now the capacity in primary was again doubled, it being expected that the streamers would be of considerable power under these conditions. This was the first undertone and it should have been fairly strong. But singularly nothing to speak of was noted although the adjustments were carefully gone through again and again. It was thought that owing to a very small arc in the primary the oscillation did not readily establish itself but this was not highly probable though such has taken place in experiments which I made before. The arc was necessarily small as the capacity was very large in the primary. The tuning was very sharp with twice the capacity in primary so that a little variation in the self-induction regulating coil made the streamers change very considerably. I expect that it was sharper still with four times the primary capacity so that, after all, the resonant condition may have been missed. This might have been the case easily as all the variation from no streamers to their *maximum* would have taken place by going through only one *quarter of one turn*, and possibly less, of the regulating coil. This sharpness of tuning noted here and in previous instances in some arrangements

again impresses me with the value of such dispositions in telegraphy, when it is of great importance to isolate messages. It seems possible to secure in such or similar ways an almost absolute privacy. The experiments with only two circuits show this sufficiently. Continuing the experiments one of the balls of 30" diameter was connected to the free end of the coil and now the resonating condition was secured with 23 jars on each side of the primary. Summing up the results the vibration with coil alone, without ball, with 9 jars on each side of primary was, approximately, taking the primary capacity equal to $\frac{9}{2} \times 0.003 = \frac{0.027}{2} = 0.0135$ mfd.

$$T_1 = \frac{2\pi}{10^3} \sqrt{0.0135 \times \frac{7}{10^5}} = \frac{2\pi}{10^3} \sqrt{\frac{945}{10^9}} = \frac{2\pi}{10^7} \sqrt{94.5} = \frac{2\pi}{10^7} \times 9.72 = \frac{61.0416}{10^7} \text{ or approx. } \frac{61}{10^7}$$

and $n=164,000$ per second.

Now when the ball was attached the primary capacity was

$$\frac{23}{2} \times 0.003 = \frac{0.069}{2} = 0.0345 \text{ mfd.}$$

and the period

$$T_2 \text{ was } = \frac{2\pi}{10^3} \sqrt{0.0345 \times \frac{7}{10^5}} = \frac{2\pi}{10^3} \sqrt{\frac{2415}{10^9}} =$$

$$T_2 = \frac{2\pi}{10^7} \sqrt{241.5} = \frac{2\pi}{10^7} \times \frac{2\pi \times 15.54}{10^7} = \frac{97.6}{10^7} \text{ and } n=102,460 \text{ per sec.}$$

The ball slows the vibration of the coil very much down. From a series of observation with capacities of varying value useful estimates may be made and the quantities of moment calculated. This mode of proceeding seems to offer features of considerable value in experimentation and it will be followed up. A curious observation in these experiments was that maximum rise was obtained always with the regulating coil practically all out. *How is this to be explained?*

Experiments with the secondary 35 turns were resumed

The probable causes of the curious phenomenon that maximum resonant rise (on the coil attached to the terminal of the secondary, as before described) took place when the self-induction regulating coil was practically all cut out – were considered. Evidently when the coil was cut out there was more energy available for the excitation of the primary turn and therefore the secondary was more strongly energized, this giving a higher electromotive force on its terminals. Owing to this the impressed e.m.f. on the coil attached to the free terminal of secondary was greater and therefore the coil was more strongly excited. Assuming then that the secondary free vibration did not take place, this explanation would be acceptable but for one thing: the maximum rise on the coil with 260 turns did not occur, when *all* the turns of the primary regulating coil were cut out, but at a point when there remained still a few turns in series with the primary. The phenomenon must be therefore interpreted differently. To all appearances the secondary free vibration *did* occur, and there was a certain inductance in the primary which gave the highest e.m.f. on the excited coil on the free terminal of secondary. But now the latter was in fairly close inductive relation with the primary hence its own vibration was more or less modified by that of the primary. In altering the primary vibration, that of the secondary must have been, therefore, correspondingly altered. Now, the secondary excited the coil with 260 turns and, to insure the maximum rise on the free terminal of the coil, the secondary vibration ought to have been of exactly the same pitch as the free vibration of the coil. From this it is plainly seen that if the primary vibration was such as to favour a rise in the secondary of the pressure at the free terminal then the impressed e.m.f. on the coil with 260 turns was greater; but this evidently, judging from the actually observed results, took place

when the secondary vibration was "out of tune", more or less with the free vibration of the coil. Thus it happened that by raising the secondary e.m.f. up to a certain point there was an increased resonant rise on the excited coil. But when, by further cutting out turns of the regulating primary coil, the secondary vibration was modified more and more and brought "out of tune" with the free vibration of the coil excited by the secondary, the resonant rise on the terminals of the excited coil was diminished. Now, with a certain small number of turns of the regulating coil still included in the primary, the relation between these opposing elements determining the resonant rise was such as to insure the maximum. I have no doubt that this is the correct explanation of the phenomenon observed. At first I thought that the *length of the primary* might have something to do with it, as I have observed before something to this effect, but now I must reject this view as improbable. From the preceding it is now quite evident that in cases when the free vibration of the secondary can assert itself, the primary capacity and self-induction has to be such that maximum e.m.f. is obtained on the secondary – then the excited coil must be such as to vibrate in accord with the secondary or (inasmuch as the secondary vibration is affected by the primary) the free vibration of the excited coil must be the same as that of the combined primary and secondary system. When the vibration in the secondary is exactly the same as the free vibration of the excited coil the maximum rise will be obtained on the coil, in any event, but for the best result the secondary must also be tuned to the primary so that greatest impressed e.m.f. is secured on the coil.

In cases where the secondary is in such intimate inductive connection with the primary then the latter condition need not be considered and it is only necessary to adjust the coil so that it will have the same period as the oscillation in the secondary. In fact, I believe this will be, in the end, the best condition in practice for, if the transformer be efficient, the connection between the primary and secondary must be a very close one. In such a case the high impressed e.m.f. on the excited coil will be obtained only by transformation and not by resonant rise.



A gratifying observation was made today which was the following: the water pipe to which the secondary lower end was connected, and which conveyed the currents to the ground, was disconnected from the secondary and the latter connected to a separate ground plate at a distance from all other ground connections. Everything was carefully examined to be quite sure that there was no other ground connection in the secondary. Nevertheless, when the secondary discharge was made to play, *strong sparks went continuously over the lightning arresters*. There was no other possible way to explain the occurrence of these sparks than to assume that the vibration was propagated through the ground and following the ground wire at another place leaped into the line! This is certainly extraordinary for it shows more and more clearly that the earth behaves simply as an ordinary conductor and that it will be possible, with powerful apparatus, to produce the stationary waves which I have already observed in the displays of atmospheric electricity. The mere observation of the sparks speaks well for the power of the apparatus used and clearly shows that it is competent to carry to a great distance even as it is when used as a transmitter in telegraphy. Assume even that the pressure would diminish as the square of the distance from the source, still the performance would be remarkable. Such an assumption seems to be justified when we consider that the density of the current passing over the earth's surface will diminish as the square of the distance from the center of the disturbance and consequently, the effective pressure at least, ought to diminish correspondingly. Now, in the experiments above described the distance between point *a*, where the lower end of the secondary was grounded to point *b*, where the sparks jumped from the ground to the line or vice versa, was 60 feet. Hence on the above assumption we can make the ratio $\frac{E}{e} = \frac{x^2}{60^2}$, where *x* will be in feet. At the lowest estimate *E* was 10,000 volts and assuming

an ordinary instrument be used as a receiver, requiring $\frac{1}{10,000}$ of a volt= e between c and d , we would have $x^2 = 60^2 \frac{10,000}{1} = 36 \times 10^{10}$ or 600,000 feet or $x=114$ miles nearly. But by making the distance between c and d much greater the transmission radius may be *greatly* extended.

Capacity of secondary 35 turns used in preceding experiments

The average length of one turn may be put at approximately 135.1 feet=4120 cm. The wire is No 10 B. & S. diam=0.102"=0.26 cm. Surface of wire in sq. cm.= $\pi \times 0.26 \times 4120 \times 35 = \pi \times 37,500$ cm. approx. The capacity was compared with that of $\frac{1}{2}$ mfd. standard condenser and was found to be $C=3600$ cm. This measurement was I expect correct within $\frac{1}{2}$ %.

Note: The measurement was made by connecting the cable with one end, or with *both* ends to the source, the other terminal of which was connected to the earth. *Result* was the *same*.

Now it is of interest to compare the value found by measurement with that which the cable would have when stretched out. Its capacity would then be $C_1 = \frac{l}{2 \log_e \frac{l}{r}}$ considered as a cylinder remote from the ground. Taking the values as above

$$C_1 = \frac{4120 \times 35}{2 \log_e \frac{4120}{0.13}} = \frac{4120 \times 35}{2 \log_e 31,700} = \frac{2060 \times 35}{\log_e 31,700} = \frac{2060 \times 35}{4.50106 \times 2.3} = \frac{2060 \times 35}{10.35244} = 6965 \text{ cm.}$$

If we consider the cable in its capacity with reference to the earth or conducting plane its capacity would then be $C_2 = \frac{l}{2 \log_e \frac{2d}{r}}$. Since we have found the measured value we may find from it the

distance d ; we have $3600 = \frac{4120 \times 35}{2 \log_e \frac{2d}{r}}$ from which $\log_e \frac{2d}{r} = \frac{4120 \times 35}{2 \times 3600} = 20.3$ and this gives

$$\log \frac{2d}{r} = \frac{20.3}{2.3} = 8.82607, \text{ hence } \frac{2d}{r} = 67,000,000 \text{ cm.}$$

$$d = \frac{67,000,000}{2} \times \frac{13}{100} = \frac{670,000 \times 13}{2} = 670,000 \times 6.5 = 67,000 \times 65 = 44,550 \text{ meters!}$$

The result only shows that the cable measures much more when straight and at some distance from the ground since d comes out so large.

It may be of further interest to compare the capacity as found with capacities which would be obtained if the surface of the cable were converted into the surface of a disc or sphere, for instance. Taking first the latter and calling its radius r' we have $4\pi r'^2 = \pi 37,500$ and $r'^2 = \frac{37,500}{4}$, $r' = \frac{\sqrt{37,500}}{2} = \frac{193.65}{2} = 96.825$ cm. and this should be the theoretical capacity C_1 of the sphere. Taking now a disk of radius R , its capacity C_2 would be $C_2 = \frac{2R}{\pi}$. Now on the above assumption of an equal surface we would have $2\pi R^2 = \pi 37,500$, $R^2 = 18,750$ and $R = \sqrt{18,750} = 136.93$ cm. Hence $C_2 = \frac{273.86}{\pi} = 87.2$ cm. This is still smaller than the capacity of a sphere of the same surface. Suppose now the surface of the cable were converted into small spherical surfaces of a diameter equal to that of the cable and inquire what capacity would be obtained in this manner with the given surface. The surface of one of the small spheres being $4\pi r^2$ and calling their number n we have $4\pi n r^2 = \pi \times 37,500$ and

$$n = \frac{37,500}{4r^2} = \frac{37,500}{4 \times 0.13^2} = \frac{37,500}{4 \times 0.0169} = \frac{37,500}{0.0676} = 554,734 = n$$

The total capacity C_3 of all these small spheres, neglecting mutual screening action, will be n times the capacity of one of the spheres and since the latter is $=0.13$ we would have total capacity $C_3 = 554,734 \times 0.13 = 72,115$ cm.! A very large value indeed, which would have been still greater if the diameter of the spheres would have been smaller. These primitive considerations show that to get the largest possible capacity with a given surface we must use the latter in the form of minute surfaces of the smallest possible curvature. This makes it obvious why exhausted bulbs show under certain conditions such comparatively large capacity. And this explains the virtue of bulbs when used in telegraphy for the purpose of supplanting a large elevated plate or wire leading to a great height. Such a bulb or tube, particularly when filled with *hydrogen*, is (as I have found) very effective and I look to a valuable use in the future of such rarefied vessels in connection with telegraphy through the media or the like. The greatest capacity with a given surface will, of course, be obtained with spheres of the smallest possible diameter, as the spheres of hydrogen. The next best form to give to the surface would be a cylinder of great length and minute diameter. The above considerations make it plain why thin wires have such a comparatively large capacity. Taking two such wires of the same length L and diameters δ and δ_1 , we would have their capacities as

$$\frac{L}{2 \log_e \frac{2L}{\delta}} : \frac{L}{2 \log_e \frac{2L}{\delta_1}} \text{ or as } 2 \log_e \frac{2L}{\delta_1} : 2 \log_e \frac{2L}{\delta}.$$

Now suppose, for the sake of illustration, that $\frac{2L}{\delta}$ were $=10$, and $\frac{2L}{\delta_1} = 1000$, then the above capacities would be as $\frac{1}{2.3 \times 3} : \frac{1}{2.3 \times 1}$ or as $\frac{1}{3} : 1$. In other words, making the diameter of one wire 100 times as great as that of another, but keeping the length of the wires the same, the capacity of the thick wire or cylinder would be only three times that of the thin one.

Colorado Springs

July 25, 1899

Experiments with the secondary of 35 turns continued

The secondary was tuned alone and more carefully, the result being that maximum rise of pressure was obtained *with one turn of the primary*, the two cables being connected in multiple, and 78 jars on each side of the primary. When best action was obtained there were a few turns in the regulating coil in series with the primary cables, the total self-induction in the primary being estimated to be $L_p = 85,000$ cm. or $\frac{85}{10^6}$ henry.

The capacity in primary was: $\begin{cases} 16 \text{ old jars} = 0.00334 \times 16 = 0.05344 \\ 62 \text{ new " 10\% larger} = 0.0036 \times 62 = 0.2232. \end{cases}$

$$\text{Total} = \frac{0.2766}{2} = 0.1383 \text{ mfd.}$$

This would give period of the system:

$$T_p = \frac{2\pi}{10^3} \sqrt{0.1383 \times \frac{85}{10^6}} = \frac{21.54}{10^6} \text{ and } n = 46,425 \text{ per. sec.}$$

It is of interest to find what value for the inductance of the secondary will be obtained by substituting in the equation for the secondary $T_s = \frac{2\pi}{10^3} \sqrt{L_s C_s}$, the value for C_s found by measurement before recorded. Since T_s must be $= T_p$ we have

$$T_p = \frac{21.54}{10^6} = \frac{2\pi}{10^3} \sqrt{L_s \times \frac{3600}{9 \times 10^5}} \quad C_s = 3600 \text{ cm.}$$

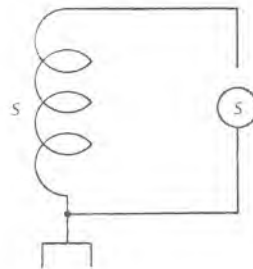
$$\text{or } \frac{2\pi}{10^3} \sqrt{0.1383 \times \frac{85}{10^6}} = \frac{2\pi}{10^3} \sqrt{L_s \times \frac{3600}{9 \times 10^5}} \text{ and from this:}$$

$$L_s = \frac{9 \times 10^5}{3600} \times 0.1383 \times \frac{85}{10^6} = \frac{0.1383 \times 765}{36,000} = \frac{0.1383 \times 85}{4000} \text{ henry or}$$

$$L_s = \frac{10^9 \times 0.1383 \times 85}{4 \times 10^3} = \frac{138,300 \times 85}{4} = 2,939,000 \text{ cm. only!}$$

While this estimate is not correct in principle it shows, nevertheless, that the capacity measured in a state of rest is not that which enters as an element of the vibration. It was thought from this result that the secondary might have responded to the first octave and the two primary cables were joined in series, but results proved inferior.

It is possible that when the primary cables were connected in series, owing to the less satisfactory working of the spark gap, the e.m.f. on the secondary was smaller than it ought to have been if both the primary and secondary vibrated at the same rate. Furthermore, it should be borne in mind that when the cables were in series and the vibration in primary reduced to half the number per second, the induced e.m.f. in the secondary turns could have been only about one half of that in the first experiment. If in the latter experiment with the primaries in series the true note of the secondary was struck then, assuming the capacity to be 3600 cm. or thereabouts, the inductance of the secondary as modified by the primary would have been still only $4 \times 2,939,000 = 11,765,000$ cm. It is, therefore, probable that the capacity which enters as an element of the secondary vibration is much smaller than that which is found by measurement, which is as might be expected, since the cable can not be fully charged and discharged at each alternation, as is evident from the constants.



Observations during the experiments today. When the secondary worked very well the spark was very noisy and nearly an inch thick, judging by the eye, and about 3 feet long. The sparks passed all the time over the lightning arresters as the secondary discharge was playing and, at times, for a short interval they were extremely vivid and thick. This seemed to occur chiefly when the secondary arc became louder and roaring, this indicating a better working of the arc and a higher e.m.f. for a given length of the path through the ground. The sparks on the arrester's arc, as is now established beyond any doubt, are due to the propagation to the ground through the earth wire, and it is now plain that although they take place when the oscillation is slow, they are more easily produced with a quicker oscillation. Perhaps the higher harmonics enter prominently into their formation. The secondary arc was adjusted to a length of 31", then the sparks on the arresters were very violent. It was thought that, if the vibration was propagated through the earth wire and caused the sparks on the arresters in this way, by adding capacity to the earth wire the action on the arresters would be increased. Accordingly, a sphere of 12" diam. *s* was

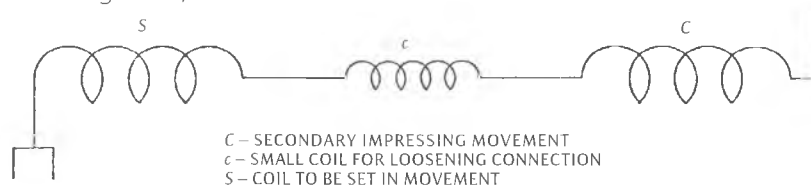
connected to the wire as shown in diagram and, indeed, the play on the *arresters* was *intensified*. By now reducing the gap still a few inches the display on the arresters seemed to increase further. When the secondary discharge was permitted to pass continuously for about 5 minutes the fuse on the supply circuit primary gave way showing that energy was taken at a rate of about 20 H.P. This also indicated that the connection between the primary and secondary of the oscillator was fairly close and that the secondary was capable of taking up considerable energy. When two external gaps were used in series, with gaps in box, less energy was taken from the supply circuit, this indicating that the arc in primary short-circuited the secondary of W.T. to some extent.

Colorado Springs

July 26, 1899

Investigating vibrations of "additional" or "extra coil"

From observations before made it would appear, as I believe it has been stated already, that when the impressed electromotive force was increased, in other words, when the movement in the secondary was made greater, the free vibration of the extra coil did not readily assert itself. At least this has been noted in a number of experiments with the object of ascertaining this. A complete analogy is afforded in mechanics. In order that free vibration may take place, and readily, there must be a loose connection with the part impressing the movement. This truth is obvious. Considerations of this kind led to experimentation with an arrangement, as illustrated in the sketch below: In this the connection with the

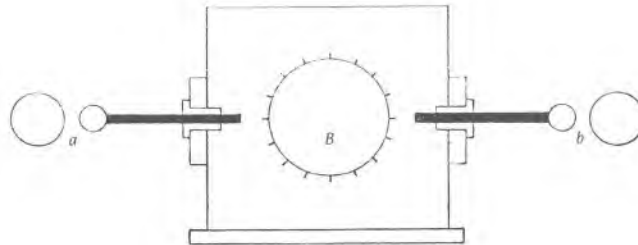


secondary S impressing the movement was loosened, so to speak, by the insertion between it and the coil C to be excited another coil c which was generally adjusted to suit the conditions. This amounted to the same as increasing the momentum of coil C and rendering it more preponderating and capable of freely asserting itself. These experiences lead to a rule long recognized, that development of the oscillator must be in two directions: either in the direction of obtaining a high impressed electromotive force by transformation ratio, when the connection between the secondary and primary is *rigid*; or obtaining a high e.m.f. by an excited extra coil in loose connection not reacting inductively.

Colorado Springs

July 27, 1899

Experiments were made today with spark gaps constituted as indicated in the sketch below:



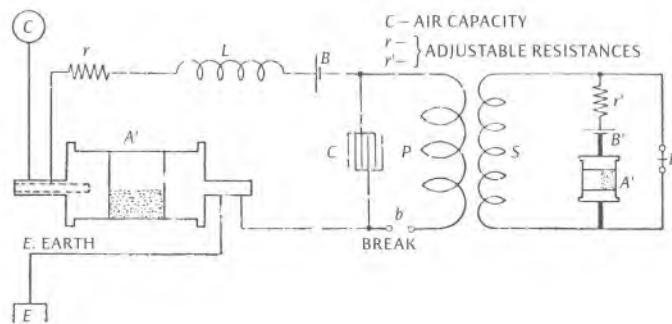
The idea in this scheme was to make gaps in the box, which varied from a very small to a great length owing to the movement of the break wheel *B*, very small and the gaps *a* and *b* very large, so large that the discharge could break through only when the gaps in the box were at their minimum length. Thus the loss in the box itself was greatly reduced and owing to the great velocity of separation of the electrodes, a greater suddenness of disruption was obtained. This was, of course, certain since the gaps in the box could not be bridged except for a short interval since gaps *a* and *b* took up the e.m.f. Thus the velocity of separation was the greater the smaller (in length) the arcs in the box were made. The adjustment of their length was effected by merely varying the length of gaps *a* and *b*. In these experiments spheres of various sizes were used to constitute the additional gaps *a* and *b* and it was observed that unless the induction coil be capable of giving a large current, spheres of considerable size were not the best to employ in the usual arrangement of apparatus. The reason was that the arc was formed with difficulty, hence it had to be made shorter, but when the current broke through, the resistance of the small arc was very low and the secondary of the induction coil was short circuited too much. This may not be always true. By using additional gaps the primary was closed during a shorter interval of time and also the secondary was less short-circuited. The latter was an advantage but the former was decidedly a disadvantage because the primary circuit could not vibrate very long. The energy taken from the supply transformer or coil was, of course, smaller. All the results obtained in these experiments seem to indicate, contrary to former opinions, that a higher economy is obtainable with one gap that with a greater number. This observation was, however, made before in the New York apparatus. Finally, two gaps in series were adopted as convenient and giving greater velocity of separation. But the best results were obtained with two electrodes in the form of toothed disks rotated in opposite directions. The apparatus in this form was more troublesome to run but worked decidedly better. In this form also an improvement was practicable, which I have since adopted in some form of mercury breaks, and that was to make the number of teeth on each disk such that the total number of the makes and breaks was the product of both the numbers. In this form a small number of teeth was found sufficient for a great number of breaks and the arc could not follow from one to an adjacent tooth.

Colorado Springs

July 28, 1899

The following arrangement was found particularly efficient in applying the method of magnifying the effects of feeble disturbances by means of a condenser. Two instruments were fixed up in the manner indicated in diagram. A similar plan of connections was used before only the sensitive device *A'* was differently placed, as it was found to disadvantage. The sensitive devices *A* and *A'* were prepared as described on a previous occasion and showed, unexcited, a resistance of over 1,000,000 ohms, but

when excited the resistance fell in both almost exactly to fifty ohms. Later, instead of the device A' another was employed of a higher resistance when in the excited state and the coil P S was replaced by one with more turns in the secondary. As finally adopted the secondary S had 160 turns in each layer and 32 layers making 5120 turns. The relay R had a resistance of 998 ohms, wire No 36. The primary P had 50 turns of lamp cord No 20. The self-induction coil L had 1900 turns of wire No 20. All coils were wound on spools 4" diam., 4" long with wooden core 1 1/4" in center. The condenser C and 1/2 mfd. Battery B : 8 cells 11.1 volts; Battery B' : 4 cells about 5.7 volts. Speed of rotation of the devices A and A' was about 24 per minute. The break b was 72 per second. The break wheel and arbors of devices A A' being driven by clockwork. The break wheel has 180 teeth, a small very thin platinum brush bearing on it.



The devices readily responded when four persons joining hands would shunt the device A' . In one instance the devices recorded effects of lightning discharges fully 500 miles away, judging from the periodical action of the discharges as the storm moved away.

Colorado Springs

July 29, 1899

As has been observed before, in order that the free vibration of an excited coil may predominate it is necessary to make the momentum of the coil very large relatively to the impressed vibration. With the object of bettering the conditions favorable for the free vibration, a new coil was wound on same drum 2 feet in diam. and 6 feet long. This coil had, instead of 260 turns as before, about 500 turns of cord No 20. Its inductance was therefore nearly 4 times that of the old coil or about 40 million centimeters roughly. The coil was connected to the free end of the secondary and resonance was observed with 32 jars on each side, there being on each side two tanks in series, so that the total capacity was only 4 jars in the primary. Taking the capacity of one jar at 0.00334 mfd. the total primary capacity was $4 \times 0.00334 = 0.01336$ mfd. The primary turns were in series, so that the primary inductance was $L_p = \frac{4 \times 7 \times 10^4}{10^9} = \frac{28}{10^5}$ henry. This would give the period of the system approximately:

$$T_p = \frac{2\pi}{10^3} \sqrt{0.01336 \times \frac{28}{10^5}} = \frac{2\pi}{10^5} \sqrt{0.037408} = \frac{2\pi}{10^5} \times 0.1934 = \frac{1.215}{10^5}$$

or $n = 82,300$ approx.

First the Westinghouse transformer was connected to give 15,000 volts, but later it was made to give 22,500 volts. The capacity in the primary was evidently too small for the best working of the transformer and the arc short-circuited the secondary considerably, this causing a great deal of energy to be drawn from the supply circuit. This is always the case when the primary arc does not work well. To insure the best working conditions the transformer should first be able to charge the condensers and

the rate of energy delivery of the latter into the primary of the oscillator should be just a little greater than the rate of energy supply by the feeding transformer. Then the arc is loud and sharp and there is no short circuit on the secondary of the latter transformer as the currents over the gap are of very high frequency and the low frequency current of supply – or if it be a direct current – can not follow. The system then works economically and the economy is much greater than might be supposed judging from the unavoidable losses in the arc. As the capacity was too small a *flaming* arc often formed in the box, a sure sign of bad working, the curious feature being that the arc was of a decidedly red color. This may be due to the alumina which was formed as the break wheel was of aluminium. As was expected, the use of two additional gaps improved the working of the apparatus, reducing the trouble due to the short-circuiting of the Westinghouse transformer. It was observed that when the gaps were made so large that the arc did not break through, a lamp on the supply circuit near the condensers – about 6 feet from the same – would brighten up. I am not quite sure that this was due to resonant rise in the Westinghouse transformer, for it may have been due simply to electrostatic action from the jars, as I have observed a similar effect before. When the electrostatic influence is strong the gas in the bulb is excited, the discharge passing through the same though, of course, it is not visible on account of the intense light of the filament. Particles are thrown off and against the carbon and the same is, on the one hand heated to a higher temperature while on the other hand, owing to the hotter environing medium it can not give the heat away so fast as normally – hence it brightens up. Possibly also a small part of the current of supply passes through the excited gas and slightly more energy is drawn from the mains. It was evident that, as was expected, the free vibration of the coil took place more readily than before when the coil with 260 turns was used, owing to the larger momentum as before explained. The streamers were larger than with the old coil but not quite so large as it was surmised they would be. Partially because of this fact, and partially also because not enough energy could be supplied from the Westinghouse transformer to the primary, owing to the small primary capacity, it was decided to change the connection so as to get the next lower or fundamental tone in the primary, this being in all probability the true note of the coil. The capacity in the primary was made 32 jars on each side in multiple, making the total capacity $16 \times 0.00334 = 0.05284$ mfd.

The primary vibration was now just an octave lower than before but the results proved inferior to those first obtained. There was now only one thing possible and that is, that the tone was right after all, in the first experiment, but the results were not quite satisfactory because the primary capacity was too small, thus unfavorable for the best working of the Westinghouse transformer. Accordingly, the same vibration was again secured in the primary but this time by using a capacity four times larger and reducing the inductance to one fourth, which was done by putting the two primaries in multiple. Now, indeed, the results were satisfactory, for the Westinghouse transformer could supply much more energy, practically four times as much as before. The streamers were now much stronger, extending to a distance of $6\frac{1}{2}$ feet from the top of the coil and they were abundant and thick. I can not understand why they should be of such a *deeply red color*. Those in New York never were such. Perhaps it is due to the smaller atmospheric pressure in this locality. Their movement, and darting about is also much quicker and more explosion like. At times a big cluster of them would form and spatter irregularly in all directions. Sometimes it appeared as if a ball would form above the coil, but this may have been only an optical effect caused by many streamers passing from various points in different directions. Many times sparks passed from the top of the coil to the point where the lower end of the coil was connected to the secondary “free” terminal. These sparks were 8’–9’ long.

New condensers proposed: old ones being inadequate to stand the strain beyond 15,000 volts on two dielectrics, it would be necessary to resort to four sets when using higher pressure and this would make condenser boxes too bulky. It is now proposed to use new bottles of lead glass (Bethesda Mineral Water). These are, as nearly as can be ascertained, twice or rather more than twice thicker than the old bottles. The comparison of capacities was made today for this purpose. The new bottles were filled up to 10” from the bottom and immersed in a tin tank. The old bottles were filled up to 9” from the bottom

and immersed in a tank. A solution was prepared from rock salt as concentrated as practicable and care was taken that the liquid was at equal height outside and inside. The readings were:

New bottle:			Old bottle:		
Volt	Defl.	Average:	Volt	Defl.	Average:
180	6.5	} Defl. Volt 6.5 181	180	9trifle less	} Defl. Volt 9 182
181	6.5+trifle		182	9 much less	
179	6.5		180	9 trifle less	

$$\frac{\text{Weight of old bottle}}{\text{Weight of new bottle}} \text{ measured} = \frac{17}{21}$$

From this result the thickness of the walls was first estimated. This not affording a sure test, some bottles were broken and the average showed that new bottles were twice as thick as old ones.

$$\frac{\text{Capacity of new bottle}}{\text{Weight of old bottle}} \text{ from measurement before made was as } \frac{65}{90}.$$

Taking for comparison specific inductive capacity of old bottle glass 1, we have $65 : 90 = 0.722$. Now, for the same glass, the capacity of a new jar would have been $0.722 \times 2 = 1.444$ times that of old, hence the new glass has 44.4% higher specific inductive capacity. It is still not certain, in view of unequal size, whether 25 or 20 or possibly only 18 will go in tank. Taking 18 to be the lowest figure for new bottles in one tank then $\frac{\text{New tank}}{\text{Old tank}}$ will be as $\frac{65}{90} \times \frac{18}{16}$ or about $\frac{8}{10}$. For 20 bottles in the new tank this ratio will be nearly $\frac{9}{10}$, for 25 jars nearly 1.11. In the *least* favorable case, the first, we shall be able to transform at least 60% more energy than with the old jars; in the best case 2.22 times as much as before. *This is good.*

Colorado Springs

July 30, 1899

Further observations in experiments with coil 500 turns before described

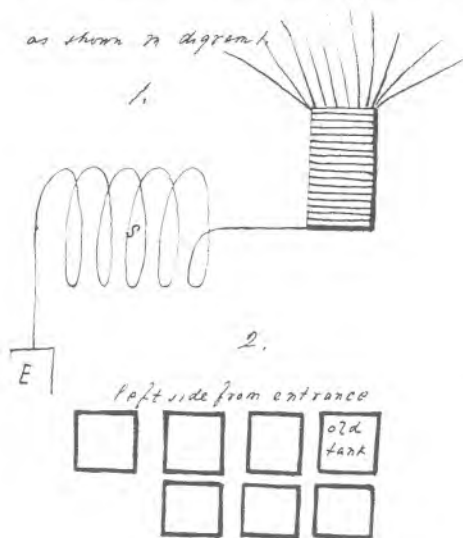
In these experiments two external gaps were used in addition to the gaps in the box, all being in series so that the total length of the spark gap varied from 2 1/8" minimum to about 5" maximum. The two outside gaps were of a fixed length, 1" each, while the gaps in the spark box varied rhythmically with the rotation of the disk. The coil was connected as shown in Diagram 1. to the free end of the secondary, the lowest points of the coil being about 6 feet from the ground. Resonance was obtained with 7 tanks of capacity on each side of the primary. As it was thought that the tanks might perceptibly differ in capacity Diagram 2. is added showing their position. The primary capacity total was from approx. 0.04336 – 0.0498 mfd., according to connections. The effects observed were in many ways interesting. The streamers produced on top of the coil were generally seven feet and sometimes eight feet long, thick and violently darting about. They did not seem so red as those produced before under similar conditions. Very often strong brilliant sparks would pass from top to bottom of the coil. The remarkable feature of the sparks was that they would go in a curve, almost a semicircle, as if they would start out originally in another direction and then be deflected to the lower end of the coil. Certainly they could have reached the lower end by a route shorter by 40 or 50%. During the display it was observed

Colorado Springs July 30. 1898



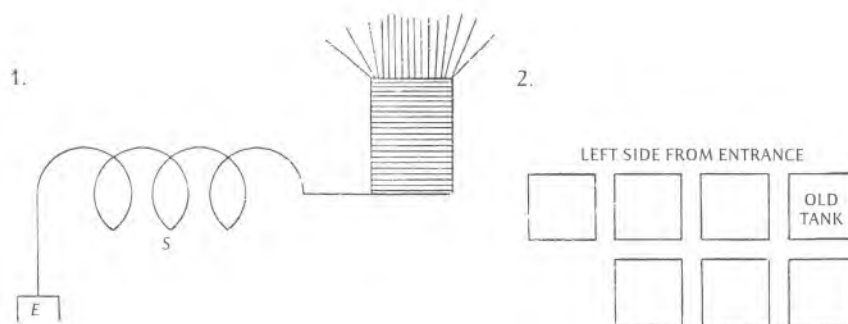
further observations & experiments with coil 500 turns before described.

In these experiments no external gaps were used in addition to the gaps in box all being in series so that the total length of sparkgap varied from $2\frac{1}{2}$ " minimum to about 5" maximum. The two outside gaps were of a fixed length, 1" each, while the gaps in the sparkbox varied rhythmically with the rotation of the disk. The coil was connected to the free end of the secondary the lowest turns



of the coil being about 6 feet from the ground. Resonance was obtained with 7 ranks of capacity on each side of the primary. As it was thought that the tanks might perceptibly differ in capacity the diagram 2. is added showing their position. The primary capacity total was from approx. 0.04336 - 0.0498 M.F. according to calculations.

The effects observed were in many ways extraordinary. The streamers produced on top of coil were generally seven feet and sometimes eight feet long, thick and violently darting about. They did not seem so red as those produced before under similar conditions. Very often strong brilliant sparks would pass from top to bottom of the coil. The remarkable feature of the sparks was that they would go in a curve, almost a semicircle, as if they would start out originally in an other direction and then be deflected to the lower end.

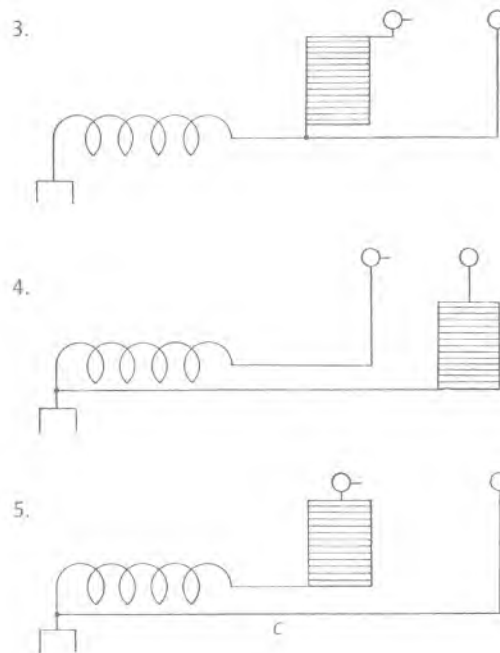


that *no sparks* passed over the *lightning arresters*. This was an indication that only a comparatively small electromotive force per unit length of ground was set up, too small to bridge the gaps on the arresters. In order to see whether the coil would respond to the next fundamental tone the primary cables were joined in series, this making the frequency of the primary oscillations just one half. The coil did respond but the effect was, as anticipated, small, about one quarter. Presently one of the large balls, 30" diam, with a wire of some 20 feet was connected to the top end of the coil. The self-induction coil being adjusted, very strong streamers were now obtained showing that the ball had reduced the period of the coil considerably. But the vibration of the coil with the ball was still too fast for the primary and another ball, 30" diam. was connected in multiple with the first. By again adjusting the regulating coil good resonating action was obtained. The sparks and streamers were now stronger, the former passing sometimes to the top of the secondary, a distance of about 8 ½ feet in a straight line. But owing to their curved path the sparks were actually much longer. The sparks passed sometimes also to the ground from a kink in the wire connecting the top of the coil with the balls, the distance of these sparks in a straight line was 103". The sparks were much fuller, thicker and louder with the balls than without them, they were particularly strong and bright when passing from top to bottom of the coil. It was plain that much longer sparks could be obtained with *more* turns in the extra coil as then the capacity on the end could be reduced. But the experiments also showed that the amount of electrical movement in the coil was not very great owing to the small section of the wire, for when an arc was established between two large balls it ceased to pass as soon as they were separated a distance of about 1 foot. The streamers were visible and sometimes strong on the wires leading to the balls and particularly on the wire leading from the top of the coil but still the sparks failed to bridge the gap. This showed that there was not enough energy available to charge the balls to a sufficiently high potential while, of course, the passage of the sparks was rendered more difficult owing to the large radius of the curvature. The density ought to be inversely as the radius of the curvature, hence the density on the wire leading to the ball is much greater than on the ball itself, in other words, which really means the same, the ball is charged to a *lower potential* than the wire. This seems to me a somewhat novel view to take. Without much thought I would at once assume that the pressure on the ball and on the wire is the same, but it must be greater on the wire since it can leak out from the same while it does not from the ball.

The thin wire, or any projection or surface of small curvature becomes thus equivalent to a small hole or leak in a pipe or reservoir containing a fluid under pressure and it is plain that such surfaces of small curvature will greatly diminish the maximum pressure obtainable in an oscillating circuit. It is very *important*, as I have often noted, in order to insure the high efficiency of the apparatus, to make provisions for overcoming the formation of the streamers and to this subject a great deal of attention has been already devoted. In signalling to a distance, the formation of a streamer on the transmitter impairs very materially its effectiveness so that the signals sometimes do not go more than a quarter of the distance or even less just on this account. By using a body of considerable surface, which should be spherical or a cylinder with hemispherical ends better results are obtained than with a wire leading to a height alone, not so much because of the increased capacity, but generally only because there is

less opportunity for a leak and the system is more economical in producing an electrical vibration in the ground. A large sphere or surface, provided it is not too large as to interfere with the vibration of the transmitting system is better than a small one for the same reasons.

I have, however, observed long ago in this connection that when the transmitting system is formed by conductors of a considerable mass of metal a greater suddenness, or a greater rate of variation per unit time is obtained and the transmitter is more effective in producing disturbances at a distance. One obvious cause of this is that usually in such a case $\frac{pL}{R}$ is larger than if the conductors are not of great mass, but as far as I have been able to judge, the chief reason is that an electromotive force, acting upon a circuit so constituted, must give rise to a much greater current, in the first moment when in any manner, as by the passage of a spark, a great and very sudden variation in the electromotive force acting in the system is produced. I make a distinction between these two effects. One raises the pressure *gradually*, the other is responsible for the great suddenness. Thus, a mass of metal of minute electrical resistance behaves towards a sudden manifestation of electrical pressure much in the same manner as a mass of metal of *great inertia* behaves towards a sudden pressure caused by a blow. In both cases there is an increase of the pressure or force. When in the experiments, presently described, a small wire was attached to one of the balls, the other ball being left as before, the sparks passed readily between them at a distance of 6 ½–7 feet.



Nevertheless although the sparks were very brilliant and to all appearance highly effective, *no sparks* very visible on the arresters when the discharge was playing. Evidently, the electromotive force developed per unit length of ground was small despite the power of the sparks. Upon thinking over the causes of the absence of the sparks on the arresters, it was soon recognized that in the connection as used only a comparatively slow vibration was transmitted upon the ground, the secondary effectively preventing the upper harmonics, which would have been competent to produce the sparks, from passing through the ground. The connection as first used, which is illustrated in Diagram 3. was now changed into the one shown in Diagram 4. Although the coil was now excited by a small impressed e.m.f. the sparks between the balls were nevertheless quite strong reaching more than 2 ½ feet. This showed that there was also an induced e.m.f. cooperating with the impressed e.m.f. in the coil to bring about the great rise. Diagram 4. suggested the connecting of the lower end of the excited coil to any

other point of the secondary thus regulating the impressed e.m.f. at will. Again, in the connection as shown in Diagram 4., there were *no sparks on the arresters*, for the reason pointed out. But when the connection illustrated in Diagram 5. was made, they appeared and became stronger when conductor c was constituted by a very heavy cable. This was to be expected from the above. It demonstrated the obvious fact that short waves are more effective giving higher e.m.f. per unit of length in the ground.

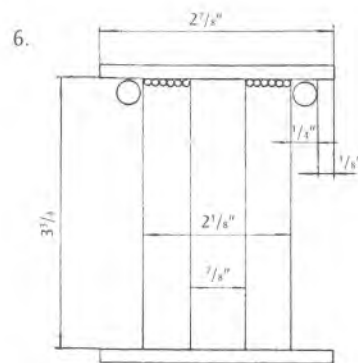
New induction coil for apparatus involving method of magnifying the effects by means of a condenser designed for the purpose of investigating: the propagation of waves through the ground and telegraphy

A quick vibrating system was constituted comprising a ball of 30" diam. and a stout cable. The period of vibration of this system was found to be, by resonance method, 240,000 per second. It was excited by sparks passing through a gap of about 7 feet, or less, from a wire connected to the top end of a coil excited by the secondary as last described. It was hoped that stationary waves might be produced by this apparatus as it seemed powerful enough. It was desirable to have an induction coil the secondary system of which would vibrate with the same period if possible, and a coil was wound on spool the dimensions of which are indicated in diagram. Now the system being $240,000=n$, this gives the wave length

$$\lambda = \frac{186,000}{240,000} = 0.775 \text{ miles or } \frac{\lambda}{2} = \frac{0.775}{2} \text{ miles}$$

or 2000 feet approx. The average length of one secondary turn is a little over 4.5", this will therefore require a little over 5000 turns. Now it is desired to use the $\frac{1}{2}$ mfd. condenser on hand for the primary of the coil. The primary must have the same period, hence we have to find the inductance of primary

$$\frac{1}{n} = \frac{1}{24 \times 10^4} = \frac{2\pi}{10^3} \sqrt{L_p \times 0.5}, \left(\frac{1}{480\pi} \right)^2 \times 2 = L_p = 9000 \text{ cm.}$$



The coil actually wound for the above object has 32 layers, 160 turns per layer in the secondary. This makes the length of the secondary very nearly $\frac{\lambda}{2}$. The primary has 50 turns= n . Calculating inductance we have: length of spool: $3.75''=9.525 \text{ cm.}$ Area= 28.3 sq.cm. , from this $L_p = \frac{28.3 \times 2500}{9.525} \times 1.257 = L_p = 9358 \text{ cm.}$ Very nearly the value required.

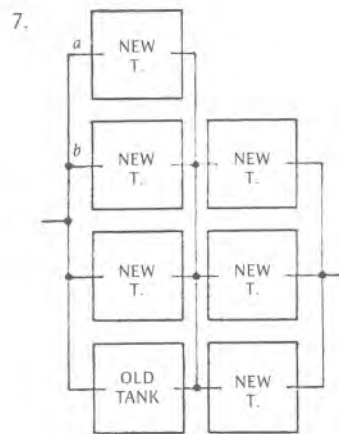
Note: It will be better, of course, to adopt plan used in New York and design coil with a lot of copper.

Observations of resonant rise on Westinghouse transformer

In order to observe the rise, the spark gap ordinarily used was made so large that the secondary discharge could not break through and the voltage on the primary, when throwing in the switch, was observed. Several values of primary capacity were experimented with. The diagram below indicates the position of the set of condensers on the right side looked at from the center of the building towards the entrance. On each side of the primary there were then 2 sets in series, the connections in one instance being indicated in diagram. In each old tank there were 16 jars, the capacity of each jar being 0.00334 mfd. In each new tank there were 16 jars, capacity of each jar 10% more, being 0.00367 mfd. With tanks *a* and *b* off we have, calling C_1 total capacity:

$$\frac{1}{C_1} = \frac{2}{(0.00334 + 0.00367) 16} + \frac{2}{0.00367 \times 16 \times 3}$$

$$\text{or } C_1 = \frac{0.00493}{0.144} = 0.03424 \text{ mfd.}$$



With this capacity on the secondary of the Westinghouse transformer the rise on the primary, as observed by Weston voltmeter, was from 102 to 122 volts. With tank *b* on each side added, the total capacity being C_2 , we have:

$$\frac{1}{C_2} = \frac{2}{(0.00334 + 2 \times 0.00367) 16} + \frac{2}{0.0367 \times 48} = \frac{1}{0.08544} + \frac{1}{0.088}$$

and from this $C_2 = 0.04336$ mfd. In this case the rise was from 102 to 126 volts. With tank *a* still added on each side to the preceding, the value C_3 of capacity in the secondary was 0.0498 mfd. and the rise in this instance was from 102 to 130 volts.

Note: In all cases when the switch was thrown in, the pressure rose higher at first and then settled down to the values recorded which are once more given in the results summed up:

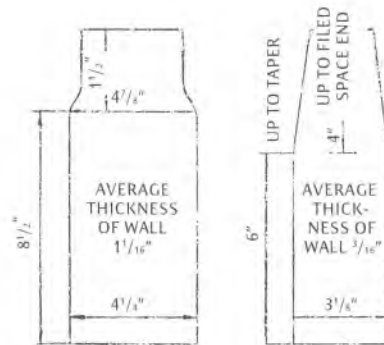
Results:

Capacity in mfd. in secondary W.T.	on primary Westing. Trans.	
	Voltage initial	Voltage res
0.03424	102	122
0.04336	102	126
0.0498	102	130

Proposed condenser from Maniton Water quart bottles

Comparative test with sample bottles showed as follows:

Defl. 7 bottles Maniton average three readings 20.66 } degrees on scale
 Defl. 7 two old bottles average three readings 19.7 }



In the first case the e.m.f. was 164 volts } average values of three readings
 In the second case the e.m.f. was 167 volts }

One new bottle defl. $\frac{20.66}{7}$. One old bottle defl. $\frac{19.7}{2}$. Reduced to the same voltage one of the new bottles would have given $\frac{20.66}{7} \times \frac{167}{164} = \frac{21}{7} = 3$ approx. This gives a ratio of capacity of one old bottle to new $\frac{2}{3} = \frac{19.7}{6} = 3.30$ or approximately

$$\frac{\text{new bottle}}{\text{old bottle}} \text{ capacity} = 0.3.$$

Now we may have in one tank 39 new bottles whereas only 16 of the old bottles could go in. This will give the capacity of the new tank to that of the old as

$$\frac{39 \times 0.3}{16} = \frac{11.17}{16} = 0.731.$$

Now mean diam. of cylindrical part of old jar outside = 4.5625". Now mean diam. of cylindrical new bottle jar outside = 3.125". Allowance for upper part on old jar 1 1/2" taken of same diam. as cylindrical or nearly cylindrical part.

Similar allowance for new bottle 8/3".

These figures would give:

$$\frac{\text{Surface of old bottle}}{\text{Surface of new bottle}} = \frac{\frac{\pi}{4} \times 4.5625^2 + \pi \times 4.5625(8.5 + 1.5)}{\frac{\pi}{4} \times 3.125^2 + \pi \times 3.125 \left(6 + \frac{8}{3}\right)} = \frac{50.829}{29.525}$$

Now a fair idea of the thicknesses of the walls in the two bottles may be obtained by taking their weight. Measured repeatedly and changing the bottles many times it was found that $\frac{\text{Weight of new bottle}}{\text{Weight of old bottle}} = \frac{24}{32} = \frac{3}{4}$. Taking into consideration the surfaces as calculated before this would give

$$\frac{\text{Thickness of new bottle}}{\text{Thickness of old bottle}} = \frac{50.829 \times 24}{29.525 \times 32} = \frac{152.487}{118.1} = 1.3 \text{ only!}$$

Since the thickness ratio is much greater as found in this way the determination of the thickness by weight as above is not practicable without making allowances. The glass is evidently uneven, much more so in the old bottles than in the new. In the former particularly the bottom is heavy which vitiates the result inferred from the weight of the bottles. Many bottles were broken and it was ascertained that the average thickness of new bottles was three times that of the old. It was quite certain at any rate, that the *weakest* spot on the new bottle was fully three times the thickness of the weakest spot on the old. This was the most important thing to ascertain for the bottles give way at the weakest place. Now since the capacity of the old bottle in relation to that of the new is found by measurement to be 1 : 0.3 approx. and the surfaces are as $\frac{50.829}{29.525}$ we can get an idea of the specific inductive capacity of the latter with respect to that of the former. The new bottle would have for the same thickness, that is one third of the actual, 0.9 instead of 0.3 and for the same surface it would have $\frac{50.829}{29.525} \times 0.9$ or 1.55 times the capacity of the old, both things considered so that the *specific inductive capacity* of the glass in the new bottle must be something like 55% greater than that of the glass in the old bottle.

Vichy water syphon bottles tested with the object of using them in the proposed new condensers. Dimensions: 3.8" outside diam.

The glass is from $\frac{1}{4}"$ to $\frac{1}{4}" + \frac{1}{64}"$ thick, **very uniform**.

Height available 6 $\frac{1}{2}"$

Compared with Maniton water bottles: $\frac{\text{Mean diam. Vichy}}{\text{Mean diam. Maniton}} = \frac{3.5"}{3"}$

$$\frac{\text{Thickness of Vichy}}{\text{Thickness of Maniton}} = \frac{17}{7} \cdot \text{Now } \frac{\text{Vichy surface}}{\text{Maniton surface}} = \frac{3.5\pi \times 6.5}{3.12\pi \times 8} = \frac{23}{25}$$

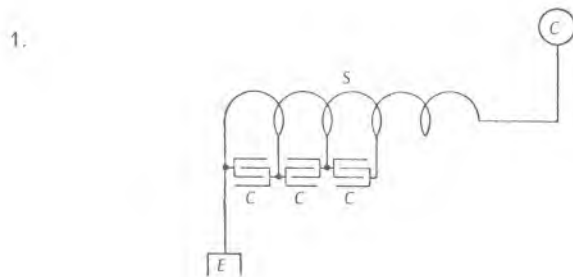
approx. Now the deflection – average of three readings was with same e.m.f.

$\frac{\text{Deflection Vichy}}{\text{Deflection Maniton}} = \frac{4.3}{9}$. The capacities are in this ratio and the test shows that, while the Vichy bottles would make excellent condensers, the capacity for two sets in series as desired would be too small. The reason is that the wall is unnecessarily thick. If it were convenient to use only one set of condensers nothing better could be desired. It having been practically decided to adopt the Maniton bottles, tests were made to see how much pressure these bottles would stand safely. Accordingly 7 of these bottles with wall rather weaker than normal, hardly $\frac{1}{8}"$ thick, were placed in a tank with the other bottles. The concentrated salt solution reached to a point about 3" from the top. Paraffin oil was poured to nearly the top. First 7500 volts were turned on, then the tension was raised up to 15,000 volts and the bottles withstood. The e.m.f. was then raised to 22,500 volts when the bottles began to give way, three being broken after some time. The conclusion was that two sets of bottles in series would withstand quite safely at least 30,000 volts. The glass is *really excellent*. These tests were made with 144 cycles per second. A curious observation was that when one bottle gave way others followed, this being due to the violent oscillations caused or else to the concussion upon explosion.

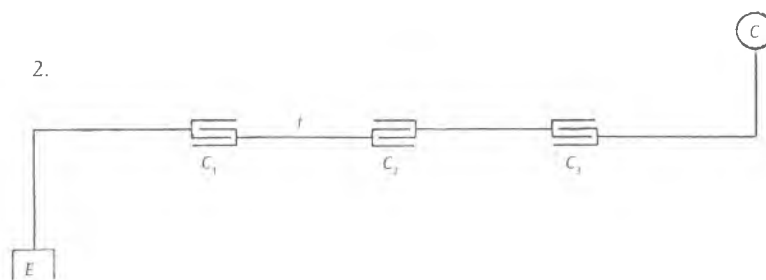
Approximate determination of secondary modified in construction for the purpose of overcoming the drawbacks of distributed capacity

As before remarked, on a number of occasions, one of the chief difficulties encountered in the operation of a large oscillator is the distributed capacity, owing to which the efficiency of the machine – in transmitting an electrical movement to the environing media – is greatly impaired. The distributed capacity becomes particularly hurtful when the turns are of large diameter or when, generally stated,

there is a great difference of potential between portions of the wire not far apart. The adjacent portion of the wire acts like a condenser in which energy is stored at each alternation, and the amount of this stored energy is proportionate to the square of the difference of potential existing between the portions of the wire constituting the condenser. Now most of this movement of electricity, occasioned by this distributed capacity, takes place within the coil and does not, unless in a very small part, appear in the external circuit. Since the movement in the latter circuit is the chief object, the charging and discharging of the condensers formed by the turns of the coil is mostly lost for the purpose for which the machine is designed. In a properly designed oscillator of this kind all the movement produced in the coil should be propagated to the external circuit, but this condition can never be rigorously realized.

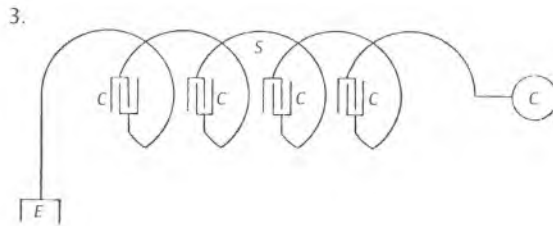


The object of the design which will be presently considered is to approach this degree of perfection as nearly as practicable. Referring to Diagram 1. illustrating a secondary as here used, the object of which is to produce the greatest possible movement of "electricity" from E into C and vice versa, it will be seen that the succeeding turns form small condensers c, c, c , in which a local movement takes place which is not transmitted through the entire wire. Such a coil S with considerable distributed capacity will, therefore, not be efficient in producing disturbances such as I contemplate using for a number of purposes. The distributed capacity is particularly hurtful when it is desired to produce a very high potential at C and, as this is generally the case, it is important to adopt a construction and observe working conditions such as will reduce the evil to the minimum. I have in similar instances attained the object more or less by constructing a secondary in parts connected in series through condensers, and a secondary to suit the present apparatus designed on this plan is now to be considered. In order to explain better how such condensers in series act in reducing the effect of distributed capacity, as pointed out before, reference is made to Diagram 2. which shows turns or portions of the secondary connected through condensers C_1, C_2, C_3 . Suppose there would be n such parts as t joined in series and let C_1 be the total capacity of the coil or secondary S , then the capacity of the turns or portion t would be $\frac{C_1}{n}$.



But now, if there be on the ends of this portion t condensers C_1 and C_2 it is plain that the distribution of electricity along the portion t will be greatly modified by the presence of these condensers and, if their capacity be very much greater than that of the wire t , almost all of the electricity will reside on the coatings of the condensers, hence there will be very little local action in the portion t , and most of the electrical movement created in the wire will be transmitted along the entire length of the same from E

to C and vice versa. The machine will then act more efficiently and will be much more suitable for the transmission of energy through the terminals E and C for whatever purpose the energy be intended and in whatever manner it be used. It should be stated that in the particular form of oscillator as here illustrated, the lower turns of portions which are closer to the earth, and therefore at a lower potential, are not nearly as hurtful as the upper ones, or to put it more generally, those which are farther away from the earth connection and closer to the free terminal. The latter are, namely, at a much higher potential and there exists generally a greater difference of potential between portions of wire of the same length when the resonant rise is considerable; as the energy stored in the distributed condensers is proportionate, as before stated, to the square of the difference of the pressure between adjacent portions, it is, as a rule, of advantage to make the upper turns of smaller diameter or to put them farther apart. But in certain instances this very drawback can be turned into an advantage and by placing a few of the turns near terminal C as close together as practicable a greater electrical movement may be produced in the lower turns or those nearer to the earth connection and the effect exerted at distance may thus be increased, though I prefer not to resort to this means as a better result is obtainable in other ways. Coming now to the consideration of the secondary to be modified in the manner proposed let Diagram 3. illustrate the arrangement as contemplated in the present instance, a condenser C being placed between each succeeding turn of secondary S . I shall make a rough estimate on the basis of *one* primary turn and the maximum primary capacity available, which is 80 jars on each side giving a total capacity of 40 jars or $40 \times 0.0036 = 0.144$ mfd. approx., there being two sets in series. This would give $n = 50,000$ per second roughly.



Assume we work with 30,000 volts from the Westinghouse transformer and retain, as at present, 35 turns of the secondary. In this case, considering the distance of the secondary turns and their decreasing diameter, the induced e.m.f. in the secondary will be much smaller than might be inferred from the ratio of transformation which will be 35 : 1; with reference to measurements of mutual inductance made before, with a secondary wound on the same frame, it may be estimated at 18 times the primary e.m.f., that is, the induced e.m.f. in the secondary may be assumed to be $18 \times 30,000 = 500,000$ volts nearly. Taking the number of breaks at 1200 per second as used in some of the preceding experiments with the apparatus, and assuming the charge of condensers always effected at an average pressure, say $\frac{6}{10}$ of 30,000 or 18,000 volts, the energy stored in the condensers per second and delivered in the primary will be $\frac{18^2 \times 10^6}{2} \times \frac{0.144}{10^6} \times 1200$ watts or 28,000 watts, that is nearly 38 H.P. will be taken by the apparatus under these conditions. This is, of course, only an approximate estimate. We may now, on this basis, estimate the current through the Westinghouse transformer's secondary, which will be roughly estimated $\frac{750 \times 38}{30,000} = \frac{285}{300}$ of an ampere, or with losses etc., say *one ampere*. The performance will thus be still much below the maximum output of the transformer as it can deliver 1 amp. at 60,000 volts pressure and continuously and, I have no doubt, much more, as so far not the slightest increase of temperature has been noted after prolonged working. Assume then the current through the supply secondary to be *one ampere*, the current through the primary of the oscillator will be increased by the factor $\frac{Lp}{R}$ approx. Here $L = \frac{7}{10^5}$ and $p = 6n$, roughly $= 3 \times 10^5$. R is difficult to estimate since the primary circuit includes the arc over the spark gap. I have adopted a method for determining the resistance of

the arc with fair accuracy and this will be the subject of a later consideration. The resistance of the primary cables in multiple is entirely negligible, there being in each 37 wires, № 9. Taking 1265 feet per ohm, the resistance of about 160 feet of such two cables would be $\frac{160}{1265 \times 74} = 0.0017$ ohm only. Not considering the resistance of the arc the factor $\frac{Lp}{R}$ would be enormous,

$$\text{being} = \frac{7 \times 10^4}{10^9} \times \frac{3 \times 10^5}{17} = \frac{21 \times 10^4}{17} = 12,353!$$

While, of course, such a condition can not be realized in practice we may approach this value more or less by doing away with the arc in the primary as, for instance, in the form of an oscillator with mercury breaks, which I have devised to work with low tension so that the arc practically does not occur. Or a condenser may be placed in shunt to the primary as has been already considered on a previous occasion. By experience I know that the initial currents in the primary reach certainly several thousand amperes showing by this that the resistance of the arc can not be great. For the present I shall assume that it is 18 ohms so that if the condensers are, as supposed above, charged to 18,000 volts during ordinary performance, the initial current would be about 1000 amperes in the primary decreasing logarithmically. With this maximum in the primary, the loss in this circuit will not be unduly great. Now the secondary condensers should be of a capacity to carry the secondary current at the frequency used. Calling now e the e.m.f. induced in the secondary per turn, c the capacity of one of the secondary condensers as before, we will have the current through the turn $i = ec\omega$, ω being here 3×10^5 as before assumed. Now the e.m.f., taking it on the average, will be per turn of secondary $e = \frac{500,000}{35} = 15,000$ volts approximately, and on the preceding assumption of 1000 amp. maximum in the primary turn, the largest value we may assign to i would be $i = \frac{1000}{35} = 30$ amperes, roughly, and this would give

$$c = \frac{30}{15,000 \times 3 \times 10^5} = \frac{3}{45 \times 10^7} \text{ farad or } \frac{3 \times 9 \times 10^{11}}{45 \times 10^7} = \frac{30,000}{5} = 6000 \text{ cm.}$$

We would thus require a capacity of about 8000 cm. in each of the condensers to carry the secondary current in the oscillator. But this is really too high an estimate and it is quite certain that a smaller capacity would do. Since a jar has a capacity of $0.0036 \times 9 \times 10^5 = 3240$ cm., two jars would be amply sufficient and possibly also one jar between each turn of the secondary. Taking it on this basis, the total capacity of the secondary would be $\frac{2 \times 3240}{35} = 185$ cm. approx., while the measured capacity was 3600 cm. The effects of distributed capacity would thus be reduced by the use of secondary condensers to about 5%. These secondary condensers will, of course, have to be so constructed as to withstand not so much the strain on the dielectric – for this they will support easily – but the sparking over the condenser coating. Let the spark length on the secondary be, say, 12 feet and suppose we had 36 secondary condensers, then on the average they ought to be able to prevent sparking when the pressure on each is such as to cause a spark of a length of $\frac{12 \times 12}{36} = 4$ ". There will not be much difficulty encountered in this respect, if the condensers are properly designed. The virtue of condensers used in such a manner is well established and I think it resides in the fact that when they are used the charge does not distribute itself along the wire, but accumulates on the coatings of the condensers thus reducing the effect of mutual electrostatic induction of the adjacent or near positions of the wire, to a large extent, and reducing in this manner the amount of energy stored in the coil itself. It now remains to consider the capacity on the end of the secondary which is "free". This capacity ought to be so large that it can take up all the current of the secondary at the frequency used. Or, to put it otherwise, it should be able to store all the

energy the secondary is able to give. There is, however, another consideration which must be made in case the secondary is capable of free vibration, and that is that the capacity on the end should be so determined as to secure resonance with the primary. As regards this capacity there are then three relations to be borne in mind when deciding upon this and they are:

$$i = Ec_s \omega \quad c_s = \frac{i}{E\omega} \dots\dots\dots 1)$$

$$\text{Watts in secondary } W = \frac{c_s E^2 \omega}{2} \text{ or } c_s = \frac{2W}{E^2 \omega} \dots\dots 2)$$

$$L_p C_p = c_s L_s \text{ or } c_s = \frac{L_p C_p}{L_s} \dots\dots\dots 3)$$

E secondary e.m.f.

ω secondary frequency

L_p inductance } in primary

C_p capacity }

L_s inductance secondary

This to follow up.

Colorado Springs Notes

August 1-31, 1899

For want of time following items, partly worked out, have been omitted:

August 4. General observations of electrical phenomena here with particular reference to stationary waves.

August 6. Experiments with stationary waves on water pipe. Note: Distance from groundplate to End of main exactly 550 feet.

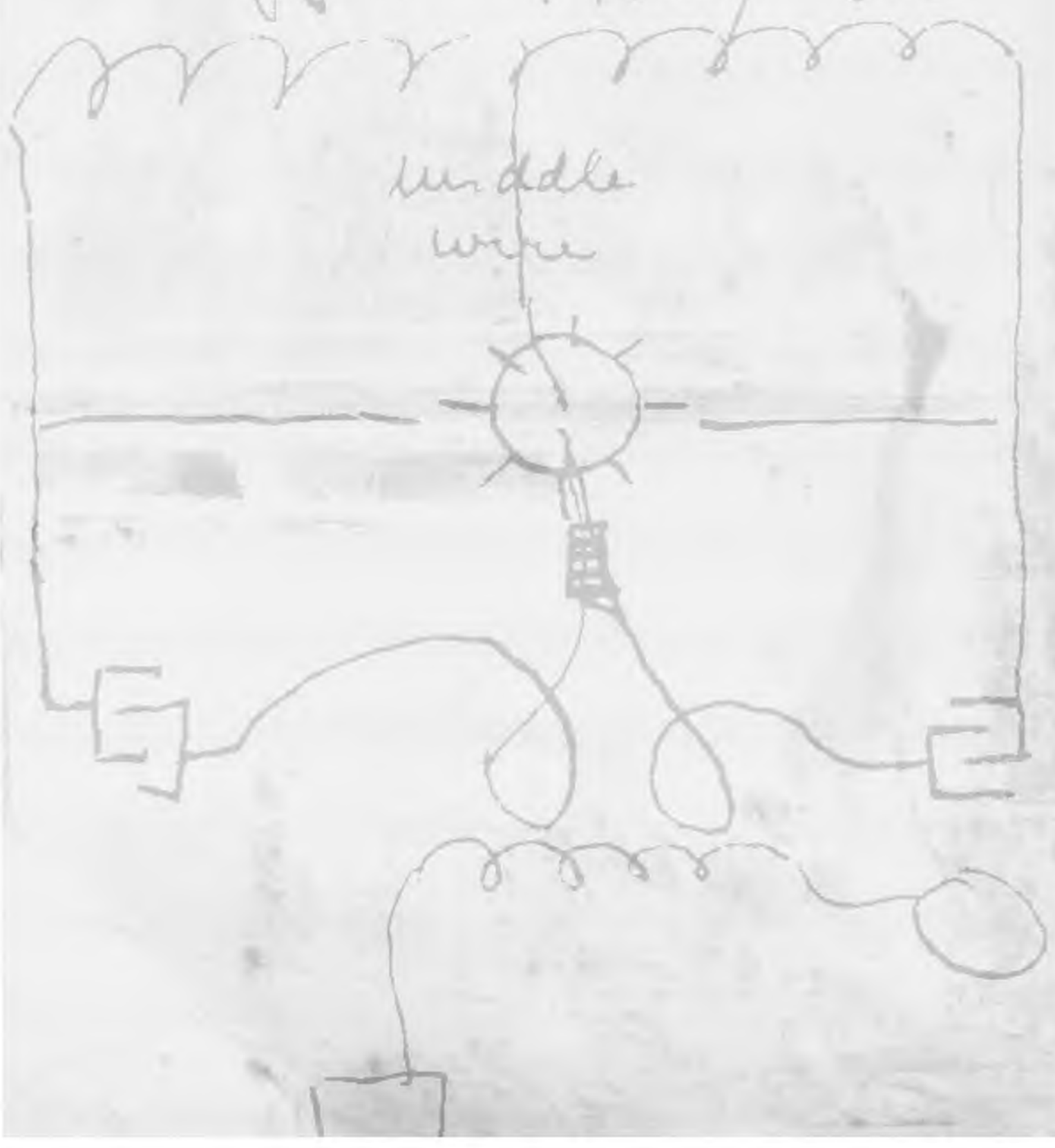
August 31. Patent matter worked on:

- 1) Production of stationary waves and use of same in general
- 2) Distribution of universal time observatories etc.
- 3) Indication of direction for ships etc.

1.

W Transf. Sec

middle
wire



August 1, 1899

Various observations. In the course of these experiments and particularly during the past month a number of highly interesting observations have been made which will be presently dwelt upon.

First of all one is struck by noting the extraordinary purity of the atmosphere which is best evident from the clearness and sharpness of outlines of objects at great distances. In low regions, especially where moisture is in excess, the outlines of objects become more or less indistinct and confuse at distances of but a very few miles while here at many times such distances the outlines appear perfectly clear and sharp. When a train is moving up Pike's Peak it is very often quite easy to distinguish not only the engine and cars but even the windows and wheels of the same perfectly, although the distance from the experimental station is from 10–12 miles. Quite frequently also the house on top of Pike's Peak can be clearly seen with the naked eye. The ranges of mountains 100–150 miles away or more can be perceived perfectly. A range at a distance of about 50 miles can be seen plainly even at night when the sky is clear. It is wonderful how at times immense objects appear dwarfed, while small objects as horses, carriages or men assume unnatural gigantic dimensions.

Pike's Peak Range appears at times so close and so ridiculously small, that anyone not knowing the reality would be apt to fire a modern rifle at some object on the mountainside believing it to be within shot. Nor is this statement exaggerated much as it seems so. At other times again Pike's Peak appears far remote and its height much beyond what would seem natural. The arc lamps at the foot of the mountains five to seven miles away or more shine with a brilliancy as though they were only as many blocks from the observer and under certain conditions an ordinary incandescent lamp of 16 c.p. seems to give out as much light, judging from a distance, as ordinarily an arc light does. It appears also as big as the latter. This penetration of the light is due to the wonderful purity and extreme dryness of the atmosphere.

The moonlight is of a power baffling description. I have been told that the best photographs of the mountains have been obtained by moonlight and I do not doubt it. Exposures of half an hour ought to give clear photographs revealing all details although the exposures are as I am told from 1 ½ to 2 hours. I have nowhere seen such a light. Italy is famous for moonlight nights but in my estimation that country can not even compare with Colorado. I think this extraordinary brightness of the moonlight is chiefly due to the absence of moisture, for there are many places, as in Central America, which are located much higher and yet the moonlight, I am told, is not so intense and I can see no other reason for this except the presence of more vapour in those places. It is not a mere saying, but literally true, that during full moon in these parts it is "as light as day". Objects can be clearly perceived at distances of many miles and one can easily recognize a friend or familiar object at a distance of something like a quarter mile if not more. The shadows cast by the moonlight are extraordinarily black and sharp. They suggest the Crookes' shadows noted in vacuum bulbs and on this account the moonlight is particularly interesting and suggesting thought and stimulating the imaginative powers. The shadows of the clouds on the plains and mountains are quite dark and clearly defined and it is interesting to behold the patches as they speed over the ground. When the moon is absent and the nights clear the number of stars visible and their brilliancy is amazing and the sky presents a truly wonderful sight. The twinkling of the stars is very pronounced, they seem to move in orbits of as much as ten or fifteen of their own diameters across. At times one observes a star burst out into great brilliancy. This is probably due to the removal of an invisible cloud or of a layer of air at a great altitude containing some kind of particles which cut off a large portion of the light. One sees shooting stars quite frequently, also colored rings around the moon, generally in the advanced hours of the night, at times when the air is slightly misty. As this happens generally during very cold nights I believe the colored rings are due to minute crystals of ice.

Owing to the extraordinary purity and dryness of the atmosphere the sounds penetrate to astonishing distances. This is particularly true of *high notes* as nearly as I can judge. Certain conditions,

entirely exceptional, concur at times and produce effects of this kind which are startling. A bell will ring in the city several miles away, and it would seem as though the bell would be before the very door of the laboratory. During certain nights when sleepless I have been astonished to hear the talk of people in the streets and sounds of this kind in a large radius around the dwelling not to speak of the grinding of the wheels, the rolling of wagons, the puffing of the engines etc. which are perceptible in such a case, and with painful loudness though coming from distances incredibly great. These phenomena are so striking that they can not be satisfactorily explained by any plausible hypothesis and I am led to believe that possibly the strong electrification of the air, which is often noted, and to an extraordinary degree, may be more or less responsible for their occurrence.

The dryness of the atmosphere, which is still further enhanced by the low pressure, is such that wood or other material is made what is called kiln-dry inside of a few hours, and is rendered an insulator far more perfect than wood is ordinarily. The nails on the hands and toes dry out to such an extent that they break off very easily, in fact one has to be careful in trimming them. I found the claws of a cat as brittle as glass. The skin on the hands dries out and cracks up and is apt to form deep sores particularly if, as often in experimentation, one has to wash the hands frequently. The hair gets perceptibly thinner owing to the drying out. Colorado is not a good country for hair. This may be of interest to people with a tendency towards baldness. People even very sick do not cough and expectorate evidently owing to the dryness of the atmosphere. One does not perspire as the sweat is immediately evaporated. It is curious how quick the body gets dry when a bath is taken. Still more this is noted when the body is rubbed with alcohol. These observations are not often made, unfortunately, as the opportunities for comfort are not such as one might desire.

In many respects one is disappointed with the aspect of the country itself although it is far famed. I think it very uninteresting and even the celebrated Pike's Peak is insignificant. Most of the country is barren, practically a desert, with little vegetable and animal life in places. Prairie dogs are about the only animals one can see on the plains. One rarely sees a bird and the country must be a tedious one to live in for any one with tastes for hunting and fishing. But as much as the country is devoid of interest and beauty, so much and far more, is the sky beautiful. The sights one sees here in the heavens are such that no pen can ever describe. The cloud formations are the most marvelous sights that one can see anywhere. The iridescent colors are to my judgement incomparably more vivid and intense than in the Alps. Every possible shade of color may be seen the red and white preponderating. The phenomena accompanying the sunrise and sunset are often such that one is at the point of not believing his own eyes. At times large portions of the sky assume a deep red almost blood-red color, so intense that superstitious people might will be frightened when first seeing it as by some other altogether unusual manifestation in the heavens. Sometimes, particularly in the forenoon, huge masses of what appears to be snow are seen floating in the air and they are so real and tangible, so sharply defined, that it is difficult to believe them to be composed merely of vapor. The purity and dryness of the atmosphere explains to a degree the sharpness of definition of the boundaries of these formations of mist, but it is quite possible that some other causes as electrification of the particles cooperate in rendering them so compact as they appear to be. Of course, the purer the air, the greater is the difference between the region filled by cloud and that surrounding it as regards the passage of light rays, and the boundaries of the cloud appear sharper and quasi-solid much on this account. The whiteness and purity of these masses of cloud is such that one has the idea that nothing, not even an angel, could come in contact with it without soiling it. Very often when the sun is setting, a considerable portion of the sky above the mountain range presents the sight of an immense furnace with white-hot molten metal. It is absolutely impossible to look at the melting away clouds without being blinded, so vivid is the light. On a few occasions I have seen the mountains covered with a white silvery veil most beautiful to see, an unusual occurrence and caused by a fine mistlike rain in the mountain region. The intensity of the light on these occasions was really wonderful. What was remarked before of the shadows of the moon is, and to a much greater degree, true of those thrown by the sun. They are inkblack and sharply outlined. The shadows on the plain and

mountains thrown by the clouds appear like big patches of inking blackness hurrying along the ground. Particularly interesting are shadows thrown across the sky resembling often large dark streamers, or those which under certain conditions are formed and are visible like dark columns extended from the ground to the sky. These shadows seem to be best visible in the middle of the afternoon or a little later when the sun is fairly down and on days when it has been extremely hot and sultry in the forenoon and the clouds are formed quickly and are of greater density than usual.

A very curious phenomenon is the rapid formation and disappearance of the clouds. One can watch them continuously forming and disappearing rapidly and one merely needs to turn away for a few moments when he may see that the aspect has changed, new clouds having replaced those he saw before. On many occasions, just after sunset, I have seen seemingly dense, white clouds appear as by enchantment below the mountain peaks. So quickly did these clouds or mist form that their appearance was much like the projection of an image on the screen. The wonderful beauty of the cloud formations as seen here is, however, enhanced not only by the incredible sharpness of the outlines and vividness of color but also by their accidental arrangement and forms they assume. Not unfrequently one can see clouds resembling all kinds of known objects, this adding much to the enjoyment one finds in observing them. In fact I have scarcely ever watched the clouds here without noting among the shapes resembling some or other familiar object. It is probably owing to the peculiar character of the clouds here that phenomena of this kind may be almost daily observed whereas in other parts they are very rare. Very often I have seen low on the horizon what appeared to be immense fields of ice as a sea frozen in the midst of a storm but so wonderfully real that it would be impossible to give an idea of it by a description however vivid. At other times there appeared ranges of mountains which one could not distinguish from the actual, on the horizon or the wide ocean, with its deep green, or dark blue, or black waters stretching out as far as the eye could reach. Nor was this an ordinary resemblance which one could banish from the mind by a small effort of will, but was rather of nature of those visions or hallucinations which make it necessary for one to pinch himself to fully realize that his senses have been deceiving him. More than once I have seen this ocean dotted with green islands or populated with glittering icebergs or sailing vessels or even steamers not less real to the eye because they were formations of mere mist or cloud.

Almost every evening, after sunset, and when the sky is clear, the horizon towards the plains becomes peculiarly tinged with colors of surprising vividness, all the colors of the rainbow being represented, the strata higher above the horizon beginning with red and passing through all nuances, the lowest strata finishing with blue, violet and black. As it grows darker the black line rises continuously above the horizon. This phenomenon illustrates in an interesting manner how the sun's rays are deviating from the straight course and are being continuously deflected downwards to the more dense strata of the atmosphere. Among the seemingly infinite variety of clouds there are four typical forms regularly observable which are of surpassing beauty. They are:

1) *Red clouds*, which are seen very frequently in the early morning hours at sunrise and, though less frequently, in the evening when owing to a greater percentage of moisture the clouds are denser, more like rain clouds. They reach an intensity of color equal to that of a ruby of the "pigeonblood" species. They are particularly beautiful when appearing in detached masses.

2) *White clouds* which are seen chiefly in the forenoon or in the early part of the afternoon though not so often. The whiteness and purity of these clouds and their sharpness of contours which has been already referred to makes them a unique sight. It would be difficult to offer to the eye a greater treat than it finds in the contemplation of these masses of mist, generally floating in big detached lumps in the blue sky. I note that these clouds are seen generally after a short rain when the wind, springing up suddenly, clears the sky, leaving only a few large and separate masses of vapor.

3) *Clouds* presenting the appearance of immense lumps of gold. These are iridescent clouds witnessed chiefly at sunset. They present a striking sight, particularly when they are small and detached from each other and the sun's rays can penetrate them more freely thus heightening at times to a degree really incredible the intensity of the iridescence. Their color is absolutely like that of gold and

the similarity is rendered complete by the forms they assume which are those of gold nuggets found in nature, but generally they pass from pure yellow to a reddish yellow of the kind peculiar to gold found in certain countries or generally gold containing a small percentage of copper. A feature of these most beautiful clouds is that they persist in their iridescence but a very short while. Usually they last only from five to ten minutes and often even not so long, although the yellow color may generally persist on the edges for as much as half an hour, more so in the morning than in the evening hours.

4) Clouds resembling lumps of incandescent metal. These clouds are most wonderful to behold and the intensity of the light emitted by them is such that it baffles description. I have never before seen anything of this kind in the Alps or elsewhere. One can see all nuances of color exhibited by heated metal or coal, from dull red to blinding white incandescence such as is seen in silver furnaces known in German as the "Silberblick". But most generally these clouds present the appearance of lumps of glowing coal surpassing, if anything, the latter in brilliancy and intensity of color and the sense of sight is still more completely deceived by the gradual burning away of the glowing mass offering to the eye the spectacle of a mass of charcoal which is being quickly consumed in a furnace with a very strong draught. How can the intensity of the light emitted by these clouds be explained? They throw out at times a light which to the eye is as intense and blinding as that of the sun's disk itself, yet they present a surface many hundred times greater than that of the sun's disk. Is it not possible that in this intense iridescence, not to say incandescence, we see not only a phenomenon of reflection and refraction of the rays of light but also, at least partially, of conversion of dark radiations of the sun into such which cause in our eye the sensation of light? Or, if not exactly this, might it not be possible that the dark rays being absorbed in the mist in some way or other reduce the absorption of the light rays and render the process of reflection and refraction of the latter more economical? I can not recollect any experiments carried on with the object of ascertaining the influence of temperature on these processes. A hot glass lens ought to be more efficient in letting the light rays through than a cold one. But, reasoning in the same strain, it would appear that reflection from a surface ought to be impaired by heating the latter. Furthermore I should think that it can not be indifferent for these two processes at what temperature the body reflecting or refracting the rays is maintained, at least one must infer so from the accepted theories according to which the dark and luminous radiations merely differ in their wave lengths but are otherwise identical. The most plausible view on the above phenomenon still seems to me that first expressed, according to which invisible radiations are partially converted into luminous rays or radiations thus supplying the additional light which it is difficult to account for otherwise. It is not impossible that a phenomenon similar to fluorescence might be produced by heat rays falling upon the particles of mist thus heightening the light effect or there may be caused, by the dark rays, a decomposition or falling apart of the vapor particles (as Tyndall demonstrated) – and this process may be accompanied by some evolution of light. Certainly the particles capable of producing such vivid iridescence must be very minute, much smaller than ordinary particles composing the clouds and their form can not be but a passing one as is evidenced by the rapid disappearance and reappearance of clouds already mentioned. These four types of cloud, which can be observed here almost *daily* and which in purity, brilliancy and depth of color and sharpness of outlines surpass by far such clouds noted in other parts, constitute the chief attractions of the incomparable beauty of this sky. These phenomena would be more appreciated if they were more rare, but the fact is that for most people they lose a large portion of their charm by forcing themselves upon the eye too frequently. We are used to speak of "Sunny Italy" but compared with Colorado that country might be almost likened to foggy England. They tell me that there are scarcely 10–20 days in a year, on the average, when the sun does not shine and even this estimate is rather exaggerated. Since my arrival here about the middle of May, with the exception of a few passing thunderstorms, the days were clear with just enough clouds in the sky to break the monotony of the blue.

No wonder that consumptives and generally people in feeble health are getting on here so well. The purity of the air, the altitude, which compels exercise of the lungs to be continuously and uncon-

sciously practised owing to the lesser density of the air and smaller percentage of oxygen (about 20% less than at sea level), the dryness of the air which is altogether exceptional, all these causes may co-operate more or less efficiently in improving the condition of the patients, but I believe that the chief cause of betterment is to be found in the profuse and cheering sunlight. Whether the light produces a specific germicidal effect is a matter of conjecture as yet, as far as I know. I learned here that experiments had been carried on to ascertain whether there are any Roentgen rays emitted by the sun or produced in other ways by the sun's rays but the results were negative. Similar experiments, I am told, were conducted for a long period on Pike's Peak but no action on a photographic film, which was the means of these investigations, was noted, at least not such as might be attributed to Roentgen rays. I think though that rays of this kind must be ultimately demonstrated to exist in the radiations of the Sun as well as of most other sources of intense light and heat. It is possible that such rays are, in a measure, active in arresting the process of decay caused by the bacillus. I conclude that, since the bacillus of tuberculosis is an organism developed under *exclusion* of light, such rays of short wave length, made by any means to penetrate the tissues and reach the affected parts of the same, must needs be inimical to the development of the microbes not used to such rays. Though this conclusion might not prove true, still there is a good foundation for it, and I am hopeful that with the apparatus I am now perfecting for other purposes as well as this, it will be possible to produce Roentgen rays of great intensity which will furnish the long sought for means of successfully combating these dreaded diseases of the internal organs. Whatever be the cause of the marvelous improvement noted in patients it is a fact that most people afflicted with these ailments, and often pronounced beyond medical help, recover and get soon seemingly quite well here. A short while ago I was induced by a friend to go to a dinner he gave in my honor where I met a number of more or less interesting people. The conversation during the entire evening was an animated one and the entertainment highly enjoyable. Everybody seemed to be in high spirits and excellent health. But my pleasure was spoiled in the end when I learned before parting, with painful astonishment, from a friend who is a very skilled and competent physician, that of the two dozen people I met scarcely one individual had more than one whole lung left, the majority of them being in fact "much farther gone" as he said, so that they would infallibly die in a very short time if they would leave here. I soon learned that there were thousands of consumptives in the place, about the only healthful people being coachman, and I concluded that while this climate is certainly in a wonderful degree healthful and invigorating, only two kinds of people should come here: Those *who have* the consumption and those *who want to get it*. That the sun's light and heat exercise a highly beneficial effect on these sick people may be inferred with certainty from its effect upon people who are quite well. It is curious to note how agreeable and indispensable the sunshine becomes here after a while. Even healthful people become sad and unstrung when the sky gets clouded and dark. I have however, observed such an effect before but it is quite natural that it should be so here where the sun shines constantly day after day. I do not suppose that in London or even in New York, where the weather is comparatively fair much attention is paid as to whether the sky is clear or clouded, but here every laborer laments when the sun does not shine. Despite the beautiful spectacle offered by the parting sun one feels sad when its disk sinks behind the mountains and one is thoroughly glad to see it rise again. These feelings are experienced, of course, everywhere, but somehow they are of greater intensity here than elsewhere. Considering the elevation, the small density and exceptional purity and extreme dryness of the air, the scantiness of the vegetation and particularly the scarcity of protecting timber, the vastness of the practically desert prairies over which the wind can sweep unimpeded, the geographical position of the country and other causes and conditions determining the character of the climate it is not difficult to guess the general nature of the weather in Colorado. Nevertheless it is a surprise to learn that the climate is mild in an extraordinary degree, the storms coming but seldom and lasting one or two days at the most, the snow remaining scarcely over more than thirty-six hours on the ground.

In fact Colorado people seem to be particularly proud of their winter climate. I expressed to a friend my delight at the wonderfully fine and bracing weather we had so far, but he astonished me by saying: "This is not a fair opportunity to judge. To form a correct opinion of the qualities of this climate

you must come here in wintertime". I could scarcely conceive how it could be possibly finer and more agreeable than so far experienced. I expect to get data as to the pressure, temperature, moisture etc. The pressure at present is about 24" average, considerably less than at sea level but, owing to the bracing air, one does not feel much the effect of the rarefaction of the atmosphere except when performing some physical work, when one gets quickly out of breath. The humidity must be extremely small otherwise one would feel both the heat and cold much more. The mean temperature presently at noon is about 80° in the shade but in sunshine it is different. I believe the good people here are more or less inclined to find the days in summer cooler than they are in reality, and they seem also to prefer to be silent about cold snaps which occasionally come in wintertime. But from some indiscreet persons I have learned that the thermometer was at times very near 40° below zero and in the plain sunshine of summer it is apt to be "way up" as my informants told me. I feel sure it can not be far from 150°. The power of the sun's rays on certain days when the atmosphere is particularly calm, dry and pure, is such as to positively surpass belief. The waterpipe passing for some distance across the field to the laboratory being partly uncovered the heat was as a rule so fierce that the water came out boiling and steaming like in a Russian bath. It would be impossible to hold the hand in it, even for a few moments, for it would at once cause a severe pain. One day, about five o'clock in the afternoon, the rays fell through the open door on a high tension transformer which I had brought from New York and, before anybody could notice it, melted out all the insulation, rendering the apparatus completely useless. I observed the danger a few days before and warned the assistants to watch the machine, but unfortunately on that day the usual precautions were omitted. Several barrels filled with concentrated salt solution were placed outside of the laboratory, and the pressure in them rose every day as in a steam boiler, and a few of them were damaged! When the cock was opened the water squirted out to a great distance across the field and it was thought advisable in order to avoid bursting and damage, to leave a small opening in the barrels for the escape of the steam. The most astonishing experience of this kind was, however, the heating of a wooden ball covered with tinfoil, which was supported above the roof, to a point it was deemed unsafe to expose it to the sun's rays. It emitted a dense vapor actually like smoke, and the tinfoil crumbled away! This excessive heating seemed to take place suddenly. I believe that it occurs when, owing to the removal of a layer of impure air, a particularly clear path is opened for the sun's rays, which then pass through the pure medium without much loss. Often I have felt a scorching pain on the cheek or neck to come on *suddenly* when working in sunshine, and I can only explain it with the above assumption. But the most interesting of all are the electrical observations which will be described presently.

Colorado Springs

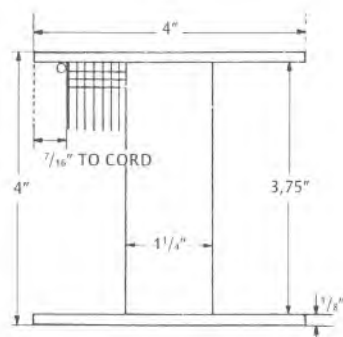
August 2, 1899

New induction coil for portable apparatus, designed for investigation outside contained in box. *Condenser method.* Particulars: Secondary wound with wire № 30, 32 layers plus one layer with thick cord. Turns 180 per layer. Total number of turns 5670. Least turn $1.25 \times 7\pi = ?$ longest turn $3.5\pi = ?$ average $2.125 \times \pi = 6.675"$ or 17 cm. approx. for average length of one turn. Resistance of secondary 375 ohm. The dimensions of spool are as in sketch below.

The available length of coil $4" - \frac{1}{4}"$ for two fibre flanges $l = 3.75"$. The primary 50 turns as a coil before wound cord № 20, Res = 0.51 ohm. The length of average turn $10.6" = 26.93$ cm. Total length of wire in primary $530" = 1346.2$ cm.

In connection with this there is to be used: a condenser to be adjusted, a charging coil experimental like wire to be adjusted to the condenser and break, a Thomas clockwork with wheel 180 teeth for break, the arbor carrying also a sensitive device so that same clockwork will serve for break and first sensitive device. A second sensitive device in secondary of oscillating transformer driven by another

Thomas clockwork. This latter need not be used when self-exciting process with condenser employed. Relay brought from New York 996 ohms or thereabouts. *This final.*

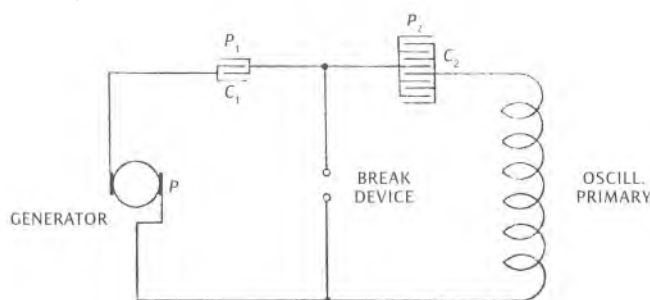


Maniton bottles to be used compared with *Champagne* bottles. The latter would seem to be better suited. The tests showed as follows: Comparing 2 bottles of each kind filled as far as practicable and placed in tank with rock salt solution as in previous instances charged to *same* potential 356 volts approximately, the average of four readings was for: *Maniton* bottles 13° defl. for *Champagne* bottles 9.5° defl.

This gives: $\frac{\text{Capacity of Maniton}}{\text{Capacity of Champagne}} = \frac{130}{95}$

How by taking weight: $\frac{\text{Weight of Maniton}}{\text{Weight of Champagne}} = \frac{23}{36}$

These figures give a slight advantage to glass in *Champagne* bottle, but the latter was larger than the *Maniton* about $\frac{1}{4}$ " outside and contained a trifle *over* one *quart*. Furthermore, there is the usual hollow bottom (to deceive customers) and this increased the surface in the *Champagne* bottle. In view of this the conclusion is that the glass is not greatly different in respect to dielectric qualities in both the bottles. The *Champagne* bottle would unquestionably break down first because of hollow bottom, as it would be difficult to exclude the air. It would also be difficult to get the required number of such bottles in this quiet town. This compels use of *Maniton*.



Consider the following case: A condenser is connected in series with another to a generator of high tension. A circuit making and breaking device is arranged in a bridge between the condensers as illustrated in diagram. When the circuit is closed through this device the condenser included in the circuit of the generator is charged to the full potential, but when the device breaks the current path, the charge is distributed over the two condensers. Such an arrangement with two condensers has certain valuable features in connection with oscillators, particularly when they are worked from a generator of very high and constant e.m.f. The condenser included in the generator circuit prevents short circuiting of the generator in case of defective action of the make and break device and the amount of energy drawn from the source is limited to a quantity which can be exactly determined beforehand. The arrangement is sometimes of value also with alternate current generators. The condenser C_1 , then performs the func-

tion of a reducing valve on a reservoir such as is used in connection with a distribution system of some gas under great pressure. By means of such an arrangement an oscillator may be worked safely from a generator of any e.m.f. and at any desired pressure. In the case as illustrated the total capacity is

$$C = \frac{C_1 C_2}{C_1 + C_2}$$

and the energy stored by one charge in the system is

$$\frac{1}{2} P^2 \frac{C_1 C_2}{C_1 + C_2}$$

Now

$$P = p_1 + p_2 \quad \dots 1)$$

and

$$\frac{1}{2} p_1^2 C_1 + \frac{1}{2} p_2^2 C_2 = \frac{1}{2} P^2 \frac{C_1 C_2}{C_1 + C_2}$$

and from this

$$p_1 C_1 = p_2 C_2 \quad \dots 2)$$

and

$$p_1 = \frac{P C_2}{C_1 + C_2}; \quad p_2 = \frac{P C_1}{C_1 + C_2} \quad \dots 3)$$

Suppose the process be such that C_1 first be charged to full pressure P and then disconnected and charge distributed over the two condensers, C_2 being the condenser belonging to the oscillator, whereas C_1 is the regulating condenser, then since

$$\frac{1}{2} P^2 C_1 = \frac{1}{2} p_1^2 C_1 + \frac{1}{2} p_2^2 C_2 \quad C_1 (P^2 - p_1^2) = C_2 p_2^2 \quad \text{and} \quad p_2^2 = \frac{C_1}{C_2} (P^2 - p_1^2)$$

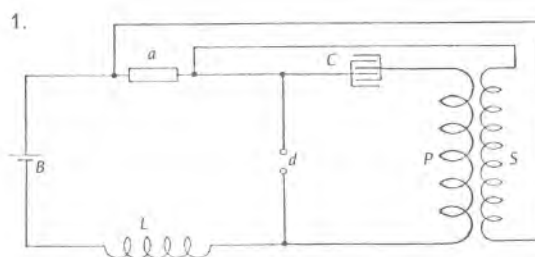
is the pressure on condenser C_2 which it was the object to find.

Colorado Springs

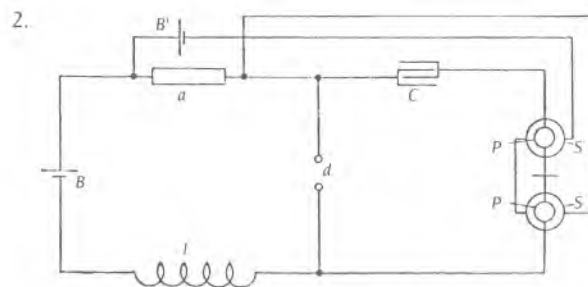
August 3, 1899

Modifications of apparatus, involving condenser method of magnifying effects, experimented with "Self-exciting" process

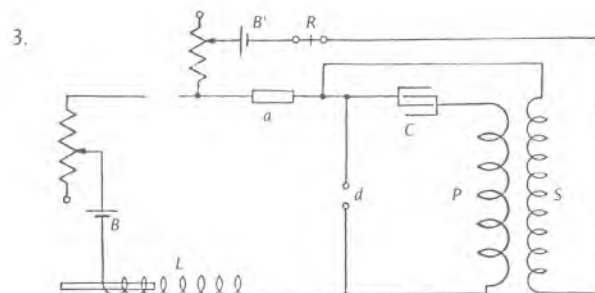
In this special modification of condenser method, an effect produced upon the sensitive device is rendered accumulative not only as in some other modifications, but more so by a process comparable to the self-excitation of a dynamo. Thus much feeble initial effects are made sufficient to cause the sensitive device to break down and the receiver to be operated. This process accomplished in this manner will certainly have many valuable uses. A few arrangements which have been experimented with are recorded below. They are self-explanatory. The lettering makes Diagram 1. fully clear with reference to previous diagrams of this kind, a is the sensitive device, d a make and break device, C a condenser P the primary and S the secondary of oscillatory transformer, B a battery and L an inductance suitably adjusted.



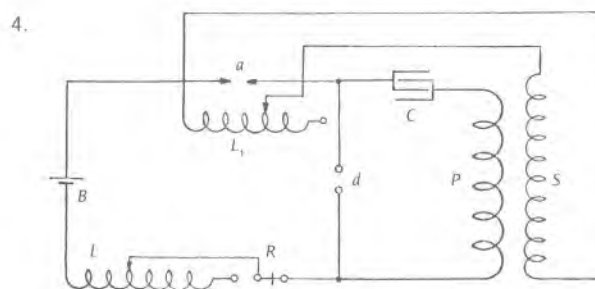
The sensitive relay usually employed may be in the circuit containing battery B , inductance L , and the devices d and a ; or, it may be in the circuit of secondary S and device a in which case this circuit will contain an additional battery. There will also be in the circuits the usual adjustable resistances to adjust the instruments and insure the best action. From the diagram it will be easily seen that when the device a is at first very slightly affected, the condenser is charged more and the secondary currents become more strongly excited in their turn, the device and so on, until the device breaks down and diminishes sufficiently in resistance so that the relay is operated. This method has been found excellent and will have besides telegraphy many valuable uses since by its means effects, too feeble to be recorded in other ways, may be rendered sufficiently strong to cause the operation of any suitable device.



A number of modified arrangements as have been experimented will now be recorded. Referring to diagrams which follow in Fig. 2. an arrangement identical with that in Fig. 1. is shown, only the relay itself is made to be the transformer by being suitably proportioned to the break and condenser and having on top of primary windings P a secondary S wound with fine wire and containing a battery B' as shown. The secondary excites the sensitive device a until it breaks down when the relay is operated. This arrangement is not the most preferable to employ as better results will be obtained with an independent transformer and relay, but it has the features of compactness and simplicity. It can be, however, still further simplified by doing away with inductance L .

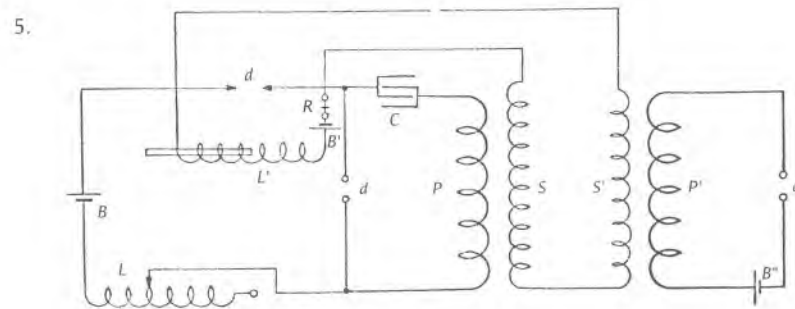


The batteries B and B' may be connected to cooperate in their acts upon sensitive device a or to oppose each other. The former seems preferable. The condenser should be of *large capacity*. In Diagram 3.



the form of connections is illustrated which was found most convenient for experimentation. An independent sensitive relay is used and adjustable dead resistances r and r' in primary and secondary circuits. The

inductance L is also made adjustable and so is also break device d though this is not indicated in the diagram. In Fig. 4. again plan is shown which is suitable when, instead of a sensitive device as has been described before and which is based on the properties of minute conducting grains, a minute gap a is employed.



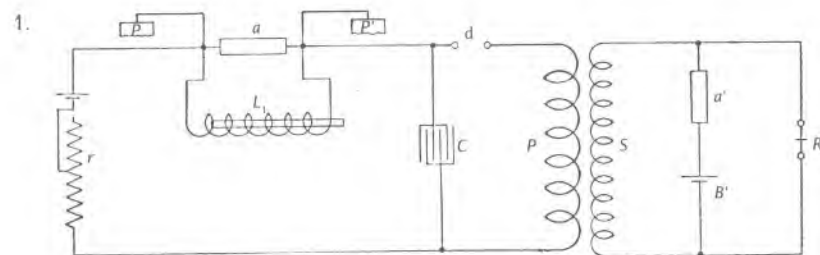
This special device comprises two points almost in contact and in an atmosphere or medium the insulating properties of which are impaired to such an extent that it breaks down readily upon a slight increase of the electrical pressure. The additional adjustable inductance L_1 serves to bridge the gap and allow normally a small current to pass and to charge condenser C , to strain sufficiently device a . The relay R may be otherwise placed. Finally, in Diagram 5. a modification is shown with an additional induction coil $P'S'$, B'' and d' , the latter device making and breaking the circuit and straining device a by currents generated in secondary S' . The diagram is otherwise self-explanatory. The relay may be, as stated before, otherwise inserted.

Colorado Springs

August 5, 1899

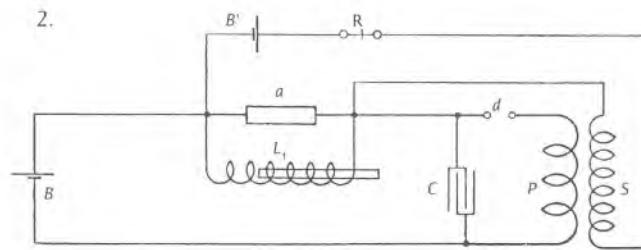
Experiments with condenser method of magnifying effects continued

More of the modifications described: In Diagram 1. a resistance, preferably inductive, is placed around sensitive device a for the purpose of regulating the charge of condenser C and thereby determining the degree of excitation of device a' in secondary circuit of transformer. The adjustable resistance r serves to regulate strain exerted upon device a by battery B . The terminals or plates $p p'$ are placed in suitable locations of medium or media, one in the air, the other in the ground generally. Otherwise the diagram explains itself.

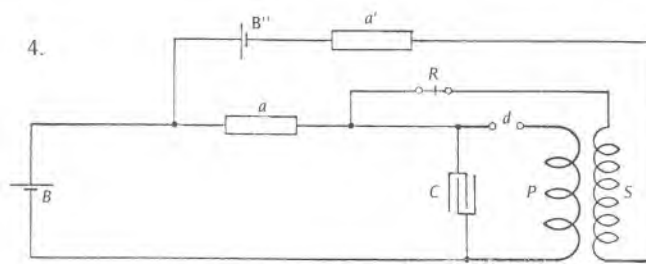
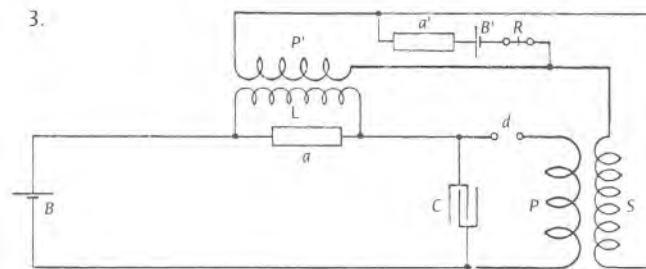


In Diagram 2. the second sensitive device is omitted and the secondary S is connected around sensitive device a . Other accessories, as adjustable resistances, are likewise omitted for sake of clearness.

In Diagram 3. again the coil L is made the secondary of another coil which is supplied from primary oscillating transformer $P S$, the latter being controlled in its performance by sensitive device a .



In Diagram 4. a similar arrangement is illustrated as shown on a previous occasion, the secondary S being connected around sensitive device *a* and containing another sensitive device, relay and battery, other accessories being omitted for reasons above given.

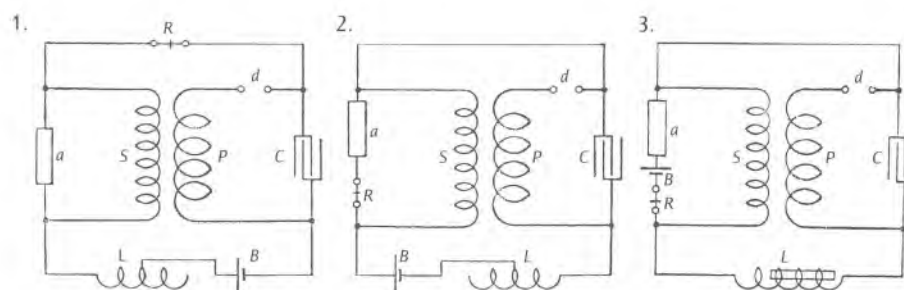


Colorado Springs

August 6, 1899

Experiments with Condenser method of magnifying effects

More of the arrangements experimented with described:

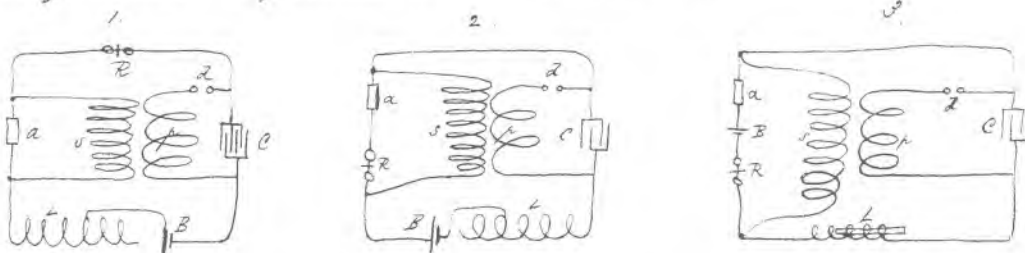


The three diagrams shown illustrate arrangements as variously carried out in a form of portable apparatus referred to before. Referring to Fig. 1. the sensitive device *a* was one consisting of a small

Cornwall Springs Aug. 6 1899.



Experiments with Condenser Method of magnifying effects. More of the arrangements experiments with describe:



The three diagrams above illustrate arrangements as various carried out in a form of portable apparatus referred to before. Referring to fig 1. The sensitive device a was one consisting of a small galvanometer and two metallic plugs, the tube being rotated by a Thomas Clockwork. Some N.ickel chips for gas as before described were used in the tube. The improvement was effected by cleaning the chips, first with dilute acid and alkaline solution and distilled water and alcohol at last. In one apparatus the plugs were $\frac{1}{8}$ " apart, tube $\frac{1}{8}$ " diam. half filled. Condenser μ H.F. one of the small ones before used. L $\frac{1}{2}$ μ and d were as described on an other occasion. The results were good. In diagram 2. the same devices were used in a slightly different way as will be plain from diagram. The receiver R was put in series with device a so as not to be affected much by operation of break device Z. This seemed better, results were very satisfactory. In diagram 3. the improvement was still carried further the same devices being again used. The delicately balanced lever of receiver R was very little affected by the sudden action of the break, the pull was steady & consequence and a better adjustment was possible. The results were now more satisfactory. One cell of Leclanche dry being quite sufficient.

evidence of stationary values magnified

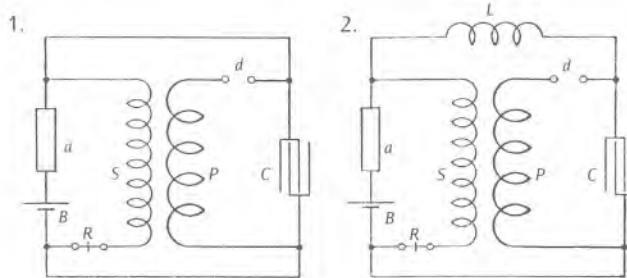
glass tube and two metallic plugs, the tube being rotated by a Thomas Clockwork. Coarse nickel chips prepared as before described were used in the tube. An improvement was effected by cleaning the chips first with dilute acid and alkaline solution and distilled water and alcohol at the last. In one apparatus the plugs were $\frac{1}{8}$ " apart, tube $\frac{1}{4}$ " diam. *half* filled. Condenser $\frac{1}{2}$ mfd. one of the small ones before used. L , S , P and d were as described on another occasion. The results *were good*. In Diagram 2. the same devices were used in a slightly different way as will be plain from the diagram. The receiver R was put in series with device a so as not to be affected much by operation of break device d . This seemed better, results are very satisfactory. In Diagram 3. the improvement was carried still further the same devices being again used. The delicately balanced lever of receiver R was very little affected by the sudden action of the break, the pull was steady in consequence and a better adjustment was possible. The results were now most satisfactory. One cell of Leclanché dry being quite sufficient.

Evidence of stationary waves water pipe

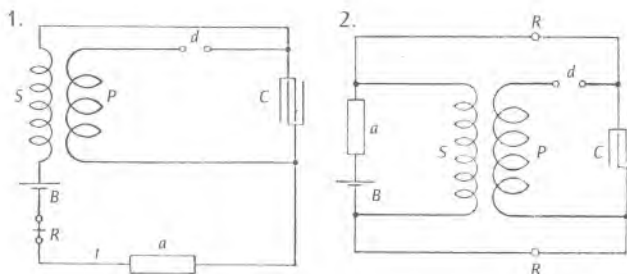
Colorado Springs

August 7, 1899

Some dispositions of apparatus experimented with in which the secondary of an oscillating transformer was used to excite the sensitive device have shown results vastly better and it seems that the increased sensitiveness is due partially at least, to the fact that one terminal of the secondary connected to a sensitive device (which unexcited has a resistance of about 100,000 ohms or more) is practically *open* and that therefore by the slightest disturbance a high pressure can freely manifest itself and break

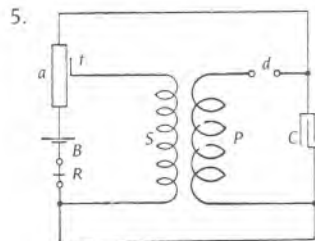


down the insulation of the device. To investigate further the capacity of such arrangements a great number were tried of which some follow: One of the earlier arrangements was as illustrated in 1. In this case the secondary S was closed by the condenser C *too* large for it, and the self-induction (very large) L was inserted to overcome this defect and for other reasons (2).



The next arrangement adopted was as shown in 3. In this case the terminal of secondary, or respectively its continuation up to t was open or insulated – at least practically so and the apparatus was more sensitive when the secondary had a great number of turns, it was better to place battery B and

receiver R between the other end of secondary and the corresponding terminal of the condenser, but when the secondary did not have as many turns the apparatus generally worked better with battery and relay placed as shown in 3. as they caused a certain rise – by their capacity and self-induction – of the electrical pressure on terminal t of sensitive device.



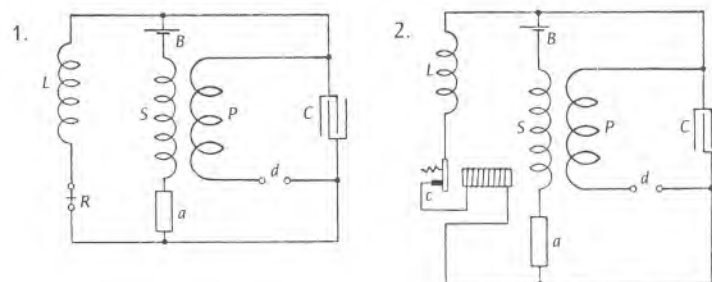
A modification of Fig. 2. is shown in Fig. 4. In this case the self-induction L was replaced by relay R which had one of its legs or coils inserted in each of the two branches of the circuit leading from the condenser as illustrated. As the relay had a very high winding and high resistance nearly 1000 ohms, this left the secondary practically opened and free to work on sensitive device a .

It was observed in some experiments that a sensitive device becomes more responsive to feeble disturbances when, instead of being excited by direct connection to a source, it is strained from a source from some distance. In some instances the apparatus was affected and the relay responded to a small bell from a great distance. It is probable that the increased sensitiveness is due to a certain freedom or looseness of the grains of nickel which were used and which does not exist to such extent by direct connection to a battery. These observations led to investigating the capacities of some such arrangements typically illustrated in Diagram 5 in which the device is excited by induction.

Colorado Springs

August 8, 1899

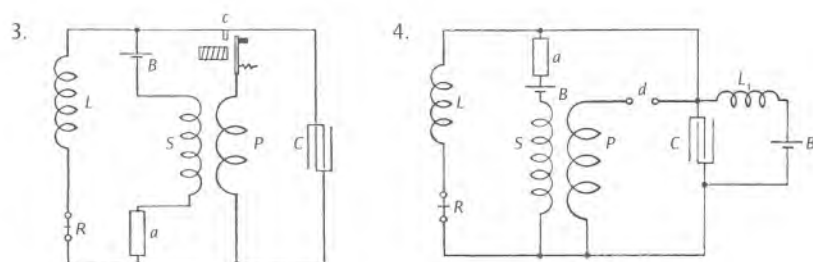
Other ways of connecting apparatus when using open acting secondary for exciting sensitive device



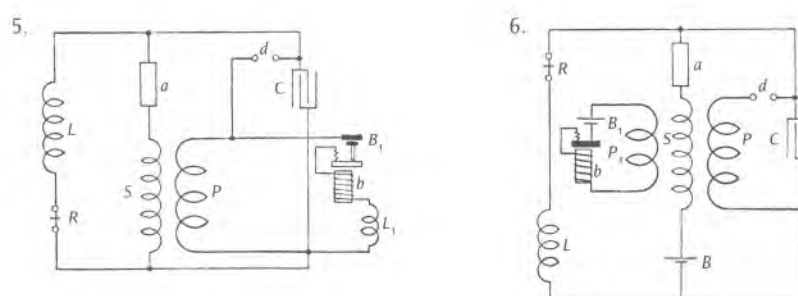
As in some previous experiments the fine relay R was affected by the break d , the relay with an adjusted high ohmic or inductive resistance l was placed in a special branch circuit (1.) It being found, furthermore, that when the sensitive device is very delicately adjusted, it often would not loose the excitation quickly enough by rotation (when a rotating cylinder as often experimented with before was used), but it would always loose the excitation by breaking the battery circuit – the disposition illustrated in 2. was adopted in which the relay R was made to break the battery circuit by opening contact c which was fixed similarly to that of an ordinary bell or buzzer with a fine spring so that the relay could complete the contact underneath (not shown) working the printing apparatus or other appliance.

The under contact was, however, dispensed with by connecting around contact c a circuit of *very high* resistance including another fine relay which was brought into action whenever the lever of relay R was pulled toward the core.

Instead of using the clockwork with break before referred to, an ordinary magnetic circuit breaker with contact was employed to operate the primary P and to generate thereby the currents in secondary S for excitation of device a . This simple arrangement is shown in Diagram 3. To provide for excitation of condenser and consequently of sensitive device up to the point desired various plans were investigated of which some follow here:



In Fig. 4. for instance, the resistance of device a unexcited being practically infinite an other battery B_1 with self-induction coil L_1 was placed around the condenser to excite the same and by the action of secondary S also sensitive device a .



Again in Fig. 5. around the ends of the primary P was connected a Battery B_1 in series with buzzer b and adjusted self-induction L_1 . The latter was so graduated that the induced currents in S would strain the device a to the point of breaking down. Still another such plan was tried by placing a separate circuit comprising coil P_1 Battery B_1 and buzzer b at a suitable distance of secondary S , such that the preparatory excitation of device a was effected.

Colorado Springs

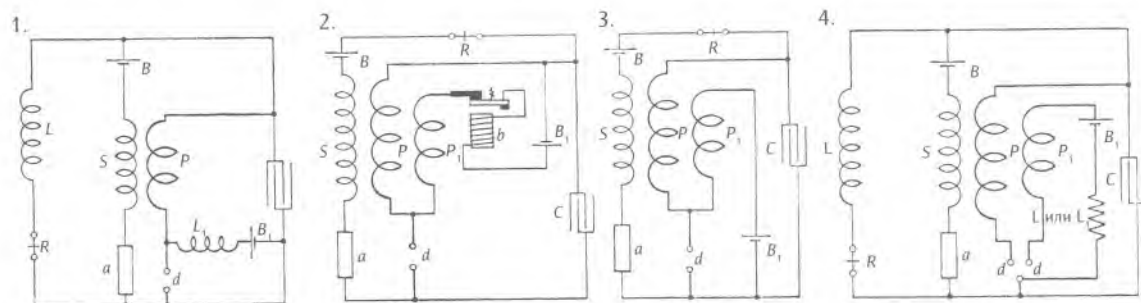
August 9, 1899

Other dispositions of apparatus experimented with

One of the plans before described was modified in the manner illustrated in 1., the battery B_1 which effected the preparatory excitation being placed as indicated so as to work through the primary P and *conjointly* with main battery B .

Fig. 2. illustrates a disposition similar to one experimented with before, only in series with buzzer b and auxiliary exciting battery B_1 , a primary which was adjustable (P_1) was used. This arrangement was modified to the one illustrated in Diagram 3. The intention being to use the same break for both prima-

ries P and P_1 . Neither of the plans (2 and 3) seemed capable of such results as were readily obtained in some previous dispositions. These experiments showed that the proper way was to modify plan 3 into one illustrated in 4.

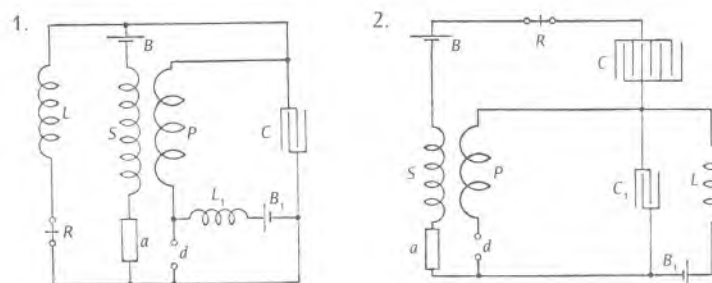


In this case a break device with *two contacts* is provided which make and break *simultaneously* both the main primary P and auxiliary primary coil P_1 . In auxiliary circuit P_1 , for purpose of adjustment, a resistance r or l dead or inductive is included.

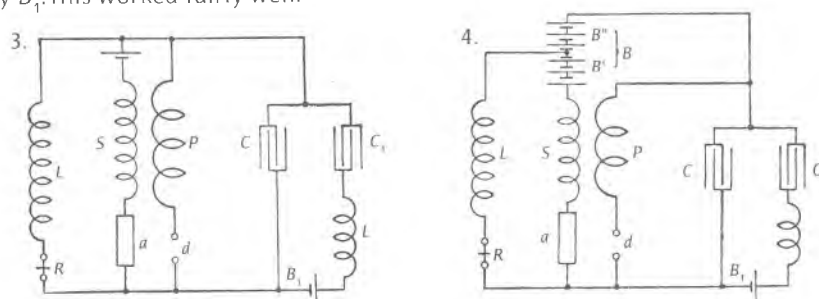
Colorado Springs

August 10, 1899

Further modifications of apparatus experimented with



An arrangement as illustrated in 1. was made to see whether excitation (preparatory) could be conveniently effected by shunting around break d a circuit including very high graduated self-induction L_1 with battery B_1 . This worked fairly well.



To avoid certain disadvantages in previous similar forms of apparatus – as the permanent closure of condenser – a number of modifications based on the use of two condenser was resorted to and experimented with, some of which are illustrated in diagrams following.

In Diagram 2. two condensers C and C_1 are placed in series, one of them being shunted by graduated self-induction l and battery B_1 . The other condenser C , being larger, allows the current from battery B to pass through break and coil l when device a is excited. Not very good. A modified plan is illustrated in 3. In this case the auxiliary battery B_1 charges the two condensers C and C_1 in series, whereupon one of them is discharged through the break d . This is fair.

In 4. the battery (main) is so placed that a high e.m.f. is charging the condenser yet current through the sensitive device is small.

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August 11, 1899

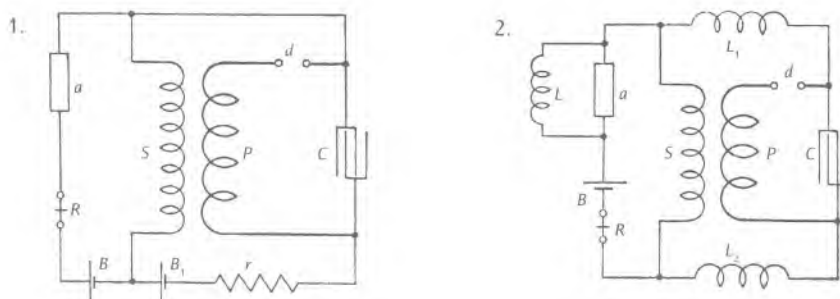
Measurement of capacity of the new condensers prepared from Maniton Water bottles

With the exception of three tanks in which bottles with green glass were used all the remaining bottles were of *dark glass*. The test did not show much difference between the two kinds of glass and all the tanks separately measured were found to be, after proper filling in of the solution, of the same capacity or very nearly so. All the bottles were first connected in quantity and the capacity compared with that of $\frac{1}{2}$ mfd. standard condenser. The deflections were almost exactly as 36 : 44, 36° for the $\frac{1}{2}$ mfd. and 44° for the bottles.

The capacity of all the latter was therefore $\frac{11}{18} = 0.611$ mfd. This would give for one bottle, since there were 576 bottles, the average value of $\frac{11}{18 \times 576} = 0.00106$ mfd. or $0.00106 \times 9 \times 10^5 = 955$ cm. As there are 36 bottles in each of the tanks we get for one tank $36 \times 0.00106 = 0.03816$ mfd. or $36 \times 955 = 34,380$ cm. As each side has 8 tanks the capacity of each side would be $0.03816 \times 8 = 0.30528$ mfd. or 275,040 cm. and when, as mostly the case, the two sides are in series the total primary capacity will be $\frac{0.611}{4} = 0.15275$ mfd. or $0.15275 \times 9 \times 10^5 = 137,475$ cm. When working with one primary turn, taking the inductance of primary as $\frac{7}{10^5}$ henry we get

$$T = \frac{2\pi}{10^3} \sqrt{0.15275 \times \frac{7}{10^5}} = \frac{2.054}{10^5} \text{ and } n = 48,700 \text{ per sec.}$$

Other modifications of signalling apparatus experimented with



Several ways of providing for initial excitation when using oscillatory transformer principle are illustrated in diagrams which follow:

Colorado Springs Aug. 12. 1899.



further modifications in signalling apparatus.

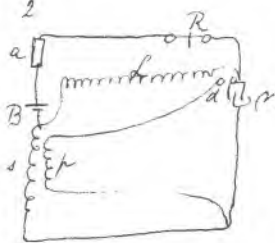
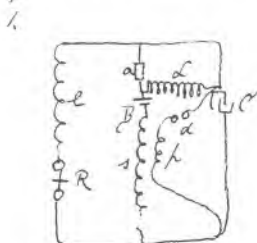
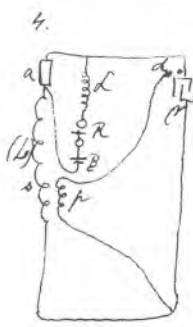
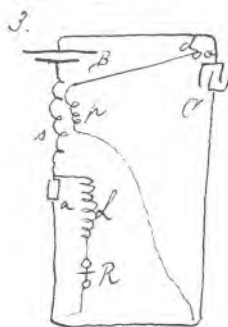
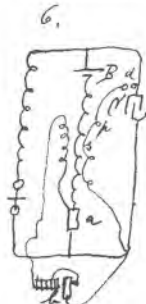
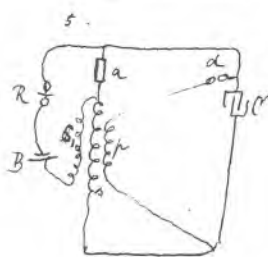


fig. 1. and 2. show ways of securing initial excitation by means of very high inductance L connected as shown.



The diagrams 3 and 4. illustrate similar plans of connection. In the former the battery B is in the main circuit, in the latter in a shunt to device a.



In fig 5. and 6. other multiple connections are shown. In 5- an auxiliary secondary s, with battery and relay in circuit around device a which is excited by main secondary s. In 6.

a similar connection is used with a battery b to excite device a through secondary s.

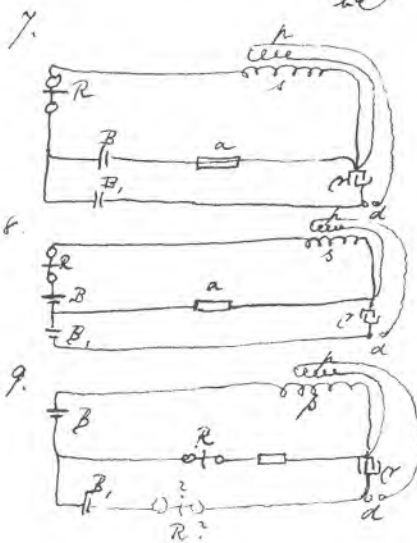
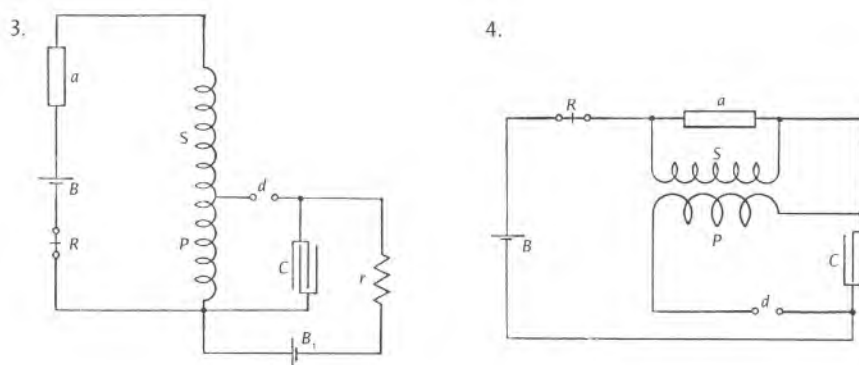


fig. 7, 8. and 9 again illustrate other arrangements in which two batteries are employed one generally to secure initial excitation

In the first diagram the excitation is provided through auxiliary battery B_1 the strength of which is regulated by adjustable resistance (inductive or ohmic) r . The two batteries B, B_1 are so connected that they join in straining device a .

In Diagram 2. an inductive resistance *very high* is connected around device a and coils l_1, l_2 are also employed to prevent the secondary S being closed and potential diminished through comparatively large condenser C . The inductance l and also l_1, l_2 are adjusted.



Again in Sketch 3. is shown a plan convenient to use when the secondary is wound in one single layer on a drum. A part of the secondary is made to serve as a primary through which condenser C , loaded to the desired point by battery B_1 (graduated by resistance r) is made to discharge. In this manner it is easy to adjust the action of the secondary on device a .

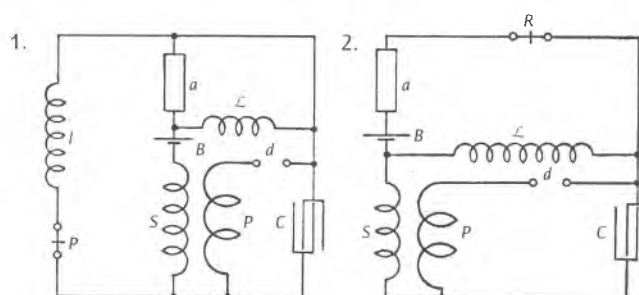
In Diagram 4. is illustrated a simple way experimented with before which secures good results. This to follow up.

Colorado Springs

August 12, 1899

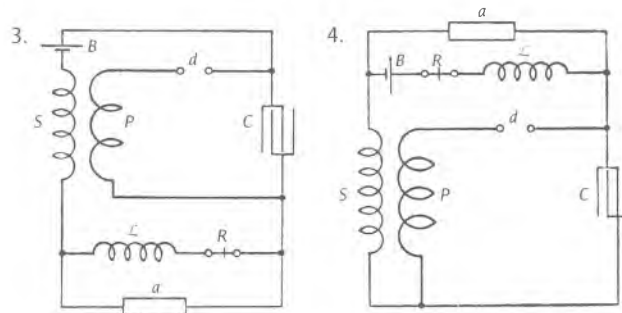
Further modifications in signalling apparatus.

Figs. 1. and 2. show ways of securing initial excitation by means of very high inductance $\mathcal{L}$ connected as shown.

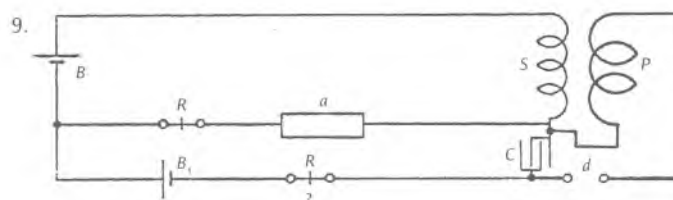
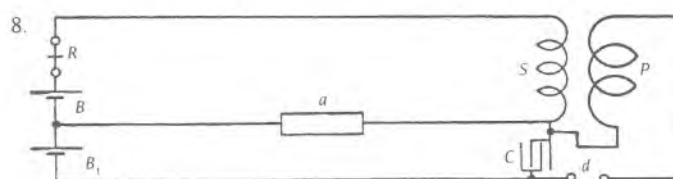
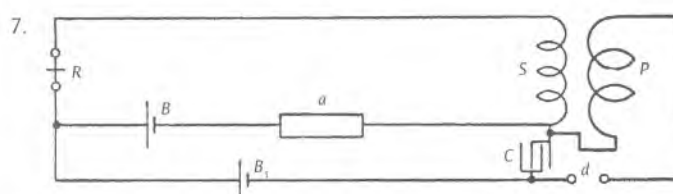
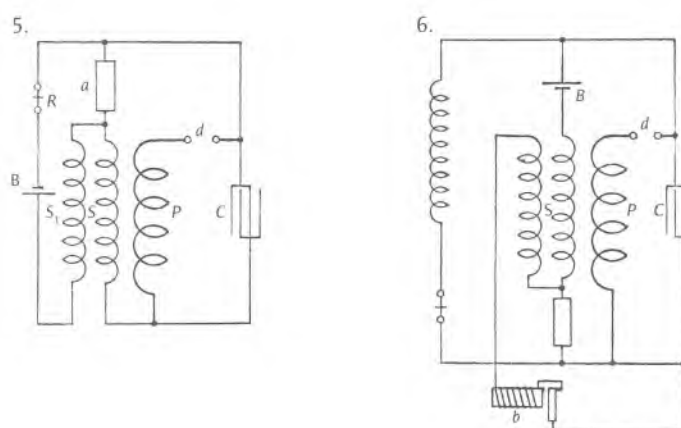


Diagrams 3. and 4. illustrate similar plans of connection. In the former the battery B is in the main circuit, in the latter in a shunt to device a .

In Figs. 5. and 6. other modified connections are shown. In 5. an auxiliary secondary S_1 with battery and relay is connected around device a which is excited by main secondary S . In 6. a similar connection is used with a buzzer b to excite device a through secondary S .



Figs. 7., 8. and 9. again illustrate other arrangements in which two batteries were employed, one generally to secure initial excitation.



Colorado Springs

August 13, 1899

Experiments with oscillator 35–35 ½ turns. Tension on Westinghouse Transformer 15,000–22,500 volts. Supply transformers connected 100 volts.

1 primary turn, all jars tension 15,000 volts, effects would indicate capacity too small.

To ascertain this the connection was changed to 2 primary turns in series and ¼ capacity (2 tanks). The capacity was now varied but resonance effects moderate. All experiments show clearly too much capacity and comparatively little self-induction in secondary. There is a large movement in the wire, but pressure can not appear on end as it would in the absence of capacity.

By adding capacity on one end better results indicate that this view is true.

One of the balls 38 cm. on end results much better, sparks on arresters much stronger.

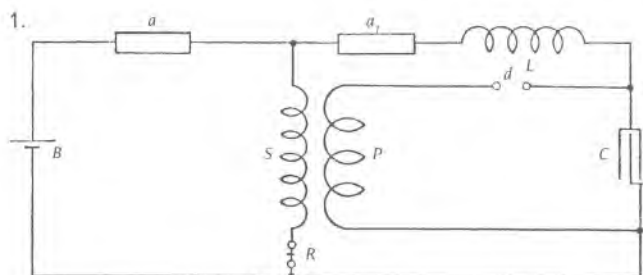
Two balls connected – effects still stronger, sparks livelier on arresters but the tension still too small. Needs much more capacity on the end to overcome internal capacity distributed along cable.

Now again changed to one turn as oscillation much better. The extra coil was added and adjustment of capacity made. Best results with 3 ⅔ tanks capacity on each side. An empty tank placed on top of the coil for capacity. The effects with 22,500 volts on W.T. remarkable. The streamers very rich red, quickly darting up to 9 feet long. Many brilliant sparks would jump up to a 10 foot distance.

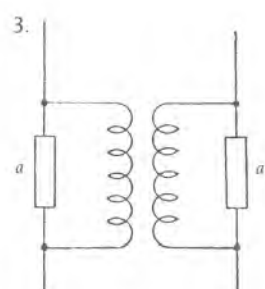
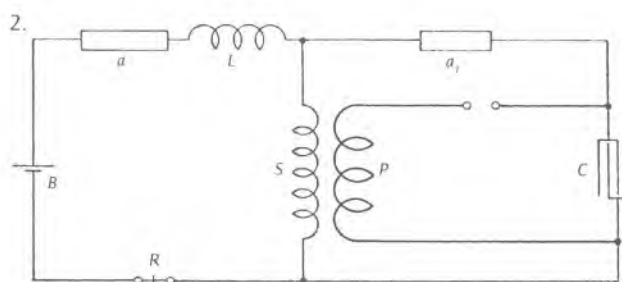
Colorado Springs

August 14, 1899

The following arrangements with two sensitive devices were the subject of consideration and experiment today:



This disposition (1.) though it worked fairly had the disadvantage that a diminishing of resistance of device *a* was not very effective in increasing the charge of the condenser, but by making the secondary and relay circuit of very high inductance and resistance this defect was to a degree remedied.

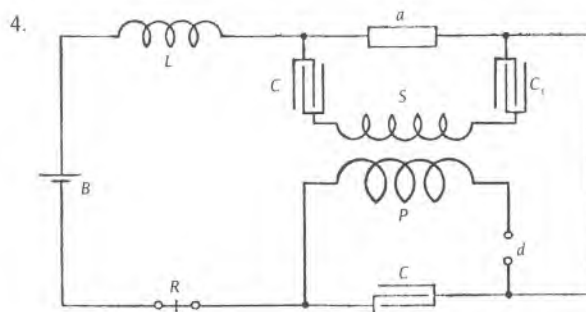


By changing connection to the one indicated in the second diagram the condenser was stronger and more effectively charged upon the falling of the resistance of either of the devices a a_1 .

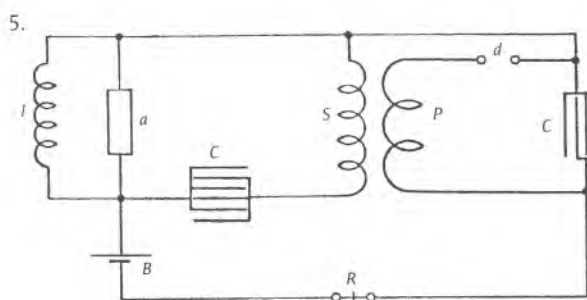
The conclusion arrived at from many experiments with two devices, which seem to indicate that two such sensitive devices are better than a single one as regards sensitiveness, was that the devices should be arranged as in Sketch 3 so that a change in one will produce a change in the other which in return should react upon the first and so on. This general scheme is to be further considered.

Other arrangements of apparatus with open secondary for exciting sensitive device.

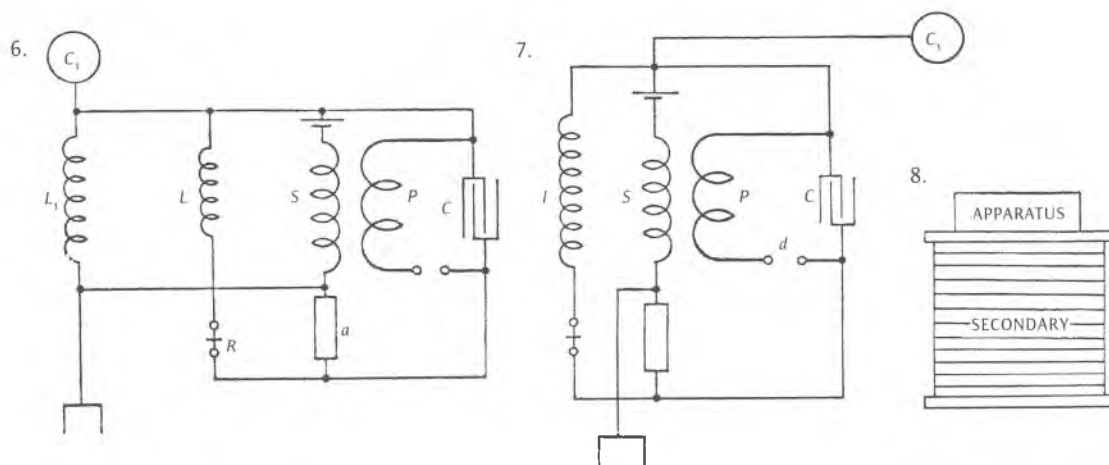
In this plan (4.) the secondary S is connected to the terminals of sensitive device a through a small condenser CC_1 . A very small condenser is sufficient to cause the excitation.



This is a modified arrangement (5.) there being only one condenser and besides a *very high* self-induction around device a to provide for initial excitation when device a is originally of practically infinite resistance. The relay R may be placed around device a instead of self-induction l .



In the diagram below (6.) is shown a manner of connecting apparatus to a circuit $L_1 C_1$ which is adjusted to be in synchronism with the primary vibrations of the oscillator and excites device a .



Again in Diagram 7. a special synchronised circuit is done away with, the secondary itself being adjusted to the primary vibrations. The plan adopted in New York apparatus of winding secondary and primary on a large drum (8.) serving at the same time as table is best. Tuning is easy, apparatus cheap, a large amount of copper may be easily placed in the synchronized circuit.

Colorado Springs

August 15, 1899

Change of secondary of oscillator to adapt it to the jars

Capacity for one tank 36 bottles 0.03816 mfd. Two sets of tanks, 8 in each, give in series a total capacity of 4 tanks that is 0.15264 mfd.

From this $T = \frac{2.054}{10^5}$ approx. and $n=48,700$ or nearly 49,000.

This gives $\lambda = 3.8$ miles, or for $\frac{\lambda}{4} = 5016$ feet.

Now resonance of present secondary 5280 feet was obtained with total capacity of 6 tanks instead of 4. Reducing the figures for length we should have for smaller length a capacity larger in proportion $\left(\frac{5280}{5016}\right)^2$, or 1.11 that is instead of 4 tanks we should have had 4.44 for 5280 feet.

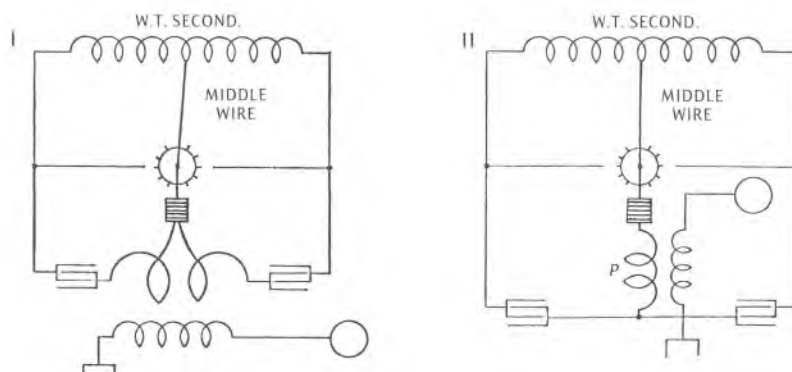
The required length for 6 tanks capacity. This length would be

5280 present length } $\sqrt{\frac{4.44}{6}} \times 5280 = \frac{2.17}{2.45} \times 5280 = 4677$ feet.
4677 required length } to take off 603 feet.

With this length the oscillator will require same capacity as extra coil and good results may be expected.

Colorado Springs

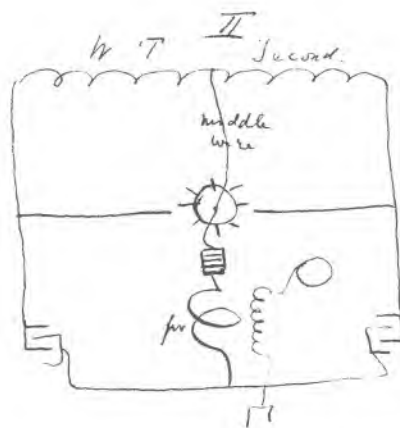
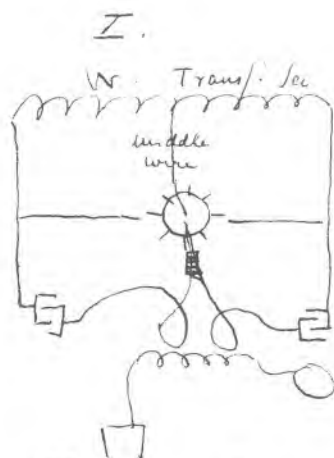
August 16, 1899





Colorado Springs Aug. 16. 1899.

owing to high self-ind. of secondary of W.T. and large ratio of transformation and also great inductive drop in supply transformers (which are poor) of inadequate capacity desirable to work with low currents is adopted in small size oscillators with heavy break. Various advantages are thereby secured chief of which: double break number, smaller resistance in gaps and increased capacity of W.T. for charging condensers. Connections may be as illustrated in I and II.



This connection shown will work in a small oscillator provided the short circuit of secondary of supply transformer avoided.

Owing to high self-ind. of secondary of W.T. and large ratio of transformation and also great inductive drop in supply transformers (which are poor) of inadequate capacity – desirable to work with two circuits as adopted in small size oscillators with mercury break. Various advantages are thereby secured chief of which: double break number, smaller resistance in gaps and increased capacity of W.T. for charging condensers. Connections may be as illustrated in I and II.

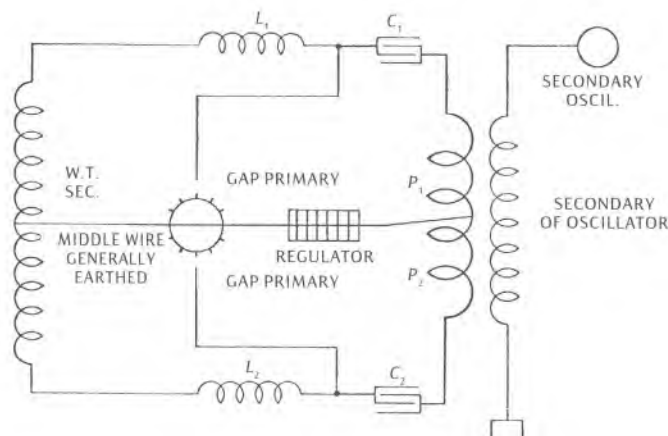
This connection shows well with small oscillators provided the *short circuit of secondary* of supply transformer avoided.

Colorado Springs

August 17, 1899

In the working of transformer as before illustrated I. or II. the short circuit of secondary is an inconvenience which is overcome by having a few teeth at a good distance, but this diminishes the number of breaks which it is practicable to secure. Another way is to adopt a process also successful with small oscillators – of charging the condenser, next disconnecting the same and finally discharging. But this has also the disadvantage of reducing the number of breaks.

Plan here illustrated seems free of these objections:



Here the short-circuit is avoided by the use of self-inductions L_1 and L_2 which must be well insulated to stand high tensions. A *single* self-induction inserted in the middle wire may also be used with like effect.

Colorado Springs

August 18, 1899

The best result with apparatus at command, that is, 3 supply transformers, West. Tr. and condensers newly constructed is obtained by employing two dielectrics giving total capacity of condensers equal to that of four tanks. This allows working with 22,500 volts safely.

The results will probably be the same with 45,000 volts connection and 4 dielectrics but then capacity is only one tank and sparks in primary are longer and more difficult to control.

With connection illustrated before (Diagr. I or II) it is also practicable to work with 45,000 volts total by connecting the tanks on each side in a series so that capacity of each of the two alternately working circuits is equal to that of two tanks. That is $2 \times 0.03816 = 0.07632$ mfd.

With *one* primary turn this gives

$$T = \frac{2\pi}{10^3} \sqrt{0.07632 \times \frac{7}{10^5}} = \frac{2\pi}{10^5} \sqrt{0.053424} = \frac{1.4553}{10^5}$$

and $n=68,710$ adding 10% for mutual induction, now smaller because smaller number of turns in secondary (29), we have

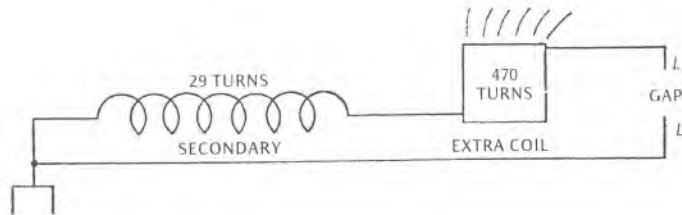
$$n = \left\{ \frac{68.700}{+6900} \right\} = 75,600 \text{ say } n=76,000 \text{ and } \lambda = 2.45 \text{ mile } \frac{\lambda}{4} = 3234 \text{ feet.}$$

Colorado Springs

August 19, 1899

Previous experiments showed in a number of cases good results with connection and quantities as indicated:

Capacity in primary circuit 6 tanks on each side; 1 turn primary about $\frac{3}{4}$ of self-ind. regulator.



From reaction of capacity on secondary of W. Transformer it was probable that more capacity was required, but the transformer was overloaded when more tanks were joined.

With 22,500 volt connection the overload was very marked and lamps would go down 50%. When the connection was changed to 15,000 volts the lamps instead of falling would go up some 35% – 40%. No other change in capacity or otherwise was made and this showed that effect not merely due to an interaction and self-induction and capacity but that the e.m.f. was also a determining factor.

With the first connection effects were brilliant, sparks in gap 8–11 feet according to charge and adjustment. Above considerations led to changing to *two* turns primary. Capacity first $1 \frac{1}{2}$ tanks on each side, e.m.f. on transformer 22,500 V would go up possibly 25%. Capacity was gradually increased to $3 \frac{2}{3}$ tanks on each side when with Regulator all out the effects were best. The rise of e.m.f. about 35–40%. The sparks were curiously fierce, no direction seemingly, darting pass terminal *L*.

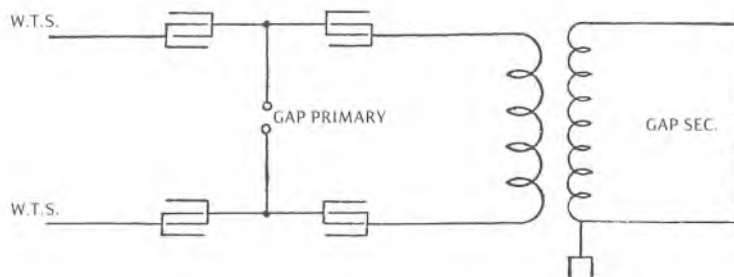
(Here fire started on coil).

Colorado Springs

August 20, 1899

Exp. with oscillator secondary 29 turns continued to ascertain free vibration more exactly. Connection 2 series on each side, 4 dielectrics, total capacity 1 tank. Tension on Westinghouse Transformer 30,000 volts approx. Spark gaps outside about 3" each, inside *one turn*. Results on the whole less satisfactory showing clearly that difficulties increase as tension becomes greater. Middle box on one side broke down, sparks following through the mahogany frame to a screw and jumping from this a distance of 4". This can be only due to rapid vibration and suddenness as tension on that box only $\frac{15,000}{2}$ volts. There are some doubts as to the distribution of e.m.f. in condensers in series when vibration takes place. Strong (probably inductive) drop on supply circuit (exceptionally so).

Observation: When lamps increase strongest on supply circuit then spark will not jump over the gaps, showing that then e.m.f. on secondary of W.T. smallest.

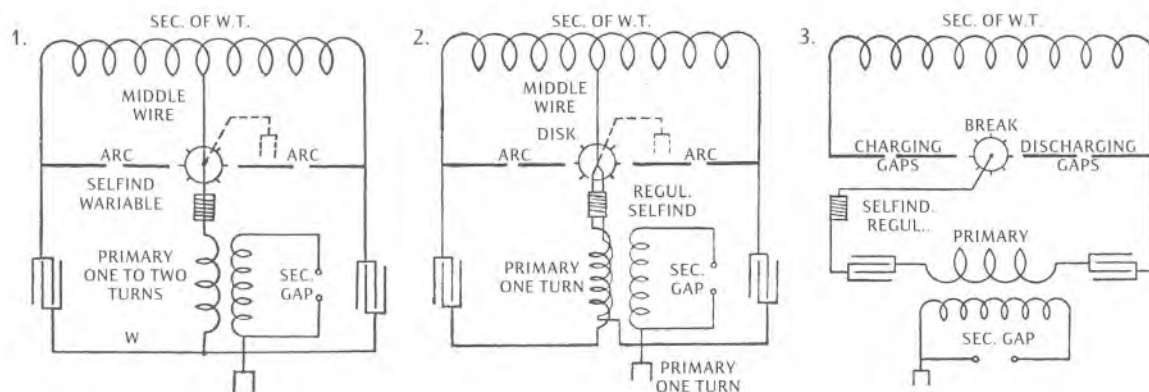


Connection was changed to that indicated in sketch for the purpose of avoiding effect of short circuit of secondary of W.T. through primary arc. Absorbed energy was great. Sparks on switch serious. Lamps would go up very much when arc would break through. But general results not satisfactory. The condensers directly on W.T.S. take strong current.

Colorado Springs

August 21, 1899

Other experiments with oscillator secondary 29 turns. Simply spark gap. Connections used:



Plan illustrated in first diagram was adopted to obtain double number of breaks with same disk and securing other advantages. Also to better utilize W. Transformer. It was found that when one side on it worked remarkably well, sparks about 4 feet. The tension on each half of transformer being 11,000 volts approx. when both parts on interaction hurtful. The chief drawback being short circuiting of secondary. The arc was *snappy* and *loud* indicating short circuit and rapid vibration through wire W. The secondary discharge was thick but spark not long about 3 feet. All tanks were in on either side and the transformer charged them full when separate. When both parts on evidently the secondary of W. T. was overloaded.

In arrangement illustrated in 2 short circuiting was largely overcome but the short circuit of secondary of W. T. remained the same. The results were similar no matter in what direction both primaries were connected. The necessity of overcoming short circuit in both arrangements became soon more and more important.

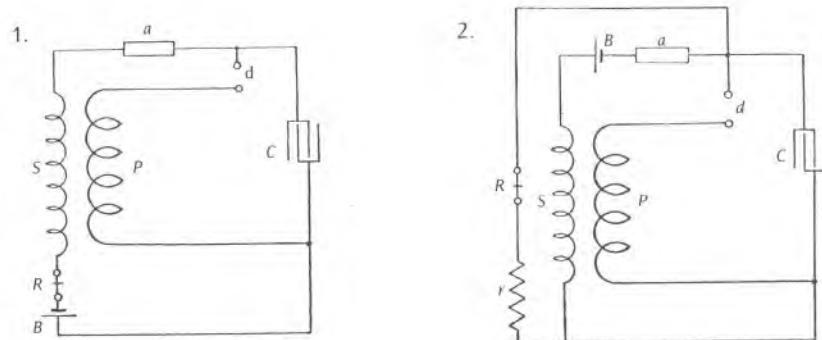
To improve – arrangement illustrated in Diag. 3. was used. It proved itself more economical but the amount of energy was limited. The hurtful short circuit was entirely obviated and the lamps were less affected.

Colorado Springs

August 22, 1899

Arrangements for telegraphy tried. In these the chief point was to keep one end of secondary spool open so to allow full rise of pressure on this end. The sensitive device, one of the before described, excited fully resistance 12 ohms approx. Not excited over 100,000 ohms.

In Diagram 1. first experimented with, a disadvantage was found to exist: namely, the receiver *R* was operated through the break device *d*. This inconvenience was done away with in arrangement illustrated in Fig. 2. which allowed more sensitive adjustment of Relay *R* and the apparatus worked better. Capacity of condenser was varied up to 20 mfd. with changing success. Best results seemingly with small capacities up to 1 mfd. Secondary about 4,000 turns, primary Lamp cord № 10 turns 28. The apparatus responded freely to small pocket coil at a distance of several feet *with no capacity attached and no adjusted circuit*. Consequently will go at great distance.



In these arrangements, as in the previous ones involving the same principle, the effect on the sensitive device is accumulative and a difficulty arises that namely the sensitive device will not readily de-sensitive. By inserting large resistance *r* in circuit with receiver *R* this effect upon the latter is largely reduced as the current through receiver and device is kept to a minimum. By adjusting speed of rotation of sensitive device the inconvenience is also overcome.

Experiments with new extra coil placed in center of primary. The spool 75" diam., 12 feet high, 160 turns in all. 120 turns wound close together in the adjacent grooves and 40 turns the upper ones at three times that distance, that is, two empty grooves between each two turns. Breaks on two sides alternately approximately 2,400 breaks per sec. On top (free end) ball of 38 cm. capacity. Resonance was obtained with $5 \frac{2}{3}$ tanks on each side, one turn primary, self-induction in box 4 turns. Gaps were $1 \frac{1}{16}$ on each side plus gaps in box 2 turns. Tuning remarkably exact, $\frac{1}{8}$ turn of self-ind. box reducing the effect very much. When exactly 4 turns in box, sometimes streamer 8 foot long would shoot out from a defective spot on wire. The ball on top reduced streamer capacity and prevented streamers from coming out all along the top turn as usual. The spark gaps work extremely well, loud explosive character indicating good vibration. Such sparks are always noted when secondary well tuned. The system worked economically, the lamps in supply circuit not falling at all. The earth connection now was taken off and oscillator of same period – (the secondary 29 turns connected). Both had now same period, the secondary and the extra coil. On first throw of switch a spark darted to roof above from the ball and the cord caught fire. Fortunately, it was extinguished before doing damage.



This accident showed that better provisions against such an accident have to be made. The roof to be fixed with a guard of wire gauze which would prevent the wood from catching fire through sparks darting up. As it was dangerous to work further without guard against such an accident another ball 38 cm. supported on high was connected to earth and placed at varying distances from the ball on the end of the extra coil. The sparks jumped from the upper turn of the coil to the Earthed ball and sparks of seven feet were easily obtained. It was evident that the distance could be much increased but this was deemed hazardous. As it was the sparks of seven feet were probably the longest obtained from such large balls or surfaces of such small curvature.

The connection of the primary circuit was now changed, two turns being used in series. This reduced the period to one half and it was thought that this would respond to the fundamental note of both secondary and extra coil. Experiments were disappointing for the display was not remarkable, the sparks were up to four feet long but much thicker and whiter. I believe that the true vibration was not struck but skipped. As time pressed, further experiments with the view of ascertaining the fundamental note were postponed and the first connection with one primary turn again made. Both balls were now connected in multiple to top of the coil and to the upper rod of a spark gap, the lower rod being earthed. There was no danger of setting fire in this way. The display was remarkably noisy. The sparks were up to 14 feet long, snapping quick, explosive and very white. Sometimes streamers would shoot out fully 11 feet. Often several sparks at once. No particular direction in striking. The capacity in the primary circuit was varied up to 8 tanks on each side. Always striking effects. The ground wire had no capacity and no sparks were seen on arresters *but before*, with only one ball and *no streamers*, sparks of $\frac{5}{16}$ " were drawn from water pipe in distant room.

Colorado Springs

August 24, 1899

Experiments with new extra coil and oscill. secondary 29 turns continued.

The ball on top was disconnected and a bare copper wire run around the upper rim of the coil to produce streamers. Capacity in primary circuit on each side was $5\frac{2}{3}$ tanks with 4 turns self-induction box in. It was not advisable to work because by the throw of switch some streamers would dart up to the roof a distance of 12–13 feet. The other ball used in previous experiments was placed at a distance of 11 feet from coil and also it was unconnected – except that it had a wire of about 8 feet hanging from it – the sparks would fly to it from the rim of the coil.

A curious feature is that the streamers are very sudden, explosive. This is due probably to the suddenness of the break. Occasionally an unusually long streamer would shoot out. This probably owing to resonance of break or temporarily short circuit over break, probably the former cause responsible. Desirable either synchronous break as worked in New York, or *a very rapid one*. The speed of motor is to be increased to double for this purpose.

Coil was disconnected from the oscillator and connected to the ground. The period corresponded to that of the primary with 7 tanks on each side, no self-induction. $5\frac{2}{3}$ tanks, 4 turns, and 4 tanks and 9 turns. Thus 3 tanks made only a difference of 5 turns on self. box. With four tanks tuning wonderfully close, twice it was missed before finally located.

(The roof of building was fixed today, cords done away with)

Colorado Springs

August 25, 1899

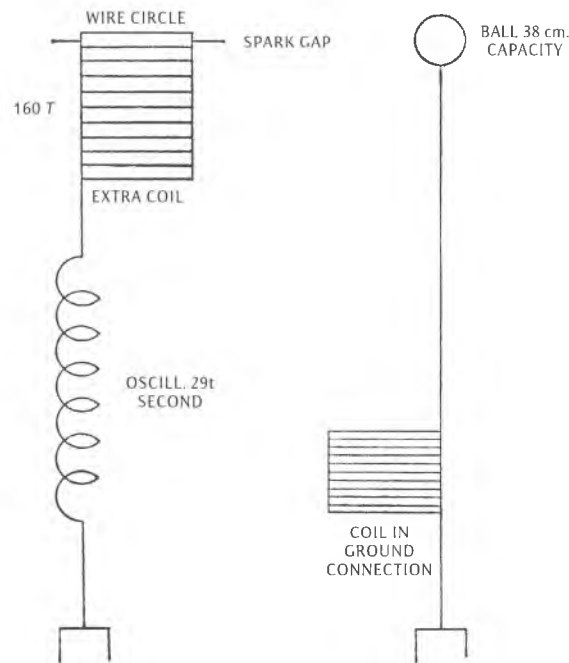
Experiments continued with extra coil on wooden frame 12 feet high, 6 feet diam., 160 turns No 10 wire. A bare copper wire was supported on top, the wire forming a circle not closed of about 8 feet diam. Another copper wire was supported 4 feet below and at a distance of about 13 feet, all around the diameter of circle being approximately 34 feet. This circle (also not closed) was connected to ground. Very powerful streamers were produced sometimes extending the full distance between the wire circles, but still they showed tendency upward in spite of presence of ground circle. Often sparks would pass in curved paths between the two circles. During the display *no sparks* on arresters, small sparks in adjacent room from water pipe. Capacity on each side from $5\frac{2}{3}$ –7 tanks. Longest streamers with former value. The circle of 8 feet diam. was then taken down and another one about 10 feet placed on top of coil. Streamers now showed some tendency to pass to grounded circle. Sparks to the latter more frequent and brilliant. *No play* on arresters and small sparks in adjacent room as before.

One of the balls was now connected to the ground but although sparks of eleven feet jumped to same *no sparks* on arresters. The vibration was evidently slow, that pertaining to extra coil and *harmonics* in earth wire from ball *did not* preponderatingly appear.

August 26, 1899

Experiments with oscillator secondary 29 turns and extra coil last described continued.

The alternate motor was put on 200 V with self-ind. coil in series, latter regulated so that motor could drive disk of break with twice the speed, that is 4200, the speed of motor being approximately 2100. This gave, since disk had 20 teeth and two alternately working breaks, $\frac{4200 \times 20 \times 2}{60} = 2800$ breaks per second.



In the first trials connections were made as in sketch. The spark gap between wire circle on top of extra coil and ball supported was 8 feet.

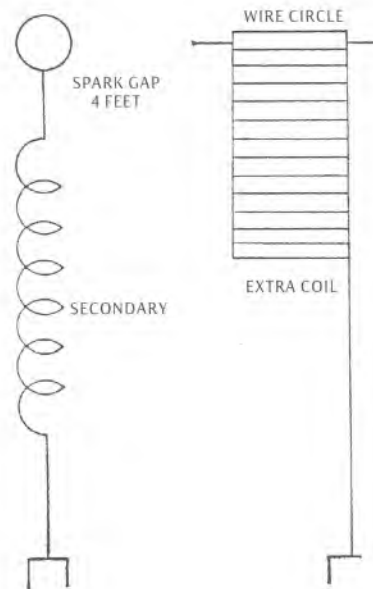
Sparks passed readily and the display on arresters was remarkable. Thick arcs joined the arrester contacts on *both lines* and jumped also through one of the choking coils. This was the strongest effect so far on arresters.

A choking coil was now inserted in ground connection to see whether by lengthening the period of the earth wire the sparks on the arresters would be diminished. This coil was 34" diam. wound with one layer wire № 16, thick rubber insulation (layer 10" high) 50 turns. This coil did not weaken the effect much probably because frequently sparks would jump between the turns. Otherwise it was surmised that the vibration of the secondary itself with the extra coil might be responsible for most of the e.m.f. generated between the ground and line. *Singularly*, despite this strong effect as evident from arresters but very small sparks were drawn from water pipe in adjacent room, this seemingly indicating that in this experiment the earth acted as a nodal region.

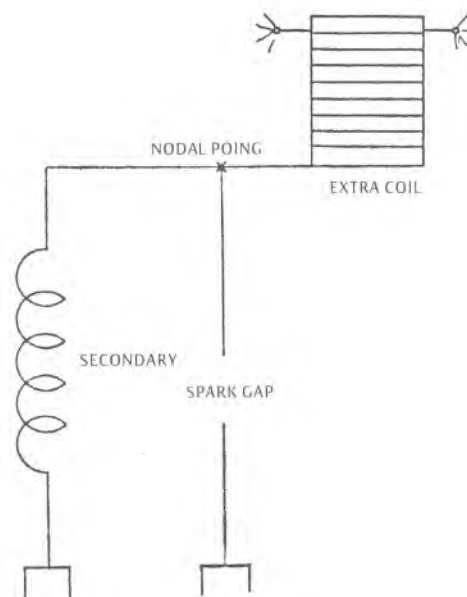
The conclusion from these first experiments as to the efficiency of the break was that double number of breaks decidedly better. Nor did it short circuit the transformer more because of the increased number, but on the contrary less as far as could be judged from the lamps on the supply circuit which went up as the switch was thrown in.

It was evident, furthermore, that the large circle of wire which was before supported above the secondary and grounded, strongly interfered with the action on arresters because it allowed local vibration which was not effectively transferred to the ground and the air.

To decide surely whether, and to what extent the *long waves* were responsible for the difference of pressure evident on the plates of arresters, the secondary and extra coil were connected as in sketch.



In this connection only *long waves* could be effectively transmitted upon the ground. It would have been desirable in this and previous experiment as well to take off the wire circle and substitute a ball on top of the extra coil but this being inconvenient the circle was left. As the extra coil had now only a small initial pressure the e.m.f. obtainable in the spark gap was much smaller and the gap was reduced

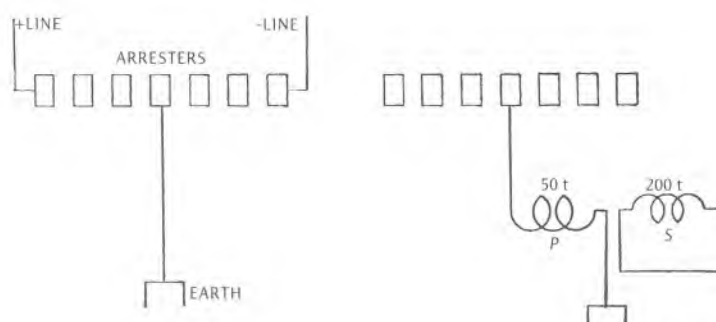


therefore to 4 feet at which distance sparks readily jumped. The play on arresters – though weaker – *took place* nevertheless, this important result showing that waves 3–4 miles long *could* produce these e.m.f. sufficient to cause the sparks to pass between the plates of the arresters. Now it is important to consider: is the earth a nodal region or the crest of a wave (that is, the region immediately adjacent to point of attachment of secondary to ground). If a nodal region then the e.m.f. set up at the small

distance of 60 feet separating the point of attachment and the ground of lightning arresters was only a small part of the total e.m.f. But if a crest then the e.m.f. set up and causing sparks was nearly the total e.m.f. produced by the apparatus. If a nodal region near the point of attachment of the secondary, then at a distance of about 4000 feet there must be a strong effect, but if a crest, then at that distance there would be no effect. This is to be decided by further observations. The connection was now changed to that indicated. It was thought that both vibrations would cooperate and produce a stronger effect, but it was at once evident that so long as streamers (which were about 10 feet) formed on top of the extra coil the effect must be smaller, since *all* energy came from the secondary and the streamers caused loss. A condenser ought to be used instead of a gap to make such an arrangement most economical. Although owing to *nodal* point the length of spark in adjustable gap was small, the display was strong on arresters, but not nearly as strong as when the extra coil was entirely left off. In the latter case the action was very rigorous so that often flames would form on arresters showing short circuit of dynamo. Also the other choking coil would break through. Evidently then the extra coil did not in this instance prove useful in intensifying vibration contemplated.

Experiments continued: extra coil was now lowered 2 feet nearer to ground, distance now being about 4 feet from floor and 5 feet from ground.

Capacity $5\frac{2}{3}$ tanks on each side in primary. The transformer (W. Co.) works very well (22,500 volts). The lamps go up 35–40% when the arc does not break through, the gap being made large for this purpose, and when the arc breaks through they still rise slightly above normal. The gaps outside $1\frac{1}{4}$ " each approx. Inside $1\frac{1}{2}$ –2 turns. Streamers produced were still more powerful being made so owing to approach of secondary. They would dart out to a distance of 12 feet sometimes.



Important. Strong arcing on arresters, although no spark would pass to the ball used before, which was placed at a distance of about 9 feet. Could the sparks be produced by static induction upon wire through the air and not chiefly by conduction through earth? To test this a coil 50 turns referred to before was inserted in the ground wire of the lightning arresters. It was expected that it would weaken discharge across, but did not probably because the current was small and the choking action likewise for this reason.

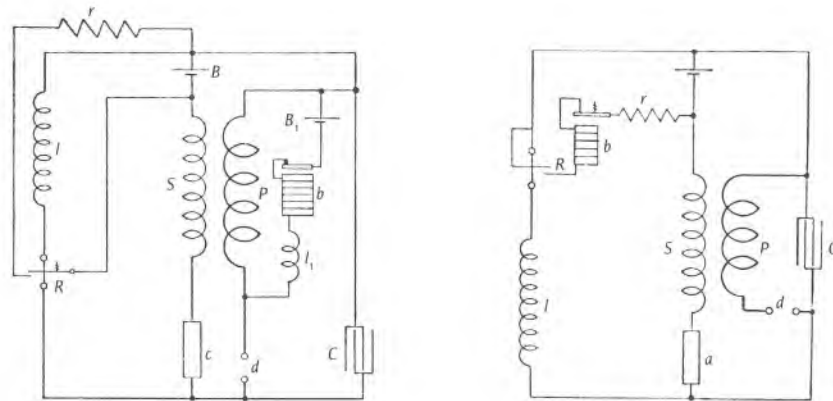
To see whether there is some current passing through the earth wire to the line, another coil was placed in inductive relation to the ground wire coil and strong sparks $\frac{3}{8}$ " were obtained on former. Sparks, lively $\frac{3}{8}$ " approx., were also obtained from coil P. Note: Sparks to ball sometimes, at other times streamers would dart past the ball. The streamers horizontal when sudden, when switch was held longer they would waver. In last experiments only half of wire circle on top of spool was used.

Colorado Springs

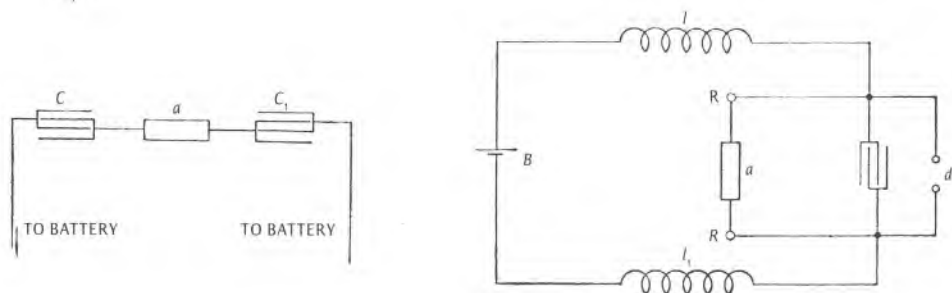
August 27, 1899

Older plans experimented with and modified arrangements of apparatus for wireless telegraphy further considered

These connections used to relieve the sensitive device from the strain of the battery after excitation. The necessity of doing this leads to the reconsideration of an old plan experimented with in New York which consists of placing the sensitive device between condensers in circuit so that each time only one current impulse can pass through the device. This is illustrated in a general way in the little diagram below. The battery strains the device a through the condensers C, C_1 but when, upon the device a becoming excited, the condensers are suddenly charged the current impulse caused by the charging automatically stops. It is then necessary to reverse the mains, or discharge the condensers to make the apparatus ready for a second operation. This plan allows use of very high pressure on the sensitive device which should be of great resistance.



Plan in last diagram illustrated consists of raising, by means of inductances L, L_1 , condenser C and break device d , the e.m.f. of battery B so far as needed to bring the device a to the point of nearly breaking down. The quantities should for a better result be adjusted as usual. Both relay coils R, R and inductances L, L_1 are placed symmetrically.



Colorado Springs

August 28, 1899

161

Experiments with oscillator, secondary 29 t. in series with extra coil before used (160 t) were continued today and showed the following:

Capacity in primary being from $5\frac{2}{3}$ –8 tanks on each side, varied to observe shifting of nodal point, play on arresters and behaviour of streamers and spark discharges.

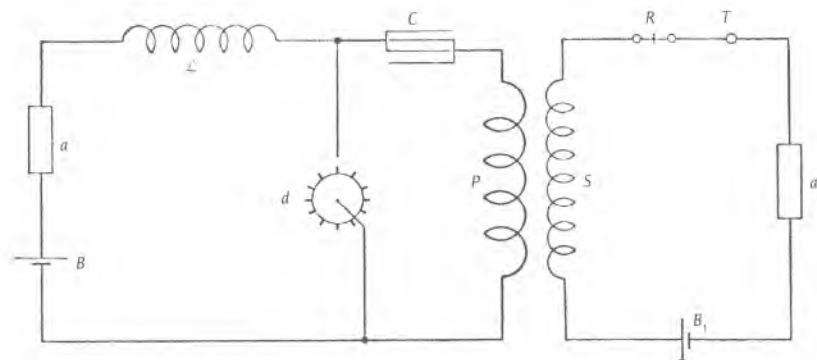
A half circle of bare wire on top of extra coil was left and in addition a larger half circle of bare copper wire (N^o 14) was supported on wooden strips 4 feet below the former half circle. Both the bare wires were connected to the free end of an extra spool. The lower half circle was $9\frac{1}{2}$ feet away from a circle of the same bare wire which was supported on oscillator secondary frame and formed the terminal of the secondary. Abundant sparks and streamers were produced. The play on arresters was also observed at each throw of the switch. The rain and lightning were just beginning. Magnificent intense white light witnessed below Pike's Peak, something very unusual. It resembled a white hot silver furnace. The lightning on the mountains was very frequent and the discharges of unusual brilliancy. Twice a curious phenomenon was noted. Lightning striking in one part of the mountains from *cloud* to *earth*, there was seen in another part a few miles away from a high *peak* a lightning discharge which to all appearances came from the peak to the *cloud*. The discharge was much thicker at the root and branched out towards the sky spattering itself in many branches and disappearing in fine streams. The astonishing phenomenon was witnessed a second time and subsequently, though there was much uncertainty about the direction in the latter cases; a few times a similar discharge took place from other peaks. Is it possible for a discharge to go from Earth to cloud? As far as the visual impression is concerned there can be no doubt. The discharge in all cases followed a preceding lightning discharge in another region, and apparently from cloud to earth. Perhaps it can be the effect of an intense vibration started by the first discharge which results in another discharge towards an oppositely charged cloud. The clouds were unusual in configuration and grouping. A large portion of the sky was quite clear. The wind at times was very strong. An instrument by its constant play indicated strong electrical disturbances through the earth, even when there was no display of lightning as far as could be seen or heard.

After some time the experiments were continued and presently it was observed that the usual sparking on the arresters was *no longer to be seen* when the switch was thrown in. The only change made was to take the upper half circle off leaving only the lower one. This gave a smaller streamer surface and consequently longer streamers. The display was fine. In order to see whether the upper half circle of bare wire was responsible for sparks on arresters the wire was replaced but still no result. Then it was thought that other causes for the sparks not appearing were responsible and everything that could have the slightest bearing upon this was investigated. Still nothing was arrived at. The sparks did not appear no matter what change was made in the adjustment of the vibratory circuits. What could be the cause? The only explanation at present is that the roof was rendered slightly conducting (although there was little rain in this locality) and that this produced the change. *Important to find out*. Observation: The lightning lighted two houses about two miles away.

Colorado Springs

August 29, 1899

Experiments were made with receiving apparatus comprising an oscillator with mercury break and two devices of the kind before described. The oscillator was of a later pattern, mercury break by 2000 rev. per minute gave $\frac{2000}{60} \times 24 = 800$ breaks per second, there being 24 teeth in the pulley. The condenser in the instrument was 1 mfd. approximately. The instrument was used as a sender and the experiments were intended to test its efficiency as a receiving apparatus. Accordingly, the connections were made as in sketch, the method of magnifying by oscillating transformer being made use of to increase sensitive-ness. As far as practicable all connections and parts of instrument were used. The connections of primary circuit including break remaining the same, only a battery B . (1–4 cells dry O.K.) and sensitive device a being inserted instead of a generator. In the high tension secondary were connected a receiver R (relay), telephone T , battery B_1 , and another similar sensitive device a_1 . The motor was driven from a small direct current generator which in turn was driven by the alternate current motor usually employed to drive the break disk of the large oscillator. This apparatus was extremely effective, merely the addition of small capacity on a was sufficient to make the receiver respond. Evidently this effectiveness is due to the efficiency of the oscillating transformer and excellent working and high frequency of the mercury break.



Experiments were continued for a short while with oscillator and extra coil. The frame of the secondary was repaired and a board for connections of the transformers put in place and other work took most of the day, it being late when the investigation was resumed. A netting of wire gauze (iron) had been placed around the opening of the roof to diminish danger of inflaming the building. But on the first throw of the switch the streamers and sparks darted against the netting a distance of about 12 feet and sparks were seen to go from netting on to the wooden structure of the roof. It was advisable to stop work and the roof was removed. Now the ball on top of the extra coil was connected to the latter by a wire No 10, 40 feet long, very heavily insulated with tape over the rubber covering. One turn on the outside and nearly another complete one in the inside were made and the end of the wire connected to the ball. The latter could not be lifted up and the experiment was tried with the ball in place. The streamers now appeared on the ball copiously when the current was turned on, their tendency being to go straight up into the air. The longest were only about 4 feet as it was deemed unsafe to strain the apparatus higher until further provisions for safe working were made. The lightning arresters were observed but *no sparking*. This showed that the absence of sparks was not due to rain or moisture as was concluded yesterday, since the weather was very warm and dry.

Colorado Springs

August 30, 1899

Experiments were resumed with resonating coil to be used in connection with receiving apparatus. The coil was wound a week before on a drum 25 ¼" diam. of bicycle hoops and a thin board, the idea carried out before in New York being followed to make the drum with coil serve, at the same time, as a table for instruments. The drum was 3 ½ feet high, only partially wound on upper part. The wire was ordinary magnet wire № 20, 516 turns. The self-induction was approximately calculated from the following data: diameter of drum 25 ¼" or 64 cm.; length of wound part 20" or 50.8 cm.

$$L = \frac{4\pi}{10} \times \frac{\pi}{4} \times \frac{d^2 n^2}{l} = \frac{d^2 n^2}{l} = \frac{64^2 \times 516^2}{50.8} = 0.02 \text{ henry approx.}$$

Taking n approximately 50,000 per second it was close enough for the purpose to assume $p=300,000$.

The resistance of wire being 34 ohms we had

$$\frac{Lp}{R} = \frac{300,000 \times 2}{3400} = 177 \text{ fairly good.}$$

The coil was now tuned with oscillator in response to a somewhat higher note with small capacity on free terminal, the other being connected to the water pipe. Sparks of ¾" were obtained while from the water pipe alone a very minute spark, scarcely perceptible, could be obtained. Induction from primary being carefully eliminated, the sparks were still ⅜" long and white.

Colorado Springs

August 31, 1899

Experiments were continued with the extra coil and secondary conditions as before. The ball in the center was connected again to the top of coil and elevated a little above the roof, the latter being opened as wide as possible. The experiments were begun in the afternoon while the Sun was very bright. Scarcely any streamers from the ball could be seen but occasionally sparks would go to the roof from the center wire leading to the ball. The distance was 12 feet. There was a pronounced tendency in the sparks to fly to the roof which might have been due to dampness of the latter owing to rain the day before. During the few trials which were cut short because of the danger threatening from the sparks, the lightning arresters were observed but no spark was noted. In the forenoon the mains were tested and it was found that one of them was fairly grounded which to some extent also made the other defective. This probably was the reason why the sparks no longer appeared on the arresters.

A number of curious observations were made during the trials with the elevated ball. A fly was seen to light on the top of the ball and when the switch was thrown in the insect disappeared evidently thrown off with great force. Another such insect alighted on the under part of the ball, and the current being thrown in just about at the moment when the fly started off, the fly was seen to fall from a distance of about one foot from the ball straight down to the floor, evidently killed in the flight. Still more curious it was to see a moth at a distance of fully eleven feet from ball, near to the wooden frame fall straight down as the switch was thrown in. The strongly electrified ball evidently exercises a strong attraction on a small insect which is drawn towards it every time the ball is electrified. This was repeatedly tried.

An observation less amusing but more useful was that when the ball with its circuit were well tuned and *no streamers* appeared, owing to good insulation of leading cable – there was a decided tendency



Colorado Springs Notes:

Aug 1 - 31, 1899.

for most of time following items,
partly written out, have been omitted:

Aug. 4. General observations of electrical
phenomena here with particular
reference to stationary waves.

Aug. 6. Experiments with stationary waves
on waterpipe. Note: distance from
pivotal plate to end of run exactly 550 feet

~~Aug. 12-13. General notes on water waves.~~

1) Production of stationary waves and
use of same in general

2) Distribution of universe time observations etc.

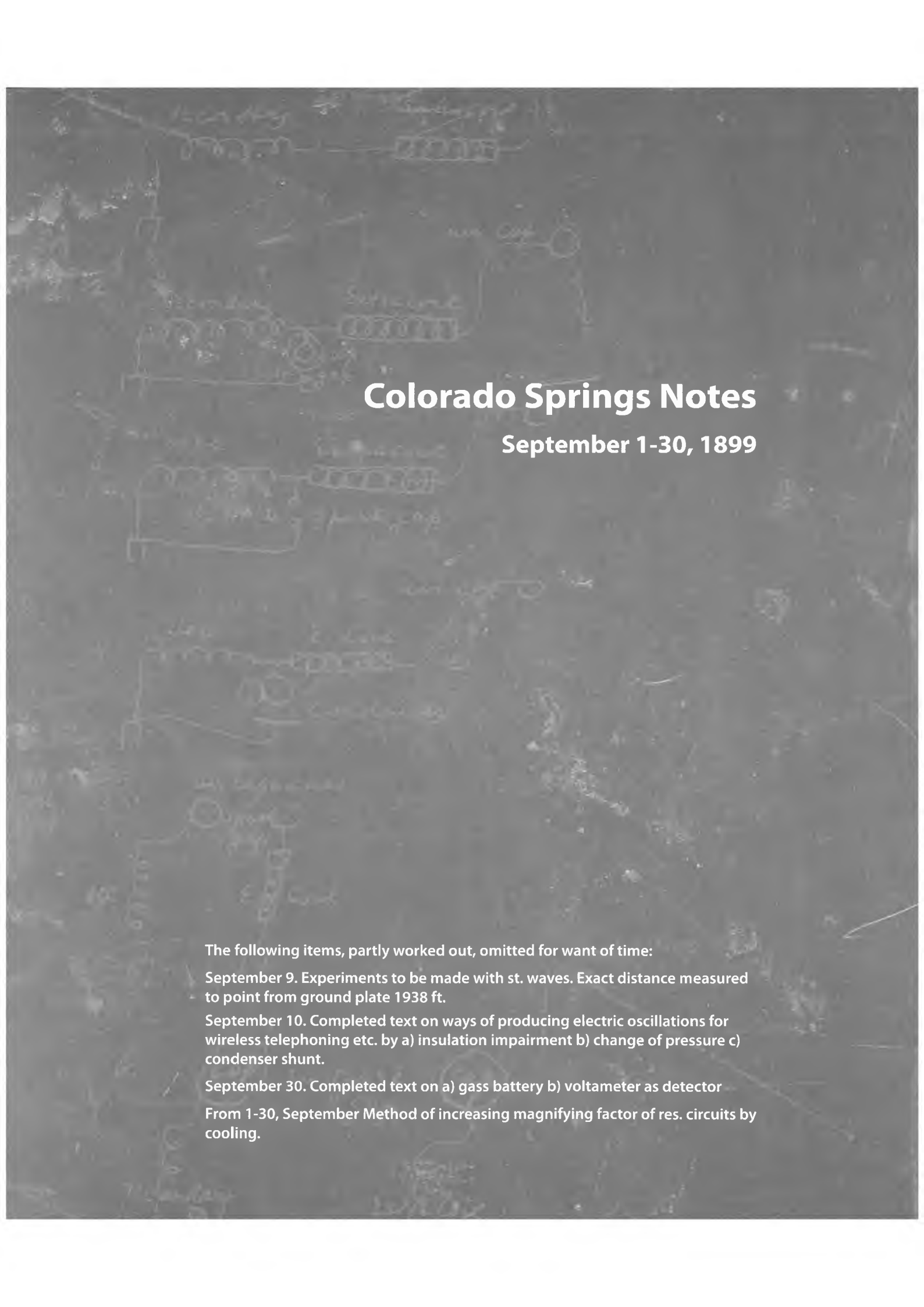
3) Indication of direction — for ships etc.

to break the jars in the primary. Evidently, when there are no streamers the vibration is effected with lesser loss and hence there is a great rise of e.m.f. reacting upon the primary. This at least appears the most plausible reason for the phenomenon observed.

Light seems to interfere decidedly with the streamers from ball and wire and it is also unmistakably noted that the noise of the discharge is lessened when the sunlight falls upon the apparatus.

Spark gaps were established in a number of ways as by connecting both coil and secondary to ground and each to one of the balls and establishing a spark gap between the latter.

Finally the ball was again connected as before and elevated, a point being first placed on top to facilitate formation of streamers. It was curious to observe that the streamers were carried away horizontally, and eventually blown out by the wind. The resonating action was strong but the length of the streamers could not be estimated. From the leading cable the discharge would sometimes leap to a distance of at least 10 feet. The action of the wind suggests the idea of preventing the formation of wasteful streamers by a current of air.



Colorado Springs Notes

September 1-30, 1899

The following items, partly worked out, omitted for want of time:

September 9. Experiments to be made with st. waves. Exact distance measured to point from ground plate 1938 ft.

September 10. Completed text on ways of producing electric oscillations for wireless telephoning etc. by a) insulation impairment b) change of pressure c) condenser shunt.

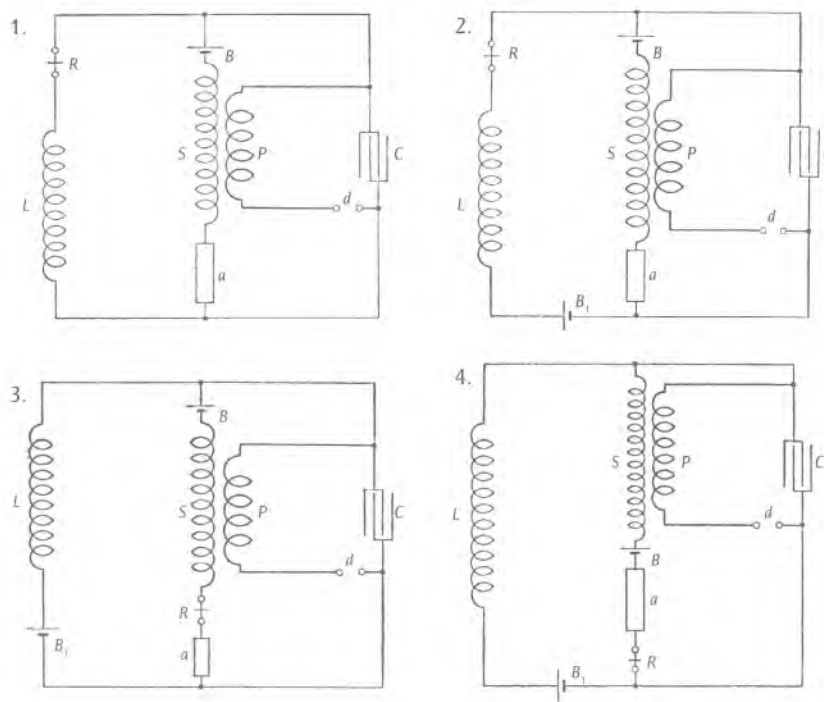
September 30. Completed text on a) gas battery b) voltameter as detector

From 1-30, September Method of increasing magnifying factor of res. circuits by cooling.

September 1, 1899

Various ways of connecting instruments on receiving station experimented with and considered as to their merits:

Diagram 1. illustrates one of the earlier dispositions involving the principle, before described, of exciting by means of energy stored in the condenser. This principle has proved itself highly effective as it secures self-excitation and great magnification of an initial feeble effect. In Fig. 1 the defect is that no initial excitation of the condenser is provided for, which makes it difficult to employ a sensitive device of *very high* resistance which, for other reasons, is desirable. This fault is overcome in Fig. 2. by providing an additional battery B_1 for charging initially the condenser and thereby exciting device a to the point of breaking down. Still in the latter diagram there is the inconvenience that the relay is traversed by a pulsating current during the time when device a is not excited.



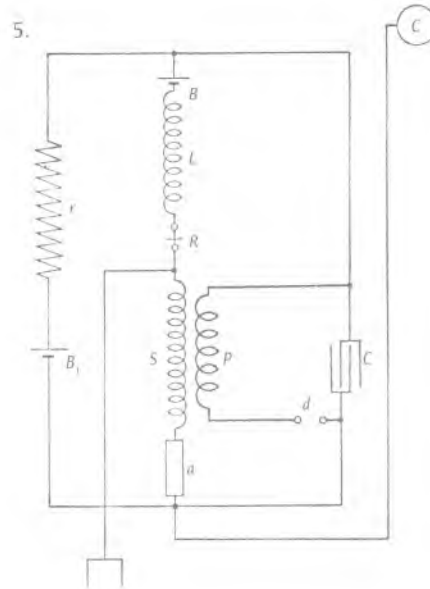
The improvement illustrated in Diagram 3. does away with this drawback and this makes it possible to adjust the relay much better. Still the relay by its self-induction is apt to interfere with the vibration of the tuned secondary s . This consideration led to the modification illustrated in Diagram 4.

In this case the battery was placed either near sensitive device a , as shown, or in series with the other end of secondary s and the rest of the apparatus.

To work best, however, it was recognized, that: there should be no capacity to speak of on the free end of the secondary which is connected to the sensitive device, and on the other end of the sensitive device there should be as much capacity as practicable. Various other considerations finally led to the adoption of the connection shown in Fig. 5 as the best suited so far.

In this plan all the advantages so far aimed at are successfully realized. The secondary is *free* on one end towards device a and the potential rise can freely take place; the earth and air connections are both very advantageously situated; the condenser is excited exactly to the degree desired by adjusting

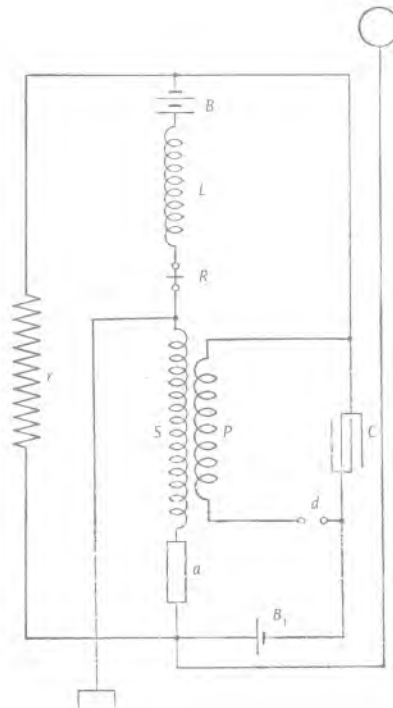
resistance r . The vibration of the secondary is not sensibly affected by attaching the air line and capacity C , and the current through the relay is made small by opposing batteries B and B_1 .



Colorado Springs

September 2, 1899

The plan of connections of the receiving apparatus, which was last described, was modified as shown in the present diagram. The battery B_1 instead of being in branch including resistance r was included in the other branch circuit containing the condenser. Furthermore the batteries B and B_1 were



disposed in a number of ways and graduated with reference to each other to study the best conditions of working with the plan. The device *a* was here chiefly strained through the induced currents in *s* the strength of these being graduated by adjusting resistance *r*. Therefore the strain by the batteries themselves was insignificant. Now these batteries were connected either so as to add together in charging the condenser when device *a* was diminished in resistance, or they were made to oppose each other. In the former case a small diminution of the resistance of *a* tended to produce a change in the same sense and the apparatus possessed the feature of self-excitation, while in the latter instance when device fell in resistance, the condenser charge was diminished and the excitation ceased automatically. This secured small current through the sensitive device. Any condition could however be readily secured graduating the batteries.

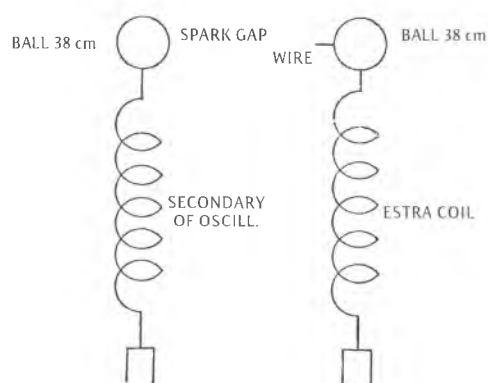
Colorado Springs

September 3, 1899

Experiments were resumed with oscillator the connection being as illustrated in diagram

The extra coil and secondary were both connected to ground and on top of each a ball was placed of 38 cm. capacity. On extra coil, to facilitate the pumping of the spark and thereby enable the balls to be placed at great distance, a wire was fastened to the ball. The spark gap being about 8 feet. As both oscillator secondary and extra coil vibrated the same period but were displaced in phase sparks passed readily and the vibration was that due to each separately, the harmonics being practically prevented to pass to earth.

An experimental coil was then fastened to the water pipe with one end and the adjustment for the same period was made. The coil was so placed as to exclude any inductive effect from the vibrating system so that the vibration in the coil was due only to that transmitted through the water pipe. The wire on the coil was previously wound upon a drum approximately 25 ¼ inches in diameter, there being 516 turns of wire № 21, res. 45 ohms all wound in a single layer. This coil gave on the free end – with induction from vibrating system aiding the vibration – a spark of ¾"; with the induction eliminated the spark was fully ⅜" long. The spark on the water pipe itself was scarcely visible, say 1/64" long, so that the coil increased the pressure many times.



Now it was of importance to increase the magnifying factor $\frac{Lp}{R}$ and for the purpose of investigating the best conditions the same wire was wound on a form 22 ½" diam., 1" wide, 1 ½" deep. 18 layers were made there being 28 turns in each. The self-induction was now nearly 20 times greater, and as the resistance was the same $\frac{Lp}{R}$ was to be much greater. It was feared though that the effect of distributed

capacity which was largely increased would be detrimental to the rise of potential on the end. This proved to be the case so that it appears again imperative to overcome also in the receiving circuit the distributed capacity. Various ways are now to be experimented upon with this object in view.

Colorado Springs

September 4, 1899

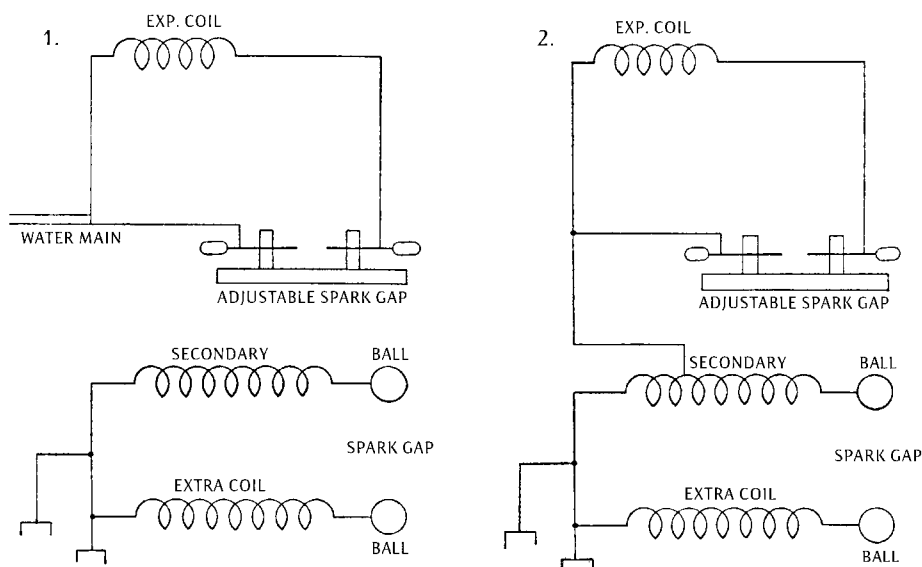
Experimental coil wound on frame made of bicycle hoop 25 1/4" diam., 16 layers, 28 turns in each, 448 turns total, self-induction about 1/2 henry. This coil was wound very close to study effect of distributed capacity. It was connected for purposes of tuning to water pipe on one end the other being left free. From free end and water pipe short wires were run to a spark gap. The sparking distance was observed from free end to body of experimenter, next from watermain to body, next between the two wires and finally with body of experimenter connected to free end, the spark between the same points. As it was sure that the vibration of coil was too slow for the impressed vibration of approximately 50,000, wire was gradually taken off.

Number of turns on coil	Longest spark from free end to body of experimenter	Longest spark from water-main end to body of experimenter	Longest spark between the two ends of coil without capacity	Longest spark between the two ends of coil with capacity of experimenter on free end	Observation
I	II	III	IV	V	VI
448	1/8"	5/64"	scarcely visible	scarcely visible	
420	1/8+d	5/64"	"	"	
392	1/8+d	5/64"	"	"	
364	3/16"	3/16"	"	"	
336	3/16+d	3/16"	small spark	small br. spark	
308	1/8	3/16"	"	spark larger	
294	5/32	5/32"	"	livelier spark	
280	1/8	1/8"	"	"	
266	5/32	3/32"	"	"	

Indications up to present confirm detrimental effect of capacity. A coil was now added in series. This coil was one used often in New York and was wound on a drum 30" diam. There were about 150 turns total length of wire 1125 feet. To this added the 266 turns of experimental coil giving length of 6.5 feet per turn made length 2100 feet for exp. coil or total 3225 feet. This was very *near quarter* wave length as it ought to be. Now results were

I	II	III	IV	V	Observation
266+150 <i>Exp. additional coil</i>	7/16"	3/32"	3/32"	3/32" lively	
Experiments were now continued with experimental coil alone and showed					

252	1/8"	1/8 less <i>d</i>	small spark	small spark livelier	Observ. The distributed capacity unmistakably prevents rise on end.
224	3/32 bright	1/16"	"	"	
196	1/16	1/16 less <i>d</i>	"	"	
168	1/16	1/16 less <i>d</i>	practically the same.		



To observe better the end of coil which was before connected to earth (or water pipe) was now connected to a wire run from one turn of secondary, that is from the turn which was nearest to earth connection of secondary. The connection was in the previous experiments as illustrated in one, then it was changed to the connection shown in 2. Nothing was, in principle, changed by this connection, only a higher e.m.f. (initial) was obtained and the tuning was made easier. This I have found to be an excellent way to adopt in tuning coils. The results were as follows:

I.	II.	III.	IV.	V.	Observ.
168	$\frac{3}{4}$ "	$\frac{3}{4}$ "	very small spark	small spark livelier	When the wire was taken off down to 19 turns there was no spark between the rods even at a distance of $\frac{1}{64}$ " but when the hand was approached to free end of coil, sparks would be drawn $\frac{3}{4}$ " long and then spark would jump between the rods. This obvious and easily explained.
140	$\frac{3}{4}$ "	$\frac{7}{8}$	$\frac{1}{16}$ "	"	
112	$\frac{5}{8}$	1"	stronger	"	
98	$\frac{5}{8}$	$\frac{7}{8}$	"	"	
84	$\frac{5}{8}$	1"	"	"	
70	$\frac{5}{8}$	1"	"	"	
56	$\frac{3}{4}$	$\frac{3}{4}$	"	"	
42	$\frac{3}{4}$	$\frac{7}{8}$	much stronger	much stronger	
28	$\frac{3}{4}$	$\frac{7}{8}$	$\frac{5}{16}$ lively	$\frac{5}{16}$ still livelier	
19	$\frac{3}{4}$	$\frac{3}{4}$	almost nothing	small spark	

The general conclusions already arrived at before were still further confirmed by these experiments.

They were: 1) distributed capacity must be done away with at any price; 2) the wire should have one quarter of wave length; 3) the last plan of tuning is the best; 4) harmonics appear prominently even under the conditions of these experiments (in the experimental coil the greatest spark between both ends of the coil was obtained when the wire was 200 feet long, this was just $\frac{1}{16}$ of the length of secondary); 5) it is most important to tune secondary and extra coil so that they are of the same period exactly, to avoid beats.

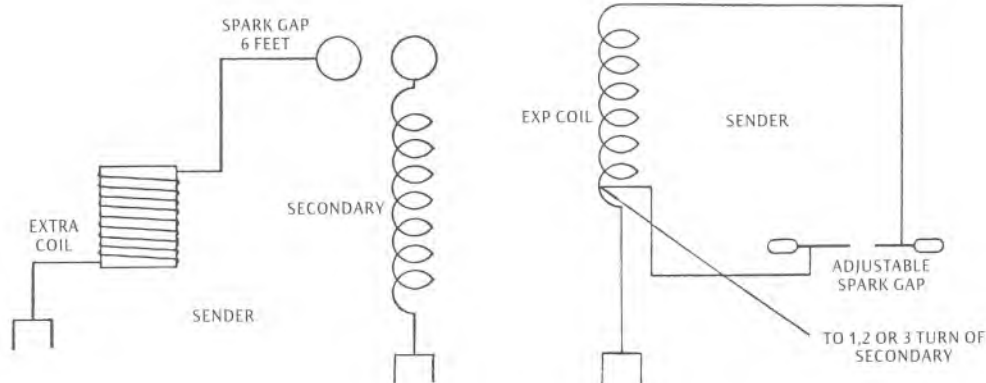
Colorado Springs

September 5, 1899

Experimental coil freshly wound on old drum 4 ft. high. Wire No 18 and a small part of No 20 covered with wax.

Turns: $\left\{ \begin{array}{l} 467 \text{ No } 18 \\ 49 \text{ No } 20 \end{array} \right\}$ Total 516

Plan of connections:



The coil had nearly $\frac{1}{4}$ wave length and the response was at once good, a 6" spark being obtained from the free end, also between both ends of coil. The spark would have been probably longer but this was the limit to which the gap could be adjusted.

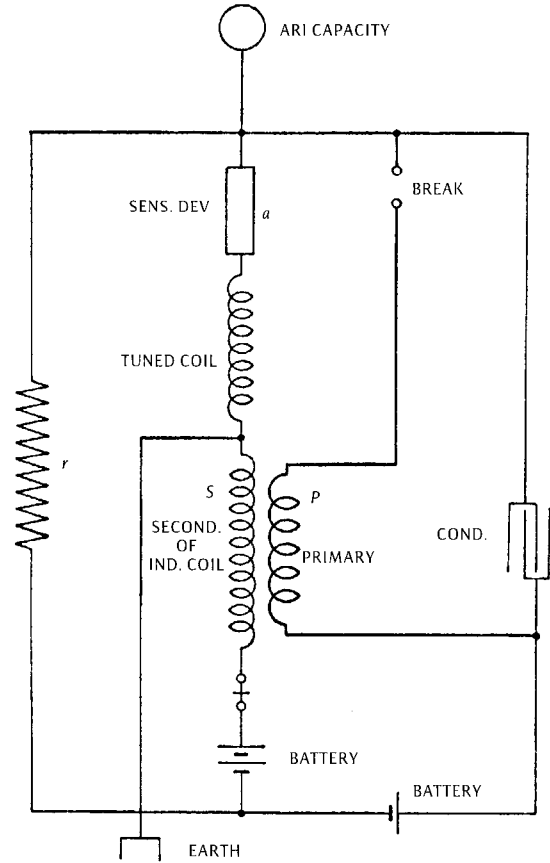
Measuring carefully the spark length to body of experimenter it was found that from the oscillator end (connection being made to 3d turn) the spark was $1\frac{1}{8}$ " long, while from the free end of the coil the spark was 5" long giving more than 4 times the former value.

As it was thought that the body of experimenter was of too large a capacity and affected therefore the vibration of the experimental coil – diminishing the potential, while it did not sensibly affect the powerful oscillator – a ball was fastened to an insulating stand and spark length tried in this way. With a ball of 4" diam. the spark from the oscillator end was $\frac{1}{2}$ " while from the free end of the exp. coil it was 4". A still smaller capacity was now used in the belief that perhaps the 4" ball was too large but the experiments showed a contrary result. It was thought that the wave length being estimated from that of the oscillator and extra coil must be longer than that of the wire on experimental coil. This led to consideration of certain advantages of long waves allowing a great length of wire to be wound up on the experimental coil, this in certain instances overbalancing the advantages of the larger magnifying factor which the short waves offer.

The connection was now made to the second and then again to the first turn of oscillator secondary and, as even in this case the effects were inconveniently strong, connection was made to the water pipe to diminish impressed e.m.f. But even now the streamers would go over the spark gap. Several balls were now experimented with. Results were as follows:

Turns exp. coil	Spark from oscill. end	Spark from free end	Spark between terminals	Ball diam.
516	$\frac{3}{8}$ "	$1\frac{1}{2}$ "	$3\frac{3}{8}$ "	no ball
516	$\frac{1}{8}$ "	$\frac{3}{8}$ "	$\frac{5}{8}$ "	18"
516	$\frac{3}{8}$ "	$\frac{9}{16}$ "	$1\frac{1}{2}$ "	8"
516	$\frac{5}{16}$ "	$\frac{15}{16}$ "	$1\frac{7}{8}$ "	5"

It was now important to get an idea of the magnifying ratio and the spark was tried on the water pipe and on the free end of coil and the lengths compared. On the water pipe it was $\frac{1}{64}$ " and on the free end $1\frac{1}{2}$ ". This was fair but the coil was not yet quite well tuned. Completing the adjustment with more care the spark on the pipe was found $\frac{1}{100}$ " and on the free end of the coil 2". This was *quite satisfactory* but not the best by far.



Further efforts to tune still more closely resulted in producing a spark between rods $2\frac{1}{4}$ " and with the capacity of the experimenter on *free rod*, the same being disconnected from everything, $3\frac{3}{4}$ ". The capacity in the primary oscillating circuit was now 5 tanks on each side and the self-ind. box 7 turns *in*. This capacity did not secure the best vibration of the sender which was a little slower but was suitable for the coil and no further attempt was made to tune still more advantageously by winding up

more turns on the experimental coil. An important fact not to be forgotten is that the experimental coil responded without *any spark* passing between the oscillator balls. Obviously it was seen that, although the experimental coil during the tuning was placed so as to avoid induction of the primary system, the same still existed to some extent. To ascertain how much induced e.m.f. was set up spark was first tried between the terminals of the coil without ground connection and the spark obtained was about $\frac{1}{64}$ ". Now the coil was reversed so that the induced e.m.f. was against the directly communicated e.m.f. through the water pipe and it was found still that a spark of 1" between the rods was obtained. The same would have been probably longer had it not been for the fact that the end of the coil was influenced by the metal of the sink which was near. As this could not be helped the effect could only be approximately estimated. All this showed that the induced e.m.f. from the primary system was not to any considerable degree responsible for the rise of pressure on free end of experimental coil.

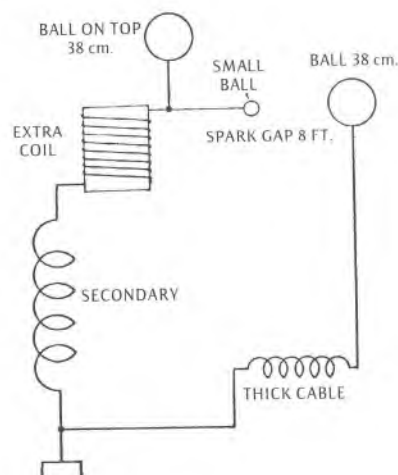
The coil (experimented with) was now taken outside the building and one end connected to a water pipe running across the field. At a distance of 250 feet from shop or rather from the connection of secondary to ground a spark between the rods $\frac{1}{4}$ " long was obtained and when the body of the experimenter was connected to the insulated sparkrod the spark was 1". At a distance of 400 feet the spark without capacity was still $\frac{1}{8}$ " and *with* capacity of experimenter $\frac{1}{2}$ " although at one place the pipe was buried for 30 feet in the ground. Strong shocks were obtained at that distance before the point of connection.

The experiments having shown the effects of distributed capacity to be very hurtful if not fatal to success with tuned coils, for convenience a winding was adopted to give very small capacity and thus the greatest possible length of wire and highest potential on the free end without *any capacity*. Capacity on the end was not needed since the free end is connected to a sensitive device practically without capacity. Since it was desirable to get the greatest possible rise of pressure on this device, it was much better to tune for a condition without capacity on the free end, for any capacity would cause diminution of pressure since the amount of energy was fixed. But wound in this way the tuned coil was not quite suitable to serve at the same time as secondary of the induction coil and, to utilize older apparatus, finally the connection shown in diagram on the left was adopted, which was found to be best.

Colorado Springs

September 6, 1899

Experimental coil for receiving apparatus with short waves



These were produced in the following manner: the extra coil, repeatedly described, was connected in series with the secondary of oscillator, both being first tuned to the same period so that there was a nodal point on the place of connection. The tension on extra coil terminal (a ball of 38 cm. capacity) was over 3 million volts, as was evident from streamers from ball. At a distance from the extra coil (8 feet) another ball 38 cm. capacity was supported, and this ball was joined by a heavy cable 400,000 circular mills section to the ground. The cable was 120 feet long and was not straight but made 3 small turns about 4 feet diam. The rest was practically straight. As the ball connected to the thick cable could not be elevated as high as the other ball of equal size on top of the extra coil a spark-gap was established as indicated in sketch. A small ball was joined to the cable leading up this ball being placed at about the height of the large ball connected to the thick cable. In estimating the vibration of the system comprising the large ball and thick cable leading to ground it was assumed for the present that the large cable was straight and self-induction calculated on this basis would, of course, give a smaller value, but this was thought sufficient to give the first idea as to how much wire should be placed on receiving coil. Assuming the cable straight we have

$$L_s = 2l \left(\log_e \frac{2l}{r} - 0.75 \right)$$

$2l = 240 \text{ ft} = 7315 \text{ cm. approx.}$

$r = 0.64$

$\frac{2l}{r} \text{ approx} = 11,600$

$\log_e \frac{2l}{r} = 9.6$

$n = 3 \times 10^6$

These figures gave approx.

$66,000 \text{ cm.} = L_s$

From this

$$T = \frac{2\pi}{1000} \sqrt{\frac{38}{9 \times 10^5} \times \frac{66}{10^6}}$$

$$T_{\text{approx}} = \frac{1}{3 \times 10^6}$$

Now λ would be $186,000 : 3 \times 10^6 = 0.062$ miles or 3273 feet. Say $\frac{\lambda}{4} = \frac{3280}{4} = 820$ feet. This wire is to be wound on a drum 10" diam. Therefore, we want 328 turns *at least*.

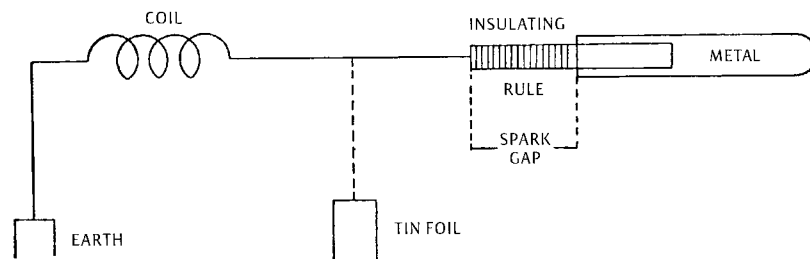
Colorado Springs

September 7, 1899

A new experimental coil wound with 400 turns on same drum 10" diam. 66" long

The coil when attached to a water pipe gave on free end spark $\frac{5}{8}$ ". To test whether the wave length is greater 72 turns were added and sparks were decidedly stronger. But adding 50 more turns the effect was weaker. The self-induction was now calculated to get a better idea of the probable wave length and L was 2,000,000 cm. approx. As with this L the capacity would have to be extremely small, far less than the coil evidently had, it was safe to proceed in taking wire off. Gradually shortening the wire increased the spark length until at 405 turns and a capacity of 15 sq. inches tinfoil the longest spark was obtained about 1". Calculating from wire length $\lambda/4$ was 1010 feet approx. giving $n = 245,500$ per sec. *approx.*

As there was a possibility of confounding the true vibration with a harmonic, wire in definite lengths was taken off. With 270 turns and small capacity on end the effect was still good. From that point on the diminution was steady.



The wire No 20 was now taken off and wire No 18 wound in place to study the effect of diminished resistance. New exp. coil wound on drum 10" diam. used before. It was estimated that for the vibrating system before described, comprising ball 38 cm. capacity and 120 feet cable 400,000 c. mills, about 400–420 turns would be needed. There was wire enough for 495 turns. The spark was taken to the body of the experimenter, the length being at once read off by a simple arrangement comprising a small rule of insulating material and a metal strip, the position of which was adjustable relative to end of the insulating rule. The metal strip was held in hand and the end of the insulating rule was maintained almost in touch with the wire forming the free terminal of the coil which was carefully placed in the proper position such that there was *no induced* e.m.f. from the primary but only through the ground connection could the coil be excited. The connection of coil and manner of reading off spark-length is indicated in the above diagram.

Results:

Turns	Spark to body of experimenter	Spark to body of exp. with small capacity attached to end of wire
495	$\frac{3}{8}"$	much less
470	$\frac{7}{16}"$	"
460	$\frac{7}{16} + \frac{1}{64}$	"
450	$\frac{7}{16} + \frac{1}{32}$	"
440	$\frac{9}{16}$	$\frac{1}{2}"$
435	$\frac{9}{16}$	$\frac{1}{2}"$
430	almost $\frac{11}{16}"$	$\frac{1}{2}"$
425	$\frac{3}{4}"$	$\frac{1}{2}"$
420	$\frac{3}{4}"$ full	$\frac{1}{2}"$
415	$\frac{7}{8}"$	$\frac{1}{2}"$
410	1"	$\frac{9}{16}"$
405	$1 \frac{3}{16}"$	$\frac{5}{8}"$

With 405 turns the limit was nearly approached. With 400 turns the spark without capacity was $1 \frac{1}{4}"$ and with tinfoil on wire $\frac{5}{8}"$; with 395 turns the former was $1 \frac{1}{4}"$ the latter $\frac{5}{8}"$ and with 390 the same also, with 385 practically the same. The system still needed a small capacity for when a hand was held at a distance of about a foot a spark of $1 \frac{3}{8}"$ could be obtained.

These data give wave length.

Colorado Springs

September 8, 1899

In some previous experiments coils were used wound on a drum 10" diam. but the inductances were not measured as the changes were made too often. The following data of a new coil built for similar purposes will be useful in connection with the preceding experiments.

The coil was wound on a new drum 10 $\frac{5}{16}$ " diam. and 41 $\frac{1}{4}$ " length. There were 550 turns of № 18 wax-covered wire.

Data for calculating inductance

diameter of coil $d=10 \frac{5}{16}"=10.3125"=26.19$ cm.

$$S = \frac{\pi}{4} d^2 = 0.7854 \times 685.9 = 538.7 \text{ cm.sq.}$$

$$N=550$$

$$l=41.25"=104.77 \text{ cm.}$$

$$N^2=302,500$$

$$L = \frac{4\pi}{l} N^2 S = \frac{12.5664 \times 302,500 \times 538.7}{104.77} = 12.5664 \times 302,500 \times 5.14$$

$$L=19,538,800 \text{ cm. or } 0.019539 \text{ henry approx.}$$

following readings to measure the inductance were taken:

E	I	ω	R	} average of three readings practically the same.
117	6.2	880	9.586	

From these data

$$\frac{E}{I} = \frac{117}{6.2} = 19 \text{ approx.} \quad \left(\frac{E}{I} \right)^2 = 361 \quad R^2 = 91.89$$

$$\left(\frac{E}{I} \right)^2 - R^2 = 269.11$$

$$L = \frac{\sqrt{269.11}}{880} = \frac{16.41}{880} \text{ or}$$

$$L=0.01865 \text{ henry}=18,650,000 \text{ cm.}$$

Colorado Springs

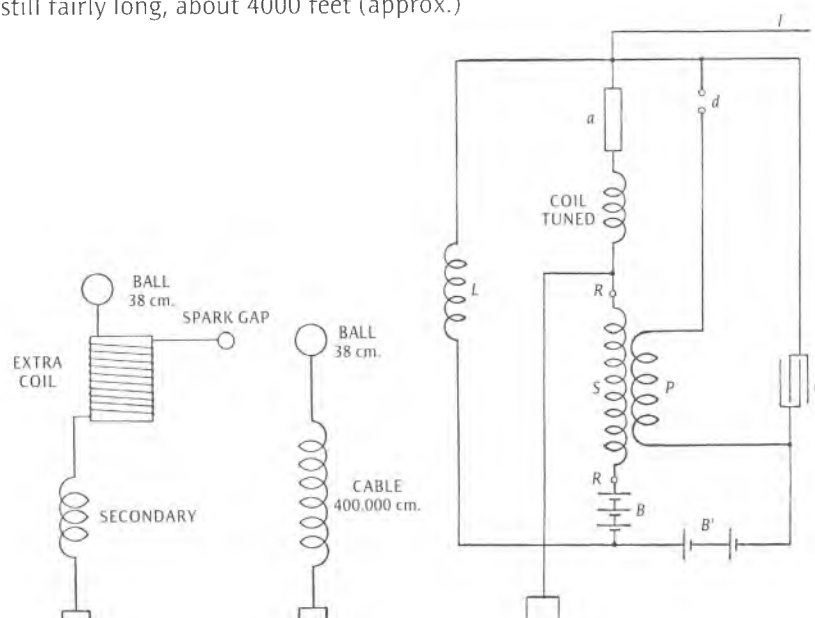
September 11, 1899

Experiments were continued with apparatus before described and the effects outside at a distance investigated, the chief object being to establish nodal points on earth's surface. The transmitting apparatus was one giving more rapid vibrations and was improvised as indicated in the left sketch.

The apparatus for investigation comprised the ten" drum, before referred to, wound with 395 turns wire № 18 B. & S. and to increase magnifying factor another layer was wound on top, thus doubling the section. It was found that the scheme of double windings is not a good one because the e.m.f. in both wires are apt to be unequal and it is more difficult to make adjustment. The connections of apparatus were as indicated in the right sketch.

The secondary of the induction coil was connected between the two legs of the receiver, this being convenient for eventually reversing. A high self-induction L was provided to give initial excitation

but the apparatus worked also without it. The batteries B and B' were connected both in the same way and opposite, the former giving best results. The tests showed that without *any* capacity or wire l the disturbances were recorded about one mile away; only the ground connection was essential as the waves were still fairly long, about 4000 feet (approx.)



Colorado Springs

September 12, 1899

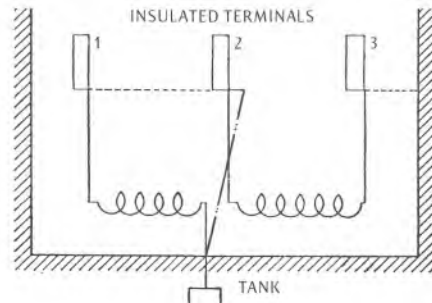
Experiments were again resumed after some changes for the better had been made. The secondary was reduced to 26 turns and the adjustment was so made that but little self-induction remained in the self-ind. box and all tanks were used. The best condition was obtained with 8 tanks on each side and self-ind. on sixth turn. The extra coil was now adjusted to the same vibration. As with the ball lifted up the vibration was somewhat too slow for the secondary, the ball was lowered to about half the height when resonance was secured with nearly the same capacity and self-induction in primary circuit as corresponded to the vibration of the secondary. Although the agreement was not quite close, the effects were remarkable. The streamers went from ball 38 cm. capacity on top as freely as though it were a small one, this showing that the e.m.f. was far in excess, possibly many times the 3 million volts which theoretically are necessary to produce streamers from a ball of this radius of curvature.

Colorado Springs

September 13, 1899

On Westinghouse Transformer the following change was made. The wire was cut in the middle and the two parts connected as shown in diagram: the end of the first half was connected to the tank which as before remained connected to the ground. The second half was left intact. This mode of connecting afforded the advantage of connecting the two parts in multiple arc for 22,500 volts or 30,000 volts – thus providing double current capacity. This was recognized as necessary as the one half previously used did not

load the jars quite fast enough as was evident from the measurement and calculation of constants. When the parts are used in multiple arc the connection is as illustrated by ----- lines. When the old connection was desirable the dotted connections were taken off and the connection indicated by ----- line.



A further change was made today by substituting for the 5" pulley on the alternating motor another pulley of 6". This gives now $\frac{6}{2} \times \frac{2100 \times 40}{60} = 4200$ breaks per sec. The tests showed best results with secondary of oscillator, 8 tanks on each side self-ind., 6 turns in. Streamers were all along on the top wire which was raised today, *very strong*, more so than before.

Colorado Springs

September 14, 1899

Experiments continued with the object of completing adjustments of secondary and extra coil with *ball elevated* to the highest position

It was found that the capacity necessary in primary for resonance with extra coil was increased 25% when ball was lifted about half way. This gave the basis for the calculation showing that about 10 turns from the extra coil had to be taken off to give the same vibration with ball elevated to top position. All in all nearly eleven turns were taken off and it was found that the vibration came out very closely as estimated. The resonance of secondary was obtained with all jars or tanks (8 on each side) and 6 turns self-induction, while resonance of extra coil with ball elevated took place with all tanks likewise and 4 turns self-induction. The coil was still a little faster than the secondary. When both were connected in series the effects were magnificent, streamers up to 12 feet from the ball. To get best effect a middle value of self-induction had to be inserted, but although with this number of turns (about 4) both the secondary and extra coil were weakened individually, their joint effect was much stronger. This showed importance of very *close tuning*.

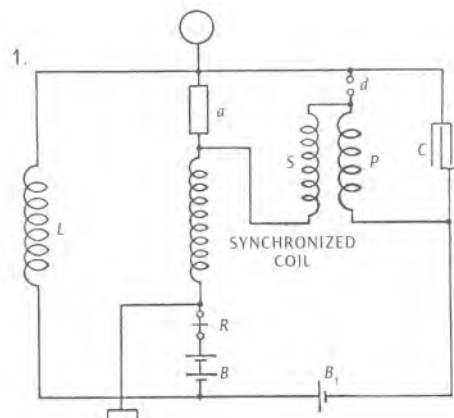
Colorado Springs

September 15, 1899

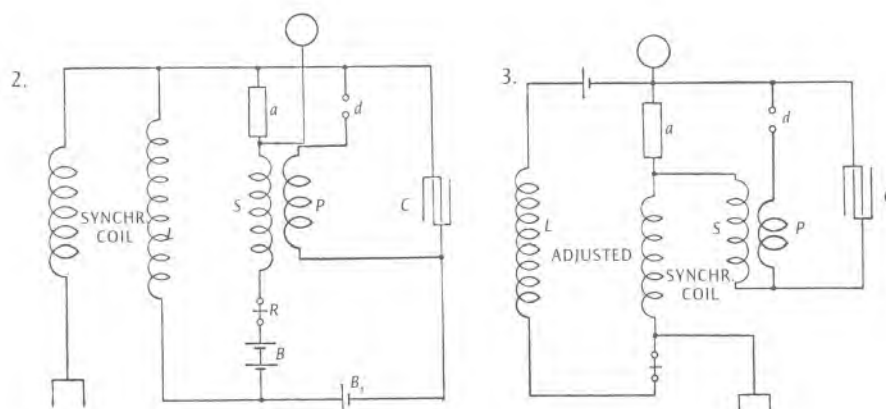
As it was impracticable in the form of apparatus used in some of these experiments to insulate the sensitive device from the break, a number of arrangements were adopted to dispense with this necessity. Some are illustrated below:

These diagrams are self-explanatory. In all of them both the secondary coil and synchronized coil have their ends free for the purpose of enabling great size of pressure. This has been found a great

advantage as has also the construction of a resonating coil in which distributed capacity is reduced to minimum.



In some of the above arrangements the secondary coil was dispensed with and a part of the synchronized coil utilized to give initial excitation. It was found in these experiments that the primary must be for the best results always on the side near the ground connection as otherwise the influence of the primary is detrimental to a great rise. In one instance results were remarkably good with ratio of transformation 1:250, that is two turns of primary and 500 turns in synchr. coil.

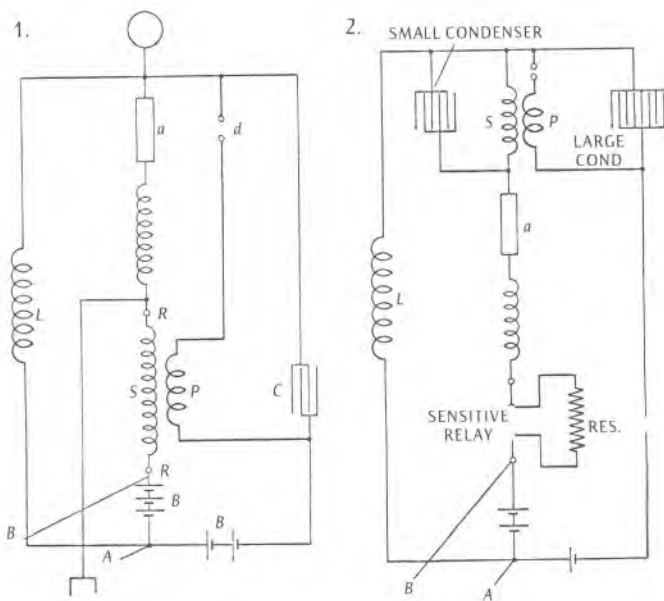
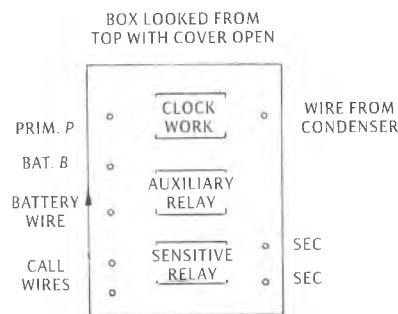


Colorado Springs

September 16, 1899

Further experimentation led to adopting one of the two arrangements illustrated according to whether an independent induction coil was used or not

The induction coil secures the advantage that the synchronized coil need not be touched and the apparatus is made suitable for any coil. On the other hand to use the synchronized coil itself has the chief advantage of having the coil entirely open. This latter advantage is secured to a large extent also when an independent induction coil is used, as in following diagram (1): The lettering is as in previous diagrams. A small condenser C_1 is connected to secondary to allow easy passage to the high frequency currents from the ground through the synchronized coil to the sensitive device and wire or capacity in the air.

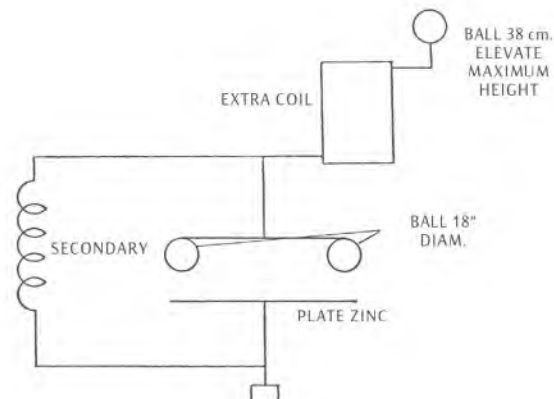


Colorado Springs

September 18, 1899

Experiments were resumed with all transformers in place, high speed break and connection in multiple arc of West. Transformer

The object was to further test the intensity of the vibrations produced particularly without spark. The connection was as in diagram. It was thought that in this arrangement, which was dwelt upon before, the disturbances were produced more economically than when using a spark discharge. The experiments fully confirm this. In the tests the capacity of the two balls of 18" diam. did not very materially derange the adjustment and period of the circuit. This is to be expected; as for the secondary the capacity was far too small and on the other hand the independent vibration of the extra coil could not be materially interfered with since the condenser formed by the two balls and zinc plate allowed free passage of currents to earth. Now the important thing was to decide whether it is better to make length of extra coil one half or one quarter of wave as before. This to be thoroughly investigated. The working was excellent with $\frac{1}{4}$ wave length.

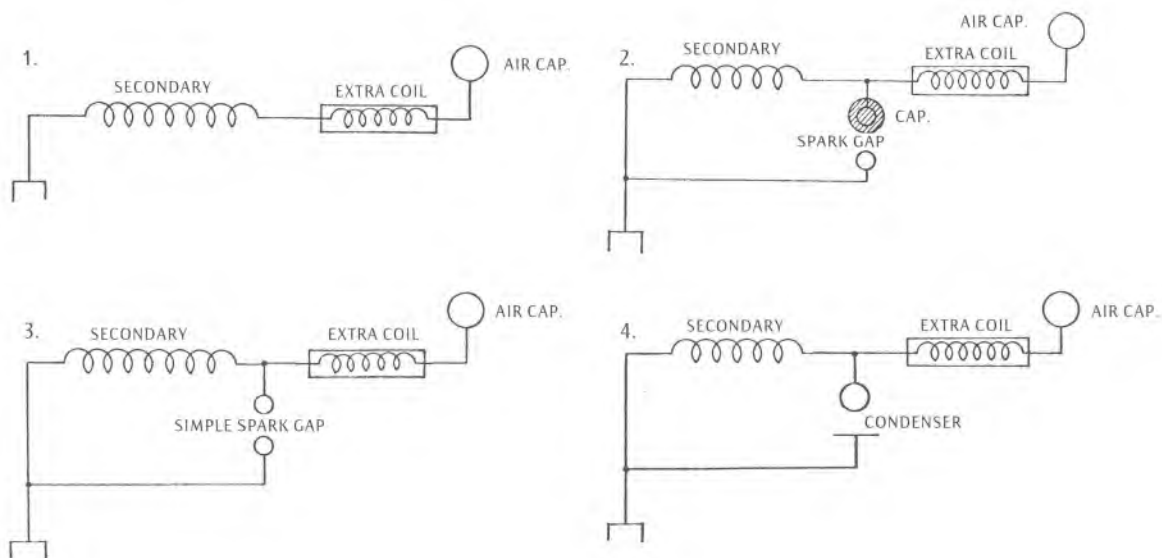


Colorado Springs

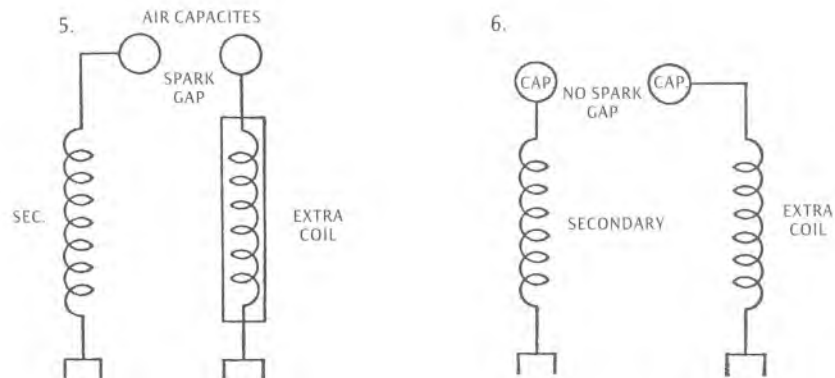
September 19, 1899

Various arrangements with oscillator and extra coil for production of most powerful disturbances

All of these arrangements have been experimented with and described before, and so far the plan illustrated in Diagram 4. seems to be best. In Fig. 1. the extra coil is merely a means of increasing pressure on the end. In Figs. 2. and 3. the vibrations through the ground are intensified by the extra coil working directly on the ground either through a gap with capacity or without same. In all cases it has been found important to have the two systems vibrate in synchronism. The same considerations apply to Diagrams 4, 5 and 6. The plan in Fig. 4. being found best, the question is what is the best length to give to the wires.



With each secondary and extra coil having one quarter of a wave length the action on the condenser is not most intense. With the extra coil $\frac{1}{2}$ wave length and the secondary $\frac{1}{4}$, they both cooperate on the condenser producing on the ball a much greater pressure. This appears the best relation in Fig. 4. In Fig. 5. and 6. it is found best to make extra coil $\frac{3}{4}$ wave length and the secondary $\frac{1}{4}$ for obvious reasons.

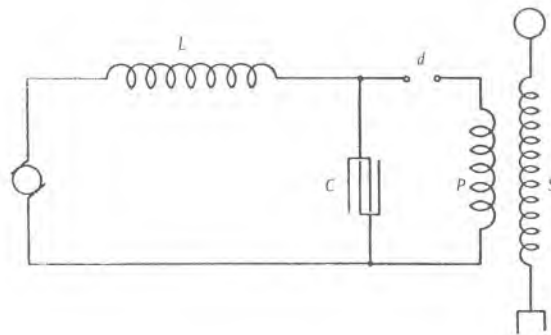


Colorado Springs

September 20, 1899

Consider a form of oscillator of great simplicity particularly adapted for telegraphy similar to type exhibited before Am. Ac. of Science

A coil of high self-induction is connected in series with a condenser and across the condenser is placed a break generally in series with the primary of the coil. Very sudden discharges are produced when using a fine stream of electrolyte or mercury to effect shortcircuit. The stream is broken by condenser current. The plan followed for some time was to produce the stream automatically by a magnet worked by a key. The connections are schematically indicated in the diagram.



The question is to get the proper capacity of condenser, the amount of self-induction and other particulars. The secondary of the oscillator may be connected as shown to the ground and elevated object of capacity or else a spark gap may be used.

If R be the resistance of charging coil and L the self-induction and E the e.m.f. of the generator the maximum current that could flow through the coil would be $\frac{E}{R}$, but as the stream has a resistance r the maximum current will be $I = \frac{E}{R+r}$. The moment of the coil will be $\frac{1}{2} I^2 L$. The condenser will be able to store each time an amount of energy $= \frac{E^2 C}{2}$ and we must have $\frac{1}{2} L I^2 = \frac{E^2 C}{2}$. This gives for C value $C = L \left(\frac{I}{E} \right)^2$ but $\frac{I}{E} = \frac{1}{R+r}$ hence $C = \frac{L}{(R+r)^2}$. Now to obtain frequency of break we should calculate the

time sufficient to evaporate a portion of the liquid column. This we can find easily from dimensions of column and its resistance, specific heat and the amount of energy which is passed through it.

(This to be followed out.)

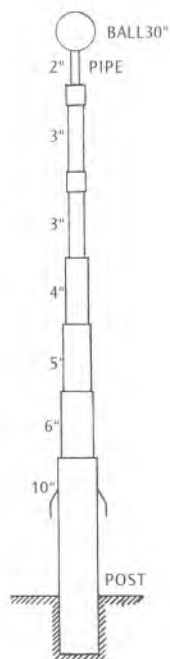
Colorado Springs

September 21, 1899

Proposed structure to elevate terminal to a height of 140 feet from ground

On a telegraph post very strong and reaching nearly to the roof of the building is to be placed a cap consisting of a pipe 10" diam., about 2 feet long with a coupling for a 6" pipe. The cap will widen out at the bottom so as to keep the wood safe against the streamers.

The pipes come in lengths of 20 feet. This will give roughly 120 feet of pipe plus cap and timber, at least 20 feet, all in all 140 feet.



The approximate area of pipe above the roof will be: $\pi \times 20 \times 12(6+5+4+3+3+2) = 17,332$ sq. inches or 120 sq. feet. The ball having nearly 20 sq. feet. We shall have 140 sq. feet+cap. There may be possibly 150 sq. feet with all joints. The electrostatic capacity will reduce turns on coil to probably less than one half.

The wind pressure will be considerable but except for an unusually strong wind it will be fairly safe.

Colorado Springs

September 23, 1899

For best results the copper masses in primary and secondary of reconstructed oscillator should be equal

There are two primary cables generally connected in multiple arc. These cables each have 37 wires Nº 9 B. & S. The area in mills from table of wire Nº 9 is 13,090, the total section of one cable being therefore

$$\begin{array}{r}
 13,090 \times 37 \\
 \hline
 39270 \\
 91630 \\
 \hline
 484330
 \end{array}
 \left. \vphantom{\begin{array}{r} 13,090 \times 37 \\ 39270 \\ 91630 \\ 484330 \end{array}} \right\} = 484,330 \text{ c. mills or}$$

$$\begin{array}{r}
 484,330 \times 0.0005067 \\
 \hline
 2421650 \\
 2905980 \\
 3390310 \\
 \hline
 2454100110
 \end{array}
 \left. \vphantom{\begin{array}{r} 484,330 \times 0.0005067 \\ 2421650 \\ 2905980 \\ 3390310 \\ 2454100110 \end{array}} \right\} = 245,41 \text{ mm. square}$$

Taking one wire in each groove (Nº 10 B. & S.) we have for 48 turns 10,380 mills being the section of wire Nº 10 total section reduced to one turn

$$\begin{array}{r}
 10380 \times 48 \\
 \hline
 41520 \\
 83040 \\
 \hline
 498240
 \end{array}
 \left. \vphantom{\begin{array}{r} 10380 \times 48 \\ 41520 \\ 83040 \\ 498240 \end{array}} \right\} = 498,240 \text{ c. mills or}$$

$$\begin{array}{r}
 498,240 \times 0.0005067 \\
 \hline
 2491200 \\
 2989440 \\
 3487680 \\
 \hline
 2524582080
 \end{array}
 \left. \vphantom{\begin{array}{r} 498,240 \times 0.0005067 \\ 2491200 \\ 2989440 \\ 3487680 \\ 2524582080 \end{array}} \right\} = 252.46 \text{ mm. square. That is very nearly the section of primary cables.}$$

Therefore, if two primary cables are used there should be two wires in each groove of the secondary as provided for. The total section of primary will then be 490.82 sq. mm. and of secondary reduced to one turn: 504.92 sq. mm., but as the wire is slightly stretched the sections or masses respectively will be more equal.

Colorado Springs

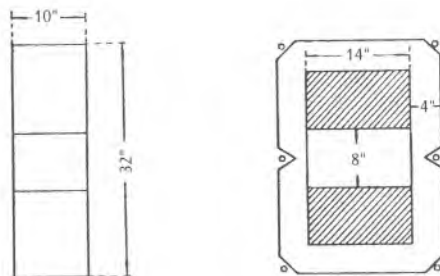
September 24, 1899

Note relative to Westinghouse Transformer

The iron core is of dimensions indicated in sketch. The insulation from core 1" thick blocks of wood. Insulation between fibre paper about ½" thick.

There are three primary coils and 4 secondary coils. For a transformation to 60,000 volts a part of primary is left out. Best way of working is to use smaller transformation ratio to 45,000 approx.

The secondary coils are connected up alternatively, that is, beginning with the first on the left, then to third, then to second and from there to the fourth coil.



The transformer gives every evidence of having a high efficiency. The leakage current is remarkably small for so large a machine. The alternate connection and disposition of coils is evidently to reduce stray field and also for convenience to enable use of similarly wound coils, that is, coils wound on one form.

The tests of mineral seal oil 300° show it to be oil of excellent quality penetrative, of high flashing point and good insulating properties.

Colorado Springs

September 25, 1899

Measurement of self-induction of primary of oscillator and regulating self-in. coil

Readings:

Conductor measured	Current	Voltage across conductor	p
2 primary turns	33.2	6.4	Computed from revolutions of synchronous single phase motor speed 35 per sec. 8 pole motor gives $n=140$ $p=880$
2 primary turns	58.9	11.7	
1 primary turn	58.9	5.85	
Self-in. coil	33.2	2.5	
Self-in. coil	58.9	4.45	

Of the above readings the one showing 58.9 amp. was taken repeatedly and is very probably closer than the other reading with smaller current. Taking this as the basis I find, neglecting resistance of both primaries and self-in. coil being very small L_{zp} of two primaries:

$$\frac{E \times 10^9}{lp} = \frac{11.7 \times 10^9}{58.9 \times 880} = 225,730 \text{ cm.}$$

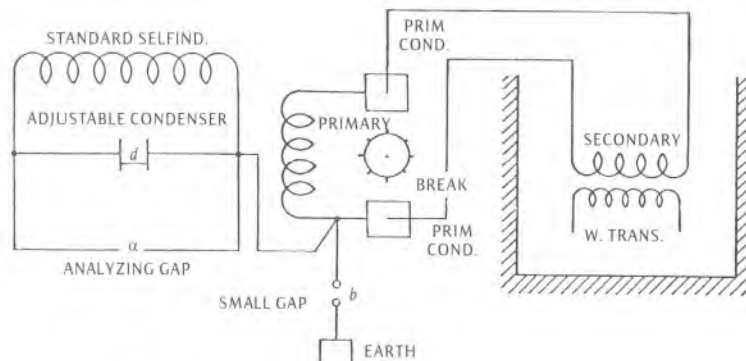
L of one primary will be $L_p = 56,432$ approx. as the coils are practically one.

$$L_e = \frac{E \times 10^9}{I \times 880} = \frac{445}{1170} \times 225,730 = 85,855 \text{ cm. approx.}$$

As there are 24 turns we may take as a rough approximation when quickly computing: 3600 cm. per turn when there are a considerable number in.

September 26, 1899

Following method for determining period of vibration, inductances and capacities is simple and convenient. The vibrating system is formed by a continuously variable and exactly determinable inductance and a capacity standard, or by an inductance standard and continuously adjustable condenser or by a system in which both these elements are continuously adjustable and can be exactly determined in one way or another. This system is then excited by a primary vibrating system in a convenient manner and one or both of the elements of the excited system is varied until resonance is obtained. This gives the period of the primary system and if in this only one more element is known all the others can be easily determined. The excitation is conveniently secured and graduated by connecting the wire leading to the system to be excited to the ground through an adjustable spark gap, which is generally very small. This method was applied to determining the period of the primary system used in these experiments in the following manner: a standard self-induction coil made long ago and used in experiments in N.Y. about 1560 turns wound on a drum $3\frac{1}{2}$ " diam. was shunted by the adjustable condenser, also frequently used and consisting of two brass plates 20" diam., and this system was connected to one of the terminals of the Westinghouse transformer as illustrated in diagram below. By varying the length of spark at b the degree of excitation was varied to any value desired, the spark at a serving to determine maximum rise of potential on terminals of excited system.



Particulars: $L=0.0176$ H. Res. of coil=59.457 ohms, drum $3\frac{1}{2}$ ", turns 1560 approx.

Readings in one case:

Capacity in primary total

Inductance primary

144 bottles=0.1526 mfd.

0.000025 H

$$T_{approx.} = \frac{2\pi}{10^3} \sqrt{0.000025 \times 0.1526} = \frac{1225}{10^8}$$

Resonance was obtained with the plates nearly 0.8 cm. apart, the period of excited system being slightly slower.

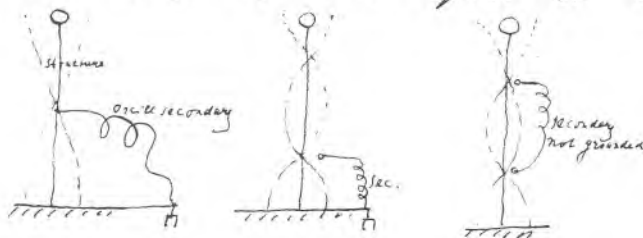
$$C_{sec} = \frac{A}{4\pi d} = \frac{2024}{4\pi \times 0.8} = approx. 200 \text{ cm.}$$

$$T_s approx. = \frac{1230}{10^8}$$

Colorado Springs Sept. 24 1891



One of the difficulties in telegraphy is to
 descend to practical introduction in the elevator
 because of ceiling as proposed by me. It is difficult
 to elevate a structure to a desired height and keep
 the same insulated from the ground and with very
 powerful vibrations as have produced even an insulator
 will breaking up offers difficulties because of streamers
 which reduce the force and the effect at distance.
 I propose to overcome this by the following
 plan. A structure is to be elevated from the
 ground up to the desired height and an insulator
 line for vibration is to be brought up to a
 point of the structure and connected to the same or
 else brought into proximity as for instance when
 a spark is used. This point should also be so
 located that there is at the same moment say
 a positive maximum on top and a negative on
 bottom or ground, that is the top and bottom should be
 one half of wave apart or a multiple thereof.



When secondary is grounded as
 usual it is probably an
 advantage to make the
 wavelength in both systems so that
 they will be in phase on the ground.

Colorado Springs

September 27, 1899

Determination of inductance of coil used in series with extra coil when no ball was used on latter, with old secondary

160 turns № 10 B. & S. wire rubber-covered Habirshaw, drum 2 feet diam. =60.96 cm.
Length=42.5"=107.95 cm.

First measurement average of readings:

$$I=5.9 \quad E=38.25 \quad R=1.054 \quad \omega=880$$

$$\frac{E}{I} = 6.483 = \sqrt{(1.054)^2 + (880L)^2}$$

$$L = \frac{\sqrt{6.483^2 - 1.054^2}}{880} = \frac{6.4}{880} = 0.00728 H \text{ or } 7,280,000 \text{ cm.}$$

Second measurement average of readings:

$$I=6.77 \quad E=43.25 \quad R=1.054 \quad \omega=880$$

$$E=6.39 \text{ from this } L=0.00716 H \text{ or } 7,160,000 \text{ cm.}$$

This variation probably due to change in on and it is probably safest to take average

$$\left\{ \begin{array}{l} 0.00716 \\ 0.00728 \end{array} \right\} \text{ or } \left\{ \begin{array}{l} 0.00722 H \\ 7,220,000 \text{ cm} \end{array} \right\} \text{ as best values.}$$

The calculated value from above dimensions is:

$$L = \frac{4\pi N^2 S}{l} = \frac{4\pi \times 25,600 \times 2919}{107.95} = 8,700,000 \text{ cm. or } 0.0087 \text{ henry}$$

$$N^2 = 25,600$$

$$S = \frac{\pi}{4} \times 60.96^2 = 2919 \text{ cm. sq.}$$

The difference must be due to the internal capacity of the coil or possibly inexactness of the dimensions above.

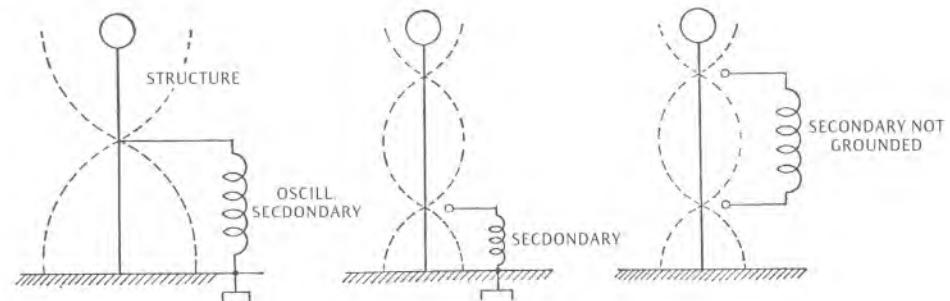
Colorado Springs

September 28, 1899

One of the difficulties in telegraphy and a drawback in practical introduction is the elevated terminal of capacity as proposed by me. It is difficult to elevate a structure to the desired height and keep the same insulated from the ground and with very powerful vibrations, as here produced even an insulated wire leading up offers difficulties because of streamers which reduce the force and the effect at a distance.

I propose to overcome this by the following plan. A structure is to be elevated from the ground up to the desired height and an insulated wire from the oscillator is to be brought up to a point on the structure and connected to same or else brought into proximity, as for instance when a spark is used. This point should now be so located that there is at the same moment, say, a position maximum on

top and a negative on the bottom or ground, that is the top and bottom should be one half of the wave apart or a multiple thereof. When secondary is grounded as usual it will probably be advantageous to make the wave length in both systems so that they work in unison on the ground.

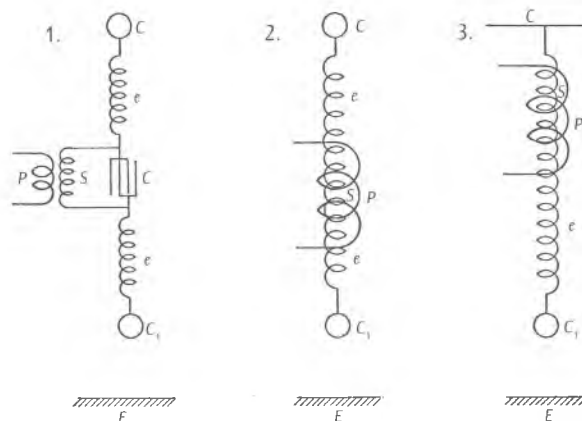


Colorado Springs

September 29, 1899

Various advantageous arrangements of oscillating circuits for producing disturbances in the natural media

The object of these arrangements is to produce especially in conjunction with an "extra coil", as before explained, disturbances in the most effective and economical manner. In such a coil the e.m.f. is raised to an extremely high value by the "magnifying ratio". The arrangements furthermore contemplate doing away with the spark which consumes energy, although in many respects it possesses advantages giving, in particular, a very high rate of energy delivery. In the diagrams three such arrangements which have been experimented with are illustrated.



In Fig. 1. the form of connection is shown most frequently experimented with here. The primary p energizes secondary s shunted by condenser c , the secondary exciting extra coils e with their capacities C C_1 at the free terminals, one of which, C_1 is at some distance from the ground or groundplate E forming a condenser with same. All the three systems, primary, secondary and extra coil have the same period of vibration. Fig. 2. illustrates a simplified way; in this instance the extra coils are partially influenced by induction from the primary p . In Fig. 3. again the extra coil e may be only electrically or also inductively excited. The upper terminal is here a very large capacity as the roof of a building and the terminal of high potential is C_1 .

This seems to be very effective.

Colorado Springs Oct. 13. 1899

Measurements of resistance of carbon and
primary circuit design

Colorado Springs Notes

$C = 5.9$ $E = 119$ $R =$ October 1-31, 1899

$$\frac{E}{C} = \frac{119}{5.9} = 20.17$$

$$L = \frac{(10.15^2 - 1.10^2)}{850} = \frac{100.025 - 1.21}{850} = 0.1176$$

$$\text{or } L = 22,648,000 \text{ C.M.}$$

Readings for secondary circuit and other

$C = 6.77$ $E = 60$ $R = 1.67$

$$\frac{E}{C} = \frac{60}{6.77} = 8.86$$

Following items partly completed omitted for want of time:

Oct. 5. More complete description of photographs taken.

Oct. 14, 22, 23 { page 5
page 6 }, 25 and 29 corrected results deduced from
experimental data recorded.

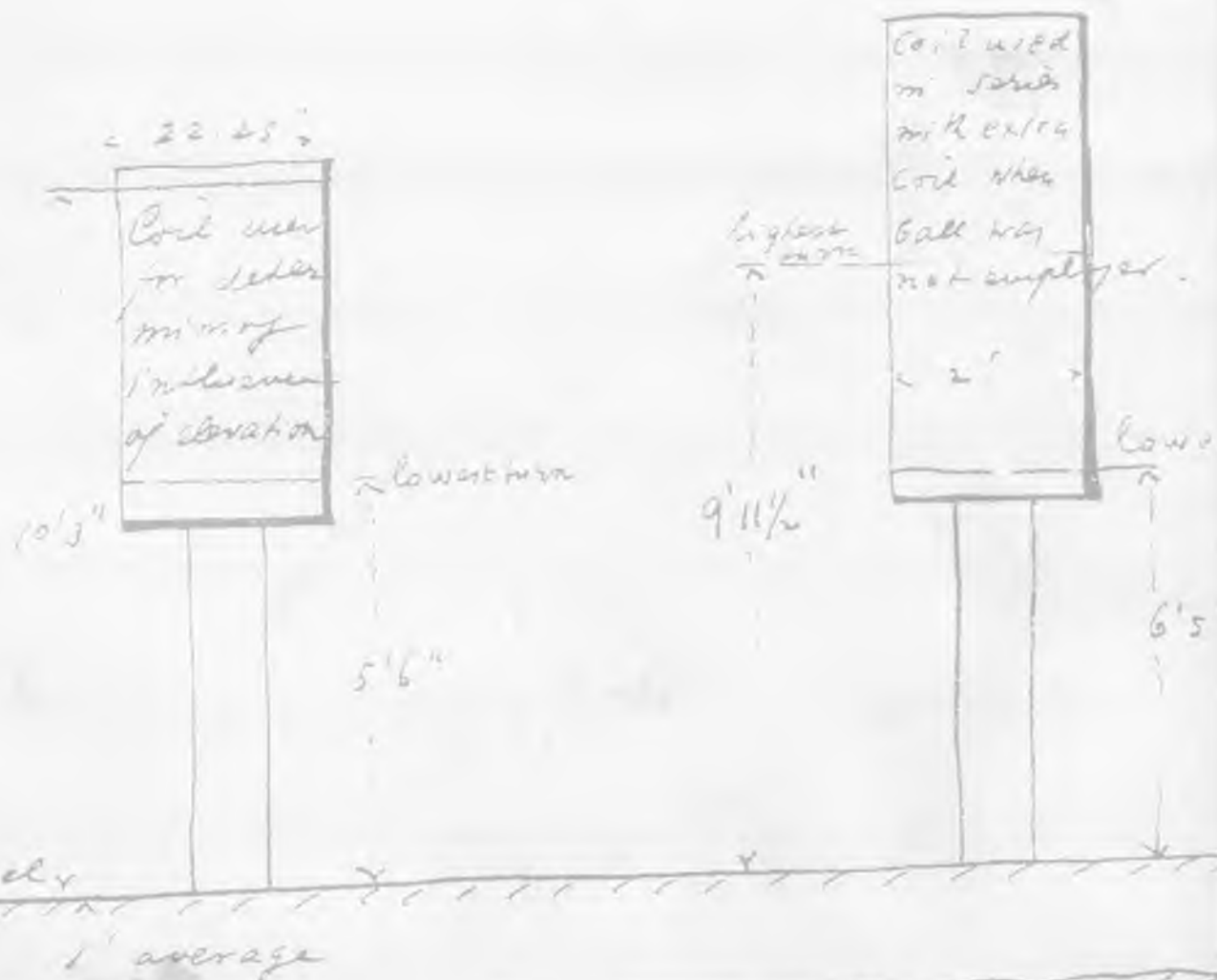
Patent matters nearly completed:

- Method securing excessive e.m.f. momenta.
- Various ways of avoiding use of elevated terminal in power transmission etc.

map RR 3 1895



in estimate of possible error
vicinity of the ground or conditions



Colorado Springs

Oct. 1, 1899

The new secondary was wound with 22 turns in all. The last turn was placed on top on porcelain insulators to prevent injury to the wood and breaking through on the last turn where danger greatest. It was evident that the coil could not stand the strain as there was only 1" between the turns. But the winding was tried for trial. The total length of coil was now – disregarding the last turn which was on top of frame – 27" approx. Now the length of the old coil was 63" (last turn excepted). Therefore, if the turns would have been of the same area the self-induction of the new coil would have been increased by a ratio of $\frac{63}{27}$ because of length and diminished by a ratio of $\left(\frac{21}{25}\right)^2$ because of turns. Now the average turn of the old coil was 44 feet dia. and of the new 49 feet approx. This made each of the new turns about 10" larger than the average of the old. On the whole then the self-induction of the new coil should have been roughly $\frac{63}{27} \times \left(\frac{21}{25}\right)^2 \times \left(\frac{11}{10}\right)^2 \times L$, where L is the self-induction of the old coil, that is $L_1 = (\text{nearly}) 2.06 L$.

The storing capacity will also be increased by a ratio of $\frac{3.125}{1.25}$ or nearly 2.5 capacity of the former. Consequently the period of the new coil should be nearly $\sqrt{2.5 \times 2.06}$ times longer or nearly 127% longer. With this distribution of turns it will be necessary to use a much smaller number.

Colorado Springs

Oct. 2, 1899

As expected the coil wound before was unable to stand the strain and a different distribution of turns of the secondary was made. The ten turns nearest to the ground were left as before and the remaining were placed one turn in each second groove making the distance between the upper turns $2\frac{5}{8}"$ and lower ones 1". Even with this arrangement, some of the upper and also some of the lower turns would break through.

A change was again made and only 4 of the turns – the lowest – were left 1" apart and all the others were placed in every second groove. The tests showed that the turns could now withstand the full charge. Perhaps up to six first turns might have been left at a distance of 1" – but it was thought that the distribution was good enough as it was.

The last change reduced the number of turns to 18 (the uppermost not counted). Compared with the last form of tapering coil of 25 turns the period of the new was now approximately estimated from rough data below:

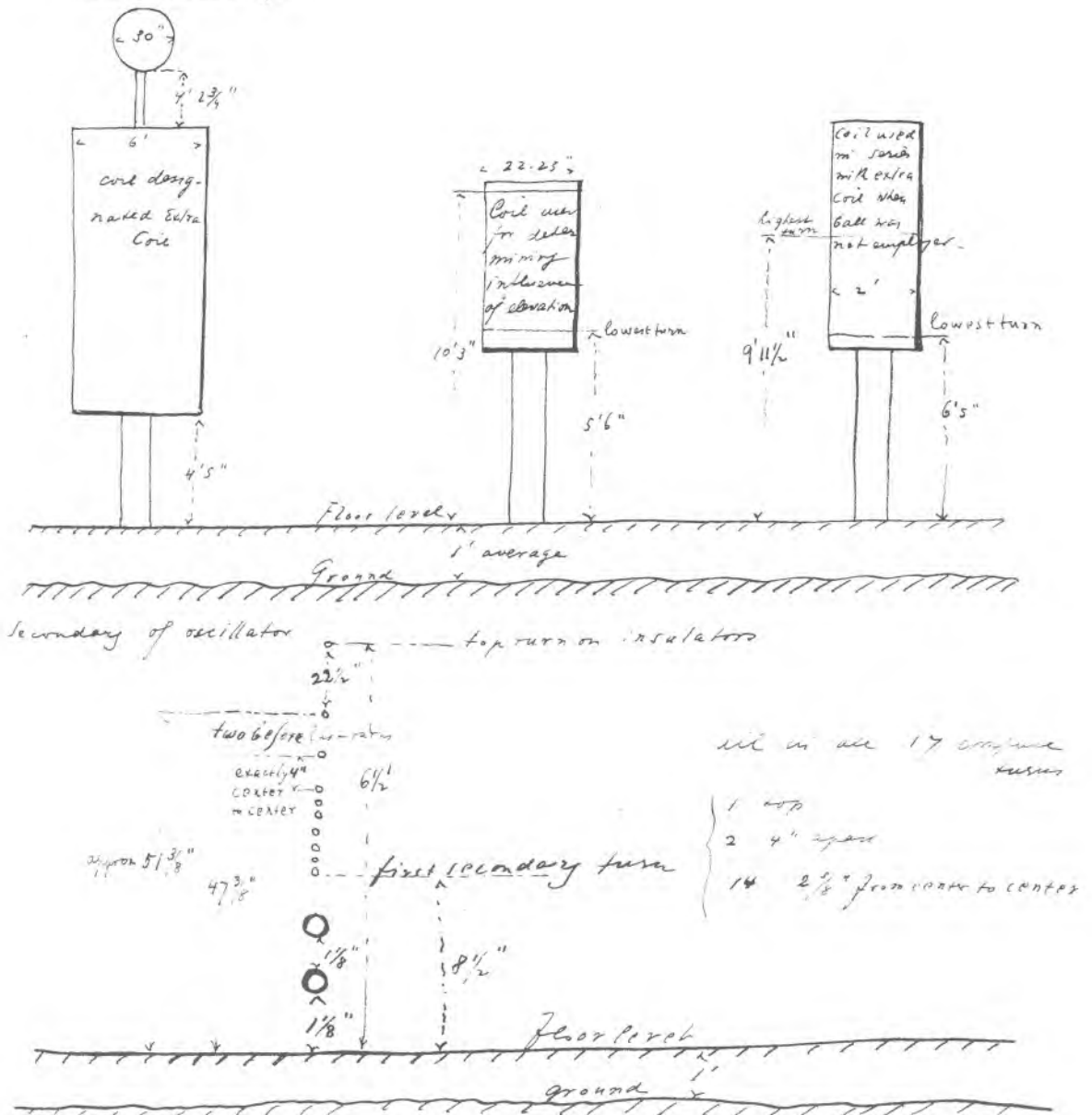
diameter of one new turn	49 f.
" average old "	44 "
turns of new coil	18
turns of old coil	25
average distance of new turns	$2\frac{5}{8}"$
average distance of old turns	$3\frac{1}{8}"$
length of new coil	42"
length of old coil	63"

Colorado Springs NR 3 1045

MAILED
NOV 15 1945

Useful data in estimating possible errors due to the proximity of the ground or conductors or other causes.

Ball adjustable height



Calling L_1 self-ind. of new coil and L_2 that of old tapering coil, we would have approximately:

$$L_1 = \frac{63}{42} \times \left(\frac{18}{25}\right)^2 \times \left(\frac{49}{44}\right) L \text{ or } L_1 = L \text{ nearly}$$

Now the capacity of new coil will be greater by a ratio of $\frac{3.125}{2.625} = \frac{25}{21}$ because of distance of turns and smaller by a ratio of $\frac{l}{l_1}$, l being length of new and l_1 that of old coil. Now

$$\frac{l}{l_1} = \frac{18 \times 49 \times \pi}{25 \times 44 \times \pi} = \frac{88}{110} = \frac{44}{55}$$

Hence the capacity of new coil to that of old will be as

$$\frac{25 \times 44}{21 \times 55} \text{ or as } \frac{110}{116}$$

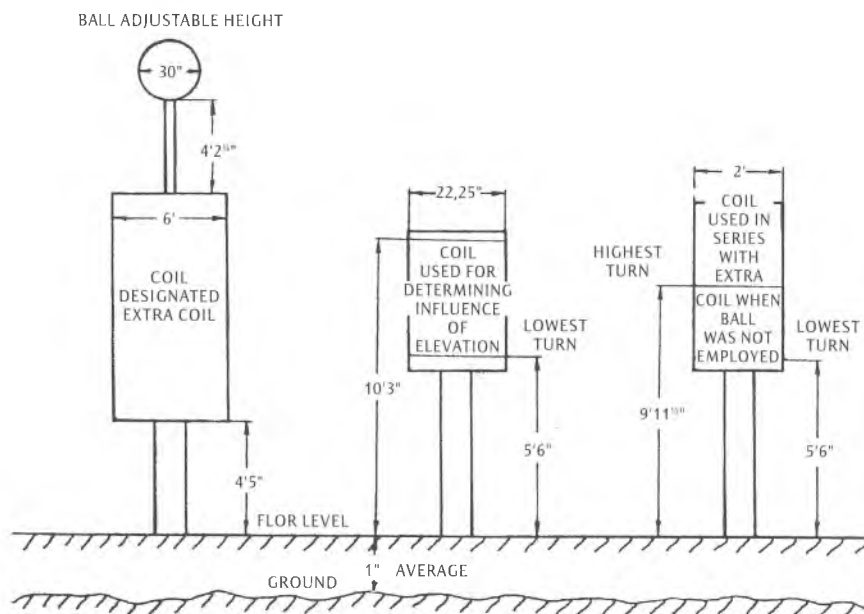
or very nearly equal.

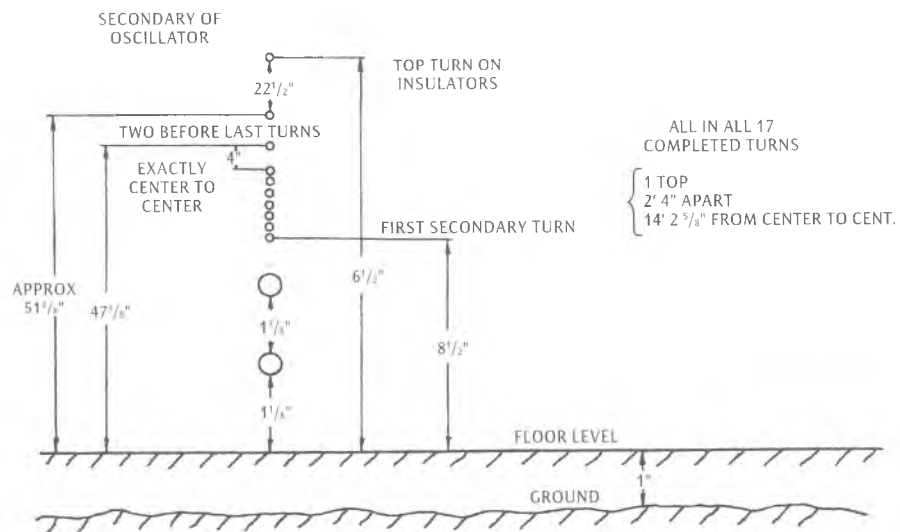
Therefore the distribution of the turns will secure nearly the same period of vibration as in the old coil.

Colorado Springs

Oct. 3, 1899

Useful data in estimating possible errors due to the proximity of the ground or conductors or other causes.





Colorado Springs

Oct. 4, 1899

Test to determine more exactly influence of elevation on capacity of an insulated body

A coil was wound to suit best the special conditions of this test. On a drum of 2 feet and $1\frac{1}{4}$ " diam. were wound 400 turns, wire cord № 20. The insulation was very thick but of small specific inductive capacity. This wire with widely separated turns was used in order to make the capacity of the coil itself as small as possible compared with capacity of insulated body. The latter was in this case the one sphere of 30" diam. arranged to be elevated at will to a height up to nearly 40 feet from the ground.

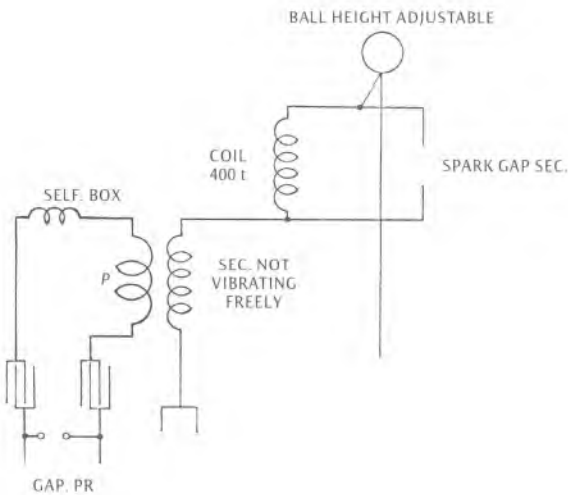
The wire had a diam. approx. № 20 B. & S.=0.032" or 0.8128 mm. The circumference of wire if solid would have been about 2.4 mm. Now one turn of wire was $\pi \times 25.25$ " or about $\pi \times 641$ mm. The total length $\pi \times 641 \times 400 = 256,400 \times \pi$ mm. Hence total surface of wire only $\pi \times 256,400 \times 2.4 = 615,360 \pi$ sq.mm. or 615471 sq.cm. Now the diam. of the sphere was 30" or 76.2 cm. The surface $\pi d^2 = 18,231$ sq. cm. approx. The utmost we could take would be $\frac{1}{2}$ surface of wire, that is 3000π sq.cm. and this would be only $\frac{1}{2}$ of surface of sphere. But other things considered, it would appear that the error due to electrostatic and distributed capacity of the coil itself would be small. This is however to be further investigated and allowance made for. It would be, of course, desirable to entirely do away with the capacity of the coil to make the results of the observations rigorously true, but this will be hardly possible.

The number of turns on the coil was selected so as to be suitable to the apparatus used normally. The total length of the coil so far as wound was $57\frac{1}{8}$ " or 145.1 cm, diam. of drum 25.25 "=64.14 cm. To calculate self-induction we have then the following data:

Turns: 400, length of coil 145.1 cm, area of one loop=3231 sq.cm. From this approximately
$$L = \frac{4\pi N^2 S}{l} = 44,772,000 \text{ cm, or } 0.044772 \text{ henry approx.}$$
 If we adopt 38.1 cm as the capacity of the sphere in the lowest position, the period of the system would be:

$$T = \frac{2\pi}{1000} \sqrt{0.44772 \times \frac{38.1}{9 \times 10^5}} = \frac{2\pi}{3 \times 10^5} \sqrt{0.1706} = \frac{2\pi}{3 \times 10^5} \times 0.413 = \frac{2.5936}{3 \times 10^5} = \frac{0.86455}{10^5} \text{ or } n=115,668 \text{ nearly.}$$

This is a vibration far too quick, in reality it will be much slower because of capacity in the coil.
Diagram shown illustrates arrangement used in experiments: The coil of 400 t. was excited by secondary of oscillator, and capacity and self-induction in primary were varied until resonance of free system comprising coil of 400 t. and ball of 38.1 cm cap. was obtained. This was evident from spark length and other indications, as streamers.



Results:

Ball position	Capacity in primary on each side	Turns in self, box	Spark gap primary	Spark second.	The experiments were interrupted here because of darkness
lowest	1 old + 3 2/3 new tanks	22	1/2" + 1turn	53"	
2 feet higher	1 old + 4 1/3 new tanks	22	1/2" + 1turn	53"	

From this computed found that by elevating 2 feet, capacity was increased by a ratio of $\frac{51/3}{42/3} = \frac{16}{14} = \frac{8}{7}$ or about 15% nearly, really 14.3%. This is a value found nearly the same before in previous tests.
To be followed up.

Colorado Springs

Oct. 5, 1899

Test of secondary last pattern, 17 turns in all

To ascertain the period a spark gap adjustable was used in the secondary from end to earth, as usual, and the capacity and self-ind. of primary was varied until maximum spark length in secondary and other indications showed maximum resonant rise.

Results:

Capacity in primary	Turns in self, box	} 1 turn primary (2 multiple) approximate
7 tanks on each side	13 "	
8 tanks on each side	10 "	

Now a ball 38.1 cm. was added on the end and placed near the earth plate at a distance of about 3 ½ feet but very little affecting the vibration. This shows that distributed capacity in secondary is very large as before.

Capacity of one tank being 0.03816 mfd. Taking approx. $L_p = 56,400$ and 13 turns box 46,800

We have:

$$T = \frac{2\pi}{1000} \sqrt{3.5 \times 0.03816 \times \frac{103,200}{10^9}} = \frac{2\pi}{1000} \sqrt{\frac{13.784}{10^6}} = \frac{2\pi}{10^6} \sqrt{13.784} = \frac{23.36}{10^6} = 0.00002336 \text{ and}$$

$$n = 42,800 \text{ approx.}$$

Some data to be preserved:

Res. of cord used in measuring resistances:	0.596 ohm
Res. of secondary 17 turns	2.804 "
Res. of 2 primary t. in series	0.004 "
Res. of Regulating self-ind. coil	0.054 "

Coil wound for W.T. outfit.: Aug. 24, 1899

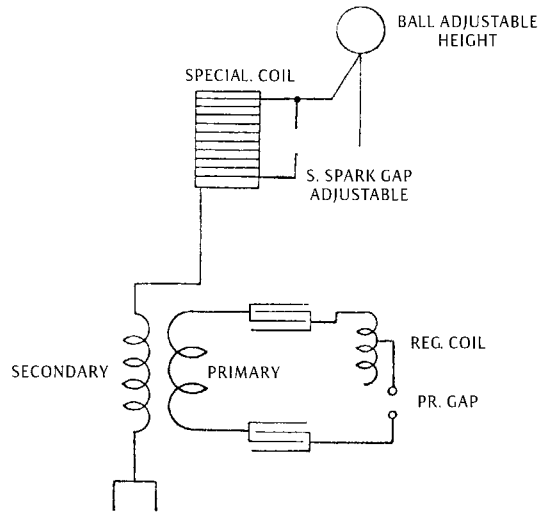
Spool about 8 ½" long:	399 turns per layer	}
	22 layers	

Latest secondary in receiving apparatus, No 30 wire, 90 turns per layer, 35 layers. Res. 424 ohms.

Tests showed best result with 56–68 primary turns. 62 turns, No 20 cord, are now used. Res. of cord 0.39 ohm.

Test with special coil for determining more accurately the law of variation of capacity with elevation. The coil with 400 turns No 20 cord was used as previously and the adjustable ball of 38.1 cm capacity. The ball was normally above the extra coil repeatedly referred to, which on account of its great internal capacity was not used. Although unconnected some error was necessarily caused by the presence of the coil near the ball when the latter was near its lowest position.

A further error was anticipated from the influence of the roof at the points when the ball, which was being gradually lifted during the test, was nearest to it. The smallest distance or nearest point was



about 11 feet. Nevertheless some action was bound to occur although the wood is very dry here and it is proposed in later tests to eliminate these errors as much as possible. The roof was covered with some sort of tar paper the influence of which can only be conjectured at present. The most reliable data will be those obtained with ball at the highest points when it is above all structures. The connections used are shown in diagram. The ball was lifted by steps of *one* foot each and the primary self-induction and capacity was adjusted until maximum resonant rise was observed on special coil, and adjustable secondary spark gap serving as analyzer, besides streamers which served even as a better guide. The results of the test are shown on the following table:

Table showing results. The capacities are all reduced to the same inductance so that as the primary capacity changes, the secondary is changed in the same ratio.

Height from ground feet	Capacity in tanks	Percent of increase	Figures reduced to self-ind. of one primary:
20.66	4.36		To correct later factor $\frac{6.24}{6.24}$ to be used
21.66	5.05	16%	
22.66	5.77	14%	
23.66	6.27	9.5%	
24.66	6.00	0	
25.66	6.24	4%	
two primary turns reduced			
25.66	6.64	10%	
26.66	8.87	33%	
27.66	11.48	40%	
28.66	14.84	30%	
29.66	18.64	26%	
30.66	21.08	13%	
31.66	22.36	6%	
32.66	23.28	4%	
33.66	24.72	6%	
34.66	25.68	4%	
35.66	27.00	5%	

Height of sphere from ground in feet	Capacity of primary expressed in tanks on each side	Turns in	Self-ind, in reg, coil		Total self-ind, in primary circuit	Arc		Capacity in primary on one side reduced to same value of self-induction in primary; minimum 106,800 m or 137,200 c	Increase of capacity of primary or sec, in percents	
			measured data cm,	calculated data cm,		in primary	in secondary		rate	absol
1	2	3	4	5	6	7	8	9	10	11
20.66	4.66	21.5	77,400	103,200	133,800 m. 173,200 c.	1/2" + 1 turn	52 1/4"	5.84 m 5.88 c.		
21.66	5.33	22	79,200	105,600	135,600 m. 175,600 c.	"	52 1/4"	6.77 m. 6.82 c.	16 16	16 16
22.66	6	22.5	81,000	108,000	137,400 m. 178,000 c.	"	52 1/4"	7.74 m. 7.78 c.	14.3 14.1	32.5 33
23.66	7	20	72,000	96,000	128,400 m. 166,000 c.	"	52 1/4"	8.41 m. 8.47 c.	8.6 8.9	44 44
24.66	8	14	50,400	67,200	106,800 m. 137,200 c.	"	52 1/4"	8.00 m. 8.00 c.	-5 -5	37 37
25.66	8 one pr. turn	15.5	53,800	74,400	112,200 m. 144,400 c.	"	52 1/4"	8.42 m. 8.42 c.	5.25 5.25	44.5 43
	* 1.66 two pr. turn	24	86,400	115,200	312,000 m. 395,200 c.	1/8" + 1 turn	20"	8.04 m. 8.07 c.	0.5 0.9	37.7 37.2

1	2	3	4	5	6	7	8	9	10	11
26.66	2.33 2.48 r	20	72,000	96,000	297,600 m 376,000 c.	"	27.75	10.71 m. 10.71 c.	33.2 32.7	83.4 82.2
27.66	3 3.2 r	19	68,400	91,200	294,000 m 371,200 c.	"	32 1/4	13.63 m. 13.7 f c.	27.26 28	133.2 133
28.66	4 4.26 r	18	64,800	86,400	290,400 m 366,400 c.	"	little less	17.93 m. 17.98 c.	31.55 31.24	207 205.8
29.66	5 5.32 r	18.5	66,600	88,800	292,200 m 368,800 c.	2" + 1 turn	still less	22.56 m. 22.6 c.	25.8 25.7	286.3 284.3
30.66	6 6.35 r	14	50,400	67,200	276,000 m 347,200 c.	2,5" + 1 turn	still less	25.4 m. 25.4 c.	12.6 12.4	335.8 332
31.66	6 6.35 r	18	64,800	86,400	290,400 m 366,400 c.	2,5" + 3 turn	still less	26.72 m. 26.8 c.	5.2 5.5	357.5 355.8
32.66	6 6.35 r	21.5	77,480	103,200	303,000 m 383,200 c.	3" + 3 turn	still less	27.94 m. 28.7 c.	4.6 7.1	378.4 388
33.66	6.33 6.86 r	22	79,200	105,600	304,800 m 385,600 c.	"	still less	30.29 m. 30.46 c.	8.41 6.13	418.6 418
34.66	6.66 7.1 r	21	75,600	100,800	301,200 m 380,800 c.	"	still less	30.96 m. 31.24 c.	2.21 2.56	430 431
35.66	7 7.5 r	21	75,600	100,800	301,200 m 380,800 c.	"	still less	32.70 m 33.00 c.	5.6 5.6	460 460

Table showing results of observations on influence of height in determining capacity of a sphere connected to the coil before described. The sphere of 38.1 cm. electrostatic capacity was gradually elevated and the period of vibration determined for every position of the sphere, by varying the capacity and self-induction of primary circuit. As the self-inductions of both circuits remained the same the secondary capacity varied exactly as the primary.

Observations:

Tuning was very sharp from line 27.66 to end. The arc in the primary was getting stronger and stronger. This probably because of lower frequency. The flaming of primary arc also because of this. For same reasons secondary arc was getting continually weaker as the ball was elevated.

m read measured data

c read calculated data

r read reduced data.

From the sign* two primary turns were used in series as the vibration got too low and not enough primary capacity was available with one turn. This was thought preferable to tuning to harmonic. From the figures on the side of 25.66 line it will be seen that the capacity with two turns was not exactly one quarter of 8, that is 2 tanks, but less. This was probably due to the fact that the tanks are not exactly equal and more so because when two primaries are used in multiple as one single turn the self-induction is less than $\frac{1}{4}$ of that of two turns in series. To reduce to same self-induction as with one turn the capacities obtained with two turns should be multiplied by $\frac{6.64}{6.24}$.

Colorado Springs

Oct. 6, 1899

Measurement of coefficient of self-induction and mutual induction

Secondary last form 17 turns of which total 16 turns disposed on frame described before, one turn in every second groove, one groove near the primary *free*.

Average of readings: $p=880$

Voltage across secondary $E=122.5$ V, $I=13.8$ amp.; Res. $R=2.804$ ohms. From this

$$L_1^2 = \frac{\left(\frac{E}{I}\right)^2 - R^2}{\omega^2} = \frac{70.94}{880^2} H^2 \quad \frac{E}{I} = 8.877; \left(\frac{E}{I}\right)^2 = 78.8$$

$$R^2 = 7.86$$

$$L_1 = \frac{1}{880} \sqrt{70.94} = \frac{8.4226}{880} H \text{ or}$$

$$L_1 = \frac{8,422,600,000}{880} = 9,571,140 \text{ cm.} = \text{approx. } 0.00957 H$$

For determining M the average of a number of readings was:

Current in secondary $I = 15$ amp., e.m.f. across two primary turns 11.2 V $= E$, $\omega = 880$.

We have from this:

$$M = \frac{E}{I\omega} = \frac{11.2}{15 \times 880} = 0.000848484 H$$

$$M = 848,484 \text{ cm.}$$

Colorado Springs

Oct. 7, 1899

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The secondary was again changed by displacing the 15th and 16th turn, the rest remaining as before: namely, 14 turns, a turn in each second groove and the 15th and 16th turn each in every third groove and the top turn on porcelain insulators as before. This changed very little the constants of the circuit.

The test was now made closed with the following results:

Capacity in primary (one turn)	Turns in regulating coil	Capacity on terminal of secondary
on each side $7 \frac{2}{3}$ tanks = total =0.14615 mfd	6	none
$7 \frac{2}{3}$ "	7	Ball 38.1 cm capacity at a distance 2 feet from a plate connected to earth terminal of secondary
$7 \frac{2}{3}$ "	nearly same, just a little more	Ball 1 foot from earth plate.
$7 \frac{2}{3}$ "	10	Ball 9" from earth plate.
$7 \frac{2}{3}$ "	13	Ball 6" from earth plate.

Tuning of extra coil to suit vibration of the secondary latest design, as specified on another sheet today.

An attempt was made to get the vibration of the coil with ball elevated exactly as that of the secondary. To adjust the vibration the ball was elevated to various positions and soon the adjustment was reached.

With an elevation of 2 feet lower than the highest point (35.66 feet from the ground) – that is 33.66 feet from the ground the maximum resonant rise on coil, as evidenced by the spark, was obtained with $7 \frac{2}{3}$ tanks capacity on each side and 13 turns in the self-induction coil. Lowering the ball just a trifle and making capacity on each side 8 tanks the resonant maximum rise in coil took place with 10 turns in regulating coil. This was almost exactly the vibration of the secondary as previously ascertained.

The two were now connected in series and discharges on a spark gap of something like 12 feet were obtained, although the W.T. was not strained to the utmost. When the spark wire was taken off and ball with a rubber covered wire № 10 specially prepared left alone, streamers formed on top of ball, but little as the wind was blowing. The ball being disconnected and rubber wire alone left, the streamers were very fierce reacting sometimes 16–18 feet. Best results were with 6 turns in coil in the last experiments.

A more careful tuning of extra coil without ball, only rubber covered wire or cord № 10 (which was referred to before), the tip of cable being brought out about 2 feet and inclined to horizontal about 45°. This wire to prevent streamers was specially made and was covered with rubber. Composition Habirshaw, 40% pure Para. The tuning of the coil alone with the self-induction coil specially wound in series, gave:

Capacity of primary
8 tanks on each side

Turns in self-ind. regulating coil
6 $\frac{1}{2}$

The coil used in series with the extra coil was one especially adjusted so as to give the same vibration to the system as when the extra coil was used alone and with ball on top at highest point. The coil has 160 turns and is wound on a drum 2 feet in diam. with wire № 10, same as used in the secondary and extra coil.

Now the secondary with a ball on the end and elevated at a height of 2.66 feet from the ground gave also exactly, with 8 tanks in primary on each side and 6 ½ turns in regulating coil, maximum effect. When the two were connected in series the display was magnificent, sparks flying to the ground a distance of over 16 feet. Their curved paths stretched out would be certainly 24 feet long. This was not the maximum of the power of the apparatus as the spark in the primary could have been still lengthened without difficulty.

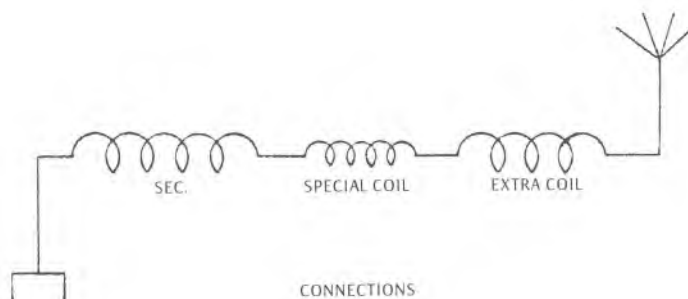
Colorado Springs

Oct. 8, 1899

Experimental data in connection with tuning of extra coil and secondary as recorded yesterday

Capacity on each side in primary circuit 8 tanks	Turns in self-ind. Regulating coil 6.5-7	With ball 38.1 centim. on free end of secondary, the ball being 2.66 feet from a grounded zinc plate, the both had exactly the same period.
--	--	--

Now the length of wire in the secondary was 803 meters, namely 17 turns each of a diameter of 15 meters.



The total length of wire in the extra coil circuit was: the extra coil itself 889 meters, namely 149 turns each of diameter of 1.9 meters plus special coil inserted in series: 307 meters, namely 160 turns each of diam. of 0.61 meter. This special coil was used when the ball on top was not employed as capacity and the coil was so adjusted that the vibration was the same without the ball as with the ball and without the special coil; it being understood that the ball was at its highest position in such case. The total length of wire was therefore:

$$\underbrace{\text{secondary}}_{\text{one system}} + \underbrace{\text{special coil+extra coil}}_{\text{one system}} = 803 + 307 + 889 = 1999 \text{ meters}$$

with all connections the length was increased to 2030 meters (17 meters rubber wire on top; 13 meters lower connecting wire).

Now capacity in primary was 4 tanks = $4 \times 0.03816 = 0.15264$ mfd.

Total self-ind. in primary circuit was approximately	}	56,400 cm one primary turn
		6600 cm approx. – all connections in primary circuit
89,000 cm		26,000 cm self-induct, coil

As the self-ind. of the regulating coil was rather a little larger we may take total self-induction as 90,000 cm, or $\frac{9}{10^5}$ H. This would give

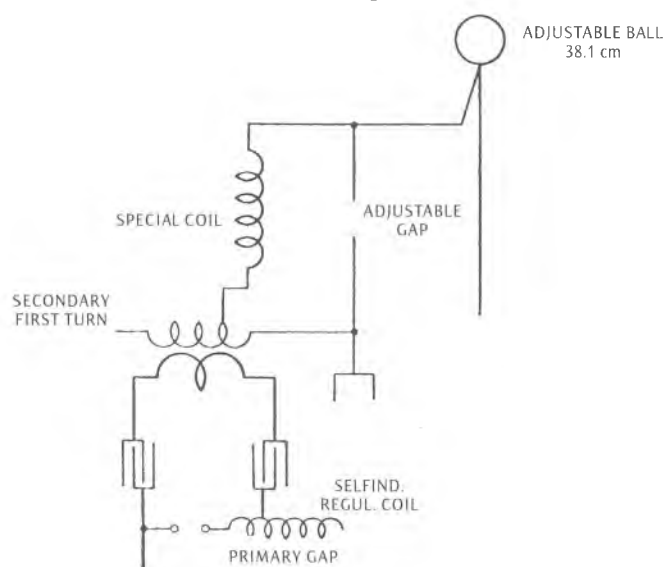
$$T = \frac{2\pi}{10^3} \sqrt{0.15264 \times \frac{9}{10^5}} = \frac{2\pi}{10^5} \sqrt{0.137376} = \frac{6.28 \times 0.37}{10^5} = \frac{2.3236}{10^5} \text{ and } n = 43,000.$$

This would give a wave length approx. $\frac{186}{43} = 4.33$ miles or $\frac{\lambda}{4} = 1.08$ miles = 5700 feet while there is a little more wire. Probably self-induction and capacity or either of them in the primary have been slightly underrated or else the wire is not quite as long as calculated before.

Colorado Springs

Oct. 9, 1899

Today an other effort was made to ascertain more closely rate of increase of capacity of a body with the height above the ground. The same adjustable sphere was used and to eliminate some influences which might cause errors the special coil, which was rewound with same wire as before and had now 404 turns, the wire being wound a trifle higher, was connected to the first turn of secondary of oscillator, that is the turn first from the ground. This gave a small initial e.m.f. and reduced the error



due to capacity very materially. (Here the distributed capacity is meant). Also, since the pressures developed were much smaller owing to small initial pressure on the special coil the streamers did not appear and did not therefore complicate the observations as in some previous cases. The plan of connections is clear from the diagram below. The object was specially to obtain a number of values which were as closely determined as possible and with the ball in positions entirely above the building. Only

three values could be obtained owing to darkness setting in, but these seemed fairly close as the tuning was done over and over with same results. These were as follows:

Height of ball above ground	Turns in Reg. coil	Total self-ind. in primary	Total capacity in pr. mfd.
35.66 feet	22	reg. coil 79,200 connections 6,600 primary 56,400 } 142,200	8 tanks each side 0.15264
34.66 feet	19	129,400	0.15264
33.66 feet	16 (trifle less)	118,600	0.15264

Now since the capacity in the primary was the same the capacity in the secondary varied directly as the self-induction of the primary. The above figures show that from 33.66 feet to 34.66 feet, that is an elevation of one foot, the increase was 9.1%, while for the next foot higher it was nearly 9.9% on the average, say, 9.5%. At this rate the increase of capacity of the elevated sphere with the rise from the ground would be greater than before found. The absolute rate of increase can be approximately estimated from the period of vibration. As before found the special coil with 400 turns had a self-induction of 44,772,000 cm. Now, however, with 404 turns this would be increased about 1% so that the self-induction would now be $\left. \begin{array}{l} 44,772,000 \\ 447,720 \end{array} \right\} = 45,219,720$ cm. But to this should still be added the self-induction of one turn of the secondary and wire leading to the ball and also the wire leading from the bottom of the special coil to the first turn of the secondary. The total length of these three wires is 240 feet and this is about 12% of the total length of the wire in the special coil which is 2854 feet. But inasmuch as the one secondary turn was very close to the primary and inasmuch as the other two wires were not coiled up, the self-induction of these wires was comparatively small, estimated a little over 200,000 cm so that the total self-induction was with fair approximation: 44,500,000 cm, or about 0.0445 henry (calculated). Now, with a ball of 38.1 cm capacity the period of secondary would have to be:

$$T_s = \frac{2\pi}{1000} \sqrt{\frac{38.1}{9 \times 10^5} \times 0.0445} = \frac{2\pi}{3 \times 10^7} \sqrt{1695.45} = \frac{86.19}{10^7} \text{ and}$$

$n=116,000$. This would be ignoring the internal capacity of the coil itself and its effect in slowing down the vibration. Now this capacity can be approximately estimated as well as the absolute increase of the capacity of the sphere from the primary vibration.

Taking the figures with the ball at a height of 33.66 feet from the ground, the primary vibration was:

$$T_p' = \frac{2\pi}{1000} \sqrt{0.15264 \times \frac{118,600}{10^9}} = \frac{26.7}{10^6} \text{ or } = \frac{267}{10^7}$$

This vibration is evidently slower than one of period T_s and it will be easily seen that

$$\frac{T_s}{T_p} = \frac{86.19}{267} = \sqrt{\frac{38.1}{C + 38.1}}$$

where C is the internal capacity of the coil. Assuming for the present this capacity as not being distributed along the coil but in one place, we get

$$C + 38.1 = 38.1 \times \left(\frac{267}{86.19} \right)^2 \text{ and } C = \left[\left(\frac{267}{86.19} \right)^2 - 1 \right] \times 38.1 \text{ cm}$$

Following this up we get for C value $C = [(3.098)^2 - 1] \times 38.1 = (11.597 - 1) \times 38.1 = 10.597 \times 38.1 = 403.75$ cm.

This is not the actual capacity of the coil but that ideal capacity by which the sphere should be increased to give the vibration of the primary.

We can now write

$$T'_p = \frac{2\pi}{10^3} \sqrt{0.0445 \times \frac{(403.75 + c)}{9 \times 10^5}} \dots\dots\dots 1)$$

This capacity c is now the actual capacity of the sphere at an elevation above considered, that is 33.66 feet. Namely, the total capacity was that of the sphere at that elevation – that is c – plus the ideal capacity of the coil derived from the computation of the primary vibration. This latter capacity has been called C . The inductance of the special coil being as before found, 0.0445 henry, and there being resonance under the conditions of the experiment at the elevation, named T'_p gives the value for the secondary period.

Now at another elevation, say 34.66 feet, we shall have similarly

$$T''_p = \frac{2\pi}{10^3} \sqrt{0.0445 \times \frac{403.75 + c'}{9 \times 10^5}} \dots\dots\dots 2)$$

where c' gives the value of the capacity of the sphere for the elevation of 34.66 feet. Computing I find, from experimental data above given

$$T''_p = \frac{2\pi}{10^3} \sqrt{0.15264 \times \frac{129,400}{10^9}} = \frac{2\pi}{10^6} \sqrt{19.75} = \frac{27.9}{10^6} \text{ or } = \frac{279}{10^7}$$

Now, from equation 1 and 2, we get:

$$\frac{T'_p}{T''_p} = \frac{267}{279} = \frac{\sqrt{0.0445 \times \frac{403.75 + c}{9 \times 10^5}}}{\sqrt{0.0445 \times \frac{403.75 + c'}{9 \times 10^5}}} \text{ or } (1.045)^2 = \frac{403.75 + c'}{403.75 + c}$$

and from this: $1.092 \times (403.75 + c) - 403.75 = c'$, but c being 38.1 we find for $c' = 78.75$ cm, which result shows that by lifting the ball from an elevation of 33.66 feet to 34.66 feet or one foot higher the capacity has been increased from 38.1 to 78.75 cm, or nearly 106.7%. Similarly we find the increase from 34.66 to 35.66 feet by computing the primary vibrations at these elevations. By analogy to the previous we have

$$T'''_p = \frac{2\pi}{10^3} \sqrt{0.15264 \times \frac{142,200}{10^9}} \text{ and, since } T''_p = \frac{2\pi}{10^3} \sqrt{0.15264 \times \frac{129,400}{10^9}},$$

we get

$$\frac{T'''_p}{T''_p} = \frac{\sqrt{1422}}{\sqrt{1294}} = \sqrt{1.099}$$

Now the vibration which corresponded to the primary vibration T''_p in the special coil was $\frac{2\pi}{10^3} \sqrt{0.0445 \times \frac{403.75 + 78.75}{9 \times 10^5}}$ and the one which corresponded to T'''_p was

$$\frac{2\pi}{10^3} \sqrt{0.0445 \times \frac{403.75 + c''}{9 \times 10^5}}$$

where c'' will stand for the capacity of the sphere at the altitude of 35.66 feet.

And now we have:

$$\frac{T_p'''}{T_p''} = \sqrt{1.099} = \sqrt{\frac{403.75 + c''}{403.75 + 78.75}} \text{ and from this}$$

$$1.099 \times (403.75 + 78.75) - 403.75 = c'' = 126.51 \text{ cm.}$$

The value at one foot lower was, as before found 78.75 cm, therefore by lifting the sphere from 34.66 to 35.66 feet, the capacity was further increased by $126.51 - 78.75 = 47.76$ cm, or about 125%. The value which would correspond to the mean would therefore be about 116% per foot. The method followed contains still some possible errors. One of them lies in the assumption that the capacity of the sphere was 38.1 cm at the starting point. Also there may be an error in the estimation of self-induction of the turns of the regulating coil.

Colorado Springs

Oct. 10, 1899

Resistances measured:

Large extra coil 149 t. wire № 10 drum 75"	with cord	3.7 ohms
	cord	0.596 ohms
	Coil alone	3.104 ohms

Coil used in series with extra coil. When ball was not used on top of latter:

160 t. № 10 wire drum 2 feet	with cord	1.65 ohms
	cord	0.596 ohms
	Coil alone	1.054 ohms

Resistance of coil used in determining influence of elevation on capacity:

400 turns № 20 cord drum 25.25"	with cord	31.20 ohms
	cord	0.596 ohms
	Coil alone	30.604 ohms

Resistance of secondary latest:

with cord	3.36 ohms
cord	0.596 ohms
Secondary alone	2.764 ohms

Colorado Springs

Oct. 11, 1899

Photographs of streamers were taken late last night again and at an early hour this morning under the following conditions

First two plates exposed to ten flashes, $\frac{1}{2}$ second duration each. These flashes issued from the tip of rubber-covered cable or wire № 10 which was on top of the extra coil. The tip was inclined about 45° degrees to the vertical and pointing downward. The full front view was taken. A curious observation was made. One of the large streamers, about 22 feet long, disappeared at that length for a space of about a

foot and continued again after that for a distance of about 2 feet, so that the total length of it was about 25 feet with a dark interval of one foot. Evidently, the current passed for a distance of a foot through air or dust particles which were better conducting and the path was of a greater section in all probability. Perhaps the air on that spot might have been electrified in such a way as to produce the phenomenon.

The next experiment was made with an exposure of two plates to about forty flashes, the view being the same as before.

After this two plates were exposed to but a single short flash about one second, the view being still the same as before. Now a round sheet zinc disk was fastened to the tip of the wire and two plates were again exposed, there being about twenty flashes. Next, the coil was turned and a side view taken with about forty flashes, two plates being again exposed as in all previous cases, two cameras being used for the sake of safety. Upon this the zinc disk was taken off and a ball of 4" diam. fastened to the tip of the No 10 rubber-covered wire. A long exposure of about 50 flashes was again made. The streamers were as expected a little stronger from the ball than from the point as the breaking out took place at a greater pressure. Two plates were used also in this instance.

The next experiment consisted of taking an impression on two plates of the secondary alone in resonating condition. The phenomenon was beautiful to an extraordinary degree. Not only did the top wire glow but from the under wire (turn next below) a steady sheet of streamers of very fine texture issued of an area which must have been many hundred square feet. The free end of the secondary had the ball of 38.1 cm connected to it at a distance of 32" from the ground but owing to the large radius of curvature sparks did not leap from the ball to the grounded zinc plate below though the distance was small comparatively. During the experiments a short but thick stream issued from the free terminal of the extra coil which had its other end connected to the ground and was thus excited through the vibration of the secondary, having, as stated on a previous occasion, the same period of vibration. The color of the light issuing from the secondary wires, particularly in the neighbourhood of the condensers, was remarkably blue, and should affect the plate strongly, though the intensity was not great. The switch was thrown in fifty times, the duration being about $\frac{1}{3}$ of one second, possibly $\frac{1}{2}$.

The last experiment consisted of establishing the resonance of the extra coil and secondary in series connected and with the ball of 38.1 centimeter on the free end of the extra coil, the ball being at its lowest position, 20.66 feet from the ground. The other ball of the same size remained as before, connected to the end of the secondary where it was joined to the lower end of the extra coil. As there was great danger of inflaming the roof the power was somewhat reduced, but the display was wonderful in spite of this. This was the most significant experiment showing streamers from the ball of 38.1 cm capacity from which is evident the enormous tension, as well as the inconceivable rate at which the energy was delivered in the vibrating system. Forty flashes were made and afterward the background was illuminated by the arc of the primary circuit to complete the picture.

Colorado Springs

Oct. 12, 1899

Measurement of inductance of 404 turns coil used in determining influence of elevation

$l=57.125''=145.1$ cm diam. of drum $25.25''=64.14$ cm.

Area of one loop 3231 square cm.

Calculated before for 400 turns when the wire was wound first a little less tight, the value was:

$$L = \frac{4\pi N^2 S}{l} = 44,772,000 \text{ cm.}$$

Colorado Springs Oct. 13. 1899.

Measurement of inductances of extra coil and
secondary circuit design:



Readings for extra coil:

$$C = 5.9 \quad E = 119 \quad R = 3.104 \quad a = 880$$

$$\frac{E}{C} = \frac{119}{5.9} = 20.17 \quad \text{from this}$$

$$L = \frac{\sqrt{20.17^2 - 3.104^2}}{880} = \frac{19.93}{880} = 0.022648 \text{ H}$$

$$\text{or } L = 22,648,000 \text{ C. m.}$$

Readings for secondary single wire later:

$$C = 6.77 \quad E = 60 \quad R = 2.764 \quad a = 880$$

$$\frac{E}{C} = \frac{60}{6.77} = 8.8626 \quad \text{and}$$

$$L = \frac{\sqrt{8.8626^2 - 2.764^2}}{880} = \frac{\sqrt{70.9060}}{880} = \frac{8.42}{880} = 0.0095682 \text{ H.}$$

$$\text{or } L = 9,568,200 \text{ C. m.}$$

After making corrections for I which upon more careful second measurement was found to be $46\frac{7}{8}$ " only, and taking $N=404$ the value was $L=45,670,000$ cm. The actual measurements gave the following data:

$$I=4.28 \quad E=194 \quad R=30.604 \quad \omega=880 \quad \frac{E}{I}=45.327$$

and from this

$$L = \frac{\sqrt{45.327^2 - 30.604^2}}{880} = \frac{33.435}{880} = 0.03788 \text{ H or } L=37,880,000 \text{ cm.}$$

The measured value should be smaller than the calculated but not so much. The internal capacity may be responsible but very likely the current was not quite exactly measured. Corrections to be taken after calibration.

Colorado Springs

Oct. 13, 1899

Measurement of inductances of extra coil and secondary, latest design: Readings for extra coil:

$$I=5.9 \quad E=119 \quad R=3.104 \quad \omega=880$$

$$\frac{E}{I} = \frac{119}{5.9} = 20.17, \text{ from this}$$

$$L = \frac{\sqrt{20.17^2 - 3.104^2}}{880} = \frac{19.83}{880} = 0.022648 \text{ H}$$

or

$$L=22,648,000 \text{ cm.}$$

Readings for secondary single wire; latest:

$$I=6.77 \quad E=60 \quad R=2.764 \quad \omega=880$$

$$\frac{E}{I} = \frac{60}{6.77} = 8.8626 \text{ and}$$

$$L = \frac{\sqrt{8.8626^2 - 2.764^2}}{880} = \frac{\sqrt{70.9060}}{880} = \frac{8.42}{880} = 0.0095682 \text{ H}$$

or $L=9,568,200$ cm.

Colorado Springs

Oct. 14, 1899

Determination of the natural period of the secondary with and without capacity on free terminal, also of the extra coil and coil of 404 turns used in investigations before described

The tuning was effected in a manner later to be more fully dwelt upon, which secured closer readings than when exciting, as in some experiments before made, by the primary current or from a turn of the secondary of oscillator.

The excitation was effected in these tests by connecting directly one of the terminals (the lower) of the coil to be tested to one of the terminals of the primary condensers (the one connected to the tank of W. Transformer).

The results of the test are given below:

Capacity in primary circuit Total	Self-ind. in primary Turns of Reg. coil + conn.	Observation:
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For secondary of oscillator:

$\frac{(8 \times 36) - 2}{2}$ bottles=0.126 mfd approx.	15+conn.	No capacity on free terminal
$\frac{(8 \times 36) - 2}{2}$ bottles=0.126 mfd approx.	15 ¼+conn.	Ball of 38.1 cm diam.
$\frac{(8 \times 36) - 2}{2}$ bottles=0.126 mfd approx.	19 ¼+conn	Structure to be described later of iron pipes with ball of 38.1 cm. diam. at an elevation of 141 feet from ground approx.
$\frac{(8 \times 36) - 2}{2}$ bottles=0.126 mfd approx.	19 ¼+conn	with above structure connected to free terminal.

For extra coil:

$\frac{(8 \times 36) - 2}{2}$ bottles=0.126 mfd approx.	19 ¼+conn	with above structure connected to free terminal.
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For coil 404 turns used in preceding investigations:

$\frac{(6 \times 36) - 2}{2}$ bottles=0.11342 mfd.	8+conn.	Tuning very sharp, no capacity on end.
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Remark: With excitation from secondary (first turn) obtained in a previous test of this coil:

$\frac{(5 \times 36) - 2}{2}$ bottles=0.094255 mfd.	17 ½+2 primary turns+connect.	Tuning was not quite sharp.
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Colorado Springs

Oct. 15, 1899

Continuing the considerations made Oct. 9 on the influence of elevation upon the capacity and taking, instead of the calculated value of the self-induction of the coil used in the experiments, the value ascertained by experiment which, with corrections for one turn secondary and connecting wires, may be put at 0.04 henry, we have, assuming now the coil to have a capacity entirely negligible:

$$T_s = \frac{2\pi}{1000} \sqrt{0.04 \times \frac{38.1}{9 \times 10^5}}$$

as secondary period of the coil with ball or

$$T_s = \frac{0.8164}{10^5} = \frac{81.64}{10^7} \text{ Now } T_p \text{ was } = \frac{267}{10^7}, \text{ from this}$$

$$\frac{T_s}{T_p} = \frac{81.64}{267} = 0.306 = \sqrt{\frac{38.1}{38.1+C}} \text{ from previous analogy – and from this}$$

$$0.306^2 = \frac{38.1}{38.1+C} \text{ or } C = \frac{38.1}{0.09364} - 38.1 = \frac{38.1 \times 0.90636}{0.09364} = 38.1 \times 9.68 = 368.8$$

Now

$$T_p' = \frac{2\pi}{10^3} \sqrt{0.04 \times \frac{368.8+c}{9 \times 10^5}} \text{ and } T_p'' = \frac{2\pi}{10^3} \sqrt{0.04 \times \frac{368.8+c'}{9 \times 10^5}}$$

but $T_p'' = \frac{279}{10^7}$ and from this

$$\frac{T_p'}{T_p''} = \frac{267}{279} = \sqrt{\frac{0.04 \times \frac{368.8+c}{9 \times 10^5}}{0.04 \times \frac{368.8+c'}{9 \times 10^5}}}; 1.045 = \frac{279}{267} \text{ and from this}$$

$$(1.045)^2 = \frac{368.8+c'}{368.8+c} \text{ now } c = 38.1$$

$$1.092 \times (368.8 + 38.1) = 368.8 + c' \text{ and } c' = 368.8 \times (1.092 - 1) + 38.1 \times 1.092 = 75.53 \text{ cm.}$$

This value is but little smaller than that before found. From this result it would then appear that by lifting the sphere from 33.66 to 34.66 feet the capacity was increased from 38.1 to 75.53 cm, or approximately 98.3%, a trifle less than before found.

Colorado Springs

Oct. 16, 1899

Inductance of secondary modified by winding another wire N° 10 in multiple with the first. All other particulars remaining:

Readings: $l=7.1$ $E=60.5$ $R=1.382$ $\omega=880$

$$\frac{E}{l} = 8.521$$

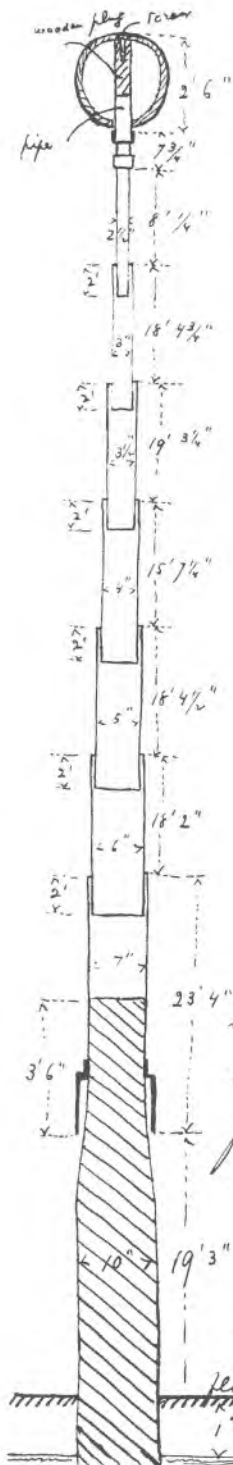
$$L = \sqrt{8.521^2 - 1.382^2} = \frac{\sqrt{70.6975}}{880}$$

$$L = \frac{8.41}{880} = 0.0095568 \text{ H}$$

$$\text{or } L=9,556,800 \text{ cm.}$$

This is closely agreeing with first measurement of a few days ago, the difference being only $\frac{1}{10}\%$.

Colorado Group OK. 17. 1899.



Structure for capturing of water cut or investigation of earth vibrations chiefly.

This structure was erected on a pole 10' x 10" square tapering on top. Dry fir was used because of toughness and also resinous quality. Pipes of steel of diameters 7", 6", 5", 4", 3 1/2", 3" and 2 1/2" were used. They were shoved one into the other and riveted, four rivets were used on each joint, the laps being 2'.

The lengths of pipes were as follows:

7" diam.	23' 4"
6" "	18' 2"
5" "	18' 4 1/2"
4" "	15' 7 1/4"
3 1/2" "	19' 3 3/4"
3" "	18' 4 3/4"
2 1/2" "	8' 1/4"

On top was supported a ball of wool ^{30" diam} hollow covered with burlap very smooth and the joints indicated so as to have no conducting points sticking out.

The joints of the pipes, heads of rivets, etc. were all covered first with sheetrubber paper and then with tape the latter being finally fastened with strong cord. The ball on shellacker several times and finally covered with weatherproof rubber paint. The pole all along was also painted with same paint.

On the lower end of 7" pipe a cap was secured clearing the wood so as to make it more difficult for the streamers to get to the ground along the pole.

Ripples on top 7 3/4"
 Total length of pipes 121' 9 3/4"
 for wood pole 19' 3"
 Total from floor 141' 3 3/4"
 to ground 1' 10' 3"
 Total height from ground 142' 3 3/4"
 to bottom of base

* To prevent lateral play 8 champagne bottles set in between were used.

Colorado Springs

Oct. 17, 1899

Structure for capacity of extra coil, for investigation of earth vibrations chiefly

This structure was erected on a pole 10"x10" square, tapering on top. Dry fir was used because of toughness and also resinous quality. Pipes of steel of diameters 7", 6", 5", 4", 3 1/2", 3", and 2 1/2" were used. They were shoved one into the other and riveted, four rivets were used on each joint, the lap being 2'.

The lengths of pipes were as follows:

7"	diam.	23' 4"
6"	"	18' 2"
5"	"	18' 4 1/2"
4"	"	15' 7 1/2"
3 1/2"	"	19' 3 1/4"
3"	"	18' 4 3/4"
2 1/2"	"	8' 1/4"
<i>Nipples on top</i>		7 3/4"
Total length of pipes		121' 9 3/4"
<i>Firwood pole</i>		19' 3"
Total from floor		141' 3/4"
<i>to ground</i>		1"
Total height from ground to bottom of ball		142' 3/4"

On the top was supported a ball of 30" diam. hollow wood covered with tin foil very smoothly and the joints indented so as to have no conducting points sticking out. The joints of the pipes, heads of rivets, etc. were all covered first with sheet rubber pure and then with tape, the latter being finally fastened with strong cord. The ball was shellaced several times and finally covered with weatherproof rubber paint. The pole all along was also painted with the same paint. On the lowest end of 7" pipe a cap was screwed clearing the wood so as to make it more difficult for the streamers to get to the ground along the pole.

* To prevent lateral play 8 champagne bottles set in beams were used.

Colorado Springs

Oct. 18, 1899

For special investigations particularly to prosecute further researches on the increase of capacity with elevation, a new coil is to be constructed as nearly as possible to exact dimensions which follow:

diam. of core 14"=35.5 cm

length of core 8x12"=243.84 cm.

The coil is to be wound with cord № 20, before used in the coil of 404 turns on 25.25" diam. drum. Allowance for thickness of insulation: 0.354 cm.

This makes total diameter d=35.854 cm.

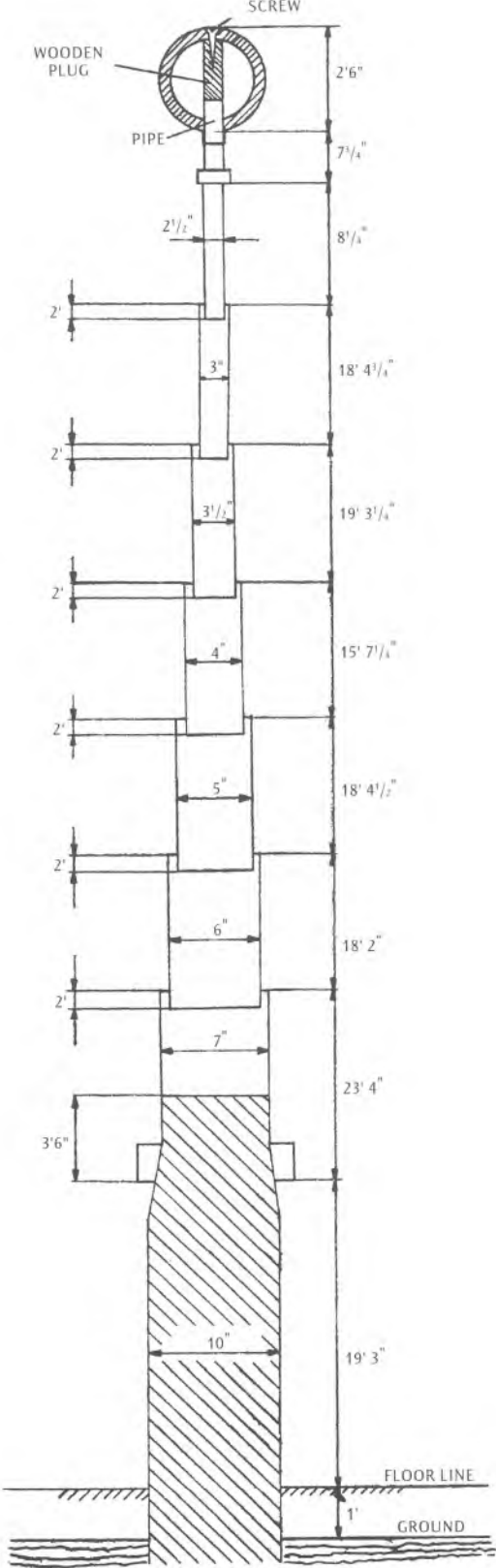
For approximate value of the surface of one loop we have then 5=1000 cm. sq. There should go on this length 689 turns and this would make

$$L = \frac{4\pi}{l} N^2 S = 24,490,000 \text{ cm. approx.}$$

or L=0.02449 henry.

For the purposes contemplated this coil will be well adapted as the self-induction is large and owing to small diameter of the core and great thickness of insulation the capacity should be comparatively small. With this coil balls of 18" and 30" diam, are to be used:

Exact diam. of core should be 14.0485"=35.6825 cm. for 5=1000 cm. sq.



Colorado Springs

Oct. 19, 1899

Experimental coil before used in investigating propagation of waves through ground. This coil was rewound and presently following particulars are good

Outside diam. of core = $10 \frac{3}{8}'' = 10.375'' = 26.3525$ cm. Turns 550, № 18 B. & S. 14" wax covered, thickness of one insul $\frac{14''}{1000}$, length of core $l = 40 \frac{7}{8}'' = 40.875'' = 103.8225$ cm.

We may neglect insulation as the core is not perfectly round and any irregularity diminishes the area and we get a larger value as a rule. Now, from above data, surface of one loop $S = \frac{\pi}{4} d^2 = 0.7854 \times 26.3525^2 = 545.241$ cm. sq. This gives

$$L = \frac{4\pi}{l} N^2 S = \frac{12.5664 \times 302,500 \times 545.42}{103.8225} = 19,970,000 \text{ cm, approx. or } 0.01997 \text{ H}$$

This coil is now to be also used in investigations of the variation of capacity with variation of height. With ball of 18" diam., the capacity of the ball assuming to be: $[18'' = 18 \times 2.54 = 45.72 \text{ cm}] - C = 22.86$ cm, the period of the system, neglecting for the present the distributed capacity of the coil, would be approximately:

$$T = \frac{2\pi}{10^3} \sqrt{0.01997 \times \frac{22.86}{9 \times 10^5}} = \frac{0.447345}{10^5}$$

or $n = 223,540$ per sec. approx.

In a test resonance was obtained with 42 bottles on each side of the break, that is 21 bottles total or 0.0229 mfd capacity in the primary, which consisted of 6 turns of heavily covered wire № 10.

As it was inconvenient to measure the primary, L_p was estimated to have a self-induction of:

$$\left[\frac{0.447345}{10^5} = \frac{2\pi}{10^3} \sqrt{0.0223 L_p} \right], L_p = 22,435 \text{ cm.}$$

This is a convenient and good method but the period must be exactly ascertained. The distributed capacity can never be neglected.

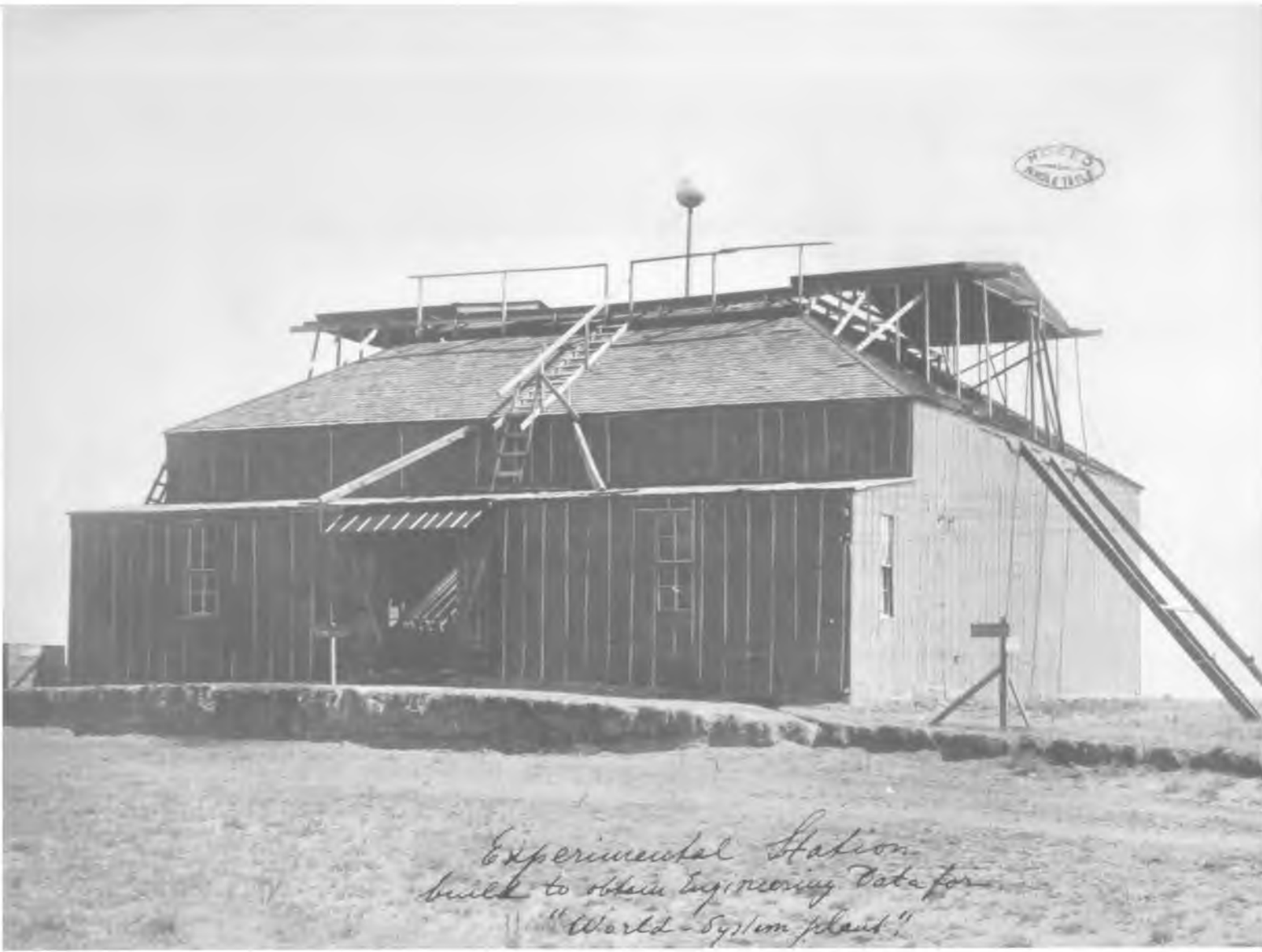
Colorado Springs

Oct. 20, 1899

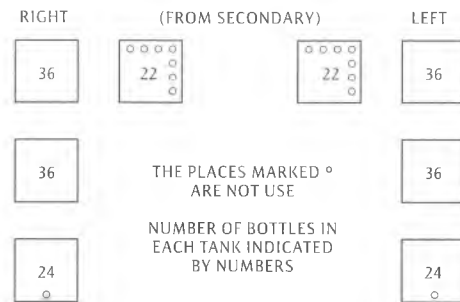
To ascertain the effect of internal capacity of the coil of 404 turns repeatedly referred to, which was used in the experiments on influence of elevation upon capacity of a conductor, the coil was tuned alone with only a short length of wire attached to it. Resonance with primary was obtained with 118 bottles on each side, one primary turn. For future reference the tanks as used are indicated in diagram.

The total capacity in primary was 118 therefore $\frac{118}{2} = 59$ bottles. Since one tank, that is 36 bottles, equals 0.03816 mfd the capacity was $\frac{59}{36} \times 0.03816 = 0.06254$ mfd.

Now the self-induction in the primary was: primary one turn + connections = $56,400 + 6600 = 63,000$ and with allowance for one half turn of self-induction coil, we may say approx. $\frac{64}{10^6}$ henry.



Experimental
Laboratory, Colorado
Springs in early phase
of development



The period was

$$T_p = \frac{2\pi}{10^3} \sqrt{\frac{64}{10^6} \times 0.06254} = \frac{8 \times 2\pi}{10^6} \sqrt{0.06254} = \frac{4\pi}{10^6} = \frac{12.5664}{10^6}$$

and from this $n=79,600$ per second. The secondary was vibrating in synchronism hence, $T_s = T_p = \frac{2\pi}{10^3} \sqrt{0.04 \times C}$, where C denotes capacity which could be associated with the coil, if it had no capacity of its own, and this capacity together with the self-induction of the coil of 0.04 H as before found would give the period $T_s = \frac{4\pi}{10^6} = \frac{2\pi}{10^3} \sqrt{0.04C}$. From this follows

$$C = \frac{1}{10^4} \text{ mfd. or } \frac{9 \times 10^5}{10^4} = 90 \text{ cm.}$$

This is the value experimentally found and more to be relied upon than that derived in other ways. Taking this value and adding to the coil a sphere of radius 38.1 cm the total capacity of the system would be $90+38.1 = 128.1$ cm and now we should find the period of the system to be

$$T'_s = \frac{2\pi}{10^3} \sqrt{0.04 \times \frac{128.1}{9 \times 10^5}} = \frac{4\pi}{3 \times 10^6} \sqrt{12.81} = \frac{4\pi}{3 \times 10^6} \times 3.58 = \frac{14.9958}{10^6}$$

or $\frac{15}{10^6}$ approx. = T'_s or $n = 66,666$ per sec.

We can now find the capacity in primary required for resonance with secondary. The primary period will be $T'_p = \frac{2\pi}{10^3} \sqrt{\frac{64}{10^6} C_p}$, where C_p is the capacity required in primary. Now we have then

$$T'_p = T'_s = \frac{2\pi}{10^3} \sqrt{\frac{64}{10^6} C_p} = \frac{4\pi}{3 \times 10^6} \times 3.58 \text{ (from above) and}$$

$$\sqrt{\frac{64}{10^6} C_p} = \frac{2 \times 3.58}{3 \times 10^3} \text{ or } \sqrt{C_p} = \frac{3.58}{12} \text{ or } C_p = \left(\frac{3.58}{12}\right)^2 = 0.096 \text{ mfd.}$$

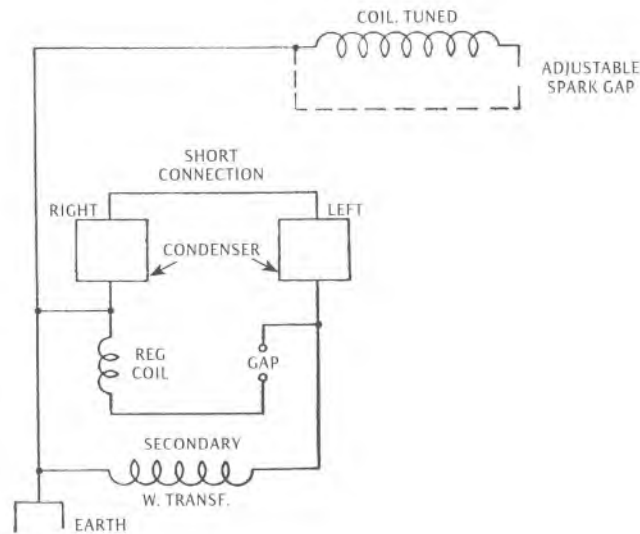
Since one bottle approximates $\frac{0.03816}{36}$ mfd we would want 0,096: $\frac{0.03816}{36} = 90.6$ bottles total

or, on each side of the break $2 \times 90.6 = 181.2$ bottles. This would suppose that the ball could have a capacity of 38.1 cm but this is physically impossible since it would have to be removed from all objects. In reality its capacity will be always much greater and the system will vibrate much slower as a rule. In fact, the test showed that resonance was attained with the ball 10–18 feet from the ground with all bottles in and in addition $5 \frac{1}{2}$ turns in the self-induction box. The tuning was naturally not sharp as the capacity was large and the maximum appeared to be with the ball 10–18 feet from the ground. To get sharper tuning a smaller ball of 18" diameter was used and now resonance was obtained with the ball 10 feet from the ground and all bottles in and no self-induction in the regulating coil.

Colorado Springs

Oct. 21, 1899

To ascertain the value of connections in terms of turns of the regulating coil and for other purposes the coil before described, 404 turns with rubber wire attached, was tuned for three different values of the regulating turns. The method was one frequently used in New York and is illustrated in the plan shown. One end of the coil was connected to that end of condensers, or respectively to that end or terminal of transformer which was grounded and the rise of potential of free terminal of tuned coil was observed by an adjustable spark gap. In this manner very close adjustments are easy. The resonating condition indicated by the longest sparks in the adjustable gap was secured with the following three values:



Capacity in the primary in
bottles on each side

Turns in
regulating coil

total		
8 tanks less 2 bottles=	286=	0.15157
7 less 2 "	=250=	0.13249
6 less 2 "	=214=	0.11341

16,5

18= L_1

21= L_2

The tuning was not quite as sharp in the first case,

but it was very sharp in the last two experiments. Taking these and calling x the self-induction of the connections we would have in the case corresponding to L_1 of the regulating coil $T = \frac{2\pi}{10^3} \sqrt{0.13249(L_1 + x)}$ and in the case corresponding to L_2 of the

self-induction coil

$$T = \frac{2\pi}{10^3} \sqrt{0.11341(L_2 + x)}.$$

From this $0.13249(L_1 + x) = 0.11341(L_2 + x)$ and

$$x = \frac{0.11341L_2 - 0.13249L_1}{0.01908}.$$

Now L_1 and L_2 should be exactly measured; resonance method will probably suit the purpose best. This is to be more rigorously carried out.

In the experiments before described, for the purpose of ascertaining the influence of elevation on the capacity of a sphere, the latter was connected to the coil of 404 turns by means of a wire No 10

heavily covered with rubber ($\frac{3}{8}$ " wall). Evidently this wire affected the period of the system and to ascertain to what extent, the wire was placed in the same position as when used in the experiments with the ball at its lowest position – 20.66 feet from the ground. The sphere was omitted but the streamers on the end were prevented by sealing the end with wax, covering with tape and sticking the end of the wire into a glass bottle with very heavy walls. Resonance was attained with $(6 \times 36) - 2$ bottles on each side and 21 turns in the self-induction regulating coil. This was 214 bottles on each side or 107 total. In making the test the primary turn of the oscillator, usually connecting the two coatings of the condensers on the bottom, was left off and the coatings joined by a short wire. The total self-induction in the primary circuit was therefore the 21 turns of the regulating coil plus the connections, or from previous figures $100,800 + 6600 = 107,400$ cm. Now in the test of Oct. 9, with the ball connected to the cable, resonance was obtained with 4.66 tanks on each side or $4.66 \times 36 = 168$ bottles approx. The total self-induction was 21.5 turns of regulating coil + 1 turn primary + connections = $103,200 + 56,400 + 6600 = 166,200$ cm, both values from calculated data. Had the self-induction been the same we would have had instead of 168 bottles $\frac{166,200}{107,400} = 260$ bottles. Thus with the sphere the capacity in the vibrating secondary system was increased by the ratio $\frac{260}{214}$ or $\frac{130}{107}$.

The period of the primary circuit in the first case can now be ascertained. The capacity was 107 bottles = $\frac{107}{36} \times 0.03816 = 0.11342$ mfd. The self-induction as before stated 107,400 cm. or 0.0001074H. The period therefore was $\frac{2\pi}{1000} \sqrt{0.0001074 \times 0.11342}$. Now the secondary vibrated with the rubber wire attached, the same period which was $\frac{2\pi}{1000} \sqrt{0.04 \times C}$, designating by C the ideal capacity associated with the self-induction of the coil. These two were equal and we have $C = \frac{0.0001074 \times 0.11342}{0.04}$ mfd, or

$$\frac{10.74 \times 0.11342 \times 9}{0.04} = 30.45 \times 9 = 274 \text{ cm.}$$

This was the capacity with the cable comprised. But before we have found the capacity of the coil alone, with no wire attached, 90 cm or nearly so. The addition of the rubber cable made therefore a considerable difference. It would not have been so high had the streamers been entirely prevented but despite the wax and glass bottle there was a leak which had the same effect as if the capacity had been increased. Since by adding the ball the capacity was increased by the ratio $\frac{216}{214}$ we have – calling now c the capacity of the sphere at the initial elevation of 20.66 feet – $\frac{260}{214} = \frac{274 + c}{274}$ and from this

$$c = \frac{274 \times 46}{214} = 58.88 \text{ cm.}$$

This then would be, according to this estimate, the actual value of the capacity of the sphere at that elevation.

Colorado Springs

Oct. 22, 1899

One of the upper terminals of the condenser (+) usually connected to the ground was joined to the lower end of the coil of 689 turns, the upper end remaining free. The ground was in this case omitted for the purpose of securing a higher initial excitation. The maximum rise was ascertained by an adjustable spark gap as shown. The results of the tests are given in the table below:

Capacity in primary circuit expressed by the number of bottles used	Self-induct, of primary or exciting circuit Turns in regul. coil+connections	Spark length on terminals of the coil	Observation relating to spark
$\frac{(8 \times 36) - 2}{2}$	1.125 + connections	4 $\frac{1}{8}$ inch	The spark was continually increasing and the excitation was reduced as the capacity was getting smaller
$\frac{(7 \times 36) - 2}{2}$	2.375 + connections	4 $\frac{3}{4}$ inch	
$\frac{(6 \times 36) - 2}{2}$	3.625 + connections	5 $\frac{5}{8}$ inch	
$\frac{(5 \times 36) - 2}{2}$	4.75 + connections	5 $\frac{3}{4}$ inch	
$\frac{(4 \times 36) - 2}{2}$	6.25 + connections	5 $\frac{7}{8}$ inch	reduced
$\frac{(3 \times 36) - 2}{2}$	8.25 + connections	6 $\frac{1}{4}$ inch	still more
$\frac{(2 \times 36) - 2}{2}$	11.625 + connections	7 inch	still more
$\frac{(1 \times 36) - 2}{2}$	22 + connections	9 inch	still more
appr. $\frac{31}{2}$	24 + connections	about same	

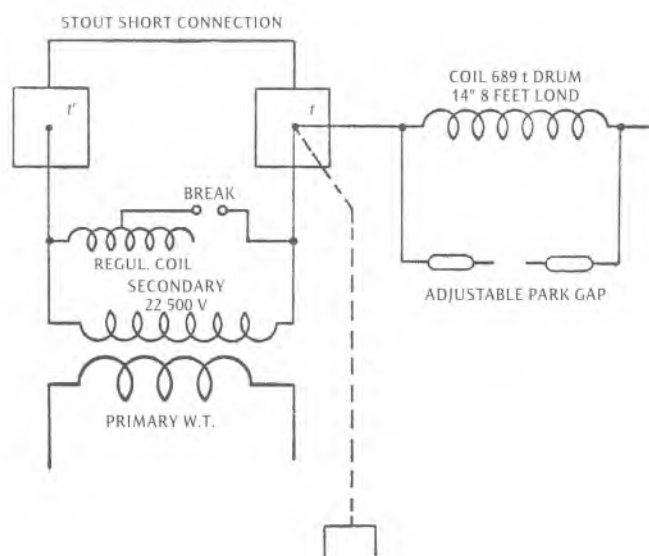
The spark was getting longer because the efficiency of the exciting circuit was increased, as the inductance of this circuit was increased and capacity diminished. There were smaller frictional losses and after each break the system vibrated longer and excited the coil better.

The short stout wire was now substituted by each of the two primary turns separately and joined in multiple with the results indicated below:

$\frac{32}{2}$	13 $\frac{1}{4}$ turns+1 primary+connections	The primary used was the upper one
$\frac{32}{2}$	14 turns+1 primary+connections	The primary used was the lower one
$\frac{32}{2}$	14 $\frac{1}{2}$ turns+1 primary+connections	The tuning was very sharp in the first two cases, not quite so in the last instance.

In order to get useful data as to the self-induction of the connections and also of the various turns of the regulating coil which were most frequently used in the experiments, tests were made as follows. A coil still to be described, built for a special purpose, was used (689 turns, drum 14" diam., 8 feet long) and was excited from one terminal of the condensers, as indicated in the sketch below. The coil

had a definite period which was ascertained with all condensers in and the least possible self-induction; the condensers were taken out and more turns of the self-induction coil inserted until resonance was again attained. Since the period was in all instances the same the self-inductance of the circuit was thus varied inversely as the capacity. When all self-inductance or nearly so was taken out and only the connections remained by a simple ratio between the known capacities and a known inductance, the inductance of the connections was given, or else this quantity was ascertained from the known period which was maintained throughout the experiments (that of the coil before referred to). The lower ends of the condensers, usually joined by the primary, were connected by a short stout conductor of inappreciable resistance and inductance.



The method used in the experiments recorded today for determining experimentally the inductance of the connections is very convenient and secures good results. The coil used in the experiments was one of very high self-induction to make the tuning very sharp and it was wound on a drum of relatively small diameter to reduce internal distributed capacity. This likewise improves the sharpness of the adjustment. It was easy to detect variations of one sixteenth of one turn of the regulating primary coil. From the preceding data, calling l the inductance of one turn and l_1 that of 22 turns, and C the capacity in the primary when 1.125 turns were used and C_1 that when 22 turns were employed, we have, since the period was the same:

$$(l \times 1.125 + \text{connections}) C = (l_1 + \text{connections}) C_1$$

Now it is not necessary to determine C and C_1 since only the ratio is needed and we may simply take the number of bottles in each case. This gives:

$$(l \times 1.125 + \text{conn.}) \times 143 = (l_1 + \text{conn.}) \times 17.$$

Now in a previous instance l and l_1 were approximately: $l = 4800$ cm, $l_1 = 105,000$ cm. Substituting these values we have:

$$(5400 + \text{conn.}) \times 143 = 17 \times (105,000 + \text{conn.})$$

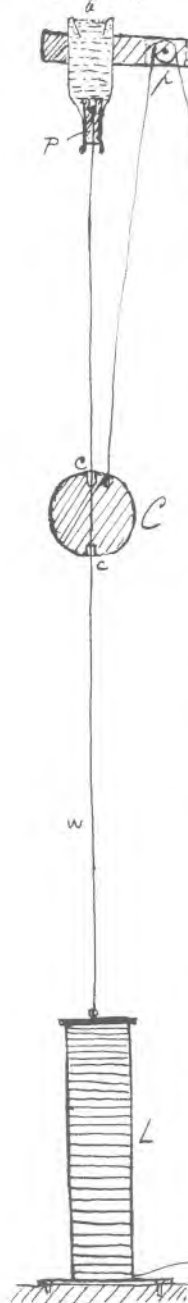
$$\text{and connect.} = \frac{(17 \times 1050 - 143 \times 54) \times 100}{126}.$$

From this the inductance of the connections would be ≈ 8040 cm, or 8000 cm. approx. It would be desirable, however, to eliminate the turns of the coil and so estimate the inductance of the connections directly.

Colorado Springs Oct. 29. 1899.



The whole arrangement is illustrated in sketch below in which B is the bottle with wooden plug P supported on beam B also carrying pulley p over which passes the cord for pulling up the



object which in this case is shown as a sphere C. The spheres are made of wood and hollow and covered very smoothly with Linford and any points of the foil were pressed in so as to be below the surface of the sphere. This is a necessary precaution to avoid possible losses of streamers when the sphere is charged to a high potential. It is desirable to work with strong effects as the greater these are the better the vibration can be determined but it is necessary to carefully avoid losses and errors owing to the formation of streamers. There have been the effect of increasing the apparent capacity so much so that a thin wire may often produce results comparable to those obtained with large capacitors. The streamers of course cause frictional loss and thereby diminish the economy of the system and impair the quality of the results. They also cause a loss of pressure just as leaks in air or water pipes. The bell to be tested or any other object was provided with two metallic bushings or contacts C.C. consisting of small split brass tubes which were in good connection with the conducting surface and also secured contact with wire W which at the same time serves to guide the bell in its

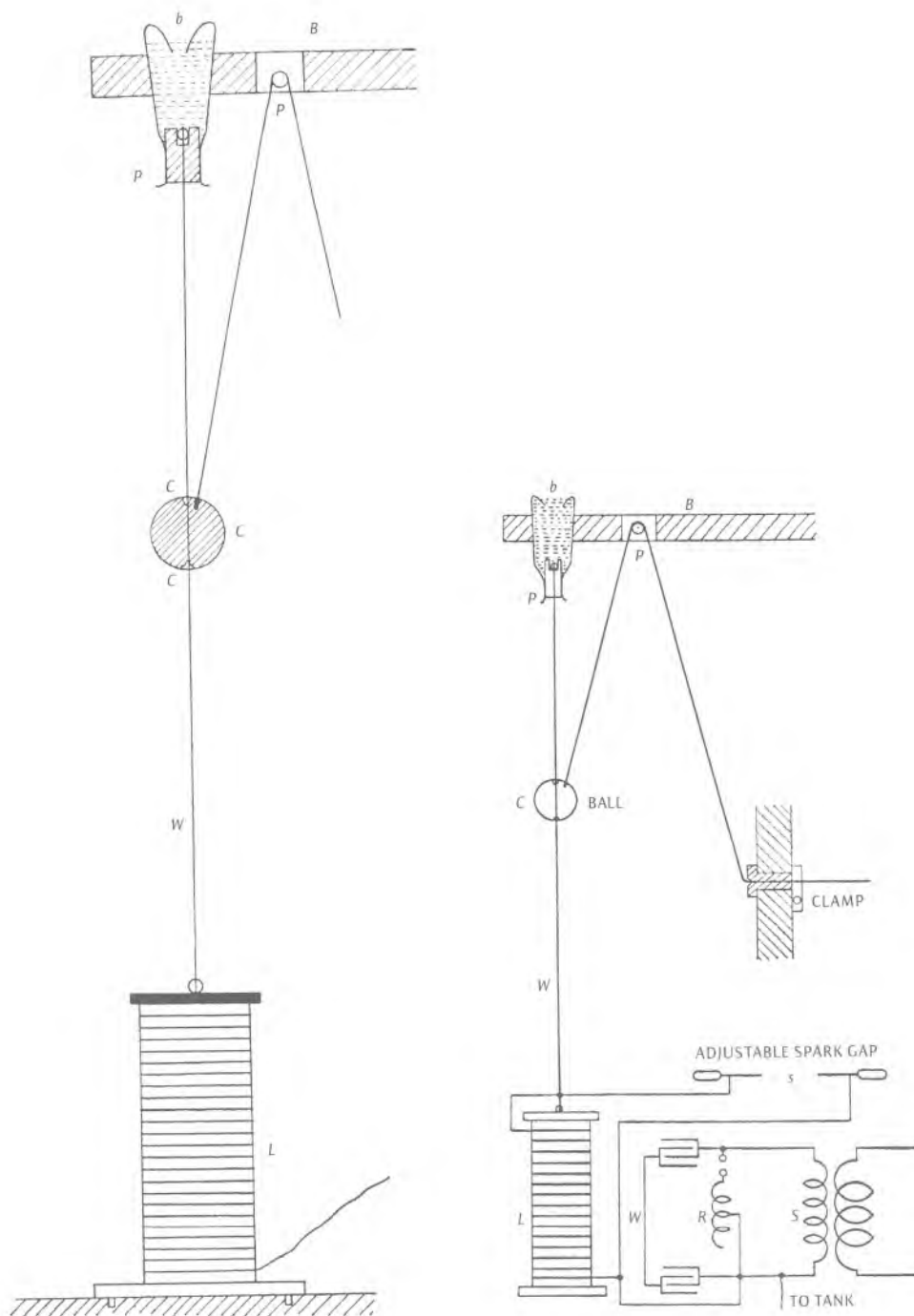
Oct. 23, 1899

Experiments to further ascertain the influence of elevation upon capacity

The coil referred to on a previous occasion was finished with exactly 689 turns on a drum of eight feet in length and 14" diam. The wire used was cord № 20 as before stated so that the approximate estimate of self-induction and other particulars holds good. The coil was set up upright outside of the building at some distance to reduce any errors due to the influence of the woodwork. From the building extended a structure of dry pine to a height of about sixty feet from the ground. This framework supported, on a projecting crossbeam, a pulley (wood) with cord for pulling up a ball or other object to any desired height within the limits permitted and this beam also carried on its extreme end and close to the pulley a strong glass bottle within which was fastened a bare wire № 10, which extended vertically downward to the top of the coil. The bottle was an ordinary Champagne bottle, from which the wine had been poured out! and the bottom broken in. It was forced neck downward into a hole bored into the beam and fastened besides with a cord. A tapering plug of hard wood was wedged into the neck and into this plug was fastened the wire. The bottle was finally filled with melted wax.

The whole arrangement is illustrated in the sketch shown in which *b* is the bottle with wooden plug *P* supported on beam *B* also carrying pulley *p*, over which passes the cord for pulling up the object, which in this case is shown as the sphere *C*. The spheres used were of wood and hollow and covered very smoothly with tin foil and any points of the foil were *pressed in* so as to be *below* the surface of the sphere. This is a necessary precaution to avoid possible losses by streamers when the sphere is charged to a high potential. It is desirable to work with strong effects as the greater these are the better the vibration can be determined, but it is necessary to carefully avoid losses and errors owing to the formation of streamers. These have the effect of increasing the apparent capacity so much that a thin wire may often produce results comparable to those obtained with large capacities. The streamers, of course, cause frictional loss and thereby diminish the economy of the system and impair the quality of the results. They also cause a loss of pressure just as leaks in air on water pipes. The ball to be tested or any other object was provided with two metallic bushings, on contacts *c c*, consisting of small split brass tubings which were in good connection with the conducting surface and also insured contact with wire *w* which at the same time served to guide the ball in its up and down movement. To avoid losses the bushings did not project beyond the surface of the ball and for the same reason the cord was not fastened to a hook but a hole was drilled into the ball, the cord with a knot on the end was slipped in and a wooden plug driven into the hole, so that nothing was sticking out capable of giving off streamers or causing leaks into the air. In the first series of experiments a ball of 18" diameter was used. The ball was not perfectly round but the error due to a slight irregularity of shape was very small. The plan of connections is shown in the sketch in which the same letters are used to designate the same parts of apparatus as before. The excitation of the coil was effected by connecting the lower end to one of the terminals of the condenser – the one which was connected to that end of the secondary of the 60,000 volt transformer which was in connection with the tank. The tank, as described on a previous occasion, was usually connected to the ground but in these first experiments the ground connection was omitted to secure stronger excitation. From the terminals of the coil two thin and heavily insulated wires were led to an adjustable spark gap *s* which was manipulated until the maximum rise of potential on the coil was ascertained. The two sets of condensers were joined by a stout short wire *W* of inappreciable self-induction and resistance and the inductance of the exciting circuit was varied by inserting more or fewer of the turns of the regulating coil *R* into the circuit through which the condensers were periodically discharged. The wires leading from the coil to the adjustable spark gap *s* were, as before remarked, very thin, as short as it was practicable to make them and heavily insulated. By observing these precautions the error due to the capacity of these wires themselves was reduced to a minimum, also the loss owing to a possible formation of streamers. To reduce the capacity the wires were led far

apart and then brought in line to the spark gap. The lower wire, which was connected to a point of comparatively low potential was of little consequence but on the top wire these precautions were imperative. The procedure was as follows: first the period of the coil L and capacity attached to the free terminal was ascertained by varying the capacity or self-induction, or both, of the primary or exciting circuit until resonance was reached which was evident from the maximum rise of potential. When the period had thus been determined with the capacity, say a sphere, in one position, the position of the body of capacity was varied by shifting it to another place along the wire w and the adjustment of the



primary circuit was again effected until resonance was reached, generally by simply varying the length of wire of the regulating coil included in the primary circuit. Now as the self-induction of the coil *L* remained the same through all experiments, the apparent capacity could be easily determined from the self-induction and the known period of the primary or exciting circuit. By keeping the capacity in the primary circuit the same or, eventually, the self-induction, the procedure was simplified and the capacity in the system including coil *L* was then at once given by a simple ratio, as in some cases previously described. It was preferable to vary the self-induction as the change of this element could be effected continuously and not step by step, as was the case with the capacity.

The apparatus being arranged as stated, the lowest position of the ball of 18" diam., which was first used, was 9' 5" from center of ball to ground and the highest 58' 9".

To ascertain the period of the system *L* the vertical wire was first disconnected and only the spark wires left on, then the vertical wire was connected and the period again determined by adjusting the primary circuit, then the ball was placed in its lowest position and finally readings were taken with the ball at various heights up to the maximum elevation. The results condensed were as follows:

Coil *L* alone only with spark wires, no vertical wire:

Capacity total in primary circuit	Total primary self-induction turns of regulating coil-f conn.	Height of ball from center to ground	Analyzing spark at s
$\frac{142}{2} = 71$ bottles	9 $\frac{7}{8}$ turns+connections	<i>no ball, no wire</i>	3 $\frac{3}{4}$ "

Coil with vertical wire and spark wires:

$\frac{142}{2} = 71$ bottles	18 $\frac{3}{8}$ turns+connect	<i>no ball</i>	3 $\frac{1}{4}$ "
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Coil with *ball, vertical wire* and spark wires:

$\frac{142}{2} = 71$ bottles	19 $\frac{1}{2}$ turns+conn.	9 feet 5"	4"
$\frac{142}{2} = 71$ bottles	20 $\frac{3}{8}$ turns+conn.	33 feet 9"	4 $\frac{3}{8}$ "
$\frac{142}{2} = 71$ bottles	21 $\frac{1}{4}$ turns+conn	58 feet 9"	4 $\frac{1}{8}$ "

Owing to the construction of the coil *L* which, as before stated, aimed at sharp tuning it was easy to detect a variation of $\frac{1}{16}$ of *one turn* of the regulating primary coil *R*.

It was desirable to take some readings with all the bottles in and the results were nearly the same and could still be read off with fair exactness, although the variation on the regulating coil *R* was reduced to one half, the capacity in the primary being just double that used in the experiments the results of which were just given.



Conical secondary
high frequency
transformer and "extra
coil" in action

The readings with all the condensers were as follows:

Capacity in primary total	Total self-induction in primary turns of reg. coil+connections	Height of ball from center to ground	Spark on terminals of L
286 bottles	10 $\frac{1}{8}$ + conn.	9' 5"	4 $\frac{1}{4}$ "
	10 $\frac{9}{16}$ + conn.	33' 9"	4 $\frac{1}{2}$ "
	11 + conn.	58' 9"	4 $\frac{3}{4}$ "

Note to above experiments:

The vibration of the coil L with vertical wire and spark wires was found to be in resonance with the primary in another series of observations with

142 bottles 18 $\frac{3}{4}$ turns+connections

whereas before it was found to be so with 18 $\frac{3}{8}$ turns. When the different value 18 $\frac{3}{4}$ turns was observed the *wind was blowing hard* and it would seem as if this would have had the effect of increasing the apparent capacity of the aerial vertical conductor. This is to be followed up.

The experiments seemed to demonstrate clearly that the augmentation of the capacity as the ball was elevated was in a simple proportion to the height, for at the middle position the value found was very nearly the arithmetic mean of the values in the extreme positions.

Colorado Springs

Oct. 24, 1899

Tests continued on the effect of elevation upon the capacity of a body connected to earth.

The same coil was used as in the tests just before recorded, but the ball of 18" diam. was substituted for by one of 30" diam.

These readings were in all probability closer as an improvement in the procedure was made.

The results were as follows:

First set of readings.

Capacity in primary circuit Bottles total mfd.	Self-inductance of primary: Turns of reg. coil+ connections	Height of ball above ground from center	Analyzing spark on terminals of excited coil
$\frac{(8 \times 36) - 2}{2} = 143 = 0.1287$	10 $\frac{3}{8}$ +connections	9' 11"	4 $\frac{1}{2}$ "
$\frac{(8 \times 36) - 2}{2} = 143 = 0.1287$	10 $\frac{3}{4}$ +connections	34' 3"	4 $\frac{3}{4}$ "
$\frac{(8 \times 36) - 2}{2} = 143 = 0.1287$	11 $\frac{1}{8}$ +connections	58' 6"	5 $\frac{1}{8}$ "

Second set of readings. Capacity reduced in primary to get greater variation on regul. coil.

$\frac{(4 \times 36) - 2}{2} = 71 = 0.0639$	19 $\frac{3}{4}$ +connections	9' 11"	4 $\frac{3}{8}$ "
$\frac{(4 \times 36) - 2}{2} = 71 = 0.0639$	20 $\frac{3}{8}$ +connections	34' 3"	5 $\frac{1}{4}$ "
$\frac{(4 \times 36) - 2}{2} = 71 = 0.0639$	21+connections	58' 6"	5 $\frac{3}{8}$ "

Note: After these readings had been taken it was found that the ball sliding on the vertical wire did not make a good contact. This might have modified the results slightly.

Colorado Springs

Oct. 25, 1899

Experiments on influence of elevation upon capacity of conductor connected to earth continued:

This time simply a wire № 10 extending vertically in the continuation of the axis of the coil was used. The coil was the same as before, 689 turns № 20 cord on drum of 14" diameter. 36 feet of wire were first taken and after each reading 3 feet were cut off. Each time resonance with the primary was attained and the constants of the primary circuit noted, this giving the necessary data for the determination of the capacity of the vertical wire. The results are indicated below:

Capacity in the primary circuit total Bottles	mfd.	Self-inductance of primary Turns of reg. coil+connect.	Length of vertical wire in feet	Analyzing spark on terminals of excited coil
$\frac{(4 \times 36) - 2}{2} = 71$	0.0639	17+connect.	36	$\frac{1}{8}$ "
$\frac{(4 \times 36) - 2}{2} = 71$	0.0639	16 $\frac{3}{8}$ +connect.	33	$\frac{1}{8}$ "
$\frac{(4 \times 36) - 2}{2} = 71$	0.0639	15 $\frac{3}{4}$ +connect.	30	$\frac{1}{8}$ "
$\frac{(4 \times 36) - 2}{2} = 71$	0.0639	15 $\frac{1}{4}$ +connect.	27	$\frac{1}{16}$ "
$\frac{(4 \times 36) - 2}{2} = 71$	0.0639	14 $\frac{3}{4}$ +connect.	24	$\frac{1}{16}$ "
$\frac{(4 \times 36) - 2}{2} = 71$	0.0639	14 $\frac{1}{4}$ +connect.	21	$\frac{1}{16}$ "
$\frac{(4 \times 36) - 2}{2} = 71$	0.0639	13 $\frac{3}{4}$ +connect.	18	$\frac{1}{16}$ "

$\frac{(4 \times 36) - 2}{2} = 71$	0.0639	13 ¼+connect.	15	1/16"
$\frac{(4 \times 36) - 2}{2} = 71$	0.0639	12 ¾+connect.	12	13/16"
$\frac{(4 \times 36) - 2}{2} = 71$	0.0639	12 ¼+connect.	9	9/16"

These readings are approximate.

Colorado Springs

Oct. 26, 1899

Measurement of inductance of 689 turn coil used in investigations on influence of elevation upon the capacity of a conductor.

Readings were as follows:

Volts av.	Current	ω	Res.
118	3.315	880	28.304

$$\frac{E}{I} = \frac{118}{3.315} = 35.6 \left(\frac{E}{I} \right)^2 = 1267.36$$

$$\frac{R^2 = 800.89}{\left(\frac{E}{I} \right)^2} - R^2 = 446.47 \text{ Large dynamometer close}$$

$$\omega^2 = 774,400$$

$$L = \frac{\left(\frac{E}{I} \right)^2 - R^2}{\omega^2} = 0.00057654 \text{ From this } L = 0.024 \text{ henry}$$

or=24,000,000 cm.

This is a value slightly smaller than that calculated before. Readings were also taken with small dynamometer. This slightly damaged. The readings are to be revised upon restandardizing.

Volts av.	Current av.	ω
69.25	2.045	880

$$\frac{E}{I} = 33.863 \left(\frac{E}{I} \right)^2 = 1146.7 \left(\frac{E}{I} \right)^2 - R^2 = 345.81$$

$$R^2 = 800.89$$

$$\omega^2 = 774,400$$

$$L = \frac{\left(\frac{E}{I} \right)^2 - R^2}{\omega^2} = 0.0004466 \text{ From this } L = 0.0211 \text{ henry}$$

or 21,100,000 cm.

Note: This value is decidedly too low owing to dynamometer indicating too large a current. Possibly during the test ω had changed.

Colorado Springs

Oct. 27, 1899

Test of condensers some of which were recently refilled. The corrections for capacity to be applied to the work of about two weeks ago.

Readings with 7 cells battery showed for *one half*

Microfarad Standard

Defl. 101 }
101 } average 101°
101 }

For set of condensers all in multiple on left side from door

51 }
51 } average 51°
51 }

For set of condensers all in multiple on right side from door

53 }
53 } average 53°
53 }

For all condensers in multiple

104 }
104 } average 104°
104 }

The difference between the two sets is probably due to different heights of solution in the tanks or bottles. In these measurements there were two bottles less on each side in the central tanks.

Taking the above data, the total number of bottles when all were in quantity was $(16 \times 36) - 4 = 576 - 4 = 572$ bottles.

The capacity was $\frac{104}{100} \times 0.5 = 0.515$ mfd approx. This would give

For one bottle an average:	0.0009 mfd or	810 cm	These are frequently needed
For two bottle an average:	0.0018 "	1620 "	
For three bottle an average:	0.0027 "	2430 "	
For 12 bottle an average:	0.0108 "	9720 "	
For 36 bottles or one tank	0.0324 "	29,160 "	
For 18 bottles or one tank	0.0162 "	14,580 "	

Note: Small mica condensers with fibre covers made for resonating circuits have a little less than $\frac{1}{20}$ mfd each; two were measured.

Oct. 28, 1899

Referring to the preceding results the period of the excited system without the vertical wire was as follows:

$$\left. \begin{array}{l} \text{Capacity in primary 71 bottles}=0.0639 \text{ mfd.} \\ \text{Self-induction of primary connections plus } 9\frac{3}{8} \text{ first} \\ \text{turns of the regulating coil measured: 32,700 cm.} \end{array} \right\} T_1 = \frac{2\pi}{10^3} \sqrt{0.0639 \times \frac{32,700}{10^9}}$$

With the vertical wire the period corresponding to that of the excited system was T_2 , which estimated is:

$$\left. \begin{array}{l} \text{Capacity in primary as before 0.0639 mfd.} \\ \text{Self-ind. in primary conn.} + 18\frac{3}{8} \text{ turns measured:} \\ \text{65,000 cm.} \end{array} \right\} T_2 = \frac{2\pi}{10^3} \sqrt{0.0639 \times \frac{65,000}{10^9}}$$

Now calling C the capacity of the excited system with only the spark wires, L the self-induction of the excited coil, before found to be $L=0.024$ H, we have for the period of the excited system:

$$T_{s1} = \frac{2\pi}{10^3} \sqrt{0.024 \times C}, C \text{ being in mfd. Now } T_{s1} = T_1 \text{ or}$$

$$0.024 \times C = 0.0639 \times \frac{327}{10^7} \text{ and } C = \frac{327 \times 0.0639}{10^7 \times 0.024} \text{ mfd or}$$

$$C = \frac{9 \times 10^5 \times 327 \times 0.0639}{10^7 \times 0.024} = \frac{0.5771 \times 327}{2.4} \text{ cm} = 78.36 \text{ cm} = C$$

Calling presently C_1 the capacity of the excited system when the vertical wire was attached, we have by similar reasoning from

$$T_{s2} = \frac{2\pi}{10^3} \sqrt{0.024 \times C_1} = T_2 = \frac{2\pi}{10^3} \sqrt{0.0639 \times \frac{65,000}{10^9}}$$

$$C_1 = \frac{65}{10^6} \times \frac{0.0639}{0.024} \text{ mfd, or } C_1 = \frac{9 \times 10^5 \times 65}{10^6} \times \frac{0.0639}{0.024} \text{ cm} = 155.76 \text{ cm.}$$

The capacity of the wire alone would from these results be

$$C_1 - C = 155.76 - 78.36 = 77.40 \text{ cm.}$$

Calculated approximately we have the following data for the wire: diam. of wire N° 10=0.2588 cm., $r=0.1294$ cm.

$$l=50 \text{ feet approx.} = 50 \times 12 \times 2.54 = 1524 \text{ cm.}$$

$$\text{From this: } \frac{l}{r} = 11,777.4 \text{ and capacity of wire } \frac{l}{2 \log_e \frac{l}{r}} = \frac{1524}{18.7} = 81.5 \text{ cm}$$

The calculated value is a little larger but not much, well within the errors of the adjustment and

determination of the quantities by experiment.

Continuing we see that when the ball was at its lowest position the period of the primary was as follows:

Capacity in primary as before 0.0639
Inductance: connections+19 ½ turns
measured 68,300 cm or $\frac{683}{10^7}$ H.

$$\left. \begin{array}{l} \text{Capacity in primary as before 0.0639} \\ \text{Inductance: connections+19 ½ turns} \\ \text{measured 68,300 cm or } \frac{683}{10^7} \text{ H.} \end{array} \right\} T_{pl} = \frac{2\pi}{10^3} \sqrt{0.0639 \times \frac{683}{10^7}}$$

Similarly, when the ball was at its highest position, we have:

Capacity in primary circuit as before 0.0639
Inductance: connections+21 ¼ turns which,
measured, were found: 76,100 cm, or $\frac{761}{10^7}$ H

$$\left. \begin{array}{l} \text{Capacity in primary circuit as before 0.0639} \\ \text{Inductance: connections+21 ¼ turns which,} \\ \text{measured, were found: 76,100 cm, or } \frac{761}{10^7} \text{ H} \end{array} \right\} T_{ph} = \frac{2\pi}{10^3} \sqrt{0.0639 \times \frac{761}{10^7}}$$

Now calling C' the total capacity of the excited system when the ball was lowest, we have the period of the excited system:

$$T_{sl} = \frac{2\pi}{10^3} \sqrt{0.024 \times C'} = \frac{2\pi}{10^3} \sqrt{0.0639 \times \frac{683}{10^7}} \text{ from which } C' = \frac{0.0639 \times 683}{0.024 \times 10^7} \text{ mfd,}$$

$$\text{or } C' \text{ in cm} = \frac{9 \times 10^5 \times 0.0639 \times 683}{0.024 \times 10^7} = 163.66 \text{ cm} = C'.$$

The ball at the lowest position effectively contributed only

$$C' - C_1 = 163.66 - 155.76 = 7.90 \text{ cm}$$

but this low value was probably due to the fact that the vertical wire extended above.

Calculating similarly the value of C'' , that is the capacity of the excited system when the ball was highest:

$$T_{sh} = \frac{2\pi}{10^3} \sqrt{0.024 \times C''} \quad C'' = \frac{0.0639 \times 761}{10^7 \times 0.024} = \text{in cm.} = 182.36 \text{ cm.}$$

Now $C'' - C' = 182.36 - 163.66 = 18.70 \text{ cm}$ gives the actual value for the ball on top. This is an increase of nearly 137% for 49' 4" or about 2.76% per foot.

Colorado Springs

Oct. 29, 1899

Experiments with coil 689 turns on drum 14" diam. were again continued to further study the influence of elevation upon capacity.

The same arrangement was used which was described on a previous occasion with vertical wire and ball 30" diam. The excitation of the coil was effected by connecting it to one of the terminals of the condensers, that which was joined to the terminal of the Westinghouse Transformer which was in connection with the tank – but the connection of the latter to the ground was not made directly but through a spark gap 1/8" long.

The spark wires leading to the spark gap, serving to observe resonant rise, were № 26 gutta-percha coated and each about 25 feet long. It was really only the upper wire leading from the free terminal which was of importance to consider. The vibration of the coil was first ascertained, nothing except the spark wires being attached. Next a sphere of 30" diam., the tin foil of which was cut through with a sharp knife to prevent formation of eddy currents, was connected to the top of the coil and the vibration again determined. Then the vertical wire was put on and the sphere taken off. After determining the vibration with the vertical wire the sphere was slipped on the same and readings taken with the sphere at different heights. The results were as follows:

Coil with spark wires alone.

Capacity in primary Bottles total mfd	Self-inductance of primary Turns of reg. coil+conn.	Analyzing spark on terminals of excited coil
$\frac{(4 \times 36) - 2}{2} = 71 = 0.0639$	10 ½+conn.	3"

Coil with ball of 30" diam. and spark wires.

Capacity in primary circuit Bottles total mfd	Self-inductance of primary. Turns in reg. coil+connections	Analyzing spark on terminals of excited coil
$\frac{(4 \times 36) - 2}{2} = 71 = 0.0639$	13+conn.	3 ½"

Coil with vertical wire № 10, fifty feet and spark wires.

$\frac{(4 \times 36) - 2}{2} = 71 = 0.0639$	19 ¾+conn.	3 ⅞"
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Readings with ball of 30" diam., vertical wire and spark wires connected to coil.

Capacity in primary circuit Bottles total mfd	Self-inductance of primary. Turns in reg. coil+conn.	Height of ball from center to ground	Analyzing spark on terminals of excited coil
$\frac{(4 \times 36) - 2}{2} = 71 = 0.0639$	20 ¾+conn.	9' 11"	4 ⅜"
$\frac{(4 \times 36) - 2}{2} = 71 = 0.0639$	21 ⅜+conn.	32' 8"	4 ⅜"
$\frac{(4 \times 36) - 2}{2} = 71 = 0.0639$	22 +conn.	55' 7"	4 ⅜"

Readings continued with primary capacity modified.

$\frac{(8 \times 36) - 2}{2} = 143 = 0.1287$	11 ⅝+conn.	10' 3"	¼"
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$\frac{(8 \times 36) - 2}{2} = 143 = 0.1287$	12 $\frac{1}{4}$ +conn.	33' 3"	1"
$\frac{(8 \times 36) - 2}{2} = 143 = 0.1287$	12 $\frac{7}{8}$ +conn.	55' 9"	1 $\frac{1}{2}$ "

The capacity in primary was now still further reduced.

The readings were as follows:

Capacity in primary Bottles total mfd	Inductance in primary. Turns in reg. coil+ conn.	Height of ball above ground from center	Analyzing spark on terminals of excited coil
$\frac{(5 \times 36) - 2}{2} = 89 = 0.0809$	16 $\frac{1}{2}$ +conn.	10' 3"	4"
$\frac{(5 \times 36) - 2}{2} = 89 = 0.0809$	17 $\frac{3}{8}$ +conn.	33' 3"	4 $\frac{1}{4}$ "
$\frac{(5 \times 36) - 2}{2} = 89 = 0.0809$	18 $\frac{1}{4}$ +conn.	55' 9"	4 $\frac{3}{8}$ "

In these experiments the excitation of the coil was varied by adjusting the small spark gap separating one terminal of the Westinghouse transformer from the ground. The tuning was not very sharp as the ball was large and the magnifying factor of the coil rather small. Taking n approx. 60,000 we have $p=360,000$ approx., $R=28.3$, $L=0.024$ we have for $\frac{pL}{R}$ value $\frac{36 \times 10^4 \times 0.024}{28.3} = 300$ approx. Not so small after all.

It was desirable to take some readings with the self-induction in the primary remaining the same, the capacity only being varied.

Following results were obtained:

Primary capacity Bottles total mfd	Primary self-induction. Turns in reg. coil.+conn.	Height of ball from center to ground	Analyzing spark on terminals of excited coil
$\frac{133}{2} = 66.5 = 0.05985$	22+conn.	10' 3"	4 $\frac{3}{8}$ "
$\frac{137}{2} = 68.5 = 0.06165$	22+conn.	33' 3"	4 $\frac{3}{8}$ "
$\frac{142}{2} = 71 = 0.0639$	22+conn.	55' 9"	4 $\frac{3}{8}$ "

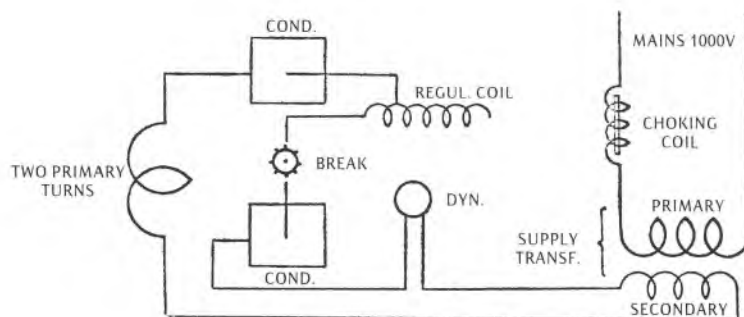
These data are to be worked out.

Oct. 30, 1899

Measurement of Inductances

The primary of the oscillator, regulating coil and connections to spark gaps and condensers as generally used were joined in series, the gaps and condensers being bridged by short pieces of wire No 2 of inappreciable resistance. The object was to determine again: the inductance of the primary turns of the oscillator, of the regulating coil for the various turns as employed and also of the connections. The two primary turns were joined in series and readings taken across both to get better values.

The generator, a 1500 light machine smooth armature Westinghouse type, was specially run, the speed being kept constant. The frequency was determined as before by taking the speed of synchronous motor running without any load and with strong excitation of field. There was no slip under these conditions as frequently ascertained.



The average speed was very closely 2070 per minute on a motor which was a 4-pole, this giving 8280 cycles per minute or 138 per second. From which $\omega=867$.

The connections as used are shown in diagram below: The connections were all left exactly as used generally with the exception that, as before stated, the gaps and condensers were bridged by short pieces of wire No 2.

Readings for: *two primary turns*, regulating coil 23.5 turns and *all connections in series*:

E	I	ω	R	}	This gave an average of:			
14.7	53.00	867			E	I	ω	R
14.8	53.22	867			14.925	53.555	867	
15.1	54.00	867						
15.1	54.00	867						

Readings for *two primary turns in series*:

E	I	ω	R	}	This gave average values:			
10.45	52.1	867			E	I	ω	R
10.35	52.1	867			10.4	52.1	867	
10.40	52.1	867						

Readings were also taken across each one of the primary turns, the e.m.f. of course being exactly one half but the e.m.f. across the *upper* turn was *slightly greater*, probably because of the greater distance from the ground, possibly because of being nearer to the open secondary.

Readings for *regulating coil* 23.5 turns and *connections of break and condensers* together in series:

E	I	ω	R	}	This gives average values:								
14.7	52.1	867											
14.8	52.1	867											
15.1	52.1	867											
					<table><tr><th>E</th><th>I</th><th>ω</th><th>R</th></tr><tr><td>4.1</td><td>52.1</td><td>867</td><td></td></tr></table>	E	I	ω	R	4.1	52.1	867	
E	I	ω	R										
4.1	52.1	867											

Readings for *regulating coil alone* for various turns:

E	I	ω	Number of turns across which e.m.f. read	Resistance of the turns included
$\frac{7.85}{2} = 3.925$	52.1	867	23.5	
$\frac{6.3}{2} = 3.15$	52.1	867	19.5	
$\frac{4.8}{2} = 2.4$	52.5	867	15.5	
$\frac{3.3}{2} = 1.65$	53.00	867	11.5	
$\frac{2}{2} = 1$	53.00	867	7.5	
0.5	53.00	867	3.5	

To get better readings for the separate turns of the regulating coil the voltage was taken again as first across the whole: 2 primary turns, connections and regulating coil all in series and the turns of the latter were then varied, readings being taken for each case. The results are indicated below:

E	I	Number of turns of the regul. coil included in the circuit	ω	Resistance total of circuit included
11.55	55.8	0.5	867	
11.675	55.8	2.5	867	
11.90	55.8	4.5	867	
12.15	55.3	6.5	867	
12.45	55.3	8.5	867	
12.80	55.3	10.5	867	
13.20	54.9	12.5	867	
13.50+a little	54.9	14.5	867	

13.90	54.9	16.5	867	
14.25	54.4	18.5	867	
14.60+a little	54.4	20.5	867	
14.15	51.1	22.5	867	
14.30	51.1	23.5	867	

To facilitate estimation of the inductance of the various turns the readings were reduced to the same value of current and are as follows:

11.55	55.8	0.5	867	
11.675	55.8	2.5	867	
11.90	55.8	4.5	867	
12.26	55.8	6.5	867	
12.562	55.8	8.5	867	
12.915	55.8	10.5	867	
13.416	55.8	12.5	867	
13.721	55.8	14.5	867	
14.128	55.8	16.5	867	
14.617	55.8	18.5	867	
14.976	55.8	20.5	867	
15.452	55.8	22.5	867	
15.616	55.8	23.5	867	

Colorado Springs

Oct. 31, 1899

Measurement of inductances: New coil for further investigating effect of altitude upon capacity of body connected to earth

The drum of 14" diam. and 8 feet long was again used, the cord № 20 being taken off and wire № 10 rubber - covered used instead. Most of the data from before remained, only the number of turns was reduced from 689 to 346.

The readings of e.m.f., current and frequency were as follows:

<i>E</i>	<i>I</i>	ω	<i>R</i>	
85	15.635	880	coil with cord	1.752
84.75	15.6	880	cord	0.596
82.5	15.3	880	coil alone	1.150 ohm
Average values:				
84.38	15.512	880		

This gives: $\frac{E}{l} = 5.44 \left(\frac{E}{l} \right)^2 = 29.5936$

$$R^2 = 1.3364$$

$$\omega^2 = 774,400$$

$$L^2 = \frac{\left(\frac{E}{l} \right)^2 - R^2}{\omega^2} = \frac{29.5936 - 1.3364}{774,400} = \frac{28.2572}{774,400} \text{ henry} = 0.00003649$$

$$\text{or } L = \sqrt{0.00003649} = 0.00604 \text{ H or } L = 6,040,000 \text{ cm.}$$

Now for calculating with reference to note Oct. 18 we have the following data:

diam. of core 14"=35.5 cm

length of core 96"=243.84 cm= l

$S = 1000 \text{ cm}^2$

$N = 346$

$N^2 = 119,716$

$$L = \frac{4\pi}{l} N^2 S = \frac{12.5664 \times 119,716,000}{243.84}$$

From this $L = 6,169,600 \text{ cm}$ or 0.00617 henry
approx. This is nearly 2% greater than measured
value – fairly close.

Colorado Springs Notes

November 1-30, 1899

Want of time compelled omission of following items partly worked out:

Nov. 27, 28 – Corrected and completed results of experiments of Nov. 3 with wire of different lengths and ball, 19 and 21

Nov. 29, 30. a) Extra coils in series exciting one another,
b) Methods of tuning by telephone,
c) Exciting receiving circuit through small sensitive arc

} complete description

Patent matter worked on Nov. 1-30:

Exclusion of messages in telegraphy:

a) Two or more synchronized receiving circuits controlling receiver
b) Key or safety combination

} text to be completed.

Colorado Springs Nov 1, 1899



Measurement of inductance of new extracoil built chiefly in investigating propagation of waves through the ground and similar objects also to investigate further the behavior of strong streamers.

The frame was made of light notched woodwork fastened to three strong wooden rings. Provision was made for 106 turns. The rings were 8 feet in diam and taking further $1\frac{1}{2}$ " on each side for the crosspieces the total diameter of coil inside was 8'3". The length was 8 feet less $1\frac{1}{2}$ " on top and $1\frac{1}{2}$ " on bottom making total length of coil 7 feet 10". The data are as follows:

Length of coil $7'10" = 94" = 238.76 \text{ C.M.} = L$; diam $8'3" = 99" = 251.46 \text{ C.M.} = d$
 Turns $n = 106 = N$ (really 105 turns round + one turn loose)

Area $S = \frac{\pi d^2}{4} = 49662.52 \text{ C.M.}^2$. from these data we

$$\text{Here } L = \frac{4\pi}{L} N^2 S = \frac{12.5664 \times 11236 \times 49662.52}{238.76} = 208 \times 12.5664 \times 11236 = 141196 \times 208 =$$

$$L = 29,368,768 \text{ C.M.} \approx 0.029369 \text{ H. approx}$$

calculator

Now the readings were:

ϵ	J	ω	R
110	6.05	680	coil with coil 3.26
110	6.05	680	coil 0.596
110	6.05	680	coil alone 2.664

$$\frac{\epsilon}{J} = 18.1818 \quad \left(\frac{\epsilon}{J}\right)^2 = 330.58$$

$$R^2 = 7.097$$

$$\left(\frac{\epsilon}{J}\right)^2 - R^2 = 323.483$$

$$\omega^2 = 774400$$

$$\text{This gives } L^2 = \frac{323.483}{774400} = 0.000417721$$

$$L = \sqrt{0.000417721} = 0.02042 \text{ H} \approx 20,420,000 \text{ C.M.}$$

Measurements show a value much lower but this was to be expected as the turns are large also far apart $\frac{1}{2}$ ". However this measurement is to be made again to be sure of the result.

Colorado Springs

Nov. 1, 1899

Measurement of inductance of new extra coil built chiefly for investigating propagation of waves through the ground and similar objects. Also to investigate further the behaviour of strong streamers

The frame was made of light notched woodwork fastened to three strong wooden rings. Provision was made for 106 turns. The rings were 8 feet in diam. and taking further 1 ½" on each side for the crosspieces the total diameter of coil inside was 8'3". The length was 8 feet less 1 ½" on top and ½" on bottom making total length of coil 7 feet 10". The data are as follows:

Length of coil 7' 10"=94"=238.76 cm= l ; diam 8'3"=99"=251.46 cm= d

Turns wire N^o 10 106=N (really 105 turns wound+one turn loose)

Area $S = \frac{\pi d^2}{4} = 49,662.52$ cm.sq. from these data we have

$$L = \frac{4\pi}{l} N^2 S = \frac{12.5664 \times 11,236 \times 49,662.52}{238.76} = 208 \times 12.5664 \times 11,236 = 141,196 \times 208$$

$$L = 29,368,768 \text{ cm, or } 0.029369 \text{ H approx.}$$

Now the readings were:

Calculated

E	I	ω	R
110	6.05	880	Coil with cord 3.26
110	6.05	880	cord 0.596
110	6.05	880	Coil alone 2.664

$$\begin{aligned} \frac{E}{I} &= 18.1818 \left(\frac{E}{I} \right)^2 = 330.58 \\ R^2 &= 7.097 \\ \left(\frac{E}{I} \right)^2 - R^2 &= 323.483 \\ \omega^2 &= 774,400 \end{aligned}$$

$$\text{This gives } L^2 = \frac{323.483}{774,400} = 0.000417721$$

$$L = \sqrt{0.000417721} = 0.02042 \text{ H or } 20,420,000 \text{ cm.}$$

Measurement shows a value much lower but this was to be expected as the turns are large also ½" apart. However this measurement is to be made again to be sure of the result.

Colorado Springs

Nov. 2, 1899

Readings were again taken today to ascertain the value found yesterday for inductance of new extra coil. The results were as follows:

E	I	ω	R	
194	10.7	887	2.664	} average of three readings very closely agreeing.

$$\frac{E}{I} = 18.13 \quad \left(\frac{E}{I}\right)^2 = 328.6969$$

$$R^2 = 7.0969$$

$$\left(\frac{E}{I}\right)^2 - R^2 = 321.60$$

$$L = \frac{\sqrt{321.6}}{887} = \frac{17.933}{887}$$

$$L = 0.0202176 \text{ H or } 20,217,600 \text{ cm.}$$

This is a value a little smaller than the one found yesterday but it is within the limits of variation of ω .

Note: When the turns are far apart the ordinary formulas for calculating do not apply, and the measured value is the more inferior to the calculated value the greater the turns and the farther apart they are. When very far apart it is better to calculate inductance of one turn and multiply or, if they are not all alike, to calculate then separately and add up, making some allowance for mutual induction.

Secondary last form, two wires № 10 in multiple 17 turns on frame described on another occasion. To test the values before found for inductance and mutual induction coefficient readings were again taken today. For secondary inductance:

E	I	ω	R		
138	16.5	} 887	} 1.382	} The first two readings were in all probability the best and they are taken.	
138	16.5				
136	16.3	} 875	}		
134.5	16.2				

From above:

$$\frac{E}{I} = 8.364$$

$$\left(\frac{E}{I}\right)^2 = 69.9565$$

$$R^2 = 1.91$$

$$\left(\frac{E}{I}\right)^2 - R^2 = 68.0465$$

$$\omega = 887$$

$$L = \frac{\sqrt{68.0465}}{887} = \frac{8.003}{887} = 0.009023 \text{ H or } 9,023,000 \text{ cm.}$$

This is smaller than before found because the turn before last was wound a little higher up as at first sparks would break through. It is to be measured once more however. Readings for *Mutual Induction Coefficient*.

Two primary turns in series:

Current through primary two turns in series	Volts on secondary	ω
I	E	
45.4	34	880
45.4	34	"
45.4	34	"

From this $E = M\omega I$, $M = \frac{34 \times 10^9}{880 \times 45.4} = 851,021 \text{ cm.}$

Readings with current through the secondary gave:

Current through secondary	Volts on primary two turns series	ω
17.8	13.4	872
17.8	13.4	872 } over

From later readings $M = \frac{13.4 \times 10^9}{17.8 \times 872} = 863,313 \text{ cm.}$

This is a little larger probably due to variation of ω . Readings were now taken for each of the primary turns separate with the following results:

Upper primary turn, nearer to secondary:

Current through secondary	E.m.f. on primary	ω
17.9	6.9	872 average three readings

From this $M_{\text{upper pr.}} = \frac{6.9 \times 10^9}{17.9 \times 872} = 442,059 \text{ cm.}$

Current through primary	E.m.f. on secondary	ω
30.1	11.8	880 average three readings

$M_{\text{upper pr.}} = \frac{11.8 \times 10^9}{30.1 \times 880} = 445,484 \text{ cm.}$

The difference again in all probability to be ascribed to variation of ω .

Lower primary turn. Readings were as follows:

Current through primary	E.m.f. secondary	ω
30.1	11.1	880 average three readings

Current through secondary	E.m.f. primary	ω
17.9	6.4	880 average three readings

From first set readings:

$$M_{\text{lower pr.}} = \frac{11.1 \times 10^9}{30.1 \times 880} = 419,060 \text{ cm}$$

From second set readings:

$$M_{\text{pr. lower}} = \frac{6.4 \times 10^9}{17.9 \times 880} = 406,300 \text{ cm.}$$

Report of experiment for 3. 1878.

Investigation for the purpose of ascertaining the influence of motion upon the capacity of a conductor considered as a vibrating system as before was continued:

The coil of 346 turns $\Phi. 10$ was wound on drum 14" diam & feet long was again used. The galleys were as before the 26 galvanized covers 24 feet long each. The readings were as follows:

Capacity of primary circuit total.	Inductance in primary turns reg coil + conn.	length of vertical wire attached to one terminal of excited coil	Steady in. of spark on terminals of excited coil
$\frac{3 \times 30}{2} - 2 = 53 \text{ turns} = 0.0474 \text{ MF}$	$7' + \text{Conn}$	45 feet	$3\frac{3}{8}"$
0.0479 MF	$6\frac{3}{4} + "$	36 "	"
"	$5\frac{3}{4} + "$	27 "	"
"	$5\frac{3}{10} + "$	18 "	$3\frac{1}{4}"$
"	$4\frac{3}{8} + "$	9 "	$3\frac{1}{4}"$
"	$3\frac{5}{8} + "$	0 "	$3\frac{1}{8}"$

Note: As repeatedly observed, the first addition of a small length of wire to a coil produces generally a great effect but a certain small length being surpassed the increase per unit of length becomes more gradual.

For two primary turns multiple

Current through primaries	E.m.f. secondary	ω
29.2	11.25	880 average three readings
Current through secondary	E.m.f. primaries	
17.9	6.7	880 average three readings

From first set of readings:

$$M_{2 \text{ prim. multiple}} = 437,811 \text{ cm}$$

From latter readings:

$$M_{2 \text{ pr. multiple}} = 425,343 \text{ cm.}$$

Colorado Springs

Nov. 3, 1899

Investigation for the purpose of ascertaining the influence of elevation upon the capacity of a conductor connected to a vibrating system as before used, continued:

The coil of 346 turns, N° 10 wire wound on drum 14" diam., 8 feet long was again used. The spark wires were as before N° 26 guttapercha covered, 24 feet long each. The readings were as follows:

Capacity in primary circuit <i>total</i>	Inductance in primary turns reg. coil+conn.	Length of vertical wire attached to free terminal of excited coil	Analyzing spark on terminals of excited coil
$\frac{(3 \times 36) - 2}{2} = 53 \text{ bottles} = 0.0479 \text{ mfd}$	7 $\frac{1}{8}$ + conn.	45 feet	3 $\frac{3}{8}$ "
0.0479 mfd	6 $\frac{3}{8}$ + "	36 "	3 $\frac{3}{8}$ "
0.0479 mfd	5 $\frac{3}{4}$ + "	27 "	3 $\frac{3}{8}$ "
0.0479 mfd	5 $\frac{3}{16}$ + "	18 "	3 $\frac{1}{4}$ "
0.0479 mfd	4 $\frac{3}{8}$ + "	9 "	3 $\frac{1}{8}$ "
0.0479 mfd	3 $\frac{5}{8}$ + "	0 "	3 $\frac{1}{8}$ "

Note: As repeatedly observed, the first addition of a small length of wire to a coil generally produces a great effect but a certain small length being bypassed the increase per unit of length becomes more gradual.

Experiments with coil 346 turns on drum 14" diam. with the view of investigating influence of elevation upon the capacity of a body connected to earth continued. This time in connection with the vertical wire a ball 30" diam. was used in the manner before described.

Coil with spark wires alone

Capacity in primary circuit <i>total</i>	Turns in regulating coil + connections } Inductance	Analyzing spark on terminals of excited coil
$\frac{(3 \times 36) - 2}{2} = 53 \text{ bottles} = 0.0479 \text{ mfd}$	3 $\frac{5}{8}$ + conn.	3 $\frac{1}{8}$ "

Coil with 50 feet wire № 10 vertical

0.0479 mfd	7 $\frac{3}{4}$ +conn.	4"
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Coil with ball 30" diam. lowest position 10'3" from center to ground

0.0479 mfd	8 $\frac{1}{2}$ +conn.	4 $\frac{1}{8}$ "
------------	------------------------	-------------------

Coil with ball mean position 33'9" from center to ground

0.0479 mfd	8 $\frac{7}{8}$ +conn.	4 $\frac{1}{4}$ "
------------	------------------------	-------------------

Coil with ball highest position 57'3" from center to ground

0.0479 mfd	9 $\frac{1}{4}$ +conn.	4 $\frac{3}{8}$ "
------------	------------------------	-------------------

Note: The excitation in this and previous case was as before described by connecting the lower terminal of coil to that terminal of the condensers (primary) which was connected to small adjustable spark gap, specially made for this purpose, to earth.

It would be desirable in these tests to do away with the spark wires as these are apt to introduce errors in the estimates of capacity. Experiments were made with new extra coil to see how close the maximum rise could be ascertained without any spark wires, merely by observing the streamers. For this purpose the extra coil was excited from the secondary of oscillator as in some previous instances. First the extra coil was tuned with spark wires, then the upper wire which is the only one of importance was taken off and the system again tuned. The results were as follows:

New Extra coil with Spark wires Guttapercha № 26, 24 feet long

Capacity in primary circuit total bottles mfd	Inductance in primary circuit Turns of regul. coil +connections
$\frac{(8 \times 36) - 2}{2} = 143 \text{ bottles} = 0.1287$	7 $\frac{5}{8}$ + connections

New Extra coil without upper Spark wire

Capacity in primary circuit total bottles mfd	Inductance in primary circuit Turns of regul. coil +connections
$\frac{(8 \times 36) - 2}{2} = 143 \text{ bottles} = 0.1287$	5 $\frac{5}{8}$ + connections

Colorado Springs

Nov. 4, 1899

Measurement of inductance of primaries

Another series of readings were taken with the object of closely determining the inductance of the primary turns. This time a different dynamo was supplying the current. The speed was kept very constant. The readings were as follows:

Current	Electromotive force across two primaries in series	ω
345°-58.8	12 a trifle less	880
345°=58.8	12	"
345°=58.8	12	"

Allowing a little for zero displacement on voltmeter the average is very closely:

I	E	ω	R two primary turns in series
58.8	11.95	880	0.004 ohm.

This gives $\frac{E}{I} = 0.2032$ $\left(\frac{E}{I}\right)^2 = 0.04129$ $R^2 = 0.000016$

Since R^2 is entirely negligible against $\left(\frac{E}{I}\right)^2$ we have:

$$L = \frac{E}{I\omega} = \frac{11.95}{51,744} = 0.000230945 \text{ henry}$$

or 230,945 cm.

This would give for one primary turn approximately

$$0.000057736 \text{ henry or } 57,736 \text{ cm.}$$

The value previously found was 56,400 cm.

Reading of today would appear more reliable.

Colorado Springs

Nov. 5, 1899

Capacity of structure of iron pipes, before described, computed:

7" pipe: Outside diam. 7.625" = 19,3673 cm = d

length of pipe with cap = $l = 23'4" = 280" = 811.2 \text{ cm} = l$

$$C_1 = \frac{l}{2 \log_e \frac{l}{r}} = \frac{811.2}{2 \times 4.42313} \quad r = 9.6837 \quad \frac{l}{r} = 83.77$$

$$C_1 = 91.7 \text{ cm.} \quad \log_e \frac{l}{r} = 1.9231 \times 2.3 = 4.42313$$

6" pipe: Outside diam.=6.625"= 16.8275 cm= d

length of pipe 18'2"=218"=553.72 cm= l

$$C_2 = \frac{l}{2 \log_e \frac{l}{r}} = \frac{553.72}{2 \times 4.182} \quad r = 8.4138 \quad \frac{l}{r} = 65.81$$

$$C_2 = 66.2 \text{ cm.} \quad \log_e \frac{l}{r} = 1.818292 \times 2.3 = 4.182$$

5" pipe: Outside diam. 5.563"=14.13 cm= d

length of pipe 18'4 1/2"=220.5"=560.07 cm= l

$$C_3 = \frac{l}{2 \log_e \frac{l}{r}} = \frac{560.07}{2 \times 4.368} \quad r = 7.065 \quad \frac{l}{r} = 79.27$$

$$C_3 = 64.11 \text{ cm.} \quad \log_e \frac{l}{r} = 1.89911 \times 2.3 = 4.368$$

4" pipe: Outside diam. 4.5"=11.43 cm= d

length of pipe 15'7 1/4"=187.25"=475.615 cm= l

$$C_4 = \frac{l}{2 \log_e \frac{l}{r}} = \frac{475.615}{8.832} \quad r = 5.715 \quad \frac{l}{r} = 83.22$$

$$C_4 = 53.85 \text{ cm.} \quad \log_e \frac{l}{r} = 1.92 \times 2.3 = 4.416$$

3 1/2" pipe: Outside diam. 4" = 10.16 cm= d

length of pipe 19'3 1/4"=231.25"=587.375 cm= l

$$C_5 = \frac{l}{2 \log_e \frac{l}{r}} = \frac{587.375}{9.49} \quad r = 5.08 \quad \frac{l}{r} = 115.6$$

$$C_5 = 61.9 \text{ cm} \quad \log_e \frac{l}{r} = 2.062958 \times 2.3 = 4.745$$

3" pipe: Outside diam. 3.5"=8.89 cm= d

length of pipe 18' 4 3/4"=220.75"=560.7 cm= l

$$C_6 = \frac{l}{2 \log_e \frac{l}{r}} = \frac{560.7}{2 \times 4.83} \quad r = 4.445 \quad \frac{l}{r} = 126.1$$

$$C_6 = 58.05 \text{ cm} \quad \log_e \frac{l}{r} = 2.1 \times 2.3 = 4.83$$

2 1/2" pipe: Outside diam. 2.875"=7.3 cm= d

length of pipe 8' 1/4" }
length nipples 7 3/4" } 8' 8"=104"=264.16 cm= l

$$C_7 = \frac{l}{2 \log_e \frac{l}{r}} = \frac{264.16}{2 \times 4.276} \quad r = 3.65 \quad \frac{l}{r} = 72.37$$

$$C_7 = 30.89 \text{ cm} \quad \log_e \frac{l}{r} = 1.859 \times 2.3 = 4.276$$

from above we have total capacity of structure

C:	7" pipe with cap	91.7 cm.
	6" pipe	66.2 "
	5" pipe	64.11 "
	4" pipe	53.85 "
	3 1/2" pipe	61.9 "
	3" pipe	58.05 "
	2 1/2" pipe	30.89 "
	Ball 30" diam.	38.1 "
	Total Capacity	C= 464.8 cm.

Note: This supposes of course that all these capacities are connected in multiple. To be true it must be assumed that only long waves are used. With short waves the calculated value would not be experimentally borne out.

Colorado Springs

Nov. 6, 1899

Determination of el. st. capacity of the structure of iron pipes by measurement

The method previously employed for such a purpose was again used. The coil described on a former occasion, wound on a drum of 10 5/16" and having 550 turns was excited from a vibrating primary system and the maximum resonant rise obtained with only the spark wires attached to the terminals of the coil. Then the upper terminal of the latter was connected to the structure and the maximum rise again obtained. From the two known periods of the primary system and the self-induction of the coil the capacity of the structure was then computed. In order to avoid errors due to the capacity of the wires connected to the coil the precaution was taken to make no change which would in any considerable way affect the result. Thus, when the vibration of the coil with only the spark wires was determined the wire which was to be later connected to the structure was likewise fastened to the upper terminal of the coil in a position such that in the second experiment or series of experiments it was only necessary to tilt the wire to bring it in contact with the structure. If this precaution would not be observed the error introduced by the connecting wire might be – and in fact it would generally be – considerable. The adjustments were first made with the spark wires and the wire which was to be connected to the structure, this wire being placed vertically and at a distance of about four feet from the latter. The maximum rise was observed on the terminals of the excited coil with:

Capacity in primary circuit total	Turns in regulating coil	Spark analyzing on terminals
$\frac{(8 \times 36) - 2}{2} = 143 \text{ Bottles or } 0.1287 \text{ mfd}$	2 1/8	2 5/8"

Now the wire was tilted and brought in contact with the structure and resonant maximum rise was observed with:

$\frac{(8 \times 36) - 2}{2} = 143 \text{ Bottles or } 0.1287 \text{ mfd}$	17 1/2	2 5/8"
--	--------	--------

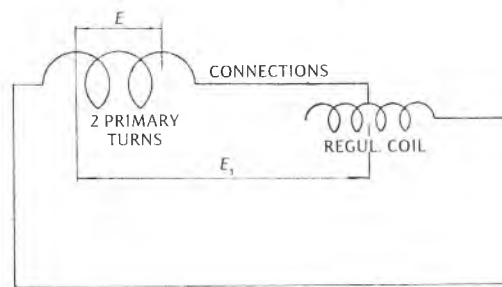
To determine more satisfactorily the self-induction in both the primary vibrations readings were taken in the following manner. The two primary turns, connections to breaks and condensers and the regulating coil were all connected in series – the breaks and condensers being of course bridged by stout and short wires (Nº 2 being used) and readings of e.m.f. across the two primary turns were first taken and then across the two primaries plus connections and turns in the regulating coil as were used in the two instances. Since the resistances were entirely negligible with respect to the inductances it was only necessary to make the ratio of the e.m.f. in two instances to determine the inductance of the connections and turns from the known inductance of the two primary turns which was carefully determined before. As the readings were taken practically at the same moments across the primaries alone and across the primaries connections and turns could not vary perceptibly, and to make sure of that the readings were taken repeatedly. The current passed through the inductances also remaining the same during the two consecutive readings, the results ought to be therefore more reliable than those obtained otherwise.

The results in the first case were as follows:

$$\left. \begin{array}{l} E_1 = 10.4 \text{ volts} \\ E = 10 \text{ volts} \end{array} \right\} I \text{ and } \omega \text{ the same.}$$

In the second case:

$$\left. \begin{array}{l} E_1 = 13.15 \text{ volts} \\ E = 10.3 \text{ volts} \end{array} \right\} I \text{ and } \omega \text{ the same.}$$



Calling now L the inductance of the two primary turns in series and L_1 that of the two primaries + connections + $2 \frac{1}{8}$ turns of the regulating coil we have in first case:

$$\frac{E_1}{E} = \frac{L_1}{L} \text{ and } L_1 = \frac{E_1}{E} L.$$

Now L was previously determined to be 230,945 cm, hence

$$L_1 = \frac{10.4}{10} \times 230,945 = 240,183 \text{ cm.}$$

From this inductance of the connections + $2 \frac{1}{8}$ turns of the regulating coil is $L_1 - L = 9238 \text{ cm.}$

In the second case we have similarly

$$L_2 = \frac{13.15}{10.3} \times 230,945 = 294,847 \text{ cm,}$$

L_2 being inductance of two primaries + connections + $17 \frac{1}{2}$ turns of regulating coil.

Hence the inductance of the connections and the turns ($17 \frac{1}{2}$) included is $L_2 - L = 63,902 \text{ cm.}$

From these data the capacity of the structure can now be estimated as follows: In the first case the primary vibration was

$$T_1 = \frac{2\pi}{10^3} \sqrt{\frac{9238}{10^9}} \times 0.1287$$

In the second case the primary vibration was

$$T_1 = \frac{2\pi}{10^3} \sqrt{\frac{63,902}{10^9}} \times 0.1287$$

Calling now C_s the capacity of the excited system when the structure was not attached to it, and C'_s that when this was the case we have:

$$T_1 = \frac{2\pi}{10^3} \sqrt{C_s L'} = \frac{2\pi}{10^3} \sqrt{\frac{9238}{10^9}} \times 0.1287$$

and

$$T_2 = \frac{2\pi}{10^3} \sqrt{C'_s L'} = \frac{2\pi}{10^3} \sqrt{\frac{63,902}{10^9}} \times 0.1287$$

L' being the inductance of the excited coil. L' was previously measured and found to be $L'=18,650,000$ cm. Now from above:

$$C_s = \frac{9238 \times 0.1287}{10^9 \times \frac{18,650,000}{10^9}} = \frac{9238 \times 0.1287}{18,650,000};$$

and

$$C'_s = \frac{63,902 \times 0.1287}{18,650,000}; \quad \frac{C'_s}{C_s} = \frac{63,902}{9238}; \quad C'_s = C_s \frac{63,902}{9238}$$

C_s expressed in centimeters is:

$$C_s = \frac{9238 \times 0.1287 \times 9 \times 10^5}{1865 \times 10^4} = \frac{11.583 \times 9238}{1865} = 57.375$$

from this $C'_s = \frac{63902}{9238} \times 57.375 = 6.92 \times 57.375 = 397.03$ cm

$$C = C'_s - C_s = 339.655 \text{ cm.}$$

This is a result inferior to the calculated value but it was to be expected as before stated since it can not be correct to assume that all pipes are connected in multiple unless the vibration is very slow. Another coil is to be used with an inductance much higher so as to examine the truth of this opinion. There is, however, a possibility that the reading, when the structure was attached to the excited coil, was too low. In this case namely, the tuning is *not sharp* owing to the large capacity of the system, but when the structure is *not* attached it is quite sharp, hence if there is any error in the adjustment of the circuits it can be only then when the structure was connected. This is to be investigated also. A slight error might have been also caused by the wire which connected the coil to the structure, for although this wire was placed at a distance of 4 feet with its nearest point there might have been enough influence exerted by the structure to make the reading with the spark wires alone larger. This will be ascertained. From previous tests on the increase of capacity with elevation I should expect to find the capacity of the structure much larger than the calculated value.

On the present occasion readings were also taken with the view of determining the inductance of the connections alone+flexible cable on regulating coil+½ turn of regulating coil. This namely is the lowest value which it is possible to give with the regulating coil in circuit. In this case the readings were $E_1 = 10.5$, $E=10.2$ across the 2 primaries+ all these connections and across the two primaries alone, respectively. With reference to foregoing and calling L_s the inductance of the two primaries+connections+flexible cable+½ turn of regulating coil:

$$L_3 = \frac{105}{102} \times L = \frac{105}{102} \times 230,945 = 237,738 \text{ cm.}$$

Hence the inductance of all these mentioned connections is $L_3 - L = 237,738 - 230,945 = 6793$ cm, for connections proper $\frac{1}{2}$ turn regulating coil, flexible cable in reg. coil.

Note: A small error is often caused by the changing position of the flexible cable which makes the readings for a small number of turns *larger* (slightly).

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Further experiments for the purpose of ascertaining the capacity of the structure of the iron pipe by resonance analysis. Two sets of readings were taken: one set with new extra coil the other with coil 346 turns wire № 10 on drum 14" diam. The readings were as follows:

With new extra coil

Capacity in primary exciting circuit <i>total:</i>	Inductance in primary circuit. Turns of regulating coil+conn.	Analyzing spark on terminals of excited coil.
$\frac{(8 \times 36) - 2}{2} = 143 \text{ bottles} = 0.1287 \text{ mfd}$	22 + conn	$2 \frac{5}{16}"$
$\frac{(8 \times 36) - 2}{2} = 143 \text{ bottles} = 0.1287 \text{ mfd}$	8 + conn	$3 \frac{3}{4}"$

With experimental coil described

$\frac{(3 \times 36) - 2}{2} = 53 \text{ bottles} = 0.0477 \text{ mfd}$	15,75 + conn	4"
$\frac{(3 \times 36) - 2}{2} = 53 \text{ bottles} = 0.0477 \text{ mfd}$	3,5 + conn	$3 \frac{1}{8}"$

*Note: The first readings are of course *with*, the second *without* structure in each case.

*Note: Readings were also taken on this occasion with coil wound on $10 \frac{5}{16}"$ drum before described (550 turns) but merely for the purpose of comparing the inductances of the primary and secondary circuits. With the same capacity as in the last case resonance was obtained with spark wires alone:

$\frac{(3 \times 36) - 2}{2} = 53 \text{ bottles} = 0.0477 \text{ mfd}$	$8 \frac{7}{8}$	$3 \frac{1}{4}"$
---	-----------------	------------------

This for *future reference*.

Returning to the two sets of observations it is to be noted that *one* turn of the new extra coil had been taken off and allowance should be made for this.

Let the primary vibration in the first case be T_{p1} and the corresponding secondary vibration T_{s1} then $T_{p1} = T_{s1}$. Similarly for the second reading with the extra coil when the structure was not attached to the coil. Calling the respective vibration T_{p2} and T_{s2} we have $T_{p2} = T_{s2}$. Now

$$T_{p1} = \frac{2\pi}{10^3} \sqrt{L_{p1} \times C} \quad \text{and} \quad T_{p2} = \frac{2\pi}{10^3} \sqrt{L_{p2} \times C}$$

where L_{p1} and L_{p2} designate the inductances of the primary circuit in the two cases. From this

$$\frac{T_{p1}}{T_{p2}} = \sqrt{\frac{L_{p1}}{L_{p2}}}$$

as useful relation to remember.

While the self-induction was varied in the primary circuit, and the capacity remained the same, in the secondary it was just the opposite, the self-induction remaining the same and the capacity being varied. Calling now the capacity of the excited system with the structure C_{s1} and without the structure C_{s2} (that of coil with spark wires alone) we have by analogous reasoning:

$$\frac{T_{s1}}{T_{s2}} = \sqrt{\frac{C_{s1}}{C_{s2}}} = \frac{T_{p1}}{T_{p2}} = \sqrt{\frac{L_{p1}}{L_{p2}}} \quad \text{or} \quad \frac{C_{s1}}{C_{s2}} = \frac{L_{p1}}{L_{p2}}$$

This is also a convenient equation and useful to bear in mind. In cases when the capacity in the excited system is very often varied it is only necessary to determine the first capacity with which the series of experiments was begun to know all the other values from the known inductances of the primary circuit in two consecutive experiments. But when there are only two values to be determined, as in the present instance, they can be at once calculated from the known primary vibrations.

In the present instance, adopting this procedure we have:

$$T_{p1} = \frac{2\pi}{10^3} \sqrt{0.1287 \times 0.000079} \quad \text{and} \quad L_{p1} = \text{Connections} + 22 \text{ turns} = 79,000 \text{ cm.} = 0.000079 \text{ H}$$

$$T_{p2} = \frac{2\pi}{10^3} \sqrt{0.1287 \times 0.00002526} \quad L_{p2} = \text{Connections} + 8 \text{ turns reg. coil} = 25,260 \text{ cm.} = 0.00002526 \text{ H}$$

$$T_{p1} = T_{s1} = \frac{2\pi}{10^3} \sqrt{C_{s1} \times 0.02}$$

$$T_{p2} = T_{s2} = \frac{2\pi}{10^3} \sqrt{C_{s2} \times 0.02}$$

Inductance of extra coil before measured was 0.02042 henry. This owing to one turn less without *change of length* should be reduced to ratio $\left(\frac{105}{106}\right)^2$ or about 2% making the inductance very approx. 20,000,000 cm. or 0.02 henry.

From the above:

$$\frac{2\pi}{10^3} \sqrt{C_{s1} \times 0.02} = \frac{2\pi}{10^3} \sqrt{0.1287 \times 0.000079}$$

and

$$C_{s1} = \frac{0.1287 \times 0.000079}{0.02} \text{ mfd.}$$

or in centimeters:

$$C_{s1} = \frac{9 \times 10^5 \times 0.1287 \times 0.000079}{0.02} = 457.5 \text{ cm.}$$

Similarly we have

$$C_{s2} = \frac{0.1287 \times 0.00002526}{0.02} \text{ mfd, or}$$

$$C_{s2} = \frac{9 \times 10^5 \times 0.1287 \times 0.00002526}{0.02} = 146.29 \text{ cm.}$$

This would give for the capacity of the structure according to this method only $C_{s1} - C_{s2} = 457.5 - 146.29 = 311.21 \text{ cm.}$

This inferior result I attribute to the fact that the capacity is partially to be taken as *distributed*, owing to the length of the structure. But determining by the same method with a vibration which would be much slower this error should be very small.

Taking now the values for the set of readings with the experimental coil of 346 turns we have:

$$T'_{p1} = \frac{2\pi}{10^3} \sqrt{0.0377 \times 0.00005486} \text{ and } L'_{p1} = \text{connections} + 15.75 \text{ turns} = 54,860 \text{ cm.} = 0.00005486 \text{ H}$$

$$T'_{p2} = \frac{2\pi}{10^3} \sqrt{0.0377 \times 0.00001116} \text{ and } L'_{p2} = \text{conn.} + 3 \frac{1}{2} \text{ turns} = 11,160 \text{ cm.} = 0.00001116 \text{ H}$$

The inductance of the experimental coil measured being 6,040,000 cm, or 0.00604 henry we have:

$$T'_{s1} = \frac{2\pi}{10^3} \sqrt{0.00604 \times C'_{s1}} \text{ and } T'_{s2} = \frac{2\pi}{10^3} \sqrt{0.00604 \times C'_{s2}}$$

from these relations follows:

$$C'_{s1} = \frac{0.0477 \times 0.00005486}{0.00604} \text{ mfd. and}$$

$$C'_{s2} = \frac{0.0477 \times 0.00001116}{0.00604} \text{ mfd.}$$

Hence

$$C'_{s1} - C'_{s2} = \frac{0.0477}{0.00604} \times (0.00005486 - 0.00001116) = \frac{0.0477}{0.00604} \times 0.0000437 \text{ mfd or}$$

$$C'_{s1} - C'_{s2} = \frac{9 \times 0.0477 \times 4.37}{0.00604} \text{ centimeters} = 310.6 \text{ cm.}$$

very nearly the same value.

It is to be expected that the value found with a quicker vibrating system should be smaller since then the structure begins to act not as one condenser but as a series of condensers or distributed capacity, all parts not being charged at the same time.

This method of determining the capacity implies therefore to be quite correct a slow vibration and, furthermore, negligible capacity in the vibrating system itself and also that the body the capacity of which is determined should not be of too great length since this must cause errors.

From reading with coil of 550 turns it follows, since the capacities both in the primary and secondary circuits remained the same, that the inductances in the primary and inductances in the secondary or excited circuit bore the same ratio, that is:

$$\frac{\text{Ind. } 8 \frac{7}{8} \text{ turns} + \text{conn.}}{\text{Ind. } 3.5 \text{ turns} + \text{conn.}} = \frac{\text{Ind. coil 550 turns}}{\text{Ind. coil 344 turns}}$$

Ind. of coil 550 turns was: 18,650,000

Ind. of coil 344 turns was: 6,040,000

$$\text{Hence } \frac{\text{Ind. } 8 \frac{7}{8} \text{ turns}}{\text{Ind. } 3 \frac{1}{2} \text{ turns}} = \frac{1865}{604}$$

This for later comparison.

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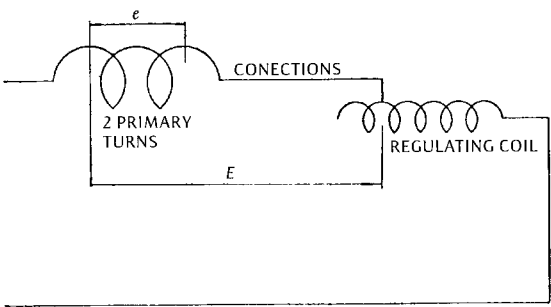
Table of inductances prepared from preceding readings.*

* This table is close enough for all general estimates.

Two primary turns in series	230,945 cm	0.000230945 H
One of the primary turns	57,736 "	0.000057736 "
All connections to condensers and breaks <i>as used</i>	5,004 "	0.000005004 "
All connections plus one half turn of reg. coil (first turn)	5,774 "	0.000005774 "
All connections plus the whole first turn of reg. coil	6,544 "	0.000006544 "
" 1 ½ "	7,314 "	0.000007314 "
" 2 "	8,084 "	0.000008084 "
" 2 ½ "	8,854 "	0.000008854 "
" 3 "	10,009 "	0.000010009 "
" 3 ½ "	11,164 "	0.000011164 "
" 4 "	12,319 "	0.000012319 "
" 4 ½ "	13,474 "	0.000013474 "
" 5 "	15,158 "	0.000015158 "
" 5 ½ "	16,842 "	0.000016842 "
" 6 "	18,526 "	0.000018526 "
" 6 ½ "	20,210 "	0.000020210 "
" 7 "	21,894 "	0.000021894 "
" 7½ "	23,578 "	0.000023578 "
" 8 "	25,262 "	0.000025262 "
" 8 ½ "	26,946 "	0.000026946 "
" 9 "	28,870 "	0.000028870 "
" 9 ½ "	30,794 "	0.000030794 "
" 10 "	32,718 "	0.000032718 "
" 10 ½ "	34,642 "	0.000034642 "

After 10 ½ turns the increase is 3850 cm. per turn so that the inductance of 10 ½ + *n* turns+conn. will be 34,642 + *n* × 3850 cm. With the entire coil in, there are 23 ½ turns having 84,692 cm. or 0.000084692 H.

In order to test the accuracy of the preceding measurements, readings of the e.m.f. across the two primaries, connections and the regulating coil – all joined in series – were taken repeatedly and in as rapid a succession as was found practicable, the number of the turns of the regulating coil being varied after each set of readings. The diagram below shows the connections of the various inductances while the readings, reduced to the same e.m.f. across: [the two primary turns+connections + ½ of one turn of the regulating coil+flexible cable] are given in table below:



Number of turns of the regulating coil included in circuit.	E.m.f. across two primary turns plus the connections, plus flexible cable+one half of one turn reg. coil					Difference of e.m.f. between successive readings:	
	first series of readings	second series	third series	fourth series	average		
23 ½	15.873	15.928	15.928	15.928	15.914	0.208	ω was in these readings smaller than 880.
22 ½	15.706	15.706	15.706	15.706	15.706	0.396	
20 ½	15.318	15.263	15.34	15.318	15.310	0.399	
18 ½	14.929	14.8185	14.929	14.929	14.901	0.4155	
16 ½	14.4855	14.4855	14.4855	14.4855	14.4855	0.3835	
14 ½	14.119	14.0415	14.1525	14.097	14.102	0.352	
12 ½	13.764	13.7085	13.764	13.764	13.75	0.3745	
10 ½	13.3755	13.3755	13.3755	13.3755	13.3755	0.3635	
8 ½	13.0425	12.9537	13.009	13.0425	13.012	0.3164	
6 ½	12.7095	12.654	12.7095	12.7095	12.6956	0.3191	
4 ½	12.3765	12.3765	12.3765	12.3765	12.3765	0.2221	
2 ½	12.1545	12.1212	12.1875	12.1545	12.1544	0.1544	
½	12.00	12.00	12.00	12.00	12.00		

Note: When reduced to the same e.m.f. across the two primaries and connections, ½ turn and flexible cable the average values agree fairly well with the readings before recorded. The table prepared on the bases of the values before found will be accurate enough for all ordinary estimates. Both sets of readings show that there is about 0.2 volt variation per turn, the few first turns excepted.

Following readings were taken today for the purpose of putting together a table of the inductances of the various turns of the regulating coil. The machine was specially run and all care was taken to get the readings as close as practicable. The method used in a previous case was again adopted which consisted in reading the e.m.f. across the two primary turns in series and simultaneously the e.m.f. across the two primary turns+connections+the turns in the regulating coil. The resistances as before stated being entirely negligible, the inductance in each case was given by the ratio of the e.m. forces and the known inductance of the two primary turns. By this method the error which might have been caused by a variation of ω which could only be determined by taking the speed of the generator, the apparatus for the more exact determination of this quantity being unfortunately left in New York. The results are indicated in the following table:

E.m.f. across two primary turns in series	E.m.f. across two primary turns + connections + turns of the regulating coil	Number of turns reg. coil	I	ω	Increase of e.m.f. from step to step
12.00	12.3	$\frac{1}{2}$	58.8	880	
12.00	12.45	$2\frac{1}{2}$	58.8	880	0.15
12.00	12.70	$4\frac{1}{2}$	58.8	880	0.25
12.00	13.05	$6\frac{1}{2}$	58.8	880	0.35
12.00	13.40	$8\frac{1}{2}$	58.8	880	0.35
12.00	13.80	$10\frac{1}{2}$	58.8	880	0.40
12.00	14.20	$12\frac{1}{2}$	58.8	880	0.40
12.00	14.60	$14\frac{1}{2}$	58.8	880	0.40
12.00	15.00	$16\frac{1}{2}$	58.8	880	0.40
12.00	15.40	$18\frac{1}{2}$	58.8	880	0.40
12.00	15.80	$20\frac{1}{2}$	58.8	880	0.40
12.00	16.20	$22\frac{1}{2}$	58.8	880	0.40
12.00	16.40	$23\frac{1}{2}$	58.8	880	0.20

This shows an increase per turn of about 0.20 V, except the few first turns.

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In some experiments it was necessary to use vibrations of lower frequencies and this made it necessary to insert additional inductances in the condenser discharge circuit. In such cases it was convenient to use the two primary turns only; in order to prevent a strong sparking on the secondary and changing reaction on the primaries it was necessary to join the ends of the secondary. Readings were taken to determine more closely the inductance of the primaries with the secondary closed.

The results were as follows:

Current	E.m.f. across two primary turns in series	ω
58.80	8.75	880
58.40	8.5	880
58.00	8.33	880
Average 58.40	Average 8.45 (with allowance for zero displacement)	880

With the secondary open the readings were exactly as before:

58.8	11.95	880
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Reduced to same current for both cases the readings with secondary closed become:

58.8	8.5	880
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The inductance of two primary turns as before found 230,945 cm.=L. We have for their inductance with *secondary closed* $\frac{8.5}{11.95}L = 164,270$ cm.

With both primaries in multiple it ought to be 41,068 cm. approx.

According to previous estimates the mutual induction coefficient with two primaries in series was: approximately 850,000 cm. The inductance of the secondary was found: 9,568,000 cm. last time, say average of two last determinations 9,560,000 cm. From this data we have for inductance with secondary closed:

$$L - \frac{M^2}{N} = 230,945 - \frac{85^2 \times 10^8}{956 \times 10^4} = 230,945 - \frac{85^2 \times 10^4}{956} = 230,945 - 75,575 = 155,370 \text{ cm.}$$

These readings above do not quite agree with the result calculated, but I think this only indicates some action of secondary on the primary when the former is *open*, or else the mutual induction coeff. measured a little *too high*. This *very likely*.

As it was not always possible to get along with the primaries alone when using them as inductances two self-induction coils were provided, one wound with wire № 6, the other with wire № 2 both on a drum of 5" diam. The particulars relating to both of these coils will be given below. To ascertain approximately their inductances readings were taken by joining them successively in circuit with the two primary cables in series and taking the e.m.f. across, this giving the inductance of each of them approximately from the ratio of the e.m.f. and the known inductance of the primaries, neglecting, of course, the resistance. The readings were as follows:

For coil wound with №6 wire:

E.m.f. across two primary turns+coil all in series	E.m.f. across two primaries in series alone	Current	ω
14.5	6.4	30.9	880
14.5	6.4	30.9	880
14.5	6.4	30.9	880

For coil with №2 wire:

13.5	8.2	40.1	880
13.5	8.2	40.1	880
13.5	8.2	40.1	880

This would give approximately inductances of coil No 6 wire

$$l = \frac{14.5}{6.4} \times 230,945 - 230,945 = \frac{8.1}{6.4} \times 230,945 = 292,290 \text{ cm,}$$

Coil No 6 wire

and for coil No 2 wire

$$l_1 = \frac{13.5}{8.2} \times 230,945 - 230,945 = \frac{5.3}{8.2} \times 230,945 = 149,340 \text{ cm,}$$

Coil No 2 wire

These figures were first utilised then separate readings were taken. All the particulars of these coils and the measured and calculated values are as follows:

Coil wound with No 6 wire:

length of wound part 38.75"=98.425 cm, drum 5"= 12.7 cm. 129 turns

Thickness of wire with insulation $\frac{98.425}{129}$ cm. Thickness of bare wire=0.162"=0.41148 cm.

Thickness of two insulations $\frac{98.425}{129} - 0.41148 = 0.763 - 0.4115 = 0.3515$ cm. This is to be added to the core 12.7 cm diam. making total diam. 13.0515 cm.

To calculate inductance we have therefore the following data:

$$d = 13.0515 \text{ cm, } l_1 = 98.425 \text{ cm, } N = 129, N^2 = 16641, S = \frac{\pi}{4} d^2 = 133.786 \text{ cm.sq.}$$

$$\text{This gives } l = \frac{12.5664}{98.425} \times 16,641 \times 133.786 = 284,247 \text{ cm.}$$

Now the readings to estimate from were:

e.m.f.	Current	ω	R calculated approx. 180 feet wire 2535ft. per ohm	$\frac{E}{I} = 0.271$ $\left(\frac{E}{I}\right)^2 = 0.073441$
13.3	49.1	880		
13.3	49.1	880	0.071 ohm	$R^2 = 0.00504$
13.3	49.1	880		$\left(\frac{E}{I}\right)^2 - R^2 = 0.0684$

from this:

$$l = \frac{\sqrt{0.0684}}{880} = \frac{0.2615}{880} \text{ H or } \frac{261,500,000}{880} = 297,160 \text{ cm.}$$

Small correction should have been made for the e.m.f. making it smaller, this would have made the agreement with the calculated value close.

Coil wound with No 2 wire

Readings were:			Resistance will be negligible	} $l_1 = \frac{E}{I\omega} = \frac{6.6}{49.1 \times 880} =$ $= \frac{6.6}{491 \times 88} \text{ H}$ or $= \frac{66 \times 10^8}{491 \times 88} \text{ cm}$ $l_1 = 152,750 \text{ cm.}$
e.m.f.	Current	ω		
6.6	49.1	880		
6.6	49.1	880		
6.6	49.1	880		

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is barely visible when the slide $\perp$ is on the point giving the maximum rise in the exciter system. By a little experience it becomes easy to thus locate the maximum within $\frac{1}{2}$ of one per cent. By resorting however to ordinary experience resources it is practicable to reach greater precision still. Of course the greater the non-variation of the exciter system the better it is. There are indeed instruments or detection of all kinds which allow the method to be applied to any degree desired. A very simple improvement, effective and ready on hand is however to provide a source of energy for bringing the filament or wire just to a point when its luminosity can be detected by the observer. I connect the loop to a battery of constant e.m.f. through the checking coils graduating the turn of the latter so that the filament is brought just to the required temperature. A small amount of surplus energy supplied from the secondary loop is then sufficient to make the filament bright. Thus, less energy is taken from the exciter system and the location of the maximum is undisturbed and more easy. Diagram below illustrates this arrangement in its simplest form. The high frequency current can not of course pass through the checking coils. This method is also



very suitable for timing circuits for many purposes as in telegraphy. In the present experiments the coil before described: 1314 turns with $\frac{1}{2}$ in. dia. on diam. 14" diam. & feet long was used the object

The dimensions are as follows:

diam. core 5" = 12.7 cm, length of core 38.25"=97.185 cm. Turns 91. The diam. of wire insulation is $\frac{97.185}{91}=1.068$ cm. Diam. of bare wire 0.2576"=0.6543 cm. This gives for 2 thicknesses 1.068 - 0.6543=0.4137 cm.

From this:

$$d=13.1137 \text{ cm.}; \quad l'=97.185 \text{ cm.}; \quad N=91; \quad N^2=8281;$$

$$S=\frac{\pi}{4}d^2=145.0644 \text{ sq. cm. } l_1=\frac{4\pi}{l'}N^2S=155,330 \text{ cm.}$$

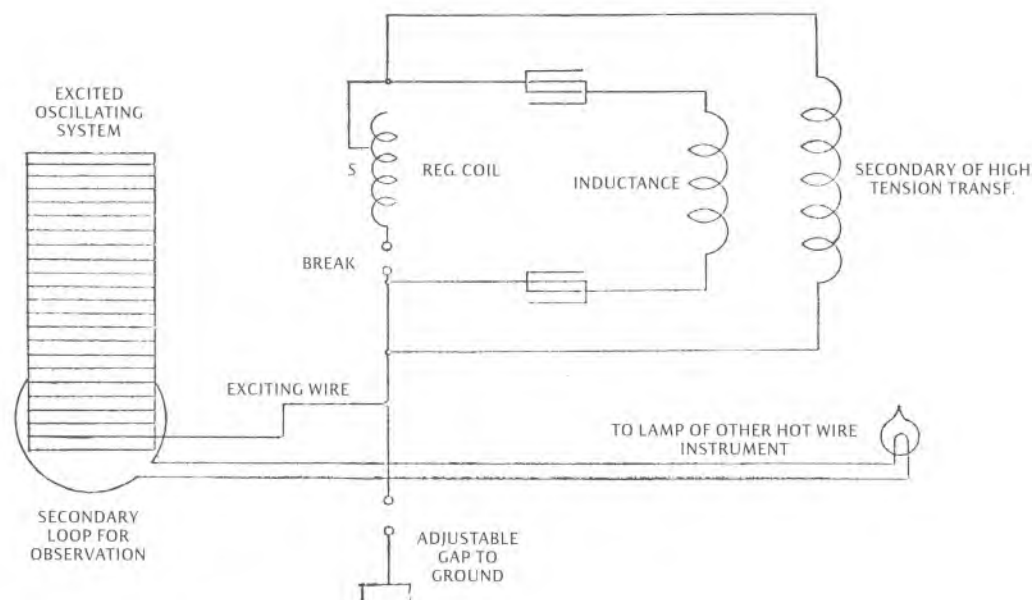
Probably resistance is not quite negligible, but results are close enough for ordinary use of coil.

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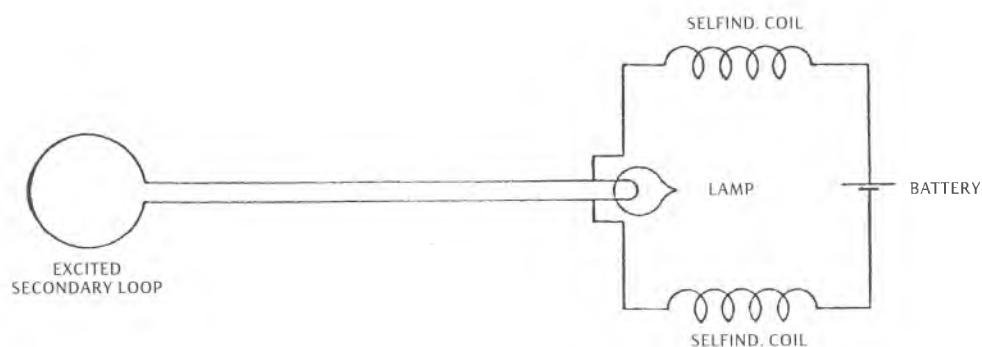
Measurements of the effective capacity of a vertical wire as modified by elevation, by resonance analysis and improved method of locating the maximum rise of e.m.f. on the excited system

In the previous experiments on the same subject the maximum was located by observing a spark, but it was found that this mode of reading has a number of defects. One of these is the necessity of using spark wires, another the impossibility of locating the maximum very closely – except in cases when the tuning is very sharp. But when considerable capacity is in the system, as it must necessarily be when investigating the modification of capacity, the tuning can never be quite sharp. When the pressures on the excited coil are large spark wires also entail considerable loss, which modifies and vitiates the results of the observations. By the spark method it is also impossible to determine the period and capacity of the excited system itself without any attachments.



In the succeeding observations a method practised in New York was resorted to. This consists of employing a small secondary circuit in feeble inductive connection with the excited system and

observing in a convenient manner by a suitable instrument the changes of current or e.m.f. in the secondary. A practical and quite convenient means is to insert a minute lamp consuming but a very small fraction of the normal current and observe the degree of incandescence of the minute carbon filament or thin platinum wire. As the small secondary circuit exercises no appreciable reaction on the excited oscillating system owing to the feeble mutual induction and minute amount of energy consumed in the secondary, the method is excellent and allows close and reliable readings much more so than the spark wire method. By taking a minute lamp with an exceptionally thin and short filament the energy consumed for the readings is quite insignificant and may be less than one millionth part of the activity of the oscillating system. In the diagram below the arrangement of apparatus as used is illustrated. The excitation was again conveniently varied by an adjustable ground gap. In the secondary circuit feeding the minute lamp it was also of advantage to provide a *continuously* regulable resistance by means of which the brightness of the filament could be reduced to any degree desired. The current from the supply transformer was also regulable as this was necessary in the course of the experiments. Usually I find it advantageous to proceed as follows: first the maximum is located on the proper place of the regulating coil by altering the capacity of the primary circuit until the maximum rise takes place with the contact slide S at the desired point of the regulating coil. A few turns to either side will generally extinguish the lamp. The maximum being thus roughly located, the brightness of the lamp is reduced by inserting resistance or otherwise – as by placing the secondary circuit feeding it farther from the excited system – until the filament is barely visible when the slide S is at the point giving the maximum rise on the excited system. By a little experience it becomes easy to thus locate the maximum within $\frac{1}{4}$ of one per cent. By resorting however to ordinary experimental resources it is practicable to reach greater precision still. Of course, the greater the momentum of the excited system the better it is. There are hot wire instruments or detectors of all kinds which allow the method to be refined to any degree desired. A very simple improvement, effective and readily on hand is however to provide a source of energy for bringing the filament or wire just, to a point when its luminosity can be detected by the observer. I connect the lamp to a battery of constant e.m.f. through two choking coils graduating the turns of the latter so that the filament is brought preliminarily to the required temperature. A small amount of surplus energy supplied from the secondary loop is then sufficient to make the filament bright. Thus, less energy is taken from the excited system and the location of the maximum is rendered much more easily. The diagram below illustrates this arrangement in its simplest form. The high frequency currents can not of course pass through the choking coils. This method is also very suitable for tuning circuits for many purposes as in telegraphy.



In the present experiments the coil before described: 1314 turns wire № 18 on drum 14" diam., 8 feet long was used, the object of the tests being to determine the effective capacity of the vertical wire № 10, 50 feet long which was used in a number of cases before dwelt upon. The readings were as follows:

Coil 1314 turns with spark wires as before used

Capacity in primary circuit	Inductance in primary circuit
$\frac{46}{2} = 23$ bottles = 0.0207 mfd.	16 Turns of regul. coil + connections + coil № 6 wire

Note: This reading was taken to test the spark wire method. The agreement was fairly close 15 ½ turns being found in the previous measurements by spark analysis instead of 16 turns as now. But this was to be expected as with the *spark wires alone*, the capacity being small the tuning is very sharp. The agreement would probably not be quite so close when a large capacity is connected to the excited system.

Coil 1314 turns alone without spark wires

$\frac{20}{2} = 10$ bottles = 0.009 mfd.	12 ½ turns + conn. + coil № 6 wire
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Coil 1314 turns with vertical wire №10 approx. 50 feet long

$\frac{70}{2} = 35$ bottles = 0.0315 mfd.	18 ½ turns + conn. + coil № 6 wire
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The inductance of primary circuit in the first case was:

Coil № 6 wire	284,000 cm	}	total 326,300 cm.
12 ½ turns + conn.	42,300 cm		

In the second case it was:

Coil № 6 wire	284,000 cm	}	total 349,400 cm.
18 ½ turns + conn.	65,400 cm		

Calling as before C_{s1} and C_{s2} respectively the capacities of the excited system with and without the vertical wire we have:

$$C_{s1} \times \frac{87,300,000}{10^9} = \frac{349,400}{10^9} \times 0.0315 *$$

$$C_{s1} = \frac{3494 \times 0.0315}{873,000} \text{ mfd.}$$

* the inductance of excited coil from data obtained before being 87,300,000 cm.

Similarly from the preceeding it follows:

$$C_{s2} = \frac{3263 \times 0.009}{873,000} \text{ mfd.}$$

This gives the capacity of the vertical wire:

$$C_{s1} - C_{s2} = \frac{3494 \times 0.0315 - 3263 \times 0.009}{873,000} = \frac{110.061 - 29.367}{873,000} = \frac{80.694}{873,000} \text{ mfd,}$$

or in centimeters:

$$C = C_{s1} - C_{s2} = \frac{9 \times 10^5 \times 80.694}{873,000} = \frac{72,624.6}{873} = 83.2 \text{ cm.}$$

The calculated value before found was 81.5 cm. It is assumed in the calculation that the length of the wire was 50 feet exactly, but this might not be so. It will be measured exactly when taken down. The inductance of the coil with wire № 6 has been taken as 284,000 cm. but the measured values are higher. Taking the average of two measurements we have about 295,000 cm. This would give a higher value for the effective capacity of the vertical wire. It is also possible that the inductance of the excited coil might be a few percent different from that serving as the basis of this estimation.

It is of interest to determine from above data the capacity of the excited coil alone. The same is:

$$C_{s2} = \frac{3263 \times 0.009 \times 9 \times 10^5}{873,000} = 30.3 \text{ cm, approx.}$$

A cylinder of the dimensions of the coil excited would have a capacity $C = \frac{l}{2 \log_e \frac{l}{r}}$.

Here $l = 8' = 243.84 \text{ cm.}$

$r = 7'' = 17.78 \text{ cm.}$

$$\frac{l}{r} = 13.71 \log_e \frac{l}{r} = 1.137037 \times 2.3 = 2.6152$$

$$C = \frac{243.84}{2 \times 2.6152} = 46.6 \text{ cm.}$$

Consider now as much of the cylindrical surface as could be covered with the bare wire on the coil:

№ 18 wire diam. = 0.0403" = 0.1024 cm. As there are 1314 turns the wire would cover $1314 \times 0.1024 \text{ cm} = 134.55 \text{ cm.}$

Compared with the cylinder of the length of 243.84 cm the capacity C_1 of the shortened would be in the proportion of 134.55 : 243.84 reduced, that is

$$C_1 \text{ would be } \frac{134.55}{243.84} \quad C = \frac{134.55}{243.84} \times 46.6 = \text{approx. } 26 \text{ cm.}$$

From this it would seem that a rough estimate of the capacity of such a coil might be obtained by comparison with a cylindrical surface which the bare wire would cover.

Further experiments to ascertain the dependence of capacity upon elevation.

In these experiments the new coil, wound with a much greater number of turns for the purpose of getting a vibration of lower frequency, was used. This coil was wound on the same drum of 14" diam. and 8 feet length repeatedly used. It had 1314 turns of № 18 wax covered wire. As the length of the coil and area of the coils remained exactly the same the self-induction was approximately estimated from the inductance of another coil experimented with before. The latter had 689 turns and its measured inductance was 24,000,000 cm. On this basis the inductance of the new coil was $L \left(\frac{1314}{689} \right)^2 = ?$, L being the self-induction of the coil referred to. This would give for $L_1 = \left(\frac{1314}{689} \right)^2 \times 20,000,000 = 3.637 \times 24,000,000 = 87,288,000 \text{ cm}$ approximately. Comparing it with another coil before described which was wound on the same drum and had 346 turns, and taking the before measured value of the inductance of the latter 6,040,000 cm we get

$$L_1 = \left(\frac{1314}{689} \right)^2 \times 6,040,000 = 14.4225 \times 6,040,000 = 87,111,900 \text{ cm},$$

which is very nearly the same value.

Rough readings gave:

$$E=200 \quad I=2.5 \quad \omega=870$$

from this: $\frac{E}{I} = 80$

$$\left(\frac{E}{I} \right)^2 = 6,400$$

R calculated: 4816 feet wire
 № 18 156.9 feet per ohm:
 $R=30.7$ ohm (31.68 meas.)

$$R^2 = 942.5$$

$$\left(\frac{E}{I} \right)^2 - R^2 = 5457.5$$

$$\sqrt{\left(\frac{E}{I} \right)^2 - R^2} = 73.88 \text{ approx.}$$

Inductance nearly 85,000,000 cm.

For the present investigation the most probably value 87,300,000 cm will be adopted, which is still to be verified.

With the coil before described experiments were made for the purpose of once more determining the capacity of the structure of iron pipes. The adjustments were as follows:

For coil with structure connected to free terminal:

Capacity in primary circuit	Inductance of primary circuit
$\frac{(6 \times 36) - 2 + 12}{2} = 133 \text{ bottles} = 0.1017 \text{ mfd}$	21 turns regulating coil+conn. +coil wound with wire № 6 before described

For coil with the spark wires alone:

$\frac{46}{2} = 23 \text{ bottles} = 0.0207 \text{ mfd}$	5 ½+conn+coil № 6 wire.
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In the first case inductance of the primary was =359,000 cm.

Coil № 6 wire 284,000 cm.
 21 turns+conn. 75,000 cm

In the second case

Coil № 6 wire 284,000 cm
 15 ½ turns+conn. 54,000 cm } =338,000 cm.

Calling C_{s1} capacity of the excited system in first and C_{s2} in the second case we have:

$$\frac{2\pi}{10^3} \sqrt{\frac{87,300,000}{10^9} C_{s1}} = \frac{2\pi}{10^3} \sqrt{\frac{359,000}{10^9} \times 0.1017} \text{ and}$$

$$C_{s1} = \frac{\frac{359}{10^6} \times 0.1017}{\frac{873}{10^4}} = \frac{359 \times 0.1017}{87,300} \text{ mfd}$$

$$\text{or in cm } C_{s1} = \frac{9 \times 10^5 \times 359 \times 0.1017}{87.300} = 376.4 \text{ cm.}$$

$$\text{Similarly we have: } \frac{2\pi}{10^3} \sqrt{\frac{87,300,000}{10^9}} C_{s2} = \frac{2\pi}{10^3} \sqrt{\frac{338,000}{10^9}} \times 0.0207 \text{ and}$$

$$C_{s2} = \frac{338,000 \times 0.0207}{87,300,000} \text{ mfd or } C_{s2} = \frac{338 \times 0.0207 \times 9 \times 10^5}{87,300} \text{ cm} = \frac{3042 \times 20.7}{873} = 71.67 \text{ cm.}$$

From this we get *effective capacity* of structure:

$$C_{s1} - C_{s2} = 376.4 - 71.67 = 304.73 \text{ cm,}$$

which is a value very closely before found with *extra coil*.

Note: The readings with spark gap as before practiced are not quite satisfactory and a new method will be tried in the next experiments.

Colorado Springs

Nov. 11, 1899

Experiments for the purpose of ascertaining rate of increase of capacity with elevation continued.

Again the coil with 1314 turns described before was used and the method of locating the maximum rise of potential on the excited system by means of a small circuit inductively connected to the system was resorted to. A few improvements carried out in the mode of using the induced circuit allowed closer readings than it was possible to obtain before with spark observation.

The coil was first tuned alone, without anything being attached to the free terminal. Next the vertical wire No 10, 50 feet long (approximately) was attached to the free terminal and the tuning again effected, both the primary vibrations being carefully noted. Then a ball 30" diam. was slipped on to the vertical wire and readings were taken in three different positions of the ball along the wire as before. The results of the observations were as follows:

I. Coil alone

Capacity in primary or exciting circuit	Inductance in primary circuit
$\frac{20}{2} = 10 \text{ bottles} = 0.009 \text{ mfd}$	Turns of reg. 13 coil+conn+coil No 6 wire

II. Coil with vertical wire No 10, 50 feet approx.

$\frac{72}{2} = 36 \text{ bottles} = 0.0324 \text{ mfd}$	17+conn.+coil No 6 wire
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III. Coil with ball 30" diam. vertical wire, the ball being at a height of 10'3" from center to ground.

Capacity in primary or exciting circuit	Inductance in primary circuit
$\frac{86}{2} = 43 \text{ bottles} = 0.0387 \text{ mfd}$	13 1/2+conn.+coil No 6 wire

IV. Coil with ball 30" diam. and vertical wire, the ball being at a height of 34 feet from center to ground.

$\frac{86}{2} = 43 \text{ bottles} = 0.0387 \text{ mfd}$	14 1/2+conn.+coil No 6 wire Note: (it seemed slightly more than 14 1/2 turns)
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V. Coil with ball 30" diameter and vertical wire, the ball being at a height of 57'9" from center to ground.

$\frac{86}{2} = 43 \text{ bottles} = 0.0387 \text{ mfd}$	16 1/2+conn.+coil No 6 wire
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In the first case the inductance of primary circuit was

$$\begin{array}{rcl} \text{Coil No 6 wire} & = & 295,000 \text{ cm} \\ 13 \text{ turns+connections} & = & 43,300 \text{ cm} \\ \text{total} & = & 338,300 \text{ cm} \end{array}$$

The primary vibration was therefore:

$$T_{p1} = \frac{2\pi}{10^3} \sqrt{0.009 \times \frac{3383}{10^7}}$$

Now calling C_{s1} capacity of excited system in the first case we have:

period of excited system

$$T_{s1} = \frac{2\pi}{10^3} \sqrt{C_{s1} \times \frac{85}{10^3}}$$

From this:

$$\begin{aligned} C_{s1} &= \frac{0.009 \times \frac{3383}{10^7}}{\frac{85}{10^3}} = \frac{0.009 \times 3383}{85 \times 10^4} \text{ mfd, or in centimeters:} \\ C_{s1} &= \frac{9 \times 10^5 \times 0.009 \times 3383}{85 \times 10^4} = \frac{0.81 \times 3383}{85} = 31.84 \text{ cm.} \end{aligned}$$

This is slightly larger than before found owing to adoption of smaller inductance for excited coil.

Note: In some estimates before the inductance of this coil was calculated to be a little over 284,000 cm. and this value was taken. But two measurements made before show average of about 295,000 cm. and this value will be assumed in present estimates as being more probable until again careful measurements will be made. The results are then to be corrected.

Note: The inductance for ex-cited coil is taken 85,000,000 cm., this being the value obtained by measurement.

Still to be verified.

In case II. the inductance of the primary circuit was:

$$\left\{ \begin{array}{ll} \text{Coil N}^\circ 6 \text{ wire as before:} & 295,000 \text{ cm} \\ 17 \text{ turns+connection} & 59,700 \text{ cm} \end{array} \right\} \text{ total} = 354,700 \text{ cm}$$

The primary period was:

$$T_{p2} = \frac{2\pi}{10^3} \sqrt{0.0324 \times \frac{3547}{10^7}} \text{ and the secondary corresponding } T_{s2} = \frac{2\pi}{10^3} \sqrt{C_{s2} \times \frac{85}{10^3}}$$

$$\text{Hence } C_{s2} = \frac{0.0324 \times 3547}{85 \times 10^4} \text{ mfd, or } C_{s2} = \frac{9 \times 10^5 \times 0.0324 \times 3547}{85 \times 10^4} \text{ cm.}$$

$C_{s2} = 121.68 \text{ cm}$. Hence capacity of the vertical wire will be approximately

$C_{s2} - C_{s1} = 89.84 \text{ cm}$. This is again larger than before found but probably closer than the former value.

In case III. the primary inductance was:

$$\left\{ \begin{array}{ll} \text{Coil N}^\circ 6 \text{ wire} & 295,000 \\ 13 \frac{1}{2} \text{ turns+conn.} & 46,200 \end{array} \right\} \text{ total} = 341,200 \text{ cm}$$

The primary vibration was therefore:

$$T_{p3} = \frac{2\pi}{10^3} \sqrt{0.0387 \times \frac{3412}{10^7}}$$

and the corresponding vibration of the excited system

$$T_{s3} = \frac{2\pi}{10^3} \sqrt{C_{s3} \times \frac{85}{10^3}}$$

from this we have:

$$C_{s3} = \frac{0.0387 \times \frac{3412}{10^7}}{\frac{85}{10^3}} = \frac{0.0387 \times 3412}{85 \times 10^4} \text{ mfd,}$$

or

$$C_{s3} = \frac{9 \times 10^5 \times 0.0387 \times 3412}{85 \times 10^4} = 139.81 \text{ cm.}$$

The effective capacity of the ball at its lowest position (10' 3") from ground was therefore only $C_{s3} - C_{s2} = 139.81 - 121.68 = 18.13 \text{ cm}$.

Now taking cases IV. and V. the primary inductance in the

first of these cases was $\left\{ \begin{array}{ll} \text{Coil N}^\circ 6 \text{ wire} & 295,000 \text{ cm} \\ 14 \frac{1}{2} \text{ turns} & 50,100 \text{ " } \end{array} \right\}$

the total would be 345,100 cm. But there is still a doubt whether there have not been 15 turns instead of 14 1/2. This is to be borne in mind. Taking for the present for the inductance 14 3/4 turns as most probable and nearer to the average value of both extreme readings in IV. and V. we have for inductance of the primary 346,000 cm.

Now in case V. the inductance was: $\left\{ \begin{array}{ll} \text{Coil N}^\circ 6 \text{ wire} & 295,000 \text{ cm} \\ 16 \frac{1}{2} \text{ turns} & 57,800 \text{ " } \end{array} \right\}$ Coil total 352,800 cm.

Now since in cases III, IV. and V. the capacity in the primary circuit was not varied we have:

$$C_{s3} : C_{s4} = 341,200 : 346,000 \text{ and } C_{s4} = C_{s3} \times \frac{346}{341} = 141.78 \text{ cm.}$$

and similarly we have:

$$C_{s3} : C_{s5} = 341,200 : 352,800 \quad \text{и} \quad C_{s5} = C_{s3} \times \frac{3528}{3412} = 144.56 \text{ cm.}$$

The effective capacity of ball at its highest position was:

$$C_{s5} - C_{s2} = 144.56 - 121.68 = 22.88 \text{ cm.}$$

In the mean position the value was: $C_{s4} - C_{s2} = 20.1$ cm. whereas the mean value between 22.88 and 18.13 would be 20.5 cm. The rise is therefore *linear*. The rise in the effective capacity for 47 feet and 6" was $\frac{18.13}{22.88 - 18.13}$ about 26.2%. Per one *hundred feet* it would be from this: 55.16% or a little over ½% per foot.

Colorado Springs

Nov. 12, 1899

Measurements of the effective capacity of the elevated structure of iron pipes were again made today in the manner described before, by means of resonance analysis, the maximum rise of potential on the excited system being determined by a minute lamp included in a secondary circuit without appreciable reaction upon the excited system. The coil with 1314 turns before described was again used, the readings being as follows:

Coil with structure attached:

Capacity in primary circuit	Inductance in primary circuit turns reg. coil
$\frac{(6 \times 36) + 12}{2} = \frac{228}{2} = 114$ bottles or 0.1026 mfd.	15+conn.+coil № 6 wire

Coil alone, without structure, only connecting wire:

$\frac{(36 - 2) + 12}{2} = \frac{42}{2} = 21$ bottles=0.0189 mfd	7 ½ + conn.+coil № 6 wire
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The inductance in primary in first case was:

Coil № 6 wire	295,000 cm
15 turns+conn.	52,000 cm
total	347,000 cm

The inductance in primary in second case was:

Coil № 6 wire	295,000 cm
7 ½ turns+conn.	23,600 cm
total	318,600 cm

If C_{s1} and C_{s2} be the capacities of the excited system *with* and *without* structure, respectively, then:

$$C_{s1} = \frac{\frac{347,000}{10^9} \times 0.1026}{\frac{87,300,000}{10^9}} = \frac{3470 \times 0.1026}{873,000} \text{ mfd.,}$$

Colorado Springs Nov. 14. 1899

on some experiments with wire having 1314 turns wound on drum 14' diam. & feet long the wire was cut in the middle and the two parts 657 turns each connected in multiple. The self-induction was then practically $\frac{1}{4}$ of the self-induction which it had when ordinary. Readings were taken to determine the inductance when the two parts were connected in series.

These readings were:

$$E.M.F. \begin{cases} 214 \\ 212 \\ 210 \end{cases}$$

$$C \begin{cases} 10.7 \\ 10.6 \\ 10.5 \end{cases}$$

$$W = 880 \quad \text{Average values:}$$

E	C	W
214	10.6	880

$$R = 7.9 \text{ ohms}$$

$$\text{from this } \left(\frac{E}{C}\right) = 20, \quad \left(\frac{E}{C}\right)^2 = 400 \quad R^2 = 62.41$$

$$\left(\frac{E}{C}\right)^2 - R^2 = 337.59 \quad \sqrt{\left(\frac{E}{C}\right)^2 - R^2} = 18.375$$

$$L = \frac{18.375 \times 10^9}{880} \text{ C.M.}$$

$$= 20880682 \text{ C.M. approx} = 20,881,000 \text{ C.M.}$$

The inductance of the wire as ordinarily used would then be approx.

$$= \underline{\underline{83,524,000 \text{ C.M.}}}$$

and similarly

$$C_{s2} = \frac{3186 \times 0.0189}{873,000}$$

and

$$C_{s1} - C_{s2} = \frac{3470 \times 0.1026 - 3186 \times 0.0189}{873,000} \text{ mfd} = \frac{356.022 - 60.2154}{873,000} \text{ mfd},$$

or

$$\frac{9 \times 10^5 \times 295.8066}{873,000} = 304.95 \text{ cm.}$$

This is again a value close to that found with new extra coil. The agreement would be closer still if some connections would be taken in the present instance. I conclude effective capacity is not far from this.

Colorado Springs

Nov. 13, 1899

An improvement in the method of locating the maximum rises in the excited system has been effected by taking a lamp with an exceptionally thin filament, consuming only a minute fraction of an ampere, for being heated to redness enough to be perceptible, and furthermore by placing the lamp in a dark box. A "fluoroscope" was used, two holes being drilled in the sides of the box for leading the wires in. By these provisions the readings were made more exact. The new extra coil was again used for trial and the capacity of the structure of iron pipes was again determined. The readings were:

With structure attached

Capacity in primary circuit	Inductance in primary circuit
$\frac{(8 \times 36)}{2} = 144$ bottles = 0.1296 mfd	Turns + connections 18 1/2 + connections

Without structure (only connecting wire)

$\frac{(8 \times 36)}{2} = 144$ 0.1296 mfd	6 5/16 + conn.
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Note: In the second case the tuning was, of course, very sharp and it was easy to locate the maximum within 1/16 of a turn of the regulating coil; in the first case, although it was naturally less sharp, it was still easy to locate within 1/4 of a turn; with great care within 1/8 of a turn. This may be said to be within 1/2% which is satisfactory, all the more as the reading is very positive.

The above results give an inductance in the primary circuit, in the first case 65,442 cm, in the second 19,578 cm, computed from the table before prepared. As the capacity in the primary remained the same in both readings we have, calling C_{s1} and C_{s2} capacities of the excited system *with* and *without* structure and L inductance of the extra coil: $L = 0.02$ henry

$$C_{s1} - C_{s2} = \frac{0.1296(65,442 - 19,578) \times 9 \times 10^5}{20,000,000} \text{ cm} = 267.48 \text{ cm.}$$

These readings seem most reliable so far.

Colorado Springs

Nov. 14, 1899

In some experiments with coil having 1314 turns wound on drum 14" diam., 8 feet long the coil was cut in the middle and the two parts, 657 turns each connected in multiple.

The self-induction was then practically $\frac{1}{4}$ of the self-induction which it had used ordinarily. Readings were taken to determine the inductance when the two parts were connected as stated.

These readings were:

e.m.f. $\left\{ \begin{matrix} 214 \\ 212 \\ 210 \end{matrix} \right\}$

$I \left\{ \begin{matrix} 10.7 \\ 10.6 \\ 10.5 \end{matrix} \right\}$

$\omega=880$

Average values:

E	I	ω
212	10.6	880

from this $\frac{E}{I}=20$, $\left(\frac{E}{I}\right)^2=400$

$R=7.9$ ohm.
 $R^2=62.41$

$\left(\frac{E}{I}\right)^2-R^2=337.59$ $\sqrt{\left(\frac{E}{I}\right)^2-R^2}=18.375$

$L=\frac{18.375 \times 10^9}{880}$ cm = 20,880,682 cm, approx.=20,881,000 cm.

The inductance of the coil as ordinarily used would then be approx.
=83,524,000 cm.

Colorado Springs

Nov. 15, 1899

Experiments with secondary of oscillator to determine capacity of structure, also capacity of secondary

The readings were as follows:

Secondary alone.

Capacity in primary	Inductance in primary
$\frac{8 \times 36}{2}=144$ bottles=0.1296 mfd	14 $\frac{3}{4}$ turns+connections.

Secondary with connecting wire leading to structure.

$\frac{8 \times 36}{2}=144$ bottles=0.1296 mfd	15 $\frac{1}{4}$ turns+connections.
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Secondary with structure connected to free terminal.

$\frac{8 \times 36}{2} = 144$ bottles = 0.1296 mfd	19 turns + connections.
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* These readings approximate.

In first case inductance of primary was 51,000 cm
 " second " " 52,900 " }
 " third " " 67,400 "

* All these readings and maybe previous ones to be revised.

Taking the inductance of secondary from measurements before made 9,557,000 cm. we have for C_{s1} , that is, capacity of secondary alone:

$$\left. \begin{aligned} T_{p1} &= \frac{2\pi}{10^3} \sqrt{\frac{51,000}{10^9} \times 0.1296} \\ T_{s1} &= \frac{2\pi}{10^3} \sqrt{\frac{9,557,000}{10^9} \times C_{s1}} \end{aligned} \right\} \begin{aligned} C_{s1} &= \frac{0.1296 \times 51,000}{9,557,000} = \frac{0.1296 \times 51}{9557} \text{ mfd} \\ C_{s1} &= \frac{9 \times 10^5 \times 0.1296 \times 51}{9557} = 622.23 \text{ cm.} \end{aligned}$$

Now calling C_{s2} and C_{s3} respectively, the capacities of the secondary system with the connecting wire and with wire and structure respectively, since the capacity in the primary was in all cases the same, we have:

$$C_{s1} : C_{s2} = 51,000 : 52,900 \text{ and } C_{s1} : C_{s3} = 51,000 : 67,400$$

and

$$C_{s2} = \frac{52,900}{51,000} \times 622.23 = \frac{529}{510} \times 622.23 = 645.41 \text{ cm.}$$

This gives capacity of connecting wire alone:

$$C_{s2} - C_{s1} = 645.41 - 622.23 = 23.18 \text{ cm.}$$

Similarly we have:

$$C_{s3} = \frac{67,400}{51,000} C_{s1} = \frac{674}{510} \times 622.23 = 822.32 \text{ cm,}$$

and from this the capacity of the structure (the effective capacity) would be:

$$C_{s3} - C_{s2} = 822.32 - 645.41 = 176.91 \text{ cm.}$$

But since

$$C_{s3} : C_{s2} = 67,400 : 52,900 = 674 : 529$$

we have $C_{s3} =$

$$C_{s3} = \frac{674}{529} C_{s2} = \frac{674}{529} \times 645.41 = 818.54 \text{ cm.}$$

This value checks those formerly found and shows that the readings were fairly close. The test shows however that this method of determining capacity will only give a correct value when the distributed capacity is quite negligible. This observation has already been made.

Colorado Springs

Nov. 16, 1899

Experiments continued on the influence of elevation upon capacity of system connected to earth

A new coil wound on drum 14" diam., 8 feet long was used. It had 344 turns № 10 wire. From the fact that another coil with 346 turns had an inductance of a little over 6,000,000 cm. it is not far away to take the inductance of this coil at that figure.

In the experiments presently described a length of wire № 12 was used (15 meters long.) The object was to ascertain the capacity of the wire used in connection with the coil. The results of the readings were as follows:

Coil alone without vertical wire.

Capacity in primary circuit	Inductance in primary circuit
$\frac{36}{2} = 18 \text{ bottles} = 0.0162 \text{ mfd}$	$4 \frac{13}{16} \text{ turns} + \text{connections.}$

Coil with vertical wire №12, 15 meters long.

$\frac{36}{2} = 18 \text{ bottles} = 0.0162 \text{ mfd}$	$14 \frac{3}{4} \text{ turns} + \text{conn.}$
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The inductance in primary in the first case was 14,530 cm. In second case 51,000 cm, approx.

If C_{s1} and C_{s2} be again the capacity of the excited system in the first and second case respectively, we have by analogy from previous experiments:

$$C_{s1} = \frac{\frac{14,530}{10^9} \times 0.0162}{\frac{6,000,000}{10^9}} = \frac{14,530 \times 0.0162}{6 \times 10^6} \text{ mfd}$$

$$\text{or } C_{s1} = \frac{9 \times 14,530 \times 0.0162 \times 10^5}{6 \times 10^6} = 35.3 \text{ cm.}$$

Since the capacity in the primary circuit remained the same in both experiments, we have:

$$C_{s1} : C_{s2} = 14,530 : 51,000 \text{ and } C_{s2} = \frac{5100}{1453} C_{s1} = \frac{5100}{1453} \times 35.3 = 121.15 \text{ cm.}$$

Hence the capacity of wire alone

$$C_{s2} : C_{s1} = 121.15 - 35.3 = 85.85 \text{ cm.}$$

This is the actual or effective capacity of the wire as used with the coil. But the calculated capacity would be

$$C = \frac{l}{2 \log_e \frac{l}{r}}$$

Here $l = 15 \text{ meters} = 1500 \text{ cm}$
 $r = 0.08081" = 0.20256 \text{ cm}$

$$\frac{l}{r} = 7308$$

$$\log_e \frac{l}{r} = 3.863799 \times 2.3 = 8.887$$

$$C = \frac{1500}{2 \times 8.887} = \frac{1500}{17.774} = 84.4 \text{ cm.}$$

According to this estimate the effective capacity would be only about 1.7% larger than the calculated capacity.

Colorado Springs

Nov. 17, 1899

Experiments to ascertain capacity of various lengths of vertical wire

Coil with 344 turns and № 10 on drum 14" diam., 8 feet long was used. The wire to be tested was № 12 of a length of 15 meters. The full length was first connected to the free terminal of the coil excited as usual and then 3 meters were cut off each time and the adjustment of the primary circuit made. The results are indicated below:

Capacity in primary circuit	Length of vertical wire	Inductance in pr. cir.
$\frac{22}{2} = 11$ bottles=0.0099 mfd	15 meters	21 ½ turns+conn.
$\frac{22}{2} = 11$ bottles=0.0099 mfd	12 meters	19 turns+conn.
$\frac{22}{2} = 11$ bottles=0.0099 mfd	9 meters	16 ¼ turns+conn. 17 turns+conn.
$\frac{22}{2} = 11$ bottles=0.0099 mfd	6 meters	13 ¾ turns+conn. 13 ⅝ turns+conn.
$\frac{22}{2} = 11$ bottles=0.0099 mfd	3 meters	10 ½ turns+conn.
$\frac{22}{2} = 11$ bottles=0.0099 mfd	0 meters	7 ⅜ turns+conn.

Approximate estimates from the above readings:

The inductance of coil 344 turns is assumed to be 6×10^6 cm. which is still to be confirmed by close measurement. The inductance of primary when no wire was attached was $7 \frac{3}{8}$ turns + conn.=23,157 cm. With 3 meters wire attached it was $10 \frac{1}{2}$ +conn. = 34,642 cm. Hence calling C_{s1} and C_{s2} the capacities of the excited system, in the two cases respectively we have:

$$T_{p1} = \frac{2\pi}{10^3} \sqrt{0.0099 \times \frac{23,157}{10^9}}$$

$$T_{s1} = \frac{2\pi}{10^3} \sqrt{\frac{6 \times 10^6}{10^9} C_{s1}}$$

$$T_{p2} = \frac{2\pi}{10^3} \sqrt{0.0099 \times \frac{34,642}{10^9}}$$

$$T_{s2} = \frac{2\pi}{10^3} \sqrt{\frac{6 \times 10^6}{10^9} C_{s2}}$$

$$C_{s1} = \frac{0.0099 \times 23,157}{6 \times 10^6} \text{ mfd, or in centimeters:}$$

$$C_{s1} = \frac{9 \times 0.0099 \times 23,157}{60} = 34.386 \text{ cm}$$

and since the capacity in the primary circuit was the same in both cases:

$$C_{s2} = \frac{34,642}{23,157} C_{s1} = \frac{34,642}{23,157} \times 34.386 = 51.44 \text{ cm.}$$

The value of effective capacity of the first 3 meters of wire was therefore $C_{s2} - C_{s1} = 51.44 - 34.386 = 17.054 \text{ cm.}$

Calling now C_{s3} the capacity of the excited system when 6 meters of wire connected to it we have, since in this case the inductance of the primary was $13 \frac{3}{4}$ turns+conn.= 47,154 cm.

$$C_{s3} = \frac{47,154}{23,157} C_{s1} = \frac{47,154}{23,157} \times 34.386 = 70.02 \text{ cm.}$$

Hence the value of effective capacity of the second piece of wire 3 meters long was

$$C_{s3} - C_{s2} = 70.02 - 51.44 = 18.58 \text{ cm.}$$

Now in the case when 9 meters of wire were attached the inductance of the primary was $16 \frac{1}{4}$ turns+conn. = 56,779 cm. Calling C_{s4} the corresponding capacity of the excited system we have:

$$C_{s4} = \frac{56,779}{23,157} \times 34.386 = 84.307 \text{ cm}$$

Hence effective value of the 3rd piece of 3 meters length was

$$C_{s4} - C_{s3} = 84.307 - 70.02 = 14.287 \text{ cm.}$$

Note* In another series of readings for 9 meters the inductance of primary was found to be 17 turns+conn. = 59,665 cm, and on this basis I find: $C_{s4} = \frac{59,665}{23,157} \times 34.386 = 88.597 \text{ cm.}$ According to this the effective value of the 3rd piece 3 meters long would then be

$$C_{s4} - C_{s3} = 88.597 - 70.02 = 18.577 \text{ cm.}$$

When 12 meters wire were attached the inductance of primary was found to be 19 turns + conn.=67,367 cm. Hence similarly $C_{s5} = \frac{67,367}{23,157} \times 34.386 = 106.034 \text{ cm,}$ and from this the value of 4th piece of wire

$C_{s5} - C_{s4} = 106.034 - 84.307 = 21.727 \text{ cm.}$ But according to second reading it would be:

$$106.034 - 88.597 = 17.437 \text{ cm, only.}$$

Finally, when 15 meters were attached the inductance in primary was: $21 \frac{1}{2}$ turns+conn.=73,142 cm, and therefore: $C_{s6} = \frac{73,142}{23,157} \times 34.386 = 108.609 \text{ cm.}$ and this would give as value of the last piece of three meters

$$C_{s6} - C_{s5} = 108.609 - 106.034 = 2.575 \text{ cm only.}$$

Here possibly inductance of wire begins to assert itself. These values as found are still to be considered.

Colorado Springs

Nov. 18, 1899

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Experiments were continued to ascertain influence of elevation upon capacity of a system connected to earth as in previous instances. Coil 344 turns referred to before was again used. Also wire vertical № 10, 50 feet length and ball 30" diam. The procedure was as in a similar case before. The results were as follows:

Coil without vertical wire.

Capacity in primary	Inductance in primary
$\frac{36}{2} = 18 \text{ bottles} = 0.0162 \text{ mfd}$	$4 \frac{13}{16} \text{ turns} + \text{conn.}$

Coil with vertical wire №10, 50 feet.

$\frac{36}{2} = 18 \text{ bottles} = 0.0162 \text{ mfd}$	$14 \frac{3}{4} \text{ turns} + \text{conn.}$
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Coil with ball 30" diam. slid on vertical wire.

Capacity primary	Height of ball from center to ground	Inductance in primary
$\frac{36}{2} = 18 \text{ bottles} = 0.0162 \text{ mfd.}$	10' 1"	$16 \frac{1}{4} \text{ turns} + \text{conn.}$
$\frac{36}{2} = 18 \text{ bottles} = 0.0162 \text{ mfd.}$	33' 8"	$16 \frac{7}{16} \text{ turns} + \text{conn.}$
$\frac{36}{2} = 18 \text{ bottles} = 0.0162 \text{ mfd.}$	57' 3"	$16 \frac{5}{8} \text{ turns} + \text{conn.}$

On the basis of these readings the following results are obtained: In the first experiment when the wire was attached, the inductance in primary was: $4 \frac{13}{16} \text{ turns} + \text{conn.} = 14,526 \text{ cm}$. Calling again C_{s1} capacity of excited system we have

$$C_{s1} = \frac{0.0162 \times \frac{14,526}{10^9}}{\frac{6 \times 10^6}{10^9}} \text{ mfd}$$

$$C_{s1} = \frac{0.0162 \times 14,526 \times 9 \times 10^5}{6 \times 10^6} = 35,298 \text{ cm.}$$

In the second case with wire 50 long attached to the excited system the capacity of primary being the same as before and the inductance of primary being $14 \frac{3}{4} \text{ turns} + \text{conn.} = 51,004 \text{ cm}$, we have:

$$C_{s2} = \frac{51,004}{14,526} C_{s1} = \frac{51,004}{14,526} \times 35.298 = 3.51 \times 35.298 = 123.931 \text{ cm}$$

Hence capacity of wire

$$C_{s2} - C_{s1} = 123.93 - 35.298 = 88.632 \text{ cm.}$$

Now with ball at its lowest position capacity in primary was as before and inductance $16 \frac{1}{4}$ turns+conn. = 56,779 cm. Hence

$$C_{s3} = \frac{56,779}{14,526} C_{s1} = 3.9088 \times 35.298 = 137.973 \text{ cm.}$$

From this effective value of ball at the height of 10'1" was

$$C_{s3} - C_{s2} = 137.973 - 123.931 = 14.042 \text{ cm.}$$

With ball at a height of 33'8" the inductance in primary was 57,502 cm. and at the height of 57'3" it was 58,223 cm. As the capacity in primary was the same the values for C_{s4} and C_{s5} , respectively, are at once found since

$$C_{s4} = \frac{57,502}{56,779} C_{s3} \text{ and } C_{s5} = \frac{58,223}{56,779} C_{s3}$$

From this we find

$$C_{s4} = 1.0127 \times 137.973 = 139.725 \text{ cm, and } C_{s5} = 1.02543 \times 137.973 = 141.482 \text{ cm.}$$

The effective value of capacity of ball at the height

of 33'8" was $C_{s4} - C_{s2} = 139.725 - 123.931 = 15.794 \text{ cm, and}$

at the height of 57'3" $C_{s5} - C_{s2} = 141.482 - 123.931 = 17.551 \text{ cm.}$

From these results it would appear that from the lowest to the highest position there was an increase of about 25% total or per foot of elevation 0.53%. These readings were made under conditions not the best.

Colorado Springs

Nov. 19, 1899

In order to further investigate effect of elevation upon the capacity of a system as before a cylinder of thin sheet iron 4" in diam. was prepared in sections 2 meter long each, there being 7 sections in all. The separate tubes were slipped one into the other so that when one was taken off each time the total length was shortened by exactly two meters. The cylinder was supported vertically above the coil used in the experiments by means of a cord extending from the wooden structure in previous instances described and the experiments were usually begun with the full length of tube and after each adjustment one length was taken off. The results were as follows:

Capacity in primary circuit	Inductance in primary	Length of cylinder
$\frac{2 \times 36}{2} = 36$ bottles = 0.0324 mfd	$10 \frac{3}{4}$ turns+conn.	14 meters

Capacity in primary circuit	Inductance in primary	Length of cylinder
$\frac{2 \times 36}{2} = 36$ bottles=0.0324 mfd	9 $\frac{7}{8}$ turns+conn.	12 meters
$\frac{2 \times 36}{2} = 36$ bottles=0.0324 mfd	8 $\frac{3}{4} + \frac{1}{16}$ turns+conn.	10 meters
$\frac{2 \times 36}{2} = 36$ bottles=0.0324 mfd	7 $\frac{13}{16}$ turns+conn.	8 meters
$\frac{2 \times 36}{2} = 36$ bottles=0.0324 mfd	6 $\frac{11}{16}$ turns+conn.	6 meters
$\frac{2 \times 36}{2} = 36$ bottles=0.0324 mfd	5 $\frac{5}{16}$ turns+conn.	4 meters
$\frac{2 \times 36}{2} = 36$ bottles=0.0324 mfd	3 $\frac{3}{4}$ less $\frac{1}{32}$ 3 turns+conn.	2 meters
$\frac{2 \times 36}{2} = 36$ bottles=0.0324 mfd	1 $\frac{3}{8} + \frac{1}{16}$ turns+conn.	0 meters

These results are to be calculated.

Note: coil used 344 turns drum 14" diam. 8 feet length.

Colorado Springs

Nov. 20, 1899

Experiments with coil 344 turns to determine influence of elevation upon capacity of system as before used were repeated.

The results were as follows:

Coil alone

Capacity in primary	Inductance in primary
$\frac{2 \times 36}{2} = 36$ bottles=0.0324 mfd	1 $\frac{3}{8}$ turns+conn

Coil with vertical wire 50 feet (Nº 10)

Capacity in primary	Inductance in primary
$\frac{2 \times 36}{2} = 36 \text{ bottles} = 0.0324 \text{ mfd}$	$8 \frac{1}{16} \text{ turns} + \text{conn.}$

Experiments with ball 30" diam.

Capacity primary circuit	Height of ball from center to ground	Inductance primary
$\frac{2 \times 36}{2} = 36 \text{ bottles} = 0.0324 \text{ mfd}$	10' 1"	$8 \frac{7}{8} + \text{conn.}$
$\frac{2 \times 36}{2} = 36 \text{ bottles} = 0.0324 \text{ mfd}$	33' 8"	9 + conn.
$\frac{2 \times 36}{2} = 36 \text{ bottles} = 0.0324 \text{ mfd}$	57' 3"	$9 \frac{1}{8} + \text{conn.}$

from this follows:

When coil was alone the inductance of primary was $13\frac{3}{8}$ turns + conn.=7121 cm. Hence, taking inductance of coil= 6×10^6 cm, we have similarly to preceding

$$C_{s1} = \frac{0.0324 \times 7121}{6 \times 10^5} \text{ mfd} \quad \text{or} \quad C_{s1} = \frac{9 \times 10^5 \times 0.0324 \times 7121}{6 \times 10^6} = 34.61 \text{ cm},$$

slightly less than found before.

Now in second experiment with wire connected to vibrating system the inductance was $8 \frac{1}{16}$ turns+conn.=25,472 cm. Since the capacity was the same we have as before

$$C_{s2} = \frac{25,472}{7121} C_{s1} = 3.577 \times 34.61 = 123.7999 \text{ cm}.$$

From this follows for capacity of wire alone

$$C_{s2} - C_{s1} = 123.7999 - 34.61 = 89.19 \text{ cm}.$$

When ball was at a height of 10'1" the inductance was $8 \frac{7}{8}$ turns+conn.=28,389 cm; in the middle position it was 9 turns+conn.=28,870 cm, and in the highest position it was $9 + \frac{1}{8}$ turns+conn.=29,351 cm. From this following values are obtained:

$$C_{s3} = \frac{28,389}{7121} C_{s1} = \frac{28,389}{7121} \times 34.61 = 3.98666 \times 34.61 = 137.9783 \text{ cm}.$$

$$C_{s4} = \frac{28,870}{7121} C_{s1} = 4.054 \times 34.61 = 140.301 \text{ cm. and}$$

$$C_{s5} = \frac{29,351}{7121} C_{s1} = 4.1218 \times 34.61 = 142.6555 \text{ cm.}$$

The effective capacity of ball at lowest position was

$$C_{s3} - C_{s2} = 137.9783 - 123.7999 = 14.1784 \text{ cm.}$$

At the middle position it was

$$C_{s4} - C_{s2} = 140.301 - 123.7999 = 16.5011 \text{ cm.}$$

and at the highest

$$C_{s5} - C_{s2} = 142.6555 - 123.7999 = 18.8556 \text{ cm.}$$

Hence from lowest to highest there was an increase of about 33% or very nearly an increase of 0.7% per foot or 70% per 100 feet.

Colorado Springs

Nov. 21, 1899

Investigation on influence of elevation upon the capacity continued: The same coil 344 turns on drum of 14" diam., 8 feet long was used. The object was to ascertain the relative capacities of a wire in vertical and horizontal position. A wire N° 14, 10 meters long was experimented with. Results were as follows:

Coil with wire vertical, lowest point being 8' 8" from ground.

Capacity in primary circuit	Inductance in primary
$\frac{22}{2} = 11$ bottles = 0.0099 mfd	17 ½ turns+conn.

Coil with same wire horizontal at distance of 8' 8" from ground.

$\frac{22}{2} = 11$ bottles = 0.0099 mfd	18 turns+conn.
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The capacity in exciting circuit was now changed and readings again taken, the results being as follows:

Coil with above wire vertical as before

Capacity primary	Inductance primary
$2 \times \frac{36}{2} = 36$ bottles = 0.0324 mfd	6 ⅝ turns-fconn.

Coil with same wire horizontal as before

Capacity primary	Inductance primary
$2 \times \frac{36}{2} = 36 \text{ bottles} = 0.0324 \text{ mfd}$	$6 \frac{3}{4} \text{ turns+conn.}$

Determination of the values of the capacities from preceeding readings:

First set of readings: With wire vertical the inductance in primary circuit was $17 \frac{1}{2}$ turns+conn.=61,592 cm, and with wire horizontal it was 18 turns+conn.=63,517 cm. Since in all cases before the capacity of the coil alone was found to be approximately $35 \text{ cm} = C_{s1}$ the capacity of the wire in the vertical and horizontal positions was as follows:

Wire in horizontal position:

$$C_{s2} = \frac{0.0099 \times 63,517}{6 \times 10^6} \text{ mfd or } C_{s2} = \frac{0.0891 \times 63,517}{60} \text{ cm} = 94.32 \text{ cm},$$

and this gives for capacity of wire in horizontal position:

$$C_{s2} - C_{s1} = 94.32 - 35.00 = 59.32 \text{ cm}.$$

Wire in vertical position $C'_{s2} = \frac{0.0099 \times 61,592}{6 \times 10^6} \text{ mfd or } \frac{0.0891 \times 61,592}{60} \text{ cm} = 91.464 \text{ cm}$, and this gives capacity of wire in vertical position:

$$C'_{s2} - C_{s1} = 91.464 - 35.00 = 56.464 \text{ cm or a little less.}$$

From second set of readings we get:

Wire vertical: Inductance in primary was $6 \frac{5}{8}$ turns+conn.=20,631 cm. Hence

$$C''_{s2} = \frac{0.0324 \times 20,631}{6 \times 10^6} \text{ mfd or } \frac{0.2916 \times 20,631}{60} \text{ cm} = 100.26 \text{ cm}$$

and hence value of capacity in this case was for wire alone

$$C''_{s2} - C_{s1} = 100.26 - 35 = 65.26 \text{ cm}.$$

Wire horizontal: Inductance in primary was $6 \frac{3}{4}$ turns+conn.=21,052 cm. Hence

$$C''_{s2} = \frac{0.0324 \times 21,052}{6 \times 10^6} \text{ mfd or } \frac{0.2916 \times 21,052}{60} \text{ cm} = 102.31 \text{ cm}$$

and the capacity of the wire in horizontal position was then:

$$C''_{s2} - C_{s1} = 102.31 - 35.000 = 67.31 \text{ cm}.$$

These readings do not agree as well as they ought to.

To be gone over.

Nov. 22, 1899

Measurement of small capacities by resonance method

This method is suitable to determine capacities too small to be measured in other ways conveniently. Coil with 344 turns before described was again used.

Results:

Coil alone with short piece of stout wire connected to the free terminal.

Capacity in primary circuit	Inductance in primary circuit
$\frac{2 \times 36}{2} = 36 \text{ bottles} = 0.0324 \text{ mfd}$	$1 \frac{1}{2} \text{ turns} + \text{connections}$

Coil with incandescent lamp 16 c.p. 100 V with two filaments attached to short thick wire

$\frac{2 \times 36}{2} = 36 \text{ bottles} = 0.0324 \text{ mfd}$	$1 \frac{19}{32} \text{ turns} + \text{connections}$
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This test gave an idea of the capacity (effective) of the lamp. The primary inductance in first case was 7314 cm. and in the second 7458 cm. from table prepared. From this follows:

$$C_{s1} = \frac{0.0324 \times 7314}{6 \times 10^6} \text{ mfd or } C_{s1} = \frac{0.2916 \times 7314}{60} \text{ cm} = 35.546 \text{ cm.}$$

$$C_{s2} = \frac{0.0324 \times 7458}{6 \times 10^6} \text{ mfd or } C_{s2} = \frac{0.2916 \times 7458}{6 \times 10^6} \text{ cm} = 36.246 \text{ cm.}$$

Here C_{s1} and C_{s2} were respectively the capacities of the system without lamp and with lamp attached. Hence the actual or effective capacity of the lamp in this system was

$$C_{s2} - C_{s1} = 36.246 - 35.546 = 0.7 \text{ cm.}$$

An approximate idea is also obtained of the capacity of the short piece of stout wire used to attach the small bodies the capacity of which was to be determined. Namely the capacity of the excited system alone being before determined about 35 cm, the capacity of the wire would be

$$35.546 - 35.000 = 0.546 \text{ cm.}$$

Colorado Springs

Nov. 23, 1899

Measurement of small capacities by resonance method and mode of determining maximum rise before described by means of diminutive circuit was continued. The coil with 344 turns was again used and in order to get better readings on the self-induction regulating coil in the primary, the primary capacity was reduced. The results were:

1.

Coil with short stout wire alone as before.

Capacity in primary circuit	Inductance in primary circuit
$\frac{36}{2} = 18 \text{ bottles} = 0.0162 \text{ mfd}$	$4 \frac{13}{16} \text{ turns} + \text{conn.}$

2.

Coil with lamp same as before.

$\frac{36}{2} = 18 \text{ bottles} = 0.0162 \text{ mfd}$	$4 \frac{15}{16} \text{ turns} + \text{conn.}$
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3.

Coil with same lamp seal broken

$\frac{36}{2} = 18 \text{ bottles} = 0.0162 \text{ mfd}$	$4 \frac{31}{32} \text{ turns} + \text{conn.}$
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Note: Curious, the increased capacity probably due to absorption.

4.

Coil with one of my Roentgen tubes as described in articles E.R.

$\frac{36}{2} = 18 \text{ bottles} = 0.0162 \text{ mfd}$	$5 \frac{1}{8} \text{ turns} + \text{conn.}$
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5.

Coil with "double focus tube" target connected.

$\frac{36}{2} = 18 \text{ bottles} = 0.0162 \text{ mfd}$	$5 \frac{1}{16} \text{ turns} + \text{conn.}$
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6.

Coil with same tube one of the electrodes connected.

$\frac{36}{2} = 18 \text{ bottles} = 0.0162 \text{ mfd}$	$5 \frac{3}{32} \text{ turns} + \text{conn.}$
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Note: all of these tubes developed rays fairly strong while tested.

7.

Coil with Lennard tube single terminal as described by me E.R., poorly exhausted, streamers passing through it.

$\frac{36}{2} = 18 \text{ bottles} = 0.0162 \text{ mfd}$	5 turns+conn.
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From these measurements the capacities can now be found.

Calling the inductances in the primary circuit in each succeeding experiment respectively $L_1, L_2, L_3, L_4, L_5, L_6$ and L_7 we have with reference to prepared table:

$L_1 = 4 \frac{13}{16} \text{ turns} + \text{conn.} = 14,526 \text{ cm}$
$L_2 = 4 \frac{15}{16} \text{ turns} + \text{conn.} = 14,947 \text{ cm}$
$L_3 = 4 \frac{31}{32} \text{ turns} + \text{conn.} = 15,053 \text{ cm}$
$L_4 = 5 \frac{1}{8} \text{ turns} + \text{conn.} = 15,579 \text{ cm}$
$L_5 = 5 \frac{1}{16} \text{ turns} + \text{conn.} = 15,368 \text{ cm}$
$L_6 = 5 \frac{3}{32} \text{ turns} + \text{conn.} = 15,473 \text{ cm}$
$L_7 = 5 \text{ turns} + \text{conn.} = 15,158 \text{ cm}$

Calling furthermore the corresponding capacities of the excited system

 $C_{s1}, \dots, C_{s7}$ all of them can be at once determined from C_{s1} since

$$C_{s2} = \frac{L_2}{L_1} C_{s1}, C_{s3} = \frac{L_3}{L_1} C_{s1}, \text{ etc.}$$

Now analogous to previous proceedings of this kind

$$C_{s1} = \frac{0.0162 \times L_1}{6 \times 10^6} \text{ mfd. or } C_{s1} = \frac{0.0162 \times 14,526 \times 9 \times 10^5}{6 \times 10^6} = 35.298 \text{ cm.}$$

Taking approximately $C_{s1} = 35.3 \text{ cm}$ we have:

$$\begin{aligned} C_{s2} &= \frac{L_2}{L_1} C_{s1} = \frac{14,947}{14,526} C_{s1} = 1.029 \times 35.3 = 36.324 \text{ cm} \\ C_{s3} &= \frac{L_3}{L_1} C_{s1} = \frac{15,053}{14,526} C_{s1} = 1.0363 \times 35.3 = 36.58 \text{ cm} \\ C_{s4} &= \frac{L_4}{L_1} C_{s1} = \frac{15,579}{14,526} C_{s1} = 1.0725 \times 35.3 = 37.859 \text{ cm} \\ C_{s5} &= \frac{L_5}{L_1} C_{s1} = \frac{15,368}{14,526} C_{s1} = 1.058 \times 35.3 = 37.347 \text{ cm} \\ C_{s6} &= \frac{L_6}{L_1} C_{s1} = \frac{15,473}{14,526} C_{s1} = 1.0652 \times 35.3 = 37.6 \text{ cm} \\ C_{s7} &= \frac{L_7}{L_1} C_{s1} = \frac{15,158}{14,526} C_{s1} = 1.0435 \times 35.3 = 36.8355 \text{ cm} \end{aligned}$$

from these
values
follow:

Capacity effective of lamp experiment	$2 = C_{s2} - C_{s1} = 36.324 - 35.3 = 1.024 \text{ cm}$
Capacity effective of lamp experiment seal broken	$3 = C_{s3} - C_{s1} = 36.58 - 35.3 = 1.28 \text{ cm}$
Capacity of my Roentgen tube exp.	$4 = C_{s4} - C_{s1} = 37.859 - 35.3 = 2.559 \text{ cm}$
Capacity double focus tube target connected	$5 = C_{s5} - C_{s1} = 37.347 - 35.3 = 2.047 \text{ cm}$
Capacity double focus electrode connected	$6 = C_{s6} - C_{s1} = 37.6 - 35.3 = 2.3 \text{ cm}$
Capacity double Lennard tube described	$7 = C_{s7} - C_{s1} = 36.8355 - 35.3 = 1.5355 \text{ cm.}$

Colorado Springs

Nov. 24, 1899

A test was made with the object of ascertaining how close the table of inductances prepared from measured data agreed with the values determined by resonance method. The procedure was as follows: the coil with 344 turns on drum 14" diam., 8 feet long was again used as suitable for the test and it was excited in the manner before described. In order to establish a different relation between capacity and self-induction of the primary circuit these constants were in each case varied and the adjustment completed until the maximum rise on the terminal or terminals of the excited coil took place. As the period of the system remained in each case the same the products of the capacity and self-inductance in primary remained constant also. Now the capacities in the primary in the succeeding experiments being known or exactly measurable, the various values of inductance in primary were obtained from the relation:

$$L_1 C_1 = L_2 C_2 = L_3 C_3 = \text{etc.}$$

The period of the secondary system was $T_s = \frac{2\pi}{10^3} \sqrt{LC_{s1}}$.

The inductance of coil 344 turns being about $6 \times 10^6 \text{ cm.}$ and the average value for C_{s1} from a number of readings with different values of inductance and capacity in primary circuit being 34.9 cm., the period of secondary or excited circuit was thus given.

A reading was now taken at random and resonance was obtained with constants in primary circuit as follows:

Capacity in primary circuit	Inductance in primary
$\frac{36}{2} = 18 \text{ bottles} = 0.0162 \text{ mfd}$	$4 \frac{13}{16} \text{ turns} + \text{conn.}$

from this the period of primary circuit was:

$$T_p = \frac{2\pi}{10^3} \sqrt{0.0162 \times L} \quad L \text{ being the inductance in primary}$$

Now $T_p = T_s$ or $0.0162 \times \frac{L}{10^9} = \frac{6 \times 10^6}{10^9} \times \frac{34.9}{9 \times 10^5}$ and from this we get L in centimeters:

$$L = \frac{6 \times 10^6 \times 34.9}{9 \times 10^5 \times 0.0162} = \frac{34.9 \times 6}{9 \times 0.0162} = \frac{698}{0.0486} = L = 14,362 \text{ cm}$$

by resonance method.

Now from table prepared:

$$\text{Inductance } L = 4 \frac{13}{16} + \text{conn.} = \begin{cases} \text{Inductance } 4 \frac{1}{2} \text{ turns} + \text{conn.} = 13,474 \text{ cm.} \\ \text{Inductance } 5 \text{ turns} + \text{conn.} = 15,158 \text{ cm.} \\ \text{Ind. of } \frac{1}{2} \text{ turns} = 1684 \text{ cm.} \\ \text{Ind. of } \frac{1}{16} \text{ turns} = 210.5 \text{ cm.} \end{cases}$$

Ind. of $\frac{5}{16}$ turn = $5 \times 210.5 = 1052$ cm approx..

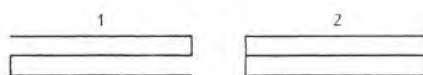
$$\text{Consequently inductance } L = \text{Ind. } \left\{ 4 \frac{1}{2} + \frac{5}{16} \text{ turn} + \text{conn.} \right\} = \\ = 4 \frac{13}{16} \text{ turns} + \text{conn.} = 13,474 + 1052 = 14,526 \text{ cm.}$$

Agreement fairly close, within about 1%. This shows readings are reliable.

Colorado Springs

Nov. 25, 1899

Experiment which follows was made to ascertain how the capacity of the same conductor may be altered by different distribution. The experiment was performed in the following manner. Two lengths of wire № 10 were taken (rubber covered) and one length was bent zigzag fashion so that a piece with three parallel wires was obtained one meter long. The other length was cut in three pieces 1 meter long each and these were connected at the ends. The difference between the two pieces so prepared will appear from the sketch in which 1. shows the zigzag wire and 2. the wire cut in three pieces joined in multiple. The distribution in both cases was radically different. These pieces were one after the other placed on the free terminal of a coil with 344 turns and in each case the primary adjusted until resonance was observed. The wires were placed vertically, in the prolongation of the axis of the coil.



An experiment was furthermore made in tuning, not to the real vibration but to a higher harmonic (the next octave) of the primary. The results (with spark gaps slightly changed) were:

Capacity in primary circuit	Inductance primary
$\frac{36}{2} = 18 = 0.0162$ mfd with wires multiple	$1 \frac{1}{8}$ turns+conn.
$\frac{36}{2} = 18 = 0.0162$ mfd with wire zigzag	$1 \frac{1}{16}$ turns+conn.

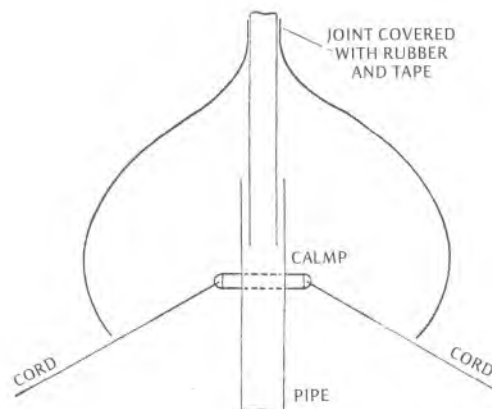
Now the primary inductance in the first case was 6736 cm and in the second case 6635 cm. Hence, the inductance remaining practically the same, the capacity (effective) of the zigzag wire was smaller to the extent of nearly 1.6%.

Colorado Springs

Nov. 26, 1899

Determination of the capacity of structure of iron pipes by improved method before described

Note: Originally the structure, to prevent lateral play, was supported sideways by 8 projecting beams at a height of about 80 feet, each beam having fastened into its end a strong champagne bottle. The necks of the bottles abutted against the iron pole and prevented sideways play. They were wrapped with tape to diminish the danger of the necks being broken. This arrangement was good enough and withstood the storm but it did not allow going beyond a certain pressure as the sparks from the iron pipes would jump to the beams which had the bottles fastened into them. To overcome this defect a plan was adopted, contrived long ago, which consisted in providing a conical roof or hood (made in two parts) rounded on the periphery to reduce loss by leakage and fastening four cords under the roof for the purpose of preventing lateral play and steadying this pole. This arrangement is excellent as the sparks can not jump upon and follow the cords to the ground being fastened under the roof where the electrical pressure was extremely small. The arrangement is indicated in the sketch. The dimensions of the hood were: outside diam. 8 feet., diam. of small circle on periphery 9". The height of the conical surface about 3 ½ feet. The cords were led to the four corners of the building and fastened to the same by means of a cable of sheet wires over which was slipped a rubber hose with very thick wall and which was wrapped around three glass insulators supported on the pole on each corner. It was thought of advantage to insulate the ropes thoroughly and for this purpose they were soaked about a week in linseed oil boiled out and dried in the sun afterward. The cords went down at an angle such that the nearest point of the hood was two feet distant. This arrangement permitted the charging of the pole easily up to a million volts. This is the best arrangement I have found so far for supporting a body to be charged to so high a potential as is necessary for instance in the transmission of messages over great distances. It has been in use since a few weeks ago but the measurements of capacity of the structure before recorded were made without the hood. Presently the readings were taken with the hood with following results:



Coil 344 turns drum 14" with iron structure connected to free terminal.

Capacity in primary circuit	Inductance in primary circuit
$\frac{2 \times 36 + 12}{2} = \frac{84}{2} = 42$ bottles = 0.0378 mfd	2 1/8 turns + conn.

Coil with connecting wire alone shifted away from structure (4 feet).

$\frac{2 \times 36 + 12}{2} = \frac{84}{2} = 42$ bottles = 0.0378 mfd	4 turns + conn.
---	-----------------

From this follows: the inductance in primary circuit in the first case was 75,548 cm, in the second case 12,319 cm referring to table of inductances before used. Hence capacity of excited system in first

$$C_{s1} = \frac{0.0378 \times 75,548}{6 \times 10^6} \text{ mfd, or } \frac{0.3402 \times 75,548}{60} \text{ cm} = C_{s1}$$

And similarly $C_{s2} = \frac{0.3402 \times 12,319}{60} \text{ cm}$, C_{s2} being capacity of excited system in second experiment. This gives for actual or effective capacity of structure with hood

$$C_{s1} - C_{s2} = \frac{0.3402}{60} (75,548 - 12,319) \text{ cm} = \frac{0.3402}{60} \times 63,229 \text{ cm} = 358.5 \text{ cm.}$$

* Small corrections for inductance may have to be taken later.

Effective capacity of structure of iron pipes with new hood again determined by resonance method. The new "extra coil" was used, its inductance being as before 0.02 H. The readings were as follows:

Coil with structure and connecting wire

Capacity in primary	Inductance in primary
$5 \times 36 - 12 = 168$ bottles = 0.1512 mfd	20 3/8 turns + conn.

Coil with connecting wire alone placed at 4 ft. distance

$4 \times 36 = 144$ bottles = 0.1296 mfd	7 turns + conn.
--	-----------------

other readings:

50 bottles = 0.045 mfd	17 1/4 turns + conn.
40 bottles = 0.036 mfd	20 turns + conn.

Capacity in primary	Inductance in primary
38 bottles = 0.0342 mfd	20 $\frac{3}{4}$ turns+conn.
39 bottles = 0.0351 mfd	(approx) 20 $\frac{3}{8}$ turns+conn.

From these readings follows:

Inductance in first case, with structure, in primary was 20 $\frac{3}{8}$ turn+conn.=72,661 cm. Inductance in second case, without structure, in primary was 7 turn+conn.=21,894 cm.

Calling C_{s1} and C_{s2} the effective capacities of the excited system in the two cases respectively, we have:

$$C_{s1} = \frac{0.1512 \times 72,661}{2 \times 10^7} \text{ mfd, and } C_{s2} = \frac{0.1296 \times 21,894}{2 \times 10^7} \text{ mfd, hence}$$

$$C_{s1} - C_{s2} = \frac{0.1512 \times 72,661 - 0.1296 \times 21,894}{2 \times 10^7} = \frac{10,986.3432 - 2837.4624}{2 \times 10^7} = \frac{8148.8808}{2 \times 10^7} \text{ mfd,}$$

$$\text{or} \quad = \frac{9 \times 8148.8808}{2 \times 10^2} \text{ cm} = 366.7 \text{ cm.}$$

effective capacity of structure with hood.

Capacity of structure without hood before found with extra coil was 311.2 cm, hence for hood alone we get 366.7–311.2=55.5 cm. From first and last reading it appears that 168 the secondary capacities in the two cases were as $\frac{168}{39}$. Now the capacity of excited system in last reading was

$$C'_{s2} = \frac{0.0351 \times 72,661}{2 \times 10^7} \text{ mfd, or } C'_{s2} = 114.77 \text{ cm.}$$

From this would follow value

$$C'_s = \frac{168}{39} \times 114.77 = 494.39 \text{ cm.}$$

$$\text{Hence } C'_{s1} - C'_{s2} = 494.39 - 114.77 = 379.62 \text{ cm.}$$

This value does not agree quite closely with that before found but the tuning was not quite exact in last case.

Note: It now seems that the tuning in all previous cases when structure was determined was made to the first octave instead of to the fundamental tone. This is to be ascertained. If this be so then capacity would be much greater.

Colorado Springs Notes

December 1-31, 1899

To be completed:

Dec. 11, 12, 13 Application for Patent for separation of gaseous mixtures by high tension discharge of oscillator.

Dec. 17 Description of phenomenon on Pike's Peak in the few days of eclipse of moon.

Patent note

Increase of capacity uses in the arts and scientific measurements.

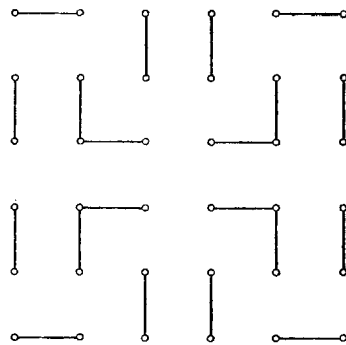
Experimental Station in another
phase of development. Discovery
of Stationary Waves "made July 3, 1899."



Dec. 1, 1899

Some particulars about the apparatus used in the experiments here

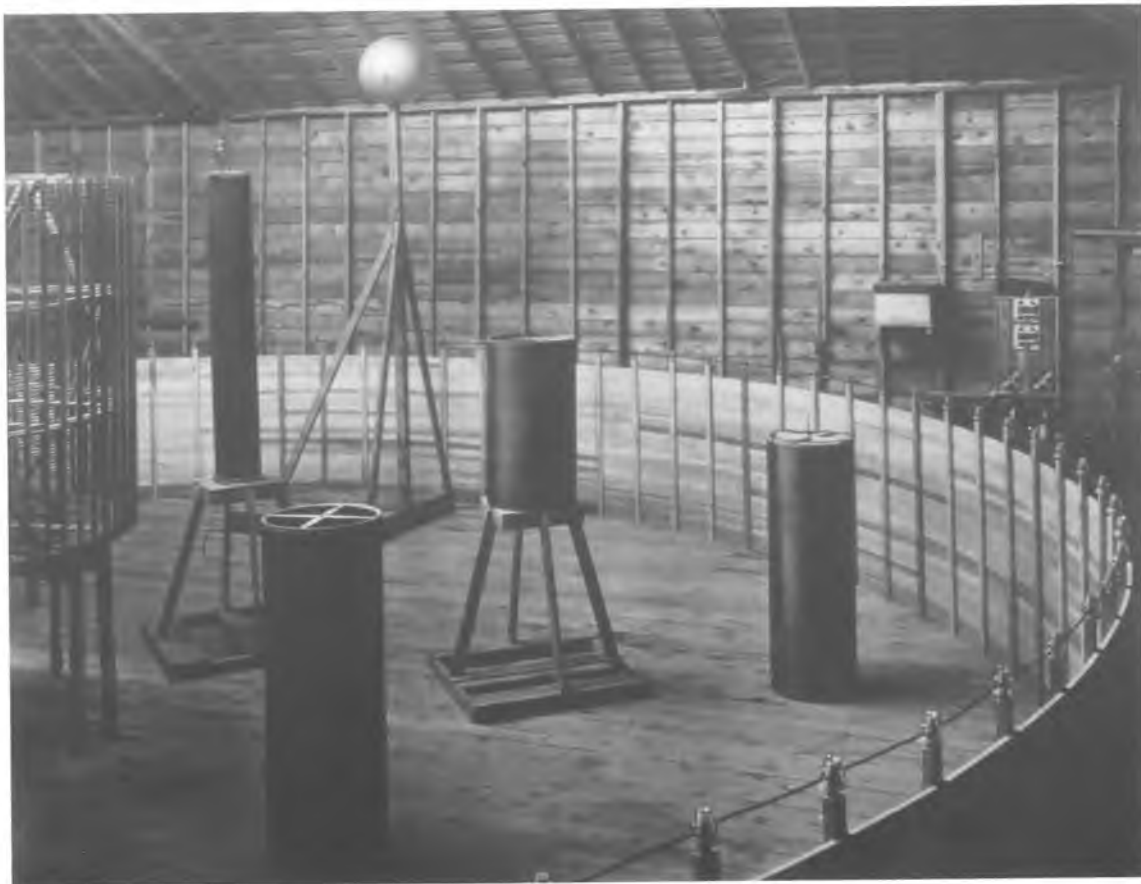
The connections of the bottles in the two tanks frequently referred to as the "old tanks", to which the primary cables and the regulating coil were usually connected and by means of which the finer adjustments of capacity in the primary circuit were made, are as shown in the sketch. The top brass plate has 16 plugs disposed at equal distances in a square and the 36 bottles in the tank being connected by copper springs as indicated, each plug enabled the cutting out or in of two bottles, with the exception of the four central plugs which cut in or out three bottles each. Thus the smallest variation of the capacity on one side was one bottle or 0.0009 mfd, approx. But with the tanks in two sets in series as usually employed it was one half of one bottle. Considering the large number of bottles the variation was small enough for most purposes. The bottles in the new tanks were divided in three sets, twelve bottles in each.



Measured length of all connections on the condenser sets in primary:

From top of right condenser to break	2' 5 ½"	=29.5"
Through break wheel and sp. rod	2' 4 ½"	=28.5"
From back to regulating coil	3' 10"	=46"
Up through second break and rod	1' 10"	=22"
Connection to left condenser	3' 7"	=43"
1" To bottom of left condenser	1' 8 ½"	=20.5"
Connection on bottom between condensers	3' 6"	=42"
1" Up to top of right condenser	1' 8 ½"	=20.5"

Total length of connections is thus 252"=641 cm, nearly or 21 feet. The section of the connections is partially that equal to the cable used in primary 1 cm radius and partially less. The inductance determined by resonance analysis is about 5000 cm total. The calculated value a trifle more.

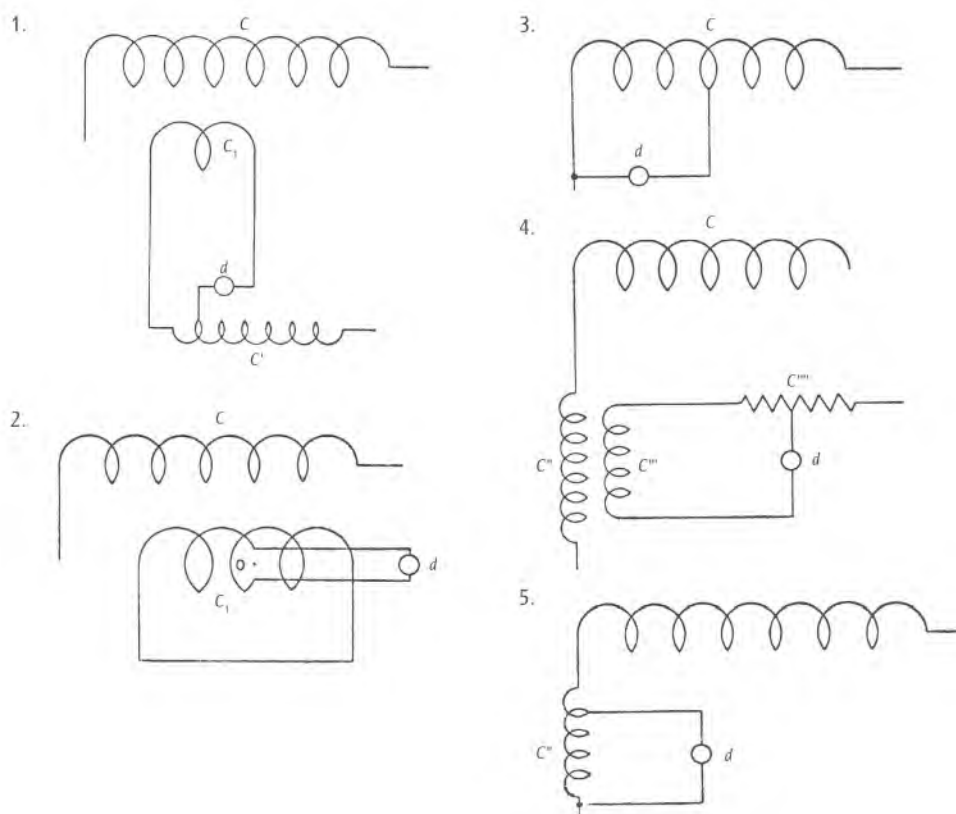


Phot. II. View of interior showing half of circle of oscillator frame with several coils inside.

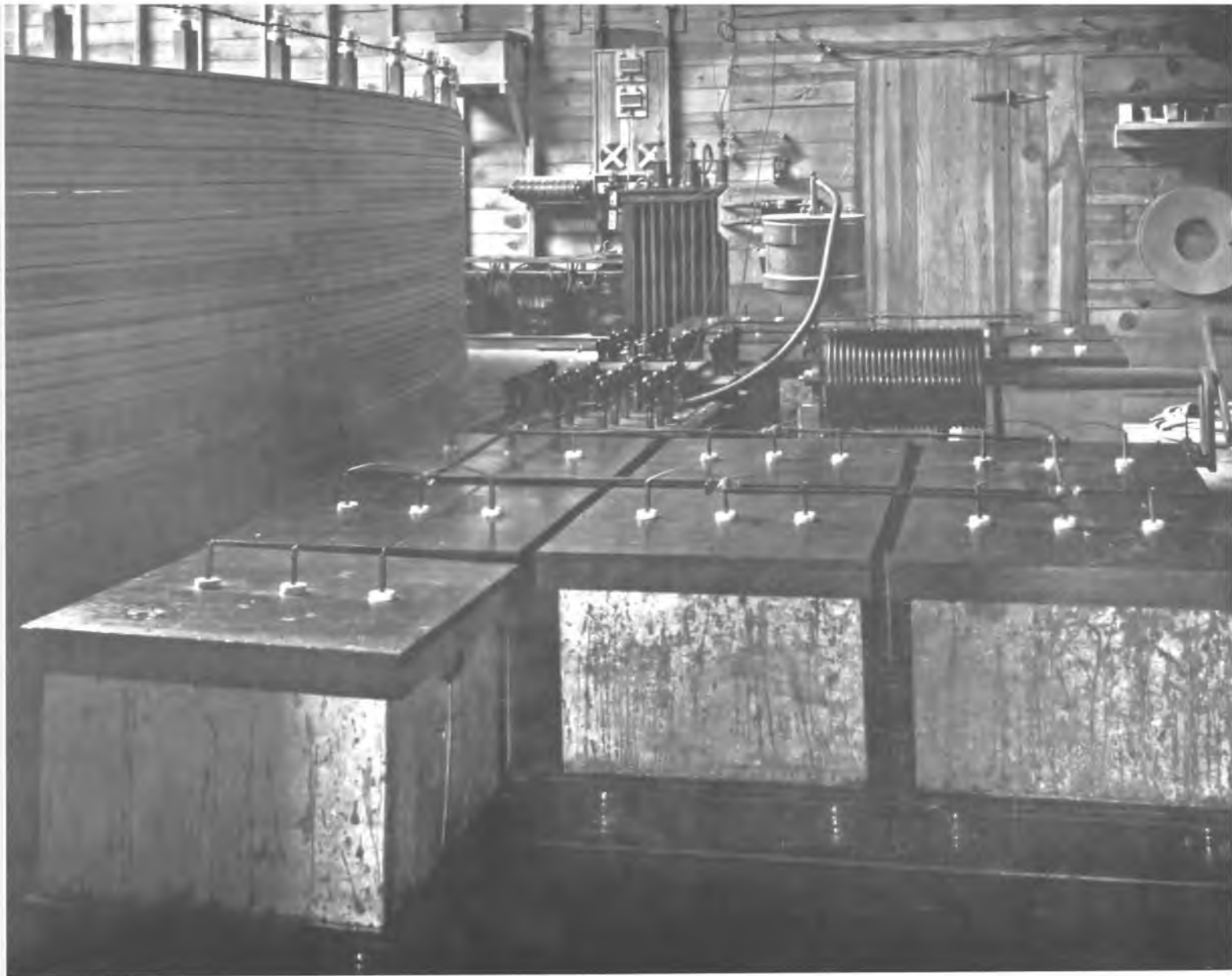
Dec. 2, 1899

Various ways of tuning circuits or determining the maximum of resonant rise

In the course of the experiments conducted here a number of such ways have been resorted to most of which have been described or at least referred to, but it may be useful to record here once more those which have been found most satisfactory. They are diagrammatically illustrated in Figs. 1–5. below:



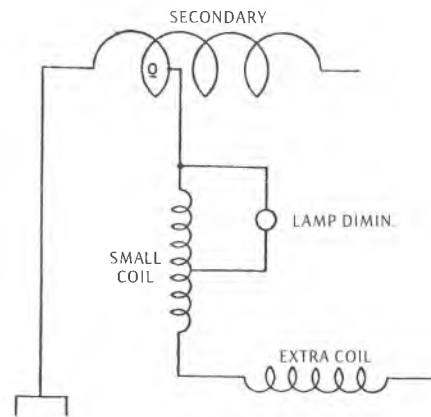
In arrangement illustrated in Fig. 1. a small circuit c_1 in very loose inductive connection with the resonating circuit C , is used to detect the maximum. This small circuit c_1 which exercises no appreciable reaction upon circuit C contains another coil c'' or else a resistance which is noninductive for the purpose of adjusting the effect to suit the indicating device d which is most generally a microscopic spark gap, vacuum tube or any hot wire instrument, as a minute lamp specially made to suit the purpose, a Cardew voltmeter or any other instrument. In Fig. 2. the adjustment of the effect upon d is effected by turning the circuit around a point o or else by approaching small circuit c_1 to or receding with same from circuit C . In Fig. 3. a number of turns of the resonating circuit C are spanned by device d , this number being adjustable. In Fig. 4. again a small coil c'' in series with coil C is placed inductively in connection with a small circuit c''' which again may be adjustable in the manner shown or in any other way. Finally in Fig. 5. a small coil c'' in series with C is spanned by device d . Coil c'' has its turns adjustable. *This method seems best.*



Phot. III. View of interior, chiefly showing condensers, break motor and regulating coil in primary of oscillator. Westinghouse high tension transformer, supply transformers and arresters in background.

Dec. 3, 1899

Determination of free vibration of new "extra coil". No 10 wire wound on frame 8' 3" diam. and 8' length modified by taking off five turns on top and placing the last five turns two grooves apart instead of one groove as the rest of turns. In this modification there are just 100 turns in the coil. The excitation



was effected from the secondary the connection being made to a point $o \frac{3}{4}$ turns from the ground plate as indicated in the diagram. The maximum rise was determined by means of a diminutive lamp shunting a few turns of an adjustable small coil in series with the extra coil, the small coil being of an inductance entirely negligible as compared with that of the extra coil. The readings for resonating condition were as follows:

Capacity in the primary or exciting circuit	Inductance in the pr. or exc. circuit
$\frac{2 \times 36}{2} = 36 \text{ bottles} = 0.0324 \text{ mfd}$	$16 \frac{1}{16}$ turns regulating coil+1 primary turn, that is two primary cables in multiple as modified by reaction of secondary.
$\frac{4 \times 36}{2} = 72 \text{ bottles} = 0.0648 \text{ mfd}$	$5 \frac{5}{8}$ turns of coil+primary as above.

From first reading, taking the inductance of primary turn as modified by the secondary 41,000 cm, the period of the oscillation was $T_1 = \frac{2\pi}{10^3} \sqrt{0.0324L}$, L the inductance of primary being that of primary turn+ $16 \frac{1}{16}$ of regul. coil=41,000+56,000=97,000 cm. This gives

$$T_1 = \frac{2\pi}{10^3} \sqrt{0.324 \times \frac{97}{10^6}} = \frac{2\pi}{10^6} \sqrt{0.0324 \times 97} = \frac{2\pi}{10^6} \times 1.773 = \frac{11.13444}{10^6}$$

and $n = 90,000$ nearly.

From second reading, the inductance of $5 \frac{5}{8}$ turns of regulating coil being 17,300 cm and total inductance of primary 41,000+17,300=58,300 cm. We have the period



$$T_2 = \frac{2\pi}{10^3} \sqrt{0.0648 \times \frac{583}{10^7}} = \frac{2\pi}{10^6} \sqrt{0.0648 \times 58.3} = \frac{6.28 \times 1.944}{10^6} = \frac{12.2}{10^6}$$

and $n = 82,000$ approx.

Note: The tuning was very sharp in both cases, but in the second case the secondary reaction was *smaller*, i.e., inductance of the primary greater.

Colorado Springs

Dec. 4, 1899

Experiments to establish equivalence between the inductance of the primary loop comprising two primary cables in multiple (with secondary reacting) and that of turns of the regulating coil in primary circuit

Resonance analysis was resorted to and the coil of 344 turns on drum 14" diam. 8 ft. long, wire № 10 was again used. The coil employed had a very small regulating coil in series, and a minute lamp placed across the few turns of this latter coil was employed to ascertain the maximum resonant rise in the coil excited. The results were as follows:

1.

Capacity in the primary circuit	Inductance in the primary circuit
8 jars on each side, that is 4 jars= 0.0036 mfd	One primary loop as above+6 ¾ turns reg. coil. * Small coil in series with coil of 344 turns had 9 turns in circuit <i>entirely negligible</i> .

2.

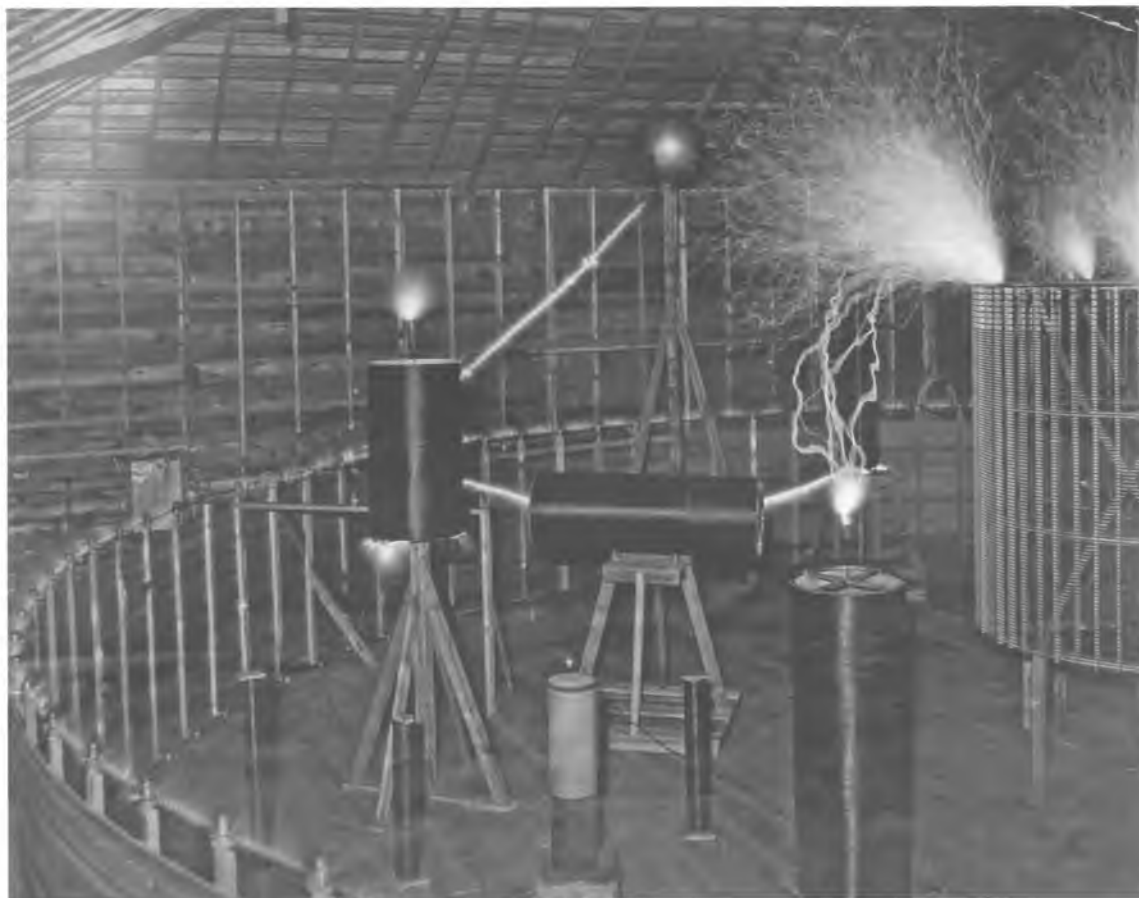
Capacity in the primary circuit	Inductance in the primary circuit
Capacity same as above	15 ¼ turns regulating p. coil <i>only</i> * Small coil had 22 turns inserted, still entirely negligible against 344 turns coil

Since resonance was obtained in both cases and the primary capacity in both tests remained the same we have the primary inductances in both cases equal and from this follows that *under the conditions* of these tests the inductance of the primary *as modified* by the *secondary* was equivalent to 15 ¼–6 ¾ turns of the primary regulating coil. Now from the table of inductances the value for the 15 ¼ turns is 52,930 cm and that for the 6 ¾ turns, inserted in the first case, is 21,052 cm. Hence the inductance of primary cables in this instance was

$$L_p = 52,930 - 21,052 = 31,878 \text{ cm.}$$

Thus the secondary, though "open", diminished in this case the primary inductance from 56,400 cm to the above value or about 43.48%.

Phot. IV. View of laboratory from the rear by moonlight.



Phot. V. View of interior showing a number of coils differently attuned and responding to vibration transmitted to them from an electrical oscillator⁽⁴¹⁾.

Colorado Springs

Dec. 5, 1899

Experiments to ascertain equivalence of inductance of primary loop (two primary cables in multiple) with secondary reacting, and inductance of turns of regulating primary coil under modified conditions

Again the coil with 344 turns was used and the maximum resonant rise in same determined in the manner described before. A greater capacity was used this time in the primary so as to come closer to the free vibration of the secondary and thus cause a stronger reaction upon the primary loop. The conditions for resonance were satisfied with the following values:

1.

Capacity in primary circuit	Inductance in primary circuit
$\frac{2 \times 36}{2} = 36$ bottles = 0.0324 mfd	21 $\frac{3}{4}$ turns pr. regulating coil <i>only</i>

2.

Capacity in primary circuit	Inductance in primary circuit
$\frac{2 \times 36}{2} = 36$ bottles = 0.0324 mfd	Inductance in primary circuit one primary loop as above + 15 $\frac{1}{2}$ turns reg. coil.

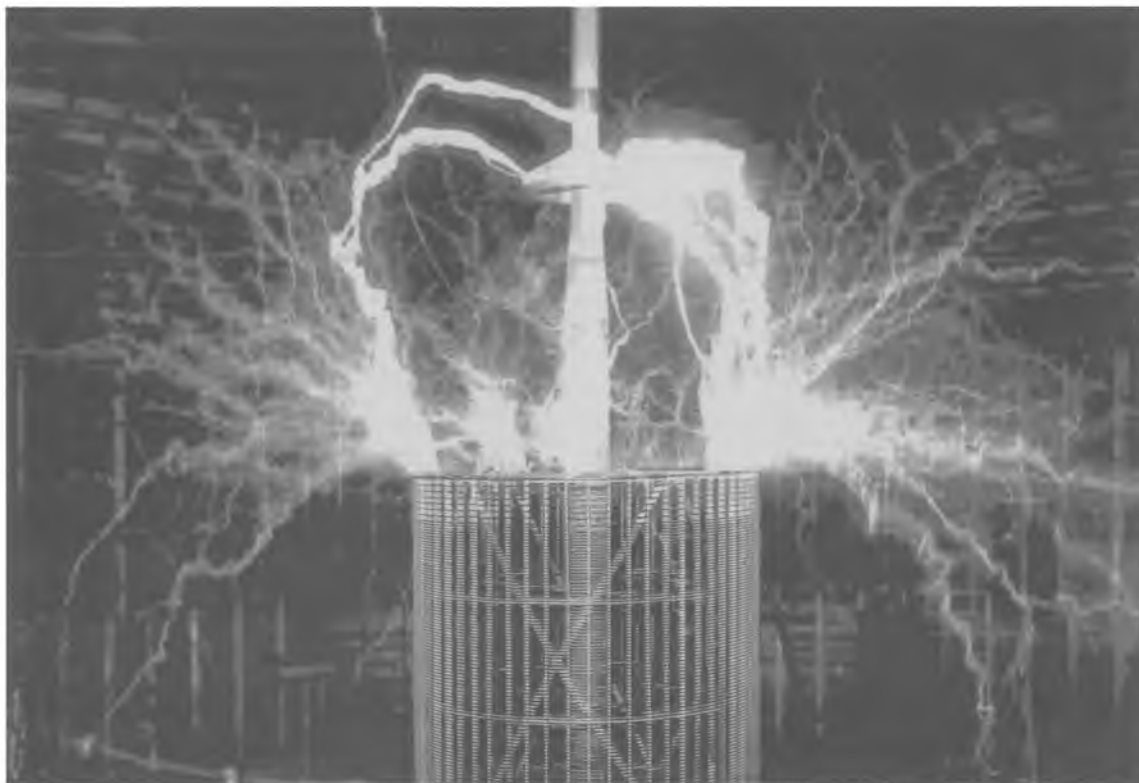
Since in both tests the primary capacity was not changed in the least the inductance of the primary loop in this instance was equivalent to that of 21 $\frac{3}{4}$ turns, less that of 15 $\frac{1}{2}$ turns of the regulating coil in the primary. This means the inductance of the primary loop was equivalent to that of 21.75–15.5 = 6.25 turns of the primary regulating coil or it was 6.25 × 3850 = 24,063 cm only. Induct, diminished 57.33%. This is a still smaller value than found yesterday but is very probably near the maximum as the secondary showed evidence of a resonating condition. These experiments show the danger of allowing for the amount of secondary reaction. This is to be borne in mind.

Colorado Springs

Dec. 6, 1899

Further experiments to ascertain equivalence of inductance of the primary loop (two primary cables in multiple) with secondary reacting, and that of turns of primary regulating coil under conditions again modified

In the present tests the "new extra coil" modified so as to have only 100 turns was used (this is to be explained). The coil was used exactly as that of 344 turns before and the maximum rise was determined in the same way and by the same means as in preceding cases. The results of the two comparative tests were as follows:



Phot. VI. Normally
excited "extra coil".

1.

Capacity in the primary circuit	Inductance in primary circuit
$\frac{5 \times 36 - 24}{2} = \frac{156}{2} = 78$ bottles = 0.0702 mfd	11 $\frac{5}{16}$ turns of primary regul. coil <i>only</i>

2.

Capacity in primary circuit	Inductance in primary circuit
same as above = 0.0702 mfd	one primary turn + 3 $\frac{1}{2}$ turns reg. pr. coil.

From these tests it follows that under present conditions the inductance of the primary loop with secondary reacting was equivalent to that of 11 $\frac{5}{16}$ turns less that of 3 $\frac{1}{2}$ turns of the primary regulating coil. Now the table of inductance gives inductance of the 11 $\frac{5}{16}$ turns = 37,775 cm, and that of the 3 $\frac{1}{2}$ turns = 11,164 cm. Hence the inductance of the primary loop under these conditions was

$$L_p = 37,775 - 11,164 = 26,611 \text{ cm.}$$

The secondary was resonating to some extent but not as well as in experiments recorded yesterday. The diminution of inductance due to secondary reaction was here 52.82 %

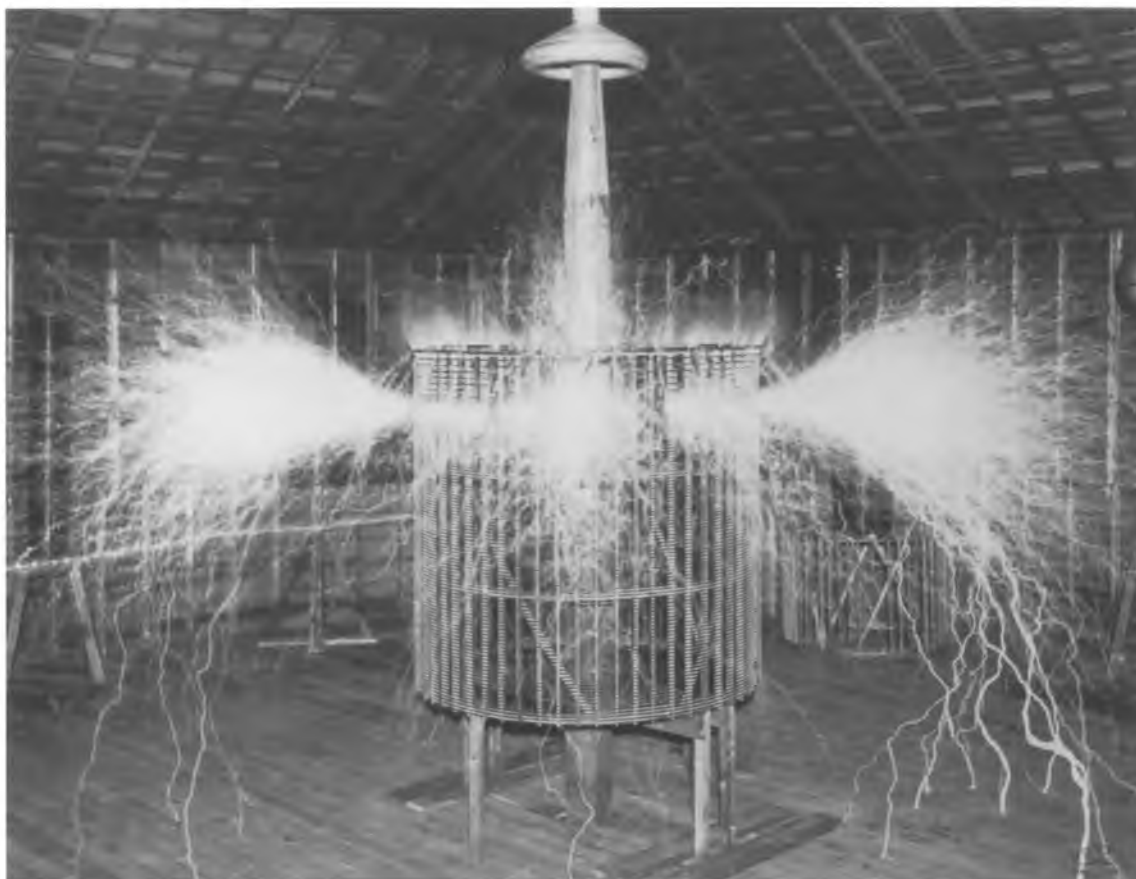
Note: These tests make it advisable to break the secondary on more points when the primary is used for inductance.

Colorado Springs

Dec. 7, 1899

Experiments to ascertain to what extent induced currents in the ground might affect the primary and secondary oscillating systems now used in the laboratory

Resonance analysis was resorted to and the experiments were performed in the following manner: a *square* frame 11' $\frac{1}{4}$ " each side and 3 $\frac{3}{4}$ " high, wound with 14 turns wire № 10 was supported horizontally above the ground, its elevation above the latter being made adjustable. This coil was tuned in various positions and the effect of the ground observed on the change of the period of oscillation in the various positions. In order however to get a better range of reading and also to reduce as much as practicable the effects of the distributed capacity in the coil wound on the square frame the same was joined in series with another coil of 344 turns wound on a 14" diameter drum, which was before used, but so that the coil on the square frame was between the ground connection and the coil of 344 turns, this for the purpose of maintaining between the turns of the square coil a comparatively small difference of potential thus reducing the effect of distributed capacity of the same. By using the additional coil the vibration was rendered slower and a better range of reading was secured. The two coils were excited in the manner repeatedly referred to and described, the maximum resonant rise being determined by means of a minute lamp shunting a few adjustable turns of a very small coil of entirely negligible inductance which was in series with both the coils used.



Phot. VII. View of
"extra coil" in action.

The results of the tests are indicated in the following table:

	Capacity in primary exciting circuit	Distance of square coil from ground	Inductance in primary circuit
1.	$\frac{4 \times 36}{2} = 72$ bottles = 0.0648 mfd	1' 3" + 0	4 $\frac{1}{4}$ less $\frac{1}{32}$ turn reg. pr. coil
2.	$\frac{4 \times 36}{2} = 72$ bottles = 0.0648 mfd	1' 3" + 2'	4 $\frac{1}{16}$ turns reg. pr. coil
3.	$\frac{4 \times 36}{2} = 72$ bottles = 0.0648 mfd	1' 3" + 4'	4 less $\frac{1}{32}$ turn reg. pr. coil
4.	$\frac{4 \times 36}{2} = 72$ bottles = 0.0648 mfd	1' 3" + 6'	3 $\frac{7}{8}$ + $\frac{1}{32}$ turn reg. pr. coil

It is to be stated by way of explanation that the *floor* was V 3" above ground. A simple inspection of the above results shows that induced currents do not prominently assert themselves. This might have been expected considering the extreme dryness of the ground which, as before pointed out, made it too difficult at the outset of these experiments to get a good ground connection. But it is evident from the above table that the electrostatic capacity is an important element. This is quite evident since the vibration of the system comprising the square coil is *quickened by elevation* of the frame. If there were *induced currents* generated in the ground it would *be just the opposite*. Since the capacity in the primary exciting circuit remained the same in all four experiments the capacity of the excited circuit, the inductance of which remained the same, was varied exactly as the inductance of the primary circuit. Now with reference to the table of inductances the inductances in experiments 1, 2, 3, and 4, respectively, were: 12,824, 12,463, 12,247 and 12,103 cm. The increase of distance from 1 to 2 was 160%; from 2 to 3 61.5%; from 3 to 4 38.2%. Putting results together we have:

Increase of distance	Amount of the diminution of capacity	The numbers indicate a general proportionality but now the capacity of the excited system should be known. <i>This will be followed up.</i>
2' 160%	361	
2' 61,5%	216	
2' 38,2%	144	

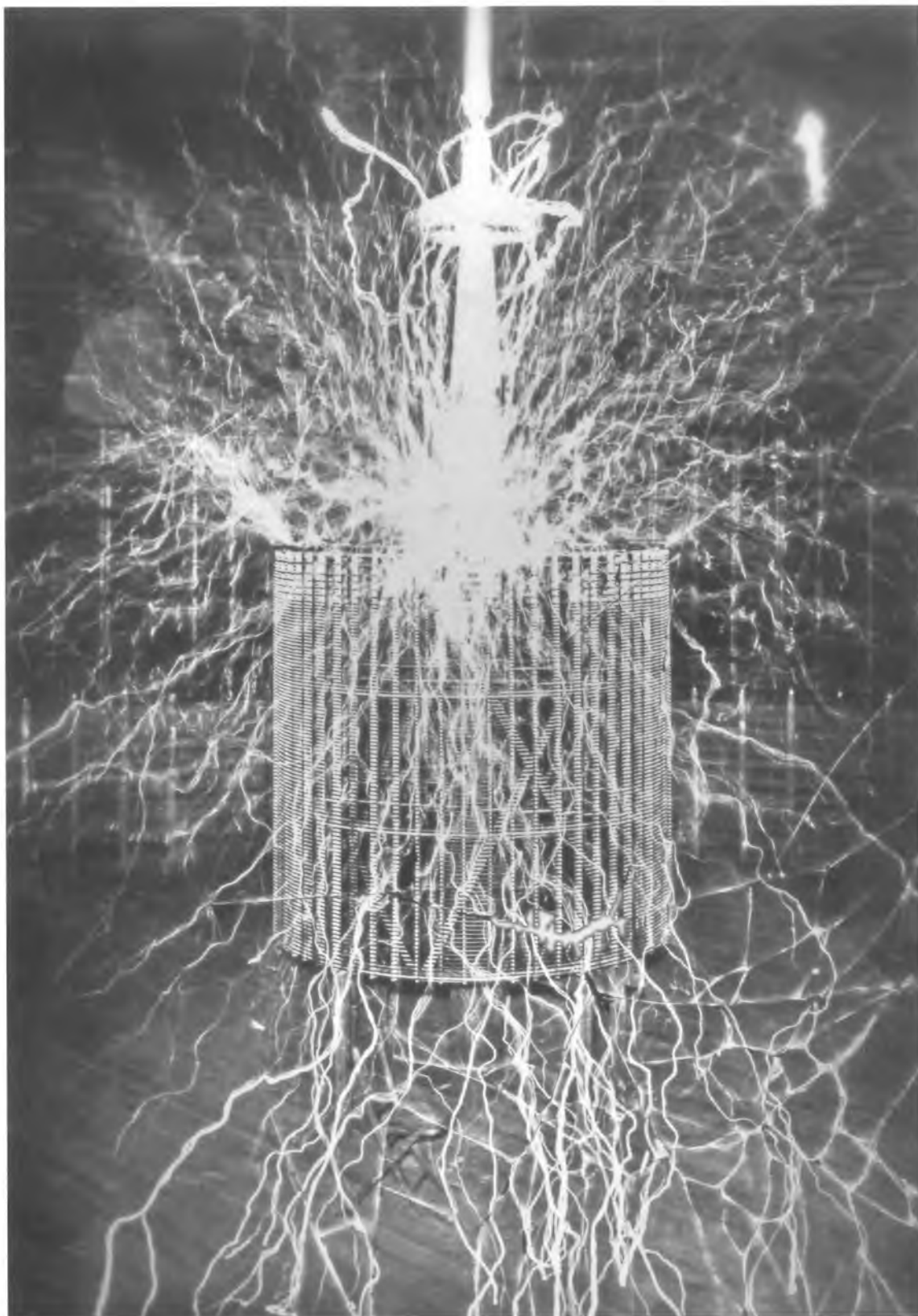
* Capacity of primary cables with reference to earth should be determined.

Colorado Springs

Dec. 8, 1899

In response to note from I. Hawthorne forwarded to "Northamerican" Philadelphia, dispatch as follows:

"In response to a request from friend I. Hawthorne the following statement: "Confining myself to my chosen sphere, I believe that the mastery of electrical forces was as great and beneficial an achievement as the Century has witnessed. As to the immediate future my thoughts are dominated by two ideas, one of which is already realized, while the other is on the eve of accomplishment. The



Phot. VIII. Central view of "extra coil" normally excited with streamers issuing from a disk turned towards the camera.

art of governing the movements and performances of distant automatons, enabling machines to act as creatures endowed with a mind, will demonstrate to the leading nations the futility of armaments and impracticability of the present life destroying implements of war and will lead to more permanent peaceful relations, in harmony with the humanitarian spirit and enlightenment of the age; while the art of transmitting electrical energy through the natural media, without the use of leading wires, over vast distances, from great centers, as Niagara, will open up inexhaustible resources of wealth and power and, by rendering immense amounts of the energy of the sun available to the wants of man, will perhaps make it possible for him to produce similar wonderful changes and transformations on the surface of our globe as are, to all evidence, now being wrought by intelligent beings on a neighbouring planet.

N. Tesla"

Experiment to determine the inductance of coil wound on the square frame before used by means of resonance analysis and another known coil:

The square coil was connected in series with coil of 344 turns as before and maximum rise was determined in the same way as described in preceding experiments. The resonant condition was obtained with

Coil 344 turns in series with square coil

Capacity in primary or exciting circuit	Inductance in primary circuit:
$\frac{36}{2} = 18$ bottles = 0.0162 mfd	5 less $\frac{1}{32}$ turns reg. coil = 15,000 cm approx.

With coil 344 turns alone

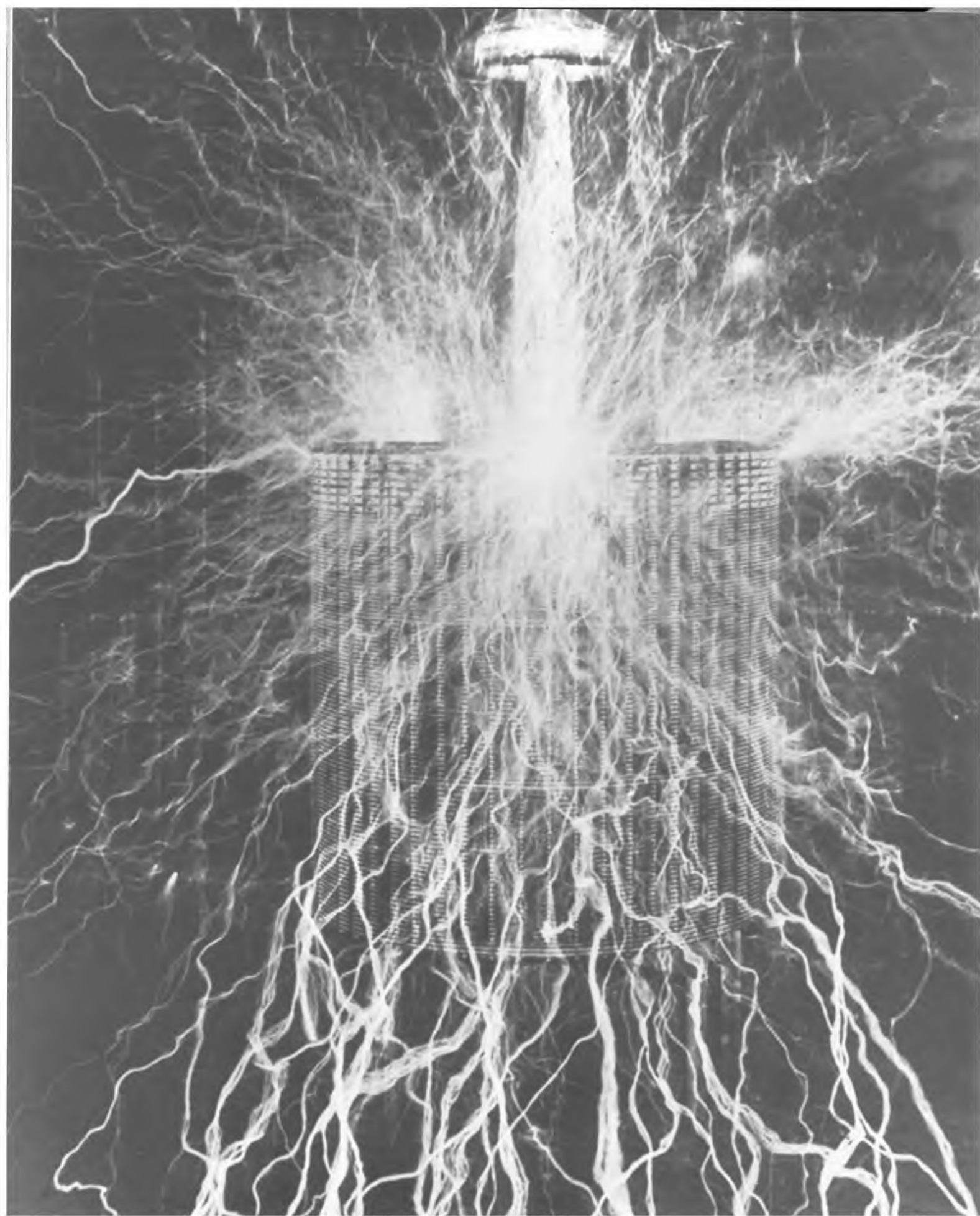
Capacity in primary or exciting circuit	Inductance in primary circuit:
$\frac{36}{2} = 18 = 0.0162$ mfd	15 less $\frac{1}{16}$ turns reg. coil = 51,700 cm

Assuming now that the addition of capacity when coil on square frame is connected in series be negligible, as will be the case when the coil which is to be measured is very small in comparison to the other we may assume, since the capacity in the primary circuit was the same in both experiments, that the inductances in the primary or exciting circuit are as the inductances of the excited circuit in both the successive tests. Calling inductance of square coil L and remembering that inductance of the coil with 344 turns was before recorded to be 0.006 henry, we have:

$$\frac{L + 0.006}{0.006} = \frac{51,700}{15,000} = \frac{517}{150} \text{ and}$$

$$\frac{517}{150} \times 0.006 - 0.006 = L = 0.006 \left(\frac{517}{150} - 1 \right) = 0.006 \times \frac{367}{150} = L = 0.01468 \text{ henry.}$$

The correctness of this estimate is of course based on the assumption that the capacity added to the excited system by the square coil is very small compared with the total capacity.



Colorado Springs

Dec. 9, 1899

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Results obtained Dec. 7, with square coil in various positions reconsidered

The results referred to indicate that the induced currents generated in the ground are of little or no moment but that the capacity owing to nearness of ground may be of great importance. To get a better idea of the variation of the capacity and also to settle any doubt as to the influence of the induced currents it is necessary to estimate the capacity of the system which was excited. For the present purpose it is thought the consideration of the "ideal" capacity of the coils will lead to results not far from the truth. Now on a previous occasion the "ideal" capacity of a coil with 344 turns was found to be 34.6 cm. Since this "ideal" capacity increases with the square of the length of the turns, owing to the fact that it increases with the energy stored in simple proportion, and the energy again in proportion to the square of the difference of pressure between each two adjacent turns, the difference of pressure is simply proportionate to the length. Now the length of one turn on square coil is $4 \times 11' \frac{1}{4} = 4 \times 132.5 = 530$ ". The coil of 344 turns being wound on a drum 14" diam., the length of each of its turns is $3.1416 \times 14 = 44$ " nearly. The "ideal" capacity of the square coil will therefore be, considering also turns, $\frac{14}{344} \times \left(\frac{530}{44}\right)^2 \times \text{ideal cap. of coil 344 turns} = \left(\frac{265}{22}\right)^2 \times \frac{14}{344} \times 34.6 = 145.1 \times 1.4 = 203.14$ cm. Hence total "ideal" capacity will be the sum of these, that is approximately 238 cm. This value obtained at a given height above ground being known, we can now calculate the increments of capacity, or decrements of same as the coil is approached to or removed from the ground and it ought to be found that these increments or decrements are proportionate to the distances of coil from ground in the successive positions of the coil. I think that it is unnecessary to go through the trouble at present because it is very probably so.

Note: Such proportionality would be destroyed if there would be any appreciable currents generated in the ground.

Colorado Springs

Dec. 10, 1899

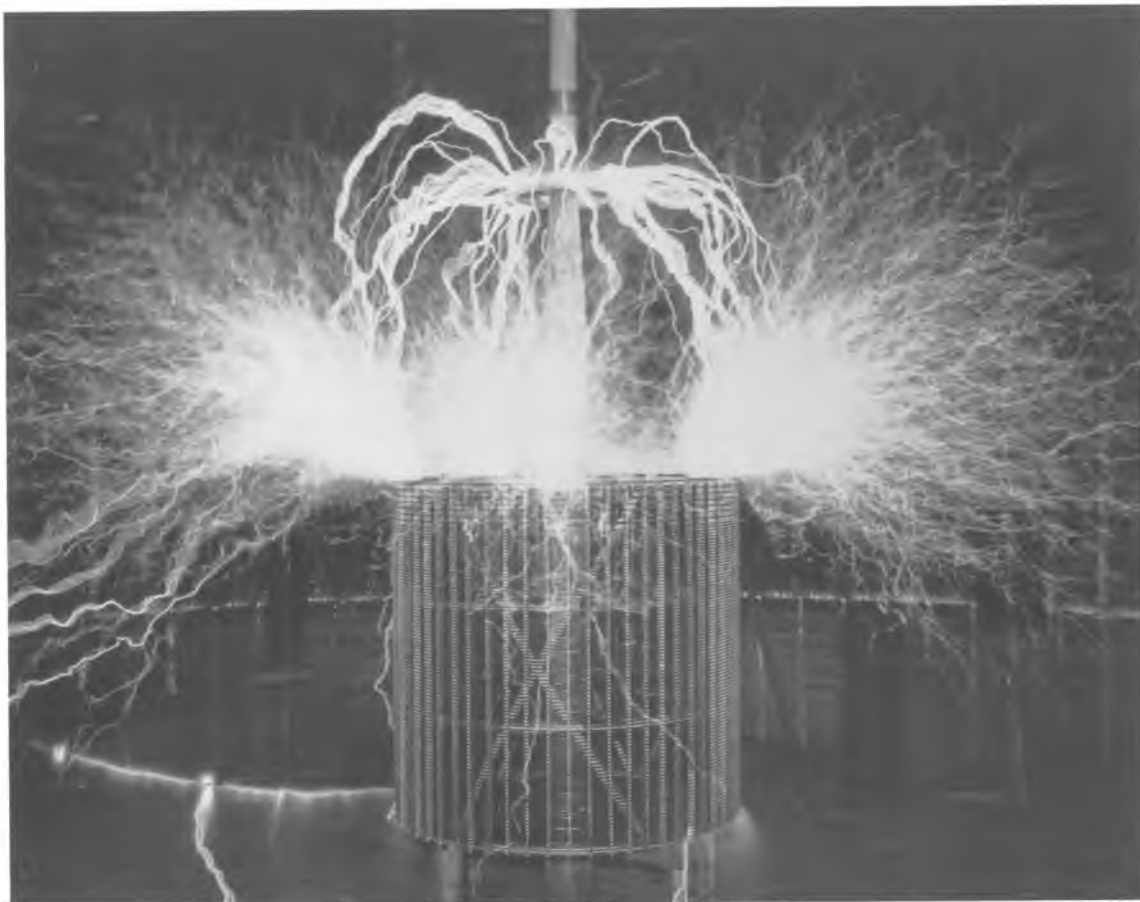
Estimate of turns of "Extra coil" to be used with the structure of iron pipes as capacity on free terminal

In a previous test resonance was obtained with new extra coil and elevated structure as capacity with

Capacity in primary exciting circuit	Inductance in primary circuit
168 bottles=0.1512 mfd	20 $\frac{3}{8}$ turns reg. coil

In this test the extra coil had 105 turns. The turns being now reduced to 100, the inductance of the coil will be smaller by a ratio off $\left(\frac{100}{105}\right)^2 = 0.907$. Hence instead of 20,000,000 cm as before, the inductance of the coil will be 20×0.907 million cm or 18,140,000 cm=0.018 henry approx. Had the above

Phot. IX. "Extra coil" with streamers and sparks from a pointed wire placed towards the camera.



Phot. X. The discharge from the brass ring on the top of "extra coil".

test been performed with the coil so modified, the capacity in the primary exciting circuit – assuming the inductance the same – would have been smaller by a ratio of $\frac{18.14}{20}$ or we would have had instead of 168 bottles about $\frac{18.14}{20} \times 168 = 153$ bottles approximately = $0.0009 \times 153 = 0.13759$ mfd capacity. We have therefore as basis for computation:

Extra coil with structure: 1.

Capacity-primary: 0.13759 mfd	Inductance-primary: 20 $\frac{3}{8}$ turns reg. coil.+conn.
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Now in another test of extra coil but without structure results were

Extra coil alone: 2.

Capacity-primary: 0.0648 mfd	Inductance-primary: 5 $\frac{5}{8}$ turns reg. coil.+conn.
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These data enable us to determine how many turns are to be left off on bottom of coil in order that it be in resonance with the primary exciting system under the *best working conditions of the latter*; the structure being connected to the coil.

Now the secondary, to be at best, should work with all jars available and the regulating coil should be *all cut out* in the primary. This is namely the condition corresponding to full output and highest economy. Under such working conditions the secondary will modify greatly the inductance of the primary and for the present approximate estimate it will be close enough to assume a diminution of about 50% of the primary inductance so that the latter may be put at 28,000 cm. This would then give in Test 2:

Extra coil alone

Capacity-primary 0.0648 mfd	Inductance-primary 28,000+5 $\frac{5}{8}$ turns reg. coil+conn=28,000+17,263=45,300 cm. approx.
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But capacity in primary with *all jars* as would be required *for best working* would be $\frac{8 \times 36}{2} = 144$ bottles = 0.1296 mfd. Reduced to this capacity the inductance in primary would have been in reading 2. instead of 45,300 cm only $\frac{0.0648}{0.1296} \times 45,300 = 22,650$ cm.

Taking now reading 1. when structure was connected to the free terminal of coil the inductance in primary was 20 $\frac{3}{8}$ turns+conn.=72,660 cm from table. But in this case the capacity was 0.13759 mfd. Reducing this to the capacity when secondary works best, that is, to 0.1296 mfd the inductance with this capacity would have been larger by 0.13759 a ratio of $\frac{0.13759}{0.1296} = 1.048$ or it would have been $72,660 \times 1.048 = 76,150$ cm, approx. Thus we have the following data:

Extra coil with structure connected: a)

Capacity in primary 0.1296 mfd	Inductance in primary =76,150 cm and
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Phot. XI. Discharge passing laterally to the camera from the central coil to another coil on a stand. Mr. Alley is sitting in the chair.

Extra coil alone without structure: b)

Capacity in primary 0.1296 mfd	Inductance in primary 22,650 cm.
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Now to secure resonance with structure attached and under best working conditions of the exciting system with possibly only a very few turns of the regulating coil in primary, we have from above to reduce inductance of extra coil by a ratio of $\frac{22,650}{76,150}$. For same length turns will be $\sqrt{\frac{2265}{7615}} \times 100 = 54.55$ t.

Colorado Springs

Dec. 14, 1899

Test to ascertain free vibration of new "Extra Coil System" (latest)

The new "extra coil" latest type is wound on same frame 8' 3" diam. and 8 feet in length, the wire being this time № 6 instead of wire № 10 as before. There are presently just 100 turns. A coil of № 6 wire wound on drum 14" diam. and 8 feet long, which was used repeatedly before, was connected in series with this latest extra coil and resonance determined by means of the adjustable small inductance as usual and a miniature lamp shunting the turns. The results with *no* capacity on the terminal which was "free" were:

Capacity in primary circuit	Inductance in primary circuit
$\frac{5 \times 36}{2} = \frac{180}{2} = 90$ bottles = 0.081 mfd	One primary turn (two cables in multiple) + 3 turns regul. coil

When a ball 30" diam. with 4 feet of wire was connected to the free terminal the readings were:

Capacity-primary: 0.081 mfd	Inductance-primary: as above, only 7 ½ turns in regul. coil
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In both cases the excitation was effected through the secondary of the oscillator from a point of the same $\frac{3}{4}$ turns from ground plate. In the first case the inductance of primary, taking into consideration the secondary reaction, is estimated at 41,000 cm. Adding to this the inductance of connections and 3 turns of regulating coil = 10,000 cm the total inductance was about 51,000 cm. This with a capacity of 0.081 mfd would give the period of the system comprising the two coils in series

$$T_s = \frac{2\pi}{10^3} \sqrt{0.081 \times \frac{51}{10^6}} = \frac{2\pi}{10^6} \times 2.03 = \frac{12.75}{10^6} \text{ approx. and } n=78,500$$

approx. per second. When the capacity of a ball of 30" diam. is associated with the system we have the inductance of the primary circuit, as before, 41,000 cm for the primary turn with secondary reacting plus 7 ½ turns regulating coil and connections = 23,580 cm, with reference to the table, that is, total = 64,580 cm. The period in the second case was therefore

$$T_s = \frac{2\pi}{10^3} \sqrt{0.081 \times \frac{6458}{10^8}} = \frac{2\pi}{10^7} \sqrt{523.098} = \frac{6.28 \times 22.9}{10^7} = \frac{143.8}{10^7}$$

and $n=70,000$ approx. The coil connected in series with the extra coil was wound on a drum used before. In one case this drum was wound with wire № 10, 346 turns and in this case it had an inductance of 6,040,000 cm. The new "extra coil" latest having 18,000,000 cm approximately, the total inductance may be placed closely enough at $18,000,000 + \left(\frac{283}{346}\right)^2 \times 6,000,000$ cm, the coil in series with the extra coil here used having 283 turns. This gives inductance total $18,000,000 + 4,000,000$ approx. = 22,000,000 cm. Now if the latter coil of 283 turns would have been omitted then the system would have vibrated quicker in proportion

$$\sqrt{\frac{22 \times 10^6}{18 \times 10^6}} = \sqrt{\frac{22}{18}} = \frac{\sqrt{11}}{3} = 1.106$$

times or since n in the first case was = 78,500, the extra coil alone will vibrate $1.106 \times 78,500 = 86,800$ approx. If the inductance in primary be left the same as in the first case then the number of bottles will be reduced by a ratio of $\frac{18}{22} = \frac{9}{11}$ or instead of bottles total we shall want $\frac{90 \times 9}{11} = \frac{810}{11} = 74$ bottles or nearly so; this means 148 bottles on each side or about 4 tanks. This is only an approximate estimate for first guidance. Perhaps the reaction of the secondary is somewhat overestimated in this case as it was not resonating in these tests or near the resonating condition.*

* With figures taken from second test the results are very nearly the same.

Colorado Springs

Dec. 15, 1899

List, for future reference, of some coils used in the experiments up to present

Coil wound on drum	25,25" diam.	cord	№ 20	404 turns	Length of this drum 71 1/2" appr
Coil "	25,25"	cord	№ 10	259 turns	
Coil "	25,25"	wire	№ 10	274 turns	
Coil "	24"	wire	№ 6	207 turns	70 3/4" long
Coil "	10 5/16"	Bell wire	№ 18	550 turns	Length of this drum 8 feet appr.
Coil "	14"	cord	№ 10	346 turns	
Coil "	14"	Bell wire	№ 18	1314 turns	
Coil "	14"	wire	№ 6	283 turns	38 1/4" long
Coil "	5"	wire	№ 2	91 turns	
Coil "	5"	wire	№ 6	129 turns	38 3/4" long
Coil "	4"	wire	№ 10	185 turns	4 ft.
Coil "	4"	wire	№ 10	141 turns	3 ft. long
Coil "	30 1/2"	wire	№ 25	132 1/2	
* Exp. resonance					

Coil on drum	26" diam.	wire	Nº 6	136 turns	upright stand
Coil on spool	12" diam	Bell wire	Nº 18	28 layers	2 1/8" long

$$\left. \begin{array}{l} \text{to 20 lay. 28} \\ \text{to 28 lay. 27} \end{array} \right\} = 20 \times 28 + 8 \times 27 = 560 + 216 = 776 \text{ turns}^*$$

* Exp. to determine periods of vibration.

New extra coil as first wound 8' 3" diam., 8 ft. long, 105 turns Nº 6 wire, between grooves 1/2". A number of these coils have been before described and their inductances measured. Since the same drums were repeatedly wound with different wires it is easy to determine the inductances on the bases of data before recorded with some of them. It is proposed to make later a complete table of the coils with the inductances and other particulars worked out.

Colorado Springs

Dec. 16, 1899

In carrying on some experiments to ascertain the effects of induction from the primary circuit of the oscillator in the laboratory, at a distance from the same, a square frame described on a previous occasion was used. This frame was 11' 1/4"=132.5"=336.55 cm long and as much wide and 3 3/4"=9.525 cm deep. It was wound with 14 turns of wire Nº 10. To ascertain the period of vibration of this coil a formula before arrived at and frequently used was again employed. This formula applies to coils of circular cross section but it was thought that the results would be close enough also for the square coil with due allowances. To apply the rule the square surface was converted into a circular one equal to it and the diameter of the latter was calculated. Finally an allowance was made for the diminished length of the wire on the circular coil for the same number of turns. Calling D the diameter of the circle we have $\frac{D^2\pi}{4} = 336.55^2$ from which follows $D=380$ cm. approximately. The formula referred to is

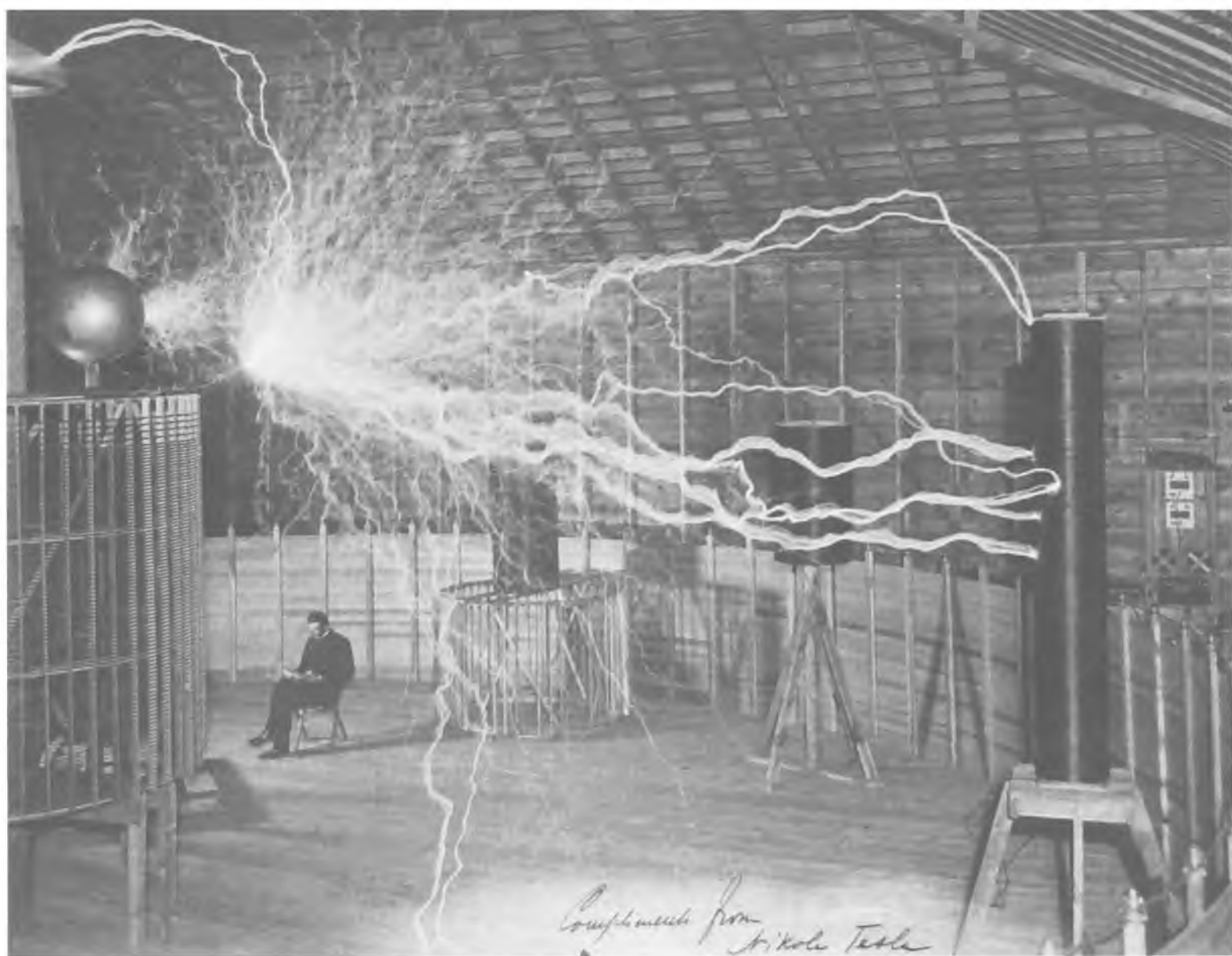
$$p = \frac{3 \times 10^{10} \sqrt{(\tau + d)\tau}}{D^2 N \sqrt{\pi^3 K} \sqrt{d}}$$

Here τ =distance of wires=0.46 cm; d =diam. of wire=0.254 cm; $(\tau + d)=0.714$; $\sqrt{\tau(\tau + d)}=0.573$; K as found = $\frac{52}{10^6}$; $\sqrt{d}=0.5$; N = number of turns=14; p =natural frequency of coil to be found.

This gives in the present case:

$$\begin{aligned} p &= \frac{3 \times 10^{10} \times 0.573}{3.1416 \times 380^2 \times 14 \times \sqrt{\frac{3.1416 \times 52}{10^6}} \times 0.5} = \frac{6 \times 10^{10} \times 573}{3.1416 \times 144,400 \times 14 \times \sqrt{3.1416 \times 52}} = \\ &= \frac{6 \times 10^8 \times 573}{44 \times 1444 \times \sqrt{3.1416 \times 52}} = \frac{3438 \times 10^8}{44 \times 1444 \times 12.8} = \frac{3438 \times 10^8}{813,300} = \frac{3438 \times 10^6}{8133} = 423,000 \text{ approximately} \\ &\text{and } n = \frac{423,000}{2\pi} = 67,360 \text{ nearly.} \end{aligned}$$

This would be for a cylindrical coil of 14 turns, but the turns of the square coil are longer and, since the inductance is proportionate to the square of the length of wire, and the frequency again proportionate



Phot. XII. Repeated experiment shown in Phot. XI, but with Tesla sitting in the chair.

to the square root of the inductance, n will be smaller in proportion $\frac{4 \times 336.55}{3.1416 \times 380} = \frac{1193}{1346}$ or the system will vibrate about $\frac{1193}{1346} \times 67,360$ or roughly 60,000 per sec. The *experiments showed* it vibrated *nearly this number* of times.

Colorado Springs

Dec. 31, 1899

Of the photographs taken here from Dec. 17 to Dec. 31, 1899 by Mr. Alley the following were forwarded through him to my friends of the Century

I. Front view of laboratory from Pike's Peak side. Isochromatic 11"×14" plate. Time – afternoon before sunset. This is a very fine photograph showing well the advantage of the pure atmosphere here. Such sharpness of outlines and amount of detail could not be obtained in New York, for instance. I conclude that the high quality of photographs obtainable in these parts is not so much due to the skill of the professionals as to the pure atmosphere and abundance of light.

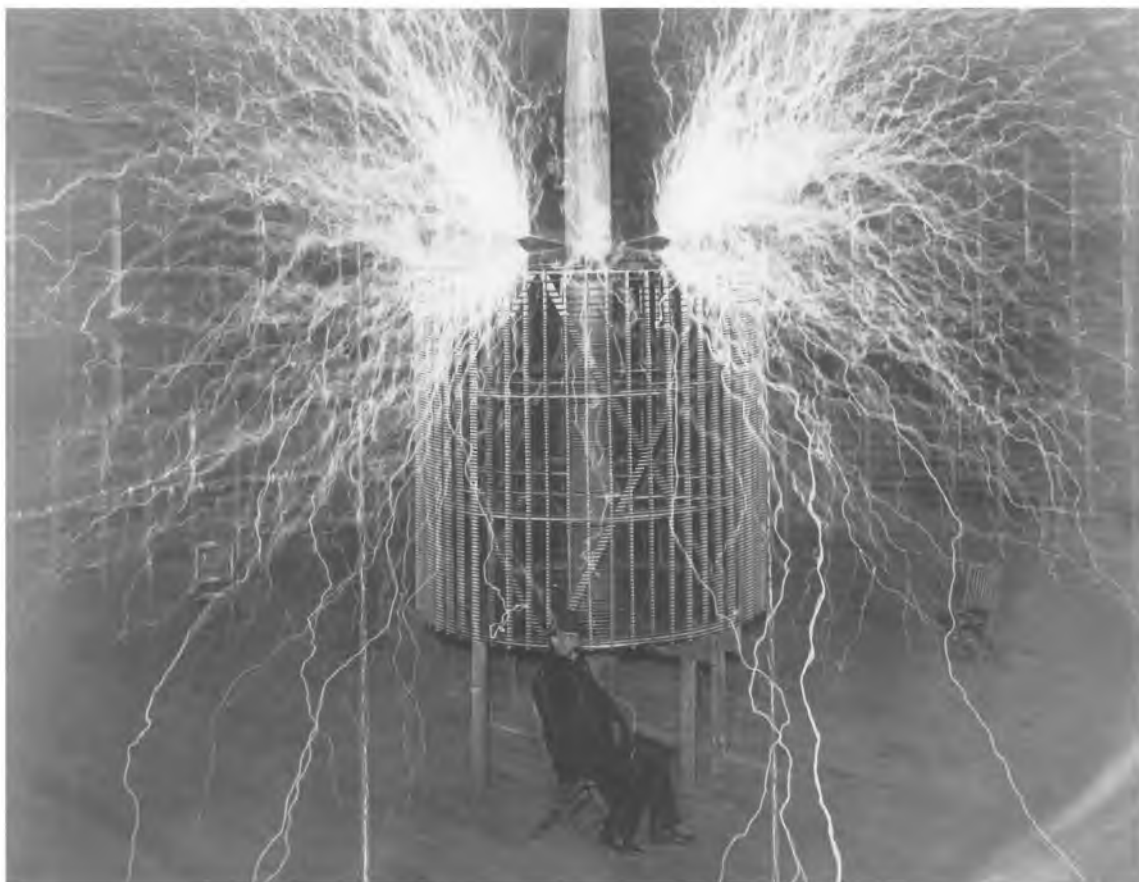
II. View of interior showing half of circle of oscillator frame with several coils grouped inside; Westinghouse transformer, lightning arresters in background, also part of central "extra coil" latest pattern and a 30" ball on stand. The photograph was taken late in the afternoon. Light was rather feebly diffused. The plate was as before, 11" × 14" isochromatic.

III. View of interior, chiefly showing condensers, break motor and regulating coil in primary of oscillator. Westinghouse high tension transformer and supply transformers in background, also arresters. Plate same as before, the photograph was taken at the same time, practically as that described under II. The diffused daylight was very feeble. Both of these plates are excellent.

IV. View of laboratory from the rear by moonlight; *1 h 20 min.* exposure. Moon about $\frac{2}{3}$ full. Showing Pike's Peak Range and all details of building very sharply. Such photographs by moonlight could be secured only in a few places. Plate same as before, 11" × 14" isochromatic.

V. View of interior much the same as in II. The secondary and various coils placed inside, particularly the central "extra coil", are resonating. The latter is connected to a point of the first secondary turn about $\frac{3}{4}$ turns from ground connection, nevertheless the streamers are powerful. Other coils are connected to the same point while a ball 30" on a stand and a coil on a stand are connected to the last turn of secondary. Strong sparks were passing from top to bottom of extra coil and the secondary last turn shows strong streamers. About 100 short flashes or throws of switch and afterwards an exposure of 15 minutes to ordinary arc lamp placed in corner of building for the purpose of photography. The arc light is much preferable to flash light as the time can be closely determined in each case. The isochromatic plate is *decidedly better*. In this plate there is a red dye used in coloring the plate, otherwise it is the same as the Cramer "Crown". The plate used was "instantaneous Cramer isochromatic", same size as those before. This observation suggests a line of experiment which might lead to useful results. It would consist in using plates each dyed with a different color to bring out specific effects. The vibrations of the system was the normal or nearly so as recorded in previous notes.

VI. View of "extra coil" excited as normally. A bare brass ring formed of tube $\frac{3}{4}$ " diam. is placed on top. The switch is thrown in once and held about 3 seconds. The roof has been slightly opened and also the door in front to create a draught. The effect of the latter is noted easily on the separation of the individual discharges. This feature is particularly noticeable on sparks passing to the hood carried by the structure of iron pipes repeatedly described. These sparks pass in curious ways preferring frequently a long path to a short one. This is peculiar to these discharges of high tension emanating from a single free terminal. Some streamers are broken in places to continue stronger afterwards. From end to end



Phot. XIII. Streamers issuing symmetrically from ball with two wires on each side. Mr. Alley is sitting.

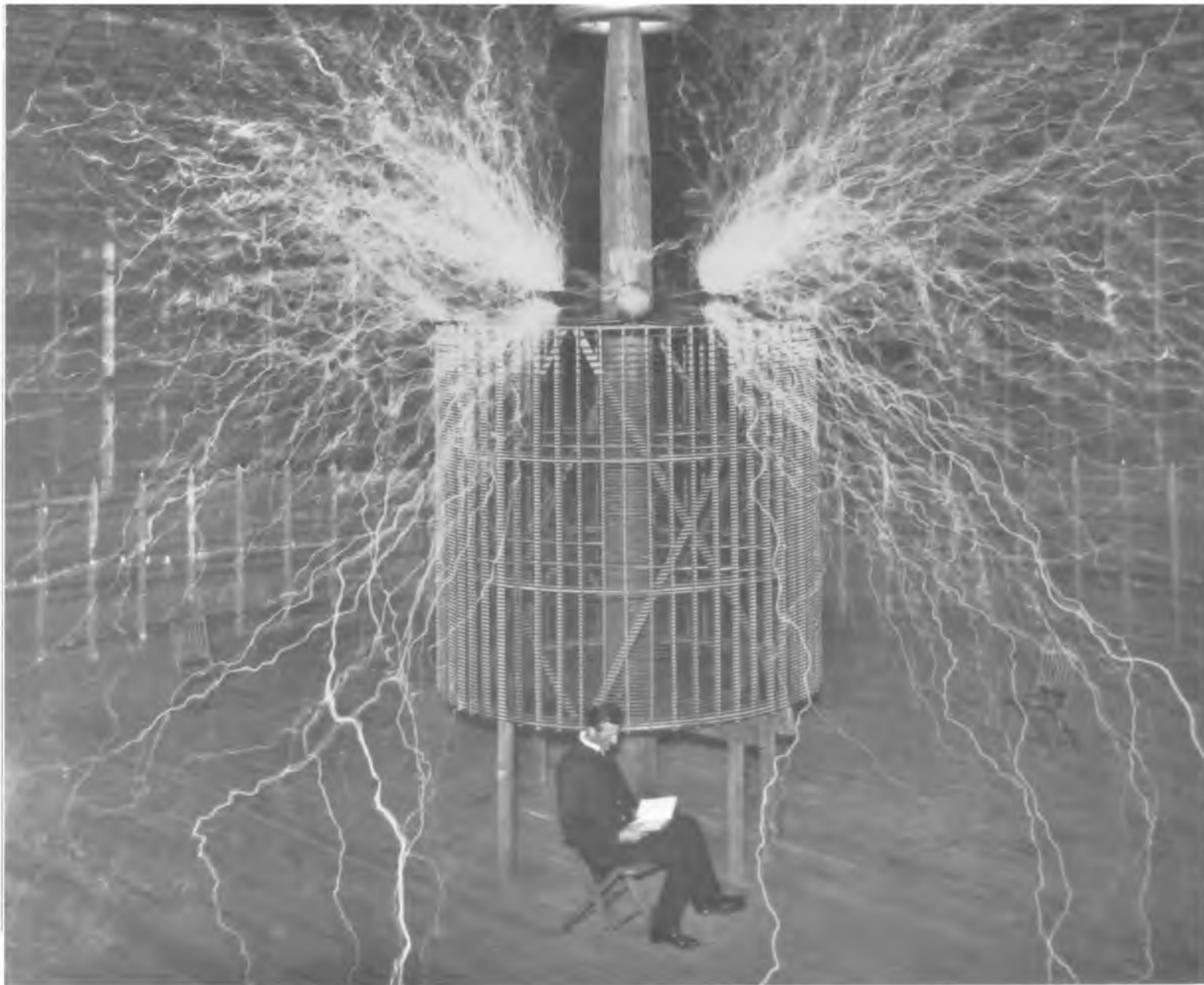
of the longest streamers about 50–55 feet in a *straight* line. This photograph is extremely beautiful on account of the character as well as arrangement of the streamers. The extra coil is excited as normally but not quite full power. The vibration is as previously recorded.

The same kind of plate as before was used and the exposure to arc light was 15 minutes, about half light cut off.

VII. View of "extra coil" in action. Wires slightly inclined to the ground, to prevent discharge from going to roof, were fastened at small distances to brass ring on top of coil. Thus a great amount of streamers was produced and they were necessarily weaker individually. The plate illustrates well this feature as is evident from the hairlike appearance of the streamers. Individual sparks passing to ground sometimes are strong. It is peculiar that discharge will break out more strongly on some wire and then keep on the same place until broken by draught created or otherwise. The path is, however, evidently accidental depending probably on the arrangement of particles floating in the air. This photograph is very beautiful and symmetrical. The length of the streamers is about the same as in preceding case. The vibration of "extra coil" system about normal only slightly modified by the wires attached to brass ring. Some streamers, curious to note when striking the ground and thus becoming *sparks* or spark discharges more brilliant in color, appeared thicker on bottom than on the point of origin. I believe I have recorded this phenomenon some time before. It may, on the plate, appear that the streamer or spark is thicker farther away from the origin without necessarily being so. This is simply caused by the end or lower part of the streamer being closer to the camera than the origin. But the eye is not deceived in this respect and the phenomenon may be frequently noted so that its existence is beyond doubt. This may be explained by assuming a volatilization of the material where the spark strikes, whereby a flame may be produced increasing the brightness of the part of the luminous path nearer to this point. In fact I observe that whenever a powerful spark strikes an object which is of a material easily disintegrated by the heat, such as wood, there is a momentary small flame produced on that point and often one may see the spark bound back as it were or splash over the object like a jet of molten metal. It will be noted on the negative that the points where the sparks hit the floor are always darker, this showing the increased development of light at these spots. The plate used is the same as before.

VIII. This shows a central view of "extra coil" normally excited with streamers issuing from a disk turned towards the camera. In this instance the streamers were longer than before as they were issuing from fewer points, chiefly from the rim of the disk which was a little more than 10" in diam. Some of the streamers darting towards the corners of the building were 30 feet in a straight line, but considering their curved path they were in all probability 50 feet long. Some of them show interesting bifurcations or splitting up in many branches while others, carried by the draught they create themselves, again show clearly the individual discharges. The brilliant sparks to the hood above the coil are also curious and interesting often passing far above the hood and then returning to the same in paths much longer than the straight route from the top of the coil to the hood which they should follow. Some of the streamers striking the floor show the increased brightness, before referred to, very clearly. It is noticeable that the streamers above the coil are of finer texture and split up, the draught being of course stronger near the opening of the roof. On some of the very long streamers one can see occasionally more brilliant points. The plate in this experiment was the same as before and the vibration of the "extra coil" system likewise normal or nearly so.

IX. This photograph illustrates again the extra coil with streamers and sparks from a pointed wire placed towards the camera. The wire or terminal was turned slightly downwards to cause the streamers or sparks to go more downward, as there was a considerable danger in this experiment of inflaming the roof of the building by the discharge taking an upward course. The streamers, when made to issue from a point as in this instance, are namely very long and in fact it was found impossible to work the apparatus to its full capacity in this account. The excitation of the "extra coil" system was pushed as far as could be done without great risk. The longest streamers reached the side of the building and even the corners sometimes. One of them reached the photographer Mr. Alley in the corner of the building,



Phot. XIV. Repeated experiment shown in Phot. XIII with Tesla sitting.

while another one struck me as I was operating the switch in another corner. They were so feeble at that distance, however, that they did not cause any injury or pain. Another one struck the camera but, as subsequently found, did not spoil the plate. These streamers were about the longest produceable in the present building, with the roof closed, measuring from 31–32 feet in a *straight line* from origin to end. Taking into account the curiously curved path the length was probably more than twice this, so that taking the discharge from tip to tip of these longest streamers, the actual path of the discharge through the air was from, say, 124–128 feet! If the building would permit I think that with the present apparatus, by putting about two to three times the copper in the oscillator a discharge extending through approximately twice this distance would be obtained, and by overcoming some defects of the present type of oscillator a further gain of about 50% could still be effected, so that I can certainly expect to reach, measured in this way, a length from 372 to 384 feet from end to end. In an industrial plant it seems to me advisable to push the pressure still further and the difficulties in this respect do not seem to me now to be very great. In the present photograph certain features before commented upon are even better shown than in the preceding plates. For instance, the high luminosity on the bottom where a spark strikes the floor, the “splashing” of the discharge, the branching out and the interruption of a streamer are all well shown. But the most curious feature is the appearance of “fire balls”. As already noted in a previous instance a streamer even when not as strong as these here described, will show sometimes one or more points of greater luminosity than the rest. On a plate an effect of this kind may be produced by a streamer suddenly bending or turning, but the actual appearance of these luminous spots or points is unmistakable. In the instance here described the streamers were very powerful and the spots when they appeared were about an inch or possibly more in diameter, actual “fire balls” as they appeared to the eye. Now what is the cause of their formation? I attribute them to the presence of some material in the air at that particular spot which is of such a nature that when heated it increases the luminosity. It is possible that sodium is concerned in the production of the phenomenon. But the luminous “ball” must be extremely short lived as it does not impress itself upon the plate sufficiently despite its high luminosity. One can barely note a small luminous patch on the streamer, the impression of the central portion of the “ball”. It is not improbable that the evolution of the “fire ball” may be connected with a process akin to explosion or sudden volatilization. Again, in this instance the same kind of plate was used and the vibration of the extra coil was but slightly quicker than normal.

X. This plate illustrates the discharge issuing from the top of the “extra coil”, from the brass ring mentioned before, all over its surface. To produce a more beautiful effect in this instance the switch was thrown in 200 times, but the closure of the circuit was as short as was practicable, only a small fraction of a second, possibly $\frac{1}{4}$ or $\frac{1}{5}$ of a second. In plates VII, VIII and IX one hundred closures of the switch were made. This photograph is extremely beautiful although the streamers were not so large as in some previous instances. The sparks darting occasionally to the hood rather heighten the effect. The streamers are of fine texture but not quite so as in the plate described under VII. The reason is that the brass ring before mentioned, being of a large diameter, does not permit the streamers to issue from it as readily as the thin wires do and therefore the streamers partake more or less of the nature of sparks, being thicker and more brilliant and bluish white in color at the origin, while the streamers issuing from pointed terminals are of a reddish hue, sometimes quite purple and also less noisy and of feebler luminosity. Owing to their color and small luminosity they do not impress themselves upon the plate as powerfully as the streamers coming from surfaces of a relatively large radius of curvature, which are more or less of a disruptive character, resembling sparks at the point of issue from the terminal. In this experiment again the vibration of the extra coil was nearly normal, the plate was of the same kind and the exposure to the arc light, as in the previous cases described, about 15 minutes, about half of the light cut off on lens.

XI. Plate illustrates discharge passing laterally to the camera from the central coil across the shop to another coil on a vertical stand. The length of the sparks I estimate about 15 feet in this instance, possibly more. The sparks are very powerful and brilliant. The discharge was produced by 50

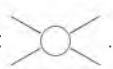
successive short closures of the switch, the experiment being, of course, performed in the dark. Then an exposure – with the arc lamp 10 min. lens almost open, with an experimenter (Mr. Alley) sitting in the chair – was made. The picture of a human figure was introduced to give an idea of the magnitude of the discharge.

XII. The same experiment was repeated with the coil on stand being placed farther from the central coil. The sparks were about 20 feet long in a straight line. Fifty throws of the switch were used as before. The procedure was slightly modified by setting off about 1/3 of an Eastman flash powder to bring out my features.

XIII.

XIV.

} In these two plates the effect was improved by making the streamers issue symmetrically

from ball 8" diam. with two wires on each side:  Fifty throws of the switch were used and the procedure was as in XII. In all the later instances described the plates and other particulars were the same as before.

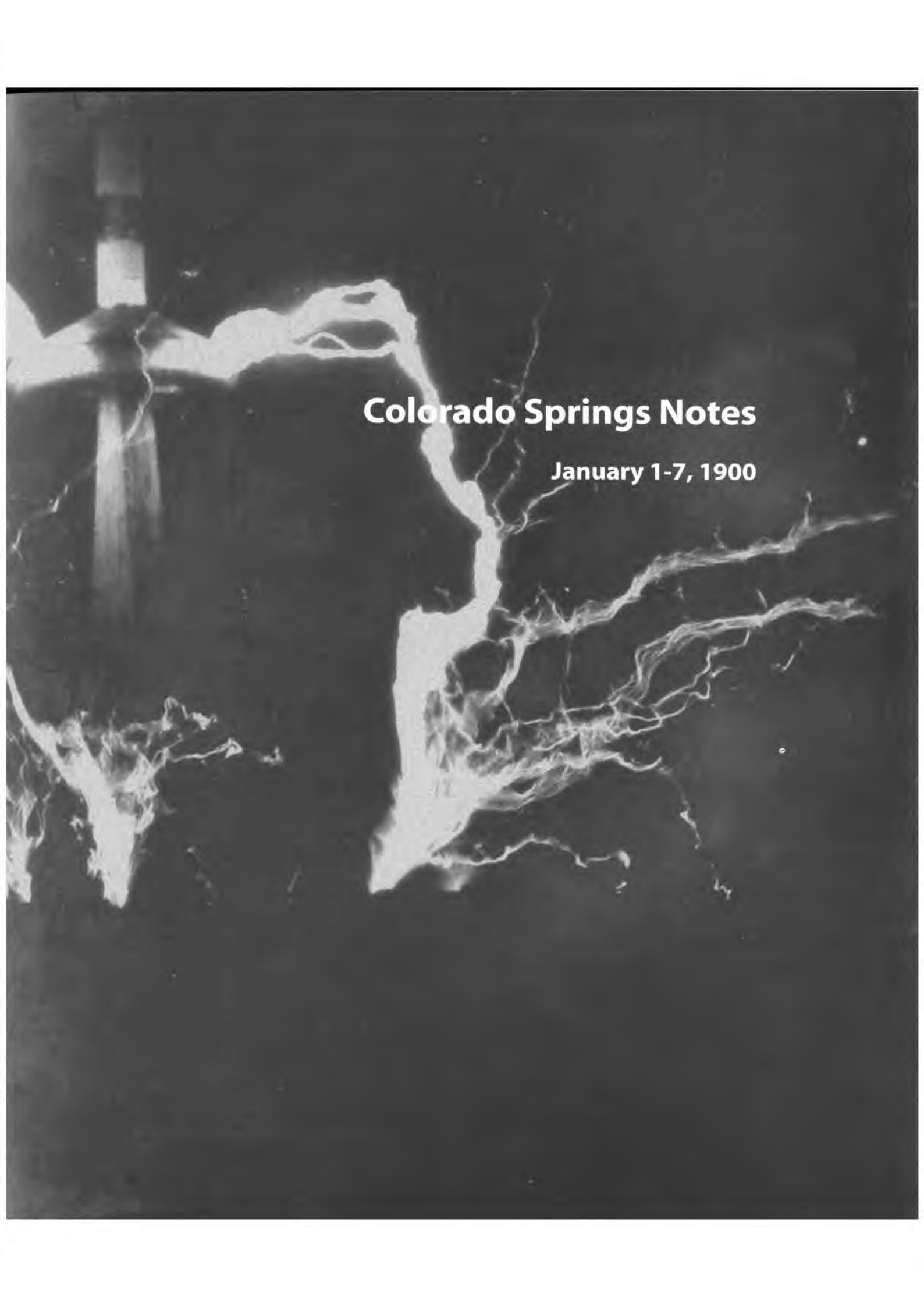
Note: open lens, arc light 5 min.

Note: to preceding description of photographs taken with Mr. Alley:

As before stated, in most cases when the "new extra coil" was shown in action, the vibration of the system including it was about the normal, only slightly modified by the attachment of terminals of comparatively very small capacity. The "extra coil" system was namely adjusted to the vibration of the primary system which took place with *one primary turn* (the two primary cables being in multiple) with *all the jars being connected in two sets in series* and with the *regulating coil all but 1/2 turn out*. Under these conditions the secondary was very strongly reacting upon the primary modifying the inductance of the latter so that the inductance of the primary turn instead of being as previously determined about 57,000 cm was diminished to 41,000 cm approx. Now the inductance of the connections to the condensers, and 1 1/2 of one turn of regulating coil, was as will be seen with reference to the table, often referred to – nearly 6000 cm. So that the total inductance of the primary circuit under these conditions, was owing to the resonating secondary, was only 41,000+6000=47,000 cm, or $\frac{47}{10^6}$ henry. Now the capacity in the primary was two sets of eight tanks in series or four tanks total, that is, 4×36=144 bottles or 144×0.009=0.1296 mfd, approx. Hence the period was

$$T_p = \frac{2\pi}{10^3} \sqrt{0.1296 \times \frac{47}{10^6}} = \frac{2\pi}{10^6} \sqrt{6.0912} = \frac{2\pi}{10^6} \times 2.47 = \frac{15.512}{10^6}$$

or $n=64,466$ per sec. or nearly so. This is a considerably quicker vibration than when the secondary is not active. As the "extra coil" did not have sufficient inductance in itself, another coil was inserted in series with the same to insure the resonating condition with the above primary vibration. This latter coil was wound with wire No 6 on an old drum 2 feet diam. and 6 feet long. Particulars about this coil will be recorded on another page.



Colorado Springs Notes

January 1-7, 1900



Colorado Springs

Jan. 1, 1900

Photographs taken Dec. 22. and 23; with Mr. Alley from Dec. 17 to Dec. 31, 1899 and particulars about the same

XV. Shows an incandescent lamp 16 c.p., 100 V placed out on the field with two wires leading to it. Snow on the ground. The lamp is lighted.

XVI. Illustrates the same with three lamps 16 c.p., 100 V placed on the snow and lighted. The lamps are connected in multiple arc.

XVII. Photograph showing once more the same with three lamps as before, the lamps being placed on black cloth to improve effect. These photographs were taken under the following conditions:

A cord of section equal to that of wire No 10 was laid on the field in the form of a square of 62' 5"=749"=1902.5 cm side, the center of the square being from the center of the primary loop of the oscillator in the laboratory a little over 60 feet=720"=1830 cm. The ends of the square were connected to two small condensers joined in multiple and each having a little less than $\frac{1}{20}$ mfd. Neglecting capacity of the cord against that of the condensers the total effective capacity of this system was, with fair approximation $\frac{1}{10}$ mfd, or 90,000 cm. The inductance of the square, taking it as consisting of two pairs of parallel wires, was

$$L_s = 2 \times 2l \left(\log_e \frac{d^2}{rr'} + \frac{1}{2} \right). \text{ In the present instance}$$

$$l = 1902.5 \text{ cm}, \quad d = 1902.5 \text{ cm}, \quad r=r'=0.254 \text{ cm}.$$

$$\frac{d^2}{r'r} = \frac{d^2}{r^2} = \left(\frac{d}{r} \right)^2 = \left(\frac{1902.5}{0.254} \right)^2 = (7500)^2 \quad \text{and}$$

$$L_s = 4 \times 1902.5 \times (\log_e 7500^2 + 1/2) = 7610 \times (17.825 + 0.5) = 7610 \times 18.325 = 761 \times 183.25$$

$$\log 7500 = 3.875061$$

$$L_s = 139,450 \text{ cm or } \frac{13,945}{10^8} \text{ henry}$$

$$2 \log 7500 = 7.750122$$

$$2 \log_e 7500 = 7.75 \times 2.3 = 17.825 \text{ approx.}$$

From the foregoing we have for the period of the secondary system:

$$T_s = \frac{2\pi}{10^3} \sqrt{0.1 \times \frac{13,945}{10^8}} = \frac{2\pi}{10^7} \sqrt{1394.5} = \frac{2\pi \times 37.34}{10^7} = \frac{234.5}{10^7}$$

and this would give $n=42,640$ approx. per second.

Now resonance in this circuit was obtained with all jars being connected as usual and two primary turns in multiple, there being besides in the primary circuit $18 \frac{1}{2}$ turns of the regulating coil. This gives approximately the capacity of primary or exciting circuit $\frac{8 \times 36}{2}$ jars=144 jars or bottles=0.0009×144=0.1296 mfd. Neglecting for the moment the secondary reaction (that is the action of the secondary of the oscillator upon the primary, the former being thrown out of step by connecting some inductance in series with it), the inductance of the primary circuit with reference to previous data for the primary turns and regulating coil was 122,000 cm. But the inductance calculated from equation

$$\frac{2\pi}{10^3} \sqrt{0.1296 \times L_p} = \frac{2\pi}{10^3} \sqrt{0.1 \times \frac{13,945}{10^8}} = \frac{234.5}{10^7}$$

Phot. XVII Experiment to illustrate an inductive effect of an electrical oscillator of great power. The photograph shown is reproduced from Tesla's article⁽⁴¹⁾ in which somewhat different circuit dimensions and position are quoted.



is smaller, being in fact only about *108,000 cm*. The smaller value is evidently the correct one, being the actual value of the inductance of the primary circuit, as modified by the secondary of the oscillator and the secondary circuit lighting the lamps. A small streamer was seen to issue from the free terminal of the secondary, hence it certainly affected the primary, reducing the inductance. The reaction of the secondary circuit lighting the lamps was comparatively small. In order not to burst the lamps the current of the supply transformers was very much cut down. I think about 30 lamps could have been lighted in this manner by pushing to the normal limit the excitation of the primary loop.

Four photographs were made of the discharge of the secondary of latest type, 20 turns of two wires № 10. The primary consisted of one turn, the two primary cables being connected in multiple arc. The ratio of conversion being thus 1:20, the e.m.f. at the terminals of secondary, with the primary excited to full power, was about 400,000 volts. Owing to the low resistance of the secondary —extremely low when considering the high e.m.f. — the discharge was very powerful, of a dazzling brilliancy, literally blinding, and caused a deafening noise. The candle power of the arc is equivalent to that of five or six arc lights of normal strength. At least I conclude so from comparative tests. Photographs were made by exposing the objects to the light of the secondary discharge and it took only a small fraction of the time needed for an arc lamp to impress the plate. The secondary discharge of this apparatus is so powerful that it was always more or less dangerous for the safety of the laboratory and machinery in the same, and elsewhere, to let it play. A number of times the shop caught fire by sparks passing from some nail, wire or any kind of conductor. When the discharge was playing sparks were seen to fly almost everywhere through the laboratory, from one to another object and it was evident that it was more or less risky to let the sparks from the free terminal pass to the ground, because short waves were produced in the conductors and these were only too apt to rupture the insulation of any apparatus in the circuit or circuits connected with the oscillator or in the neighbourhood of the same. The danger resides chiefly in the *short* waves and the risk was considerably diminished when the secondary, instead of discharging directly into the short ground connection, was made to discharge through a coil or inductance, slowing down the vibration and preventing the formation of very high harmonics. When the discharge was effected as in the experiments photographed, a continuous and brilliant arcing took place over the lightning arresters and the dynamo at the supply station was short-circuited in rapid succession. When considering that the arc on the arresters is almost continuous one must admit that these arresters work extremely well. The discharge, owing to the terrible noise it creates is highly irritating and I think also dangerous to the timpanum of the ear. Often pain is experienced in the ears afterward and the buzzing in the ears continues for hours. If signalling with *very short* waves were desirable, nothing better could be used than such a secondary discharge. Although I have not tested its effects at extremely great distances, I conclude, from comparison with other induction apparatus experimented with, that it would affect a sensitive device certainly at one thousand miles and very likely at a greater distance, even on land. The great brilliancy of the discharge is in part due to the comparatively large capacity of the secondary which, as before shown, is without further provision inseparable from such a coil of very large diameter. When looking at the arc for a moment one can clearly perceive the arc proper forming the central and comparatively narrow part of the luminous path, around which there is on each side a brilliant band of $\frac{1}{2}$ " to 1" width apparently. When the discharge is playing, generally sparks pass on some places between the secondary top turns, this showing that they are by no means too far apart.

Of the four plates: XVIII., shows the secondary discharging from the free end or terminal formed by a wire to the ground plate visible on the bottom.

Plate XIX. illustrates the discharge taking place between a ball 30" diam. and the ground plate. In the former case the discharge is about $3\frac{1}{2}$ feet, in the latter about 3 feet long. These photographs were taken through about half of the full lense opening, nevertheless the discharge is not sharp for although the focusing was carefully effected the wide luminous band on each side of the arc proper, which was referred to, blurs the image. To improve the photographs two more plates were exposed, one the same as plate XVIII., marked XX., showing discharge between a wire and ground plate, and the other, marked



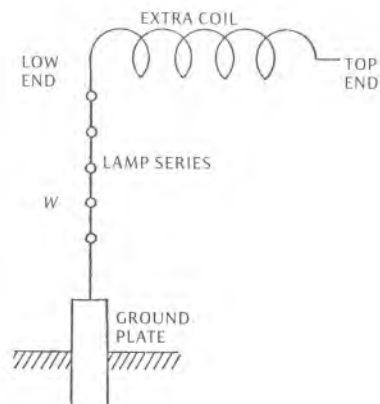
XXL, illustrating discharge playing between a ball 18" diam. and the ground plate. In these instances a small opening was used and the images are sharper. To be quite sharp a pin-hole diaphragm should be used. The vibration in these four instances was the normal as before determined, all jars and one turn in primary, 25 throws of switch, very short, flash afterwards.

Colorado Springs

Jan. 2, 1900

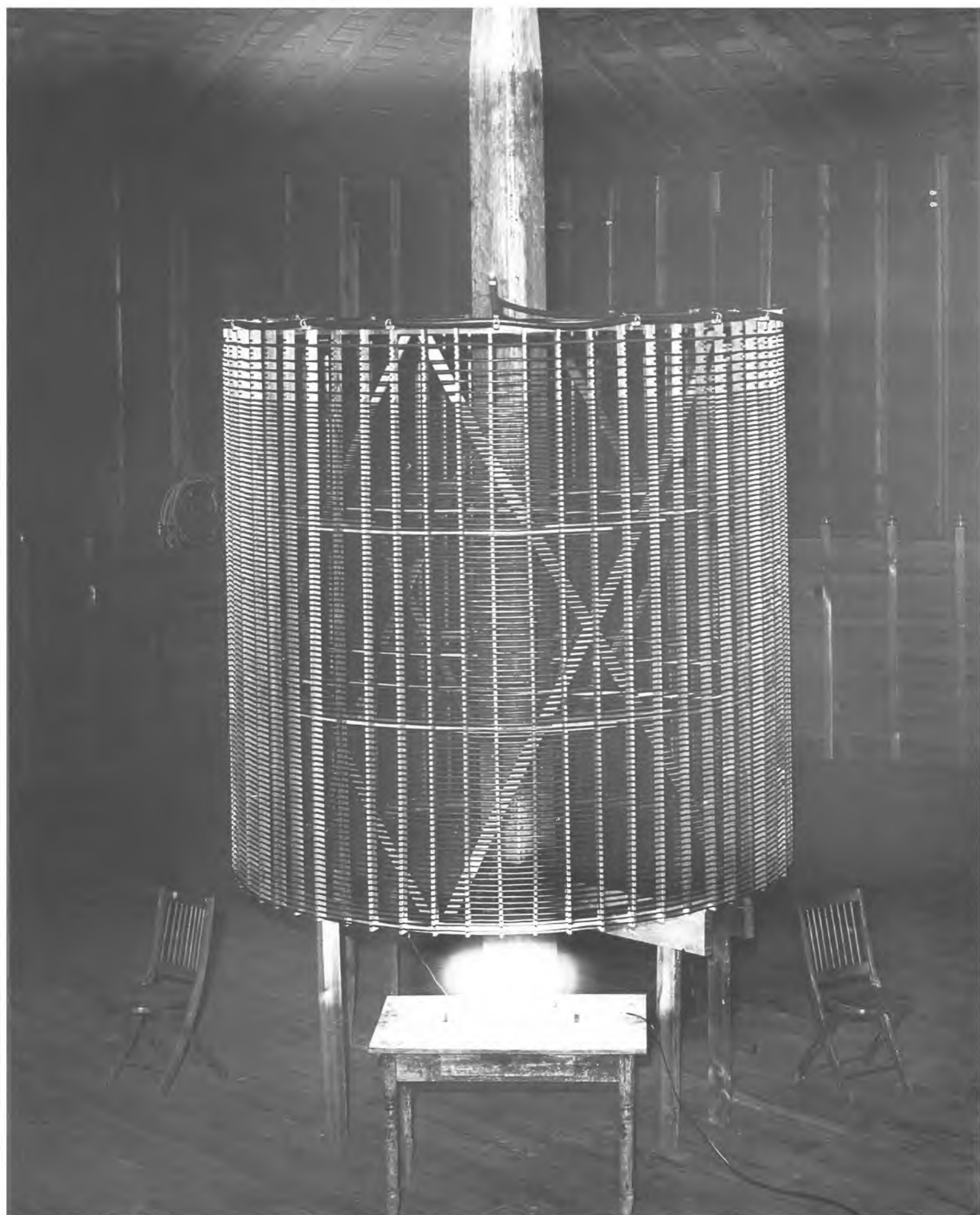
Photographs taken with Mr. Alley from Dec. 17 to Dec. 31, 1899 and particulars about the same

XXII. This photograph shows the "new extra coil" as last modified, having 98 turns wire No 6 and on top two turns or nearly so of wire No 10 covered with a thickness of $\frac{3}{8}$ " rubber. This wire was repeatedly referred to in previous notes. It was necessary to use it in many of the experiments recorded for the purpose of preventing or at least reducing leaks. In many cases despite the excellency and great thickness of the insulation the latter was found inadequate to withstand the strain, as is evident from a number of photographs showing the coil in action energized to full power. The picture illustrates five incandescent lamps lighted – and to much more than normal candle power – on a table in front of the coil. The lamps are in series, one end of the series being connected to the ground by a wire seen on the bottom while the other end of the lamp series is joined to the lower end of the coil, the upper end being entirely insulated and remote from objects which might act upon it inductively. The connection will be best understood from the diagram below. In the experiment illustrated there is no appreciable induction



exerted upon the extra coil as the wires of the oscillator proper, wound on the wooden structure seen in the back behind the coil, are *short-circuited*. One of the terminals of the condensers is grounded so that when they are discharging through the circuit, chiefly composed of a number of turns of the regulating coil, there is a strong vibration propagated through the ground which through the ground wire reaches the "extra coil". Now, generally, the energy which can thus be transmitted to the coil would be minute, but when the oscillations passing through the ground are exactly of the frequency of the "extra coil" system itself, a considerable current passes into the coil which then acts just as a hole would in a pipe through which a fluid is pumped by means of a pulsating piston. As the magnifying factor of the coil is very large the feeble impulses reaching the ground wire and lamps magnify the impressed e.m.f. and create considerable movement of electricity through the lamps which are thus brilliantly lighted, as shown in the photograph. In the experiment the capacity in the exciting oscillating circuit, impressing the vibrations upon the ground and wire w, was 3 tanks on each side or $1\frac{1}{2}$ tanks total, that is 54 bottles or $0.0009 \times 54 = 0.0486$ mfd, approx. The total inductance was 41,000 cm+ind. of $6\frac{1}{4}$ turns of regulating

Phot. XIX. Discharge between a ball of 30" diam. and the ground plate.



coil = 41,000 + 19,368 = 60,000 cm, approx. or 0.00006 henry. From this the approximate period of the vibration impressed upon the ground would be

$$T_p = \frac{2\pi}{10^3} \sqrt{0.0486 \times \frac{6}{10^5}} = \frac{2\pi}{10^5} \sqrt{0.02916} = \frac{2\pi}{10^5} \times 0.1708 = \frac{1.074}{10^5}$$

approx. and $n=93,110$ and $p=585,000$ approx. λ would be very nearly 2 miles and $\frac{\lambda}{4} = \frac{1}{2}$ mile or about

2640 feet. In reality the length of the wire in the excited system – that is extra coil and ground wire, was found by measurement to be 2660 feet (98 turns, wire No 6, 25' 11" each turn = 2540' + $\frac{3}{4}$ turn of cable inside of secondary frame = 112' + continuation of ground cable outside of circle to ground plate = 28' + wire $w = 20'$ + rubber covered wire on top of coil = 50' that is, total 2450' + 112' + 28' + 20' + 50' = 2660 feet.

From above data and taking resistance of extra coil at 1 ohm (in reality a little less) we get magnifying factor for coil alone $\frac{pL}{R} = \frac{585,000 \times 0.018}{1} = 10,530$.

Taking, however, into consideration that the resistance of the lamps was about 1000 ohms roughly, when including the latter in the system the factor would be only about $\frac{1}{1000}$ of this, or approximately only 10.5. But I believe that the resistance of the lamps when operated by currents of such extreme frequencies is much smaller than the measured resistance according to the usual methods. The currents, namely, when produced in such ways as these here employed, have very high maximum values and the carbon is brought periodically to a much higher temperature than when operated with steady currents or currents of ordinary frequencies. I have observed this repeatedly. Furthermore when such currents as these here are used some part of the discharge also passes through the rarefied gas in the bulb and there is a corresponding diminution of the effective resistance of the lamp on this account. In fact, I think that it is chiefly owing to this that the resistance becomes very small, it being a fact that such currents pass with the greatest freedom through the rarefied gas particularly when it is maintained at a high temperature, as in the case here considered. The heating of the gas has the effect of increasing the incandescence of the carbon and it is well demonstrated that an incandescent lamp takes, for a given luminosity, less energy when operated with currents of such extreme frequencies. Owing to these reasons the magnifying factor of the excited system even with the lamps included must have been very much larger than the figure last mentioned. It was astonishing to note, in the experiment recorded on the plate, how much energy can be in this manner conveyed to such a carefully synchronized coil through the ground. The supply transformers were cut down by a regulating coil in the primary to less than one half, in fact to about $\frac{1}{3}$ of full capacity and inasmuch as only 3 tanks on each side in the primary or exciting circuit were used while 8 tanks were available, it is evident that, if the excited system would have been designed to work with full output of the exciting apparatus it would have been quite practicable to light, say $3 \times \frac{8}{3} = 8$ times as many lamps, or about 40 lamps. However, inasmuch as the five lamps were far above candle power it would have been, in all probability, possible to light 60 lamps or so to normal candle power by a specially designed coil, with a liberal allowance of copper, vibrating in unison with the system exciting the portion of the ground containing the ground plate. Nothing could convey a better idea of the tremendous activity of this apparatus and a simple comparison with well ascertained data, obtained with other induction apparatus, shows that one of the problems followed up here, that is the establishment of communication with any point of the globe irrespective of distance, is very near its practical solution. The existence of stationary waves proves the feasibility of the project almost beyond any doubt. The great amount of energy which can be conveyed to such a synchronized circuit, by conduction through the ground, makes it appear possible, that the necessity of elevating terminals in my system of energy transmission to a distance may be dispensed with in many instances and that, with a very moderate elevation of, say, a few hundred feet enough energy may be conveyed to a circuit to serve for one or another useful purpose beyond mere signalling, or such uses of the system in

Five incandescent lamps lighted by current passing from "extra coil" to the ground plate.



which a minute amount of energy is required. Certainly, the amount of energy conveyed in this manner was, in some experiments with this apparatus, surprising at first. An interesting consideration in this connection may be the following: As before stated the period of the exciting or primary circuit, when resonance with the extra coil was attained, was $T_p = \frac{2\pi}{10^3} \sqrt{0.0486 \times \frac{6}{10^5}}$. Now the period of the excited system was $T_s = \frac{2\pi}{10^3} \sqrt{0.018 \times C_s}$, in which C_s is the "ideal" capacity as designated in previous instances, that is the capacity which would have to be joined to the free end of the "extra coil" of inductance of

0.018 henry but devoid of all distributed capacity. Since $T_p = T_s$ we find $C_s = \frac{0.0486 \times \frac{6}{10^5}}{0.018}$ mfd, or

$$C_s = \frac{9 \times 10^5 \times 0.0486 \times \frac{6}{10^5}}{0.018} = \frac{54 \times 0.0486}{0.018} = \frac{54 \times 486}{180} = \frac{3 \times 486}{10} = 145.8 \text{ cm.}$$

Suppose an ideal system of this kind excited in the manner described, so that capacity on the free end is charged each time as the current alternates to a potential P . Then, since as before stated, the system in experiment illustrated was vibrating about 93,000 times per second, the total energy set in movement in the system would be

$$2 \times 93,000 \times \frac{P^2 \times 145.8}{2 \times 9 \times 10^{11}} \text{ watts.}$$

Let it be further assumed that 1% of the total energy set in movement is frittered down in the lamps and that the number of these were 60, as might have been the case in the presently described experiment. Suppose each lamp to take 50 watts, the total energy consumed in the lamps would be 3000 watts hence, under the above assumptions, the total energy set in movement in the excited system would have to be 100 times this amount or 300,000 watts. To satisfy this condition we would have

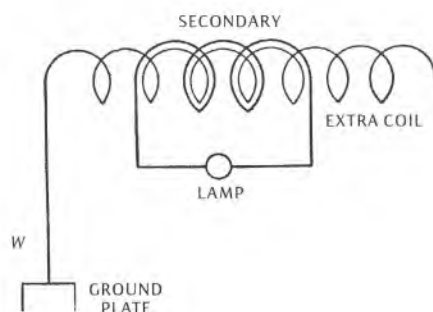
$$2 \times 93,000 \times \frac{P^2 \times 145.8}{2 \times 9 \times 10^{11}} = 300,000$$

and

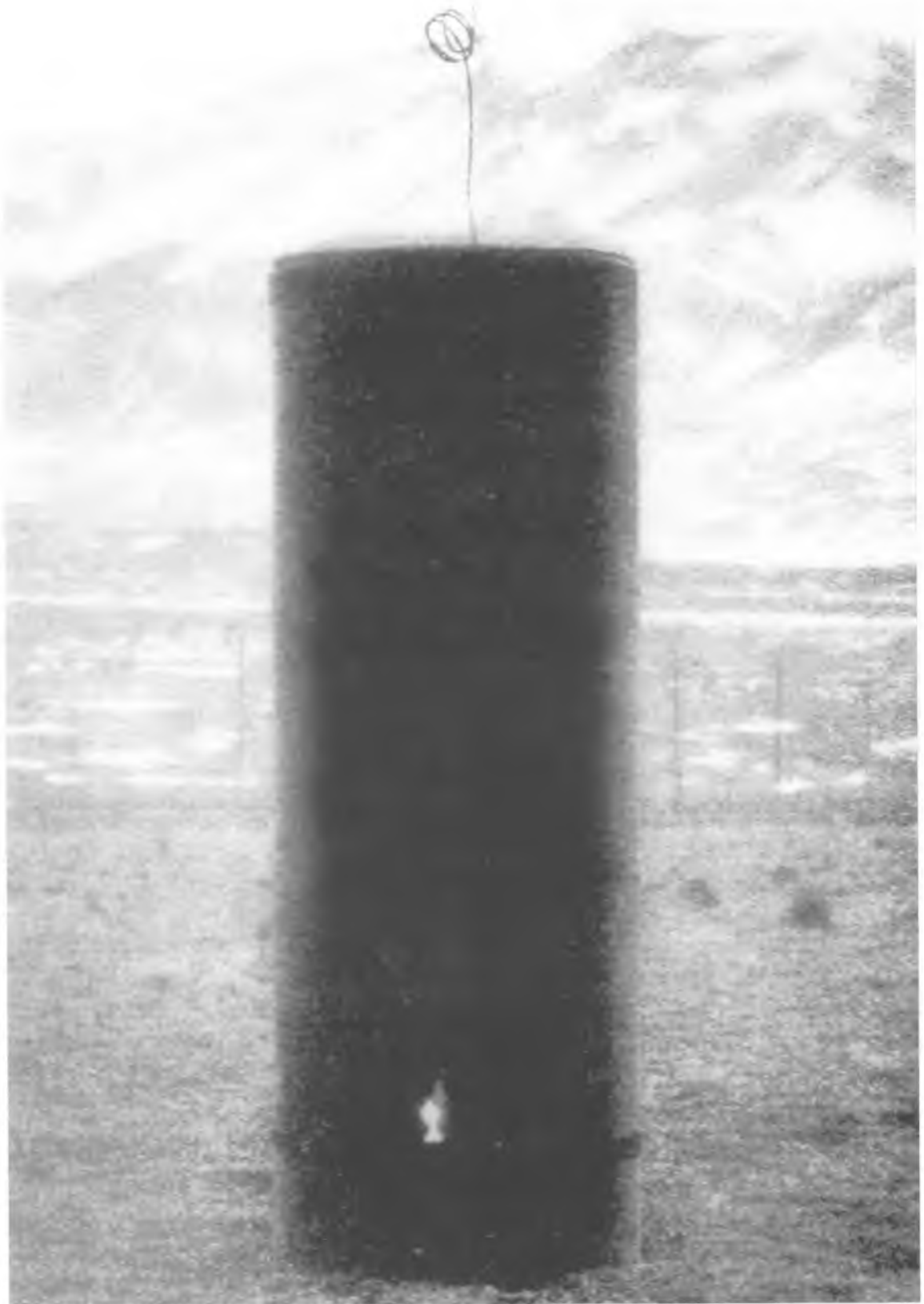
$$P^2 = \frac{54 \times 10^{13}}{186 \times 145.8} = 10^{12} \times \frac{540}{186 \times 145.8} \text{ or } P = 10^6 \sqrt{\frac{540}{186 \times 145.8}} = 10^6 \sqrt{\frac{540}{27,118.8}} = 10^6 \sqrt{0.02}$$

$$\text{Approx. or } = 10^6 \sqrt{\frac{2}{100}} = 10^5 \sqrt{2} = 10^5 \times 1.414 \text{ or } P = 141,400 \text{ volts.}$$

Not very much, as will be seen, for such a pressure is extremely small with apparatus of the kind used here. Taking P roughly as 140,000 volts and assuming that the ground plate be at such a distance that only 1000 volts are impressed upon the same then the magnifying factor would have to be only 140. Of course, this is merely an example to support the above statement that considerable energy may in this way, and by such apparatus, be conveyed to a distant circuit which is connected to the ground at only one point directly or, if desired, through a condenser.



Phot. XXV. A coil outside laboratory with the lower end connected to the ground and the upper end free. The lamps is lighted by the current induced in the three turns of wire wound around the lower end of the coil.



Phot. XXVI.
Experiment to illustrate
the transmission
of electrical energy
without wire. The
photograph shown
is reproduced from
Tesla's article⁽⁴¹⁾

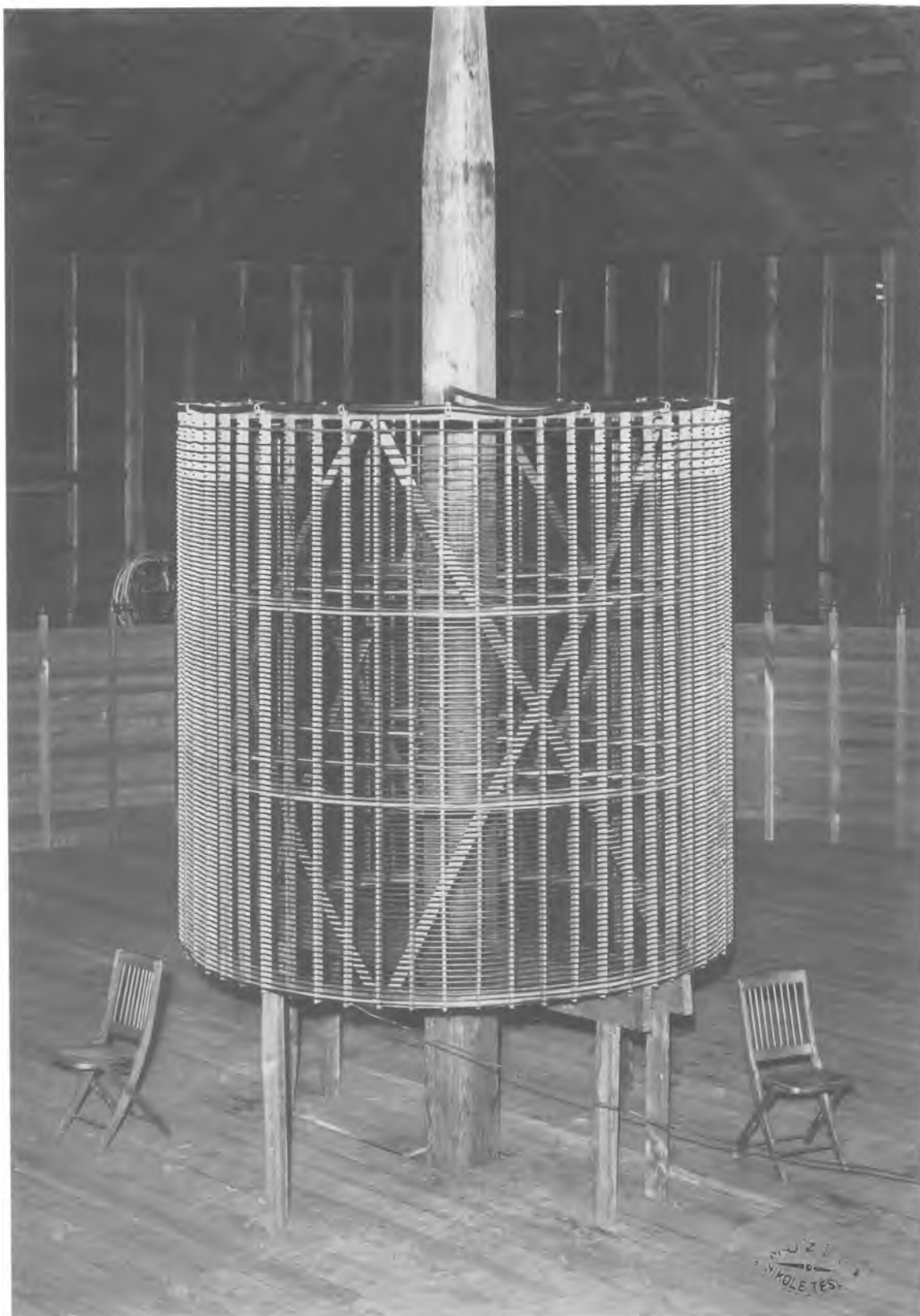
In another photograph, marked Plate XXIII., taken with same apparatus a similar experiment is illustrated. Here the extra coil as indicated in the diagram above is connected directly through the wire *w* to the ground plate and another coil designated in the diagram as "secondary" is placed in inductive relation to the extra coil excited in the same manner as in experiment before described, and a lamp is lighted by the currents generated in this "secondary". Only one lamp was used as it was the object of the photograph merely to illustrate a novel experiment, but with reference to the above it will be understood that as many as 60 lamps, or nearly so, might have been lighted with the apparatus used in this manner. All the particulars were practically the same as before. The "secondary" had four turns, the excitation of the extra coil being reduced so that the lamp was somewhat above normal candle power. In this, as well as in the preceding experiment, the switch on the Westinghouse high tension transformer was thrown in and out about 50 times and after this, as usual, an exposure to arc light for the detail of the apparatus was made, the time being 10 minutes with a small opening.

In order to make these two experiments still more interesting they were performed outside with a smaller receiving coil and photographs were taken, which are numbered and of which Plate XXIV. shows a coil standing outside on a table to which a groundwire leads, which is connected to one of the terminals of a small lamp, while the other terminal of the same is joined to the lower end of the coil. The upper end of the coil is free, a metal tube being connected to the same, as shown clearly in the picture. This tube is placed axially and serves to increase slightly the capacity of the excited system.

In another experiment, with the same coil illustrated in Plate XXV., the coil is placed on the ground away from the laboratory and the lower end is connected to the nearest ground, while the upper end or terminal is free. Three turns of wire are wound around the lower end of the coil and the ends of this wire are connected to a lamp socket with its lamp which is, as shown, lighted by the currents induced in the three turns of wire through the oscillations transmitted through the ground to the coil.

One more experiment of this kind was photographed, the same coil being again used and placed far out into the field, this being shown in Plate XXVI., giving a clear view of the Pike's Peak Mountain Range in the background. The diagrams and several remarks before made apply to some extent also to these three photographs which were taken after sunset when the dark began to set in, as it was impracticable to take them at another hour of the day. They might have been taken by moonlight but the time was otherwise occupied. During the hours when the light was strong it would have been necessary to exclude first the daylight in some way, flash the lamp in the dark and finally make a short exposure to the full daylight to get the detail of the apparatus. It was found impracticable to get a good photograph by flashing the lamp in full daylight as the latter was too strong and the lamp did not have enough time to impress the plate as strongly as was desirable, even if it was pushed to much higher candle power than the normal. In getting the photographs, generally about 100 throws of the switch were sufficient with the lamp being pushed considerably above the normal. When the daylight was still deemed too strong Mr. Alley helped himself by covering the lens during the short interval when the lamp was not lighted and thus regulated the effect of the daylight, keeping it down to the required value.

The *particulars* were as follows: The coil used in these three experiments was wound on a drum before referred to of 25.25" diam. and had 274 turns of wire N° 10, rubber covered. Since another coil wound on the same drum had 404 turns and an inductance of approximately 40,000,000 cm. or 0.04 henry the inductance of the present coil was with fair approximation $\left(\frac{274}{404}\right)^2 \times 0.04$ henry or $\left(\frac{137}{202}\right)^2 \times 0.04$ henry. The wire leading from the ground plate to the lower end of the coil placed on the table or ground consisted of two pieces of cord N° 10, one 308 feet and the other 84 feet long. The inductance of these two pieces of wire was estimated at 113,000 cm and compared with the inductance of the coil itself was very small, almost negligible. Calling the total inductance of the excited circuit comprising the two pieces of wire and the coil used L_1 we have for this inductance value $L_1 = \left(\frac{137}{202}\right)^2 \times 40,000,000 + 113,000 = 18,400,000 + 113,000 = 18,513,000$ cm, or $L_1 = \frac{185}{10^4}$ henry. This in-



Phot. XXVII. An incandescent lamp connected with one of its terminals to the top or free end of "extra coil", the lower end of the latter being connected to the ground plate.

ductance, with its distributed capacity, gave a system responding to the primary vibration when the capacity in the primary or exciting circuit was $1\frac{2}{3}$ tanks or 60 bottles on each side, or 30 bottles total, that is, $30 \times 0.0009 = 0.027$ mfd, total.

The vibrations were impressed on the ground plate by the oscillator with normal connection, that is, two primary cables in multiple or *one* primary turn, the approximate inductance of which was 56,400 cm or, say, 56,000 cm, which is close enough for the present consideration. This inductance may have been modified by the secondary, but the effect of the latter must have been very slight as, with the capacity used, it was "out of tune" and the current through it was necessarily very small. Taking then the inductance of the primary exciting circuit at 56,000 cm, the period of this circuit was

$$T_p = \frac{2\pi}{10^3} \sqrt{0.027 \times \frac{56}{10^6}}$$

Now calling C_s the "ideal" capacity of the excited circuit, the period of the same was

$$T_s = \frac{2\pi}{10^3} \sqrt{\frac{185}{10^4} \times C_s} \text{ and equating we have } C_s = \frac{10^4}{185} \times 0.027 \times \frac{56}{10^6} = \frac{56 \times 0.027}{185 \times 10^2} \text{ mfd,}$$

$$\text{or } C_s = \frac{9 \times 10^5 \times 56 \times 0.027}{185 \times 10^2} = \frac{243 \times 56}{185} = 75.2 \text{ cm, approx. From above}$$

$$T_p = \frac{2\pi}{10^3} \sqrt{0.027 \times \frac{56}{10^6}} = \frac{2\pi}{10^6} \sqrt{1.512} = \frac{6.28}{10^6} \times 1.23 = \frac{7.7244}{10^6}$$

and $n=129,500$ per second nearly.

The theoretical wave length would thus be $\lambda = \frac{186,000}{130,000} = \frac{186}{130} = 1.43$ miles approx. or $\frac{\lambda}{4} = \frac{1.43}{4} = 0.3575$ miles or $0.3575 \times 5280 = 1888$ feet $= \frac{\lambda}{4}$.

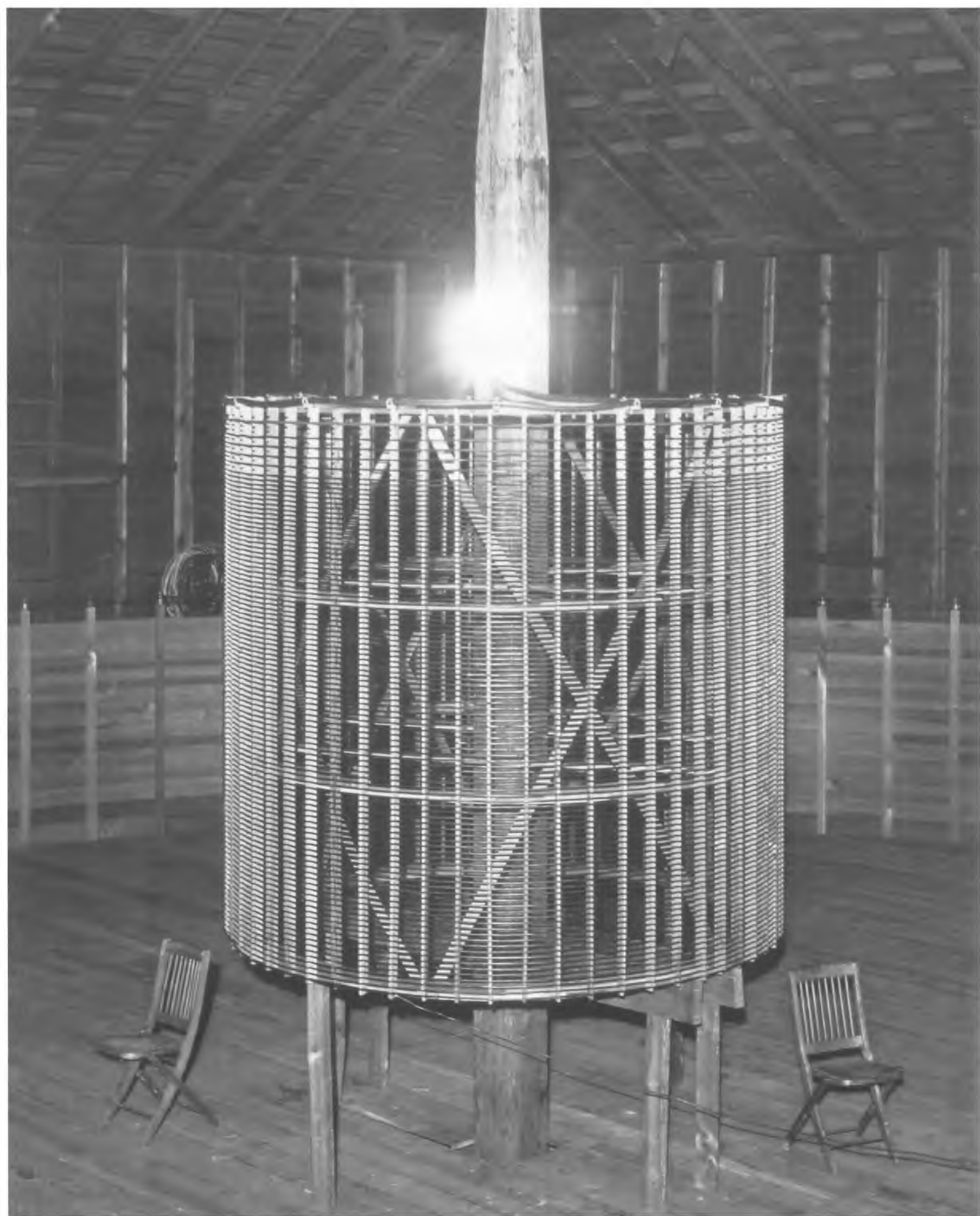
The actual length of wire in the experiment was: 274 turns of the coil, each 79.29" = 1810 feet + one piece of wire 304 feet + one piece of wire 84 feet = 1810 + 304 + 84 = 2198 feet or nearly 15% more than the theoretical value. The fact is, the adjustment for resonance was not quite close as the lamp lighted could not withstand the current by closer adjustment. Two of these lamps were broken. The energy transmitted through the ground to the coil was, of course, small in this instance, since only a small part of the available primary capacity was used, that is, $\frac{1.66}{8}$ of the available capacity and the current of the sup-

ply transformers was reduced as far as practicable. If a coil especially adapted for the full output of the oscillator would have been used it would have been practicable to transmit many times the amount of energy needed for lighting the lamp. The lamps used in this experiment were special ones each taking, under the conditions of the experiment, perhaps 10 watts or nearly so. Assuming again a circuit under ideal conditions with the capacity of 75.2 cm on the free end of a coil without distributed capacity, and calling the potential to which this capacity would be charged P , the total energy set in movement in the excited system would be $2 \times 129,500 \times \frac{P^2 \times 75.2}{2 \times 9 \times 10^{11}}$ watts. If we assume that, as before, 1% of the total energy of the system is frittered down in the lamp we would have, in conformity with what was stated before for determining P , the equation

$$2 \times 129,500 \times \frac{P^2 \times 75.2}{2 \times 9 \times 10^{11}} = 1000 \text{ or } P^2 = \frac{18 \times 10^{11}}{259}$$

or

$$P = 10^5 \sqrt{\frac{180}{259}} = 10^5 \sqrt{0.695} = 10^5 \times 0.834$$



or 83,400 V nearly, which is a small e.m.f. The length of wire in excited circuit was as before stated 2198 feet; the wire being № 10, with a resistance of 1 ohm per one thousand feet, the resistance of the circuit was about 2.2 ohm. From above $p=2\pi n$ was $=6.28 \times 129,500 = 813,260$ or, say, $813,000 = p$. The induct-

ance being, as shown, $\frac{185}{10^4}$ henry, the magnifying factor in the coil was $\frac{\frac{185}{10^4} \times 813 \times 10^3}{2.2} = 6840$ nearly.

The lamp was one with a very short filament and its resistance may have been possibly 6 ohms. Thus with the lamp comprised the magnifying factor was still very considerable, that is, $\frac{185 \times 813}{82} = 1830$ or

nearly so. Taking it at 1800 we see that it was necessary, under the conditions assumed, to impress upon the ground plate, or near portions of the ground an electromotive force of only $\frac{83,400}{1800} = \frac{834}{18} = 52$ volts

or nearly so! This seems very little indeed, it can be scarcely believed, but the figures seem to be not far from truth. These remarks refer particularly to the experiment illustrated on the plate marked XXIV. in which the connections were the same as in the diagram shown when discussing Plate XXII., the lamp or lamps being in series with the excited coil or system.

In the experiments illustrated in the Plates marked XXV. and XXVI., the connections were schematically the same as in diagram shown a propos Plate XXIII. and the vibrations and other particulars were practically the same as in experiment shown in Plate XXIV. just described. It is to be stated that when a secondary circuit is used, as in experiments described under XXIII., XXV. and XXVI., in connection with the excited coil, this secondary should for maximum effect be placed near the lower end of the coil; the exact position may be determined by experiment or approximately calculated. Namely, if the coil which is excited were devoid of capacity and the necessary capacity were all on the upper or free end of the coil, then the secondary circuit should, for maximum effect, be just at the center of the coil. But in the experiment as shown, the capacity is distributed and the current is strongest in the first or lowest turn, diminishing towards the top of the coil in each turn. The resultant maximum effect is thus always found near the lower end of the coil, but not quite at the end, since the upper turns also effect the secondary circuit, though proportionately less than the lower ones. The calculation of the maximum position of the secondary is complicated by the fact that generally neither the capacity nor the potential is uniformly distributed, the distribution being greatly varied by very slight irregularities in the dimension of the individual turns or their position, or the position of the nodal point or points on the wire and many other causes. It is proposed to investigate this subject specially when time permits.

XXVII. This photograph shows an incandescent lamp 16 c.p., 100 V connected with *one* of its terminals to the top or free end of the extra coil, the lower end of the latter being connected to the ground plate. The carbon filament is brought to incandescence by the currents transmitted from the ground plate and the rarefied gas is also glowing as evident from the photograph. It is instructive to note the great actinic power of the glowing gas which, though appearing to the eye of feeble luminosity as compared with the lamp filament, nevertheless impresses the plate at least as strongly, if not more so, than the incandescent filament.

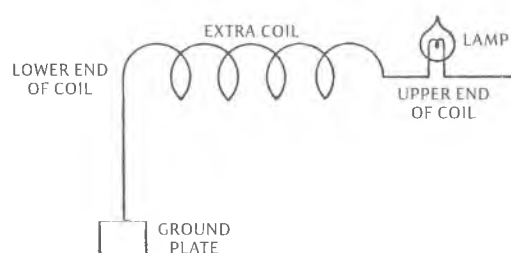
In many experiments made a few years ago I observed this and also that certain gases are particularly adapted to impress the plate. This fact, again observed, impresses me more and more with the value of powerfully excited vacuum tubes for purposes of photography. Ultimately, by perfecting the apparatus and selecting properly the gas in the tube, we must make the photographer independent of sunlight and enable him to repeat his operations under exactly the same conditions, which is almost indispensable in order to attain the best results. Such tubes will, however, enable him to regulate the conditions and adjust the light effects at will. Such a facility would offer a very great advantage to the artist as with the sunlight, particularly in large cities where the air is not very pure, he has to rely much on chance and where it is almost impossible for him to perform two successive operations under the same conditions or to adjust beforehand the light effects. The photograph described shows also the

Phot. XXVIII. An incandescent lamp lighted by the current passing from "extra coil" to the structure of iron pipes. The lower end of the coil is connected to the ground plate.

Supermarket Station fully developed
activity (power delivery) and
hundred thousand horsepower.



high actinic power of streamers when they are of a bluish or violet color as frequently, which is the case in this instance. The red streamers are comparatively very slow in their action, but it should be stated that apart from the color the action on the plate is determined much by the power or intensity of the streamers. Thus with the powerful apparatus which I have perfected here the actinic rays are much more powerful than with the New York apparatus. In the experiment illustrated the results would have been the same if *both* of the terminals of the lamp would have been connected to the free end of the "extra coil" instead of only one, as illustrated in the diagram, which is added for the purpose of showing more clearly how the connections in this case were made.



Now, as to the other particulars of the experiment, the capacity in the primary or exciting circuit was 3 tanks on each side or $1\frac{1}{2}$ tanks total, that is 54 bottles or $54 \times 0.0009 = 0.0486$ mfd. As to inductance of the exciting circuit there was the primary turn with closed secondary $= 41,000$ cm. and $5\frac{3}{4}$ turns of regulating coil, including connections, making an inductance, according to the table, of $17,684$ cm, that is, the total inductance of the exciting circuit was $58,684$ cm, or, with fair approximation, $59,000$ cm $= \frac{59}{10^6}$ henry. These data give

$$T = \frac{2\pi}{10^3} \sqrt{0.0486 \times \frac{59}{10^6}} = \frac{2\pi}{10^6} \sqrt{2.8674} = \frac{6.28}{10^6} \times 1.7 = \frac{10.676}{10^6}$$

and $n = 93,700$ approx. and $588,000 = p$ nearly.

If we assume, as in previous cases, that one percent of the total energy of the vibrating system is used up in the lamp in unrecoverable form, the energy of the system would then be 100 wats per each watt used in the lamp, or taking the lamp at 16 c.p. consuming, say, 50 wats the energy of the system would have to be 5000 wats. From this we get the potential P on the free end of the coil approximately by equating:

$$5000 = \frac{c}{9 \times 10^{11}} \times \frac{P^2 \times 93,700 \times 2}{2}$$

Here c would be the capacity of the lamp or other object, in centimeters, and taken in the same way as before explained. In previous measurements by resonance analysis the capacity of such a lamp was found to be only 1 cm, approximately. Taking this value for c we have:

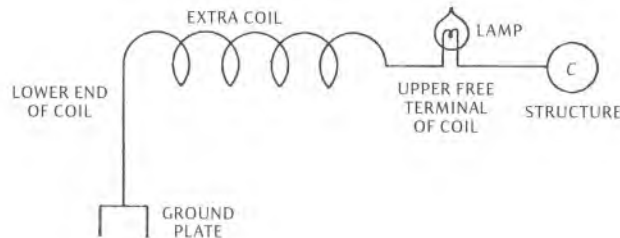
$$P^2 = \frac{5 \times 10^3 \times 9 \times 10^{11}}{937 \times 10^2} = \frac{45 \times 10^{12}}{937} \text{ and } P = 10^6 \sqrt{\frac{45}{937}} = 10^6 \sqrt{0.048} = 10^6 \times 0.22$$

or $= 220,000$ volts $= P$. This shows that P would be rather large on the assumption of but 1% frictional work in the lamp. In reality, as I know by experience, there will be generally much more energy, of the total energy of the system, used up in the lamp so that the potential P will be found in practice much smaller. But it is to be stated that *owing* to the *small capacity* of the lamp it will be relatively very high.

Phot. Colorado Springs
laboratory fully
developed.



By providing capacity in any way, so as to enable the lamp to take more energy, the potential required may be reduced at will.



This will be apparent from another photograph which is marked XXVIII. In this instance the same connections were used as before, only the free terminal of the lamp was connected by a wire to the structure of iron pipes above. The wire can be scarcely distinguished. In this experiment resonance with the exciting circuit was obtained with 6 tanks on each side, this would mean a capacity of three tanks or 108 bottles= $108 \times 0.0009 = 0.0972$ mfd.

The inductance of the exciting circuit comprised a primary turn with secondary short-circuited=41,000 cm, as before, and all the turns of the regulating coil with connections, that is about 85,000 cm, giving total inductance at $41,000 + 85,000 = 126,000$ cm or $\frac{126}{10^6}$ henry. From this follows

$$T = \frac{2\pi}{10^3} \sqrt{0.0972 \times \frac{126}{10^6}} = \frac{2\pi}{10^6} \sqrt{12.2472} = \frac{6.28 \times 3.5}{10^6} = \frac{21.98}{10^6}$$

and

$$n = 45,496 \text{ or approx. } 45,500 = n.$$

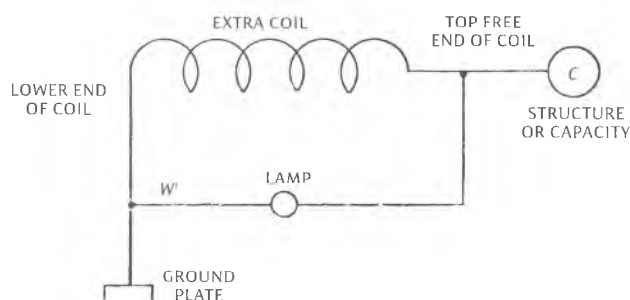
As will be seen from the consideration of the diagram above, in this experiment the *entire* energy supplied to the structure or capacity *C* had to pass through the lamp. Suppose the latter to consume 50 watts, and taking the capacity *C* with reference to previous estimates roughly at 500 cm. with the protecting hood, and designating with *P* again the potential to which the structure is charged, we have

$$50 = \frac{500}{9 \times 10^{11}} \times \frac{P^2 \times 45,500 \times 2}{2} \text{ or } P^2 = \frac{9 \times 10^8}{455}$$

and

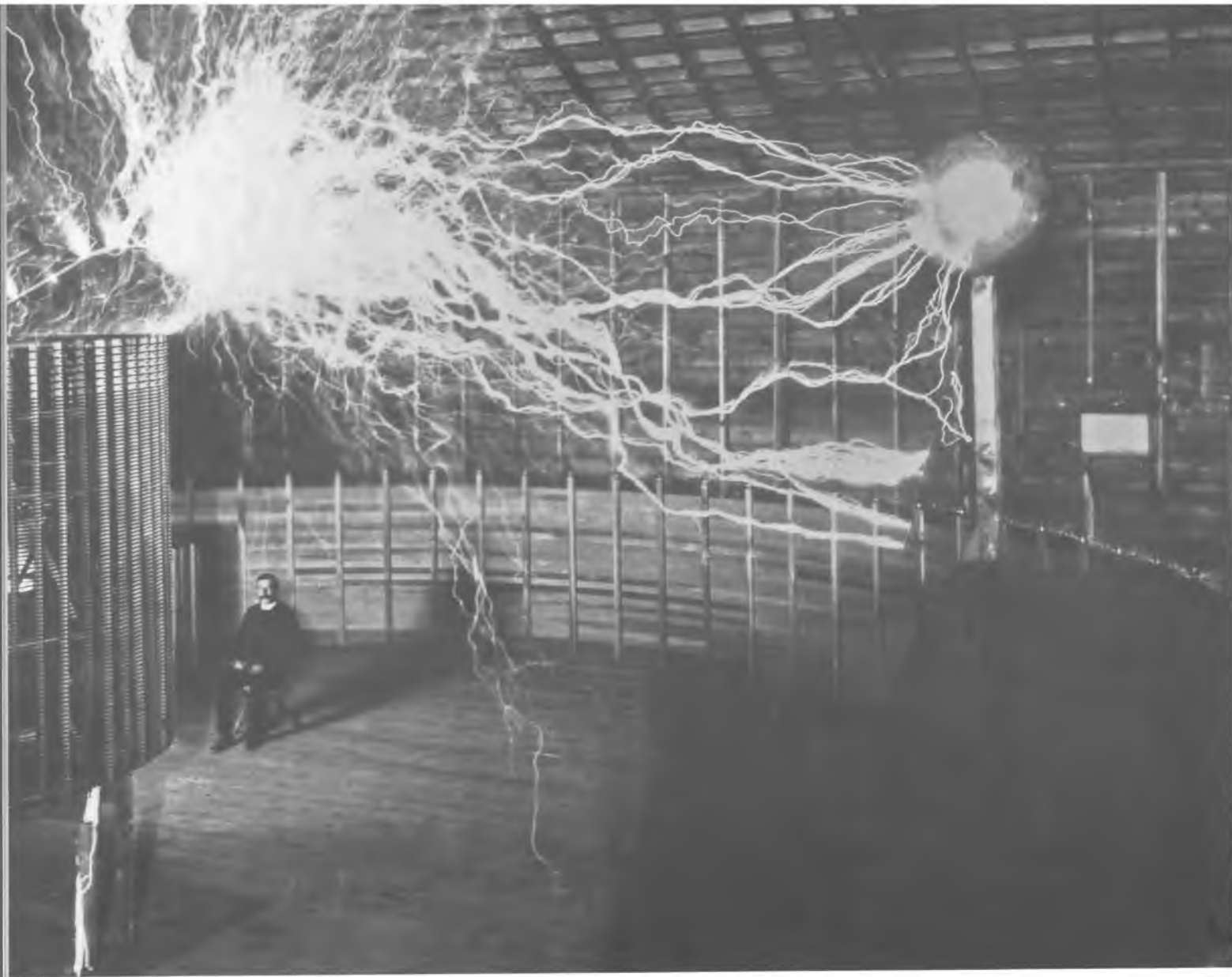
$$P = \frac{3 \times 10^4}{\sqrt{455}} = \frac{3 \times 10^4}{21.3}$$

approx. or=1409 volts=*P*, which is a very small pressure indeed. This pressure could have been, of course, still further reduced by using a resonating circuit of still higher frequency. In the manner just described and illustrated a great many lamps could have been lighted by the vibrations transmitted to



the ground and some of the facts pointed out before will enable one to make an approximate estimate in this respect. However, by connecting the "extra coil" as in normal operation, that is, to the free end

Phot. XXXVIII. View of the laboratory from the Pike's Peak side.



Phot. XLIII The discharge of "extra coil" laterally across the shop. Mr. Alley is sitting.

of the secondary instead of to the ground, a number of lamps might have been lighted corresponding to the full output of the oscillator, say, one thousand lamps or more. Even through the ground, as in the experiment described, the action of the exciting circuit was so intense that the current of the supply transformers had to be cut down to but a very small fraction of the current taken by full output.

It should be remarked that also in the experiment described before (Plate XXVII.) a considerable number of lamps might have been lighted, but not nearly as many as in the case presently described, owing to the very small capacity of the lamps, as before stated.

Coming now to the other experiments, a lamp was lighted in the manner illustrated in Plate XXIX. in which case the lamp was connected in a shunt to the extra coil instead of in series with the same, as in the previous case. The diagram illustrates the connections clearly. In this experiment resonance with the exciting circuit was obtained with 22 bottles on each side, that is, 11 bottles total capacity or $0.0009 \times 11 = 0.0099$ mfd total capacity. There were $4\frac{1}{2}$ turns in the regulating coil of an inductance according to the table of 13,474 cm. This, with the 41,000 cm as before, would give an approximate inductance of 54,500 cm for the exciting circuit and from this

$$T_p = \frac{2\pi}{10^3} \sqrt{0.0099 \times \frac{545}{10^7}} = \frac{2\pi}{10^6} \sqrt{0.00099 \times 545} = \frac{2\pi}{10^6} \times \sqrt{0.53955} = \frac{2\pi}{10^6} \times 0.735 = \frac{4.6158}{10^6}$$

and $n = 217,000$ per sec. approx.

As in this case the capacity may be put approximately at 500 cm, we may roughly estimate the effective inductance in the excited circuit. Namely, calling this inductance L_s , we have, for the condition of resonance,

$$T_p = T_s \text{ or } \frac{2\pi}{10^3} \sqrt{0.0099 \times \frac{545}{10^7}} = \frac{2\pi}{10^3} \sqrt{\frac{500}{9 \times 10^5} L_s}$$

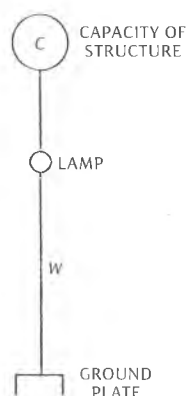
and from this

$$L_s = \frac{0.0099 \times 545 \times 9}{5 \times 10^4} = \frac{48.56}{5 \times 10^4} \text{ henry}$$

or

$$\frac{48.56 \times 10^5}{5} = \frac{4,856,000}{5} = 971,200 \text{ cm.}$$

This was the effective or actual inductance, or nearly so, of the combined system of extra coil and lamp as connected in the diagram on p. 361. Evidently, in the experiment the lamp might have



been lighted by doing away entirely with the extra coil and in fact I have done so. Time did not permit taking a photograph of the experiment thus modified. In such a case, the inductance of the wire w (see diagram) need be very small, hence the frequency of the currents impressing the vibration upon the ground plate will be very high and the potential, to which the capacity C will have to be charged in or-



Phot. LII. Discharge from the top of "extra coil", produced by a single closure of the circuit of very short duration.

der to pass enough energy through the lamp or other working circuit, will be comparatively very small. By way of example, suppose wire w , forming practically all the inductance of the excited circuit, had 10,000 cm and C were the same structure as in the experiment last described of a capacity of 500 cm; then calling P_2 the potential to which the capacity is to be charged in order to supply 50 watts to the lamp or working circuit, we would have:

$$50 = \frac{P_2^2 \times 2n}{2 \times 9 \times 10^{11}} \times 500 \text{ or } P^2 = \frac{9 \times 10^{10}}{n}$$

Now, calling T the period, we have

$$T = \frac{2\pi}{10^3} \sqrt{\frac{10,000}{10^9} \times \frac{500}{9 \times 10^5}} = \frac{2\pi}{3 \times 10^7} \sqrt{5} = \frac{6.28 \times 2.236}{3 \times 10^7} = \frac{4.68}{10^7}$$

and from this

$$n = \frac{10^7}{4.68} = 2,137,000 \text{ per sec.}$$

Substituting this for n we get

$$P^2 = \frac{9 \times 10^{10}}{2,137,000} \text{ or } P^2 = \frac{9 \times 10^{10}}{214 \times 10^4} = \frac{9 \times 10^6}{214}$$

and

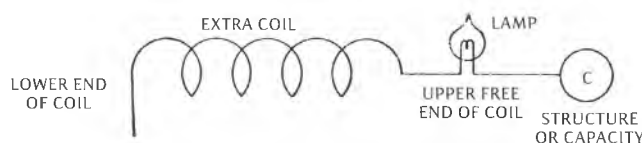
$$P = \frac{3000}{\sqrt{214}} = \frac{3000}{14.63} = 205 \text{ volts only!}$$

We see that with such an extreme frequency the voltage of the ordinary incandescent lamp supply circuit would be sufficient to pass enough current through the lamp. Under the above conditions the current would be

$$I = EC\omega = \frac{205 \times 500 \times 2\pi \times 214 \times 10^4}{9 \times 10^{11}} = 1.5313 \text{ amp. approx.}$$

In the experiment illustrated in Plate XXIX. it will be seen that while the inductance of the "extra coil" was greatly reduced by shunting the same with the lamp, yet the coil was still effective, as is evidenced from the streamers visible on the wire leading from the lower end of the coil to the lamp, which is the wire marked w' in the corresponding diagram.

Passing now to the experiment illustrated in plate designated number XXX., the connections in this case are shown in diagram below. Here the lamp was lighted only by induction from the primary

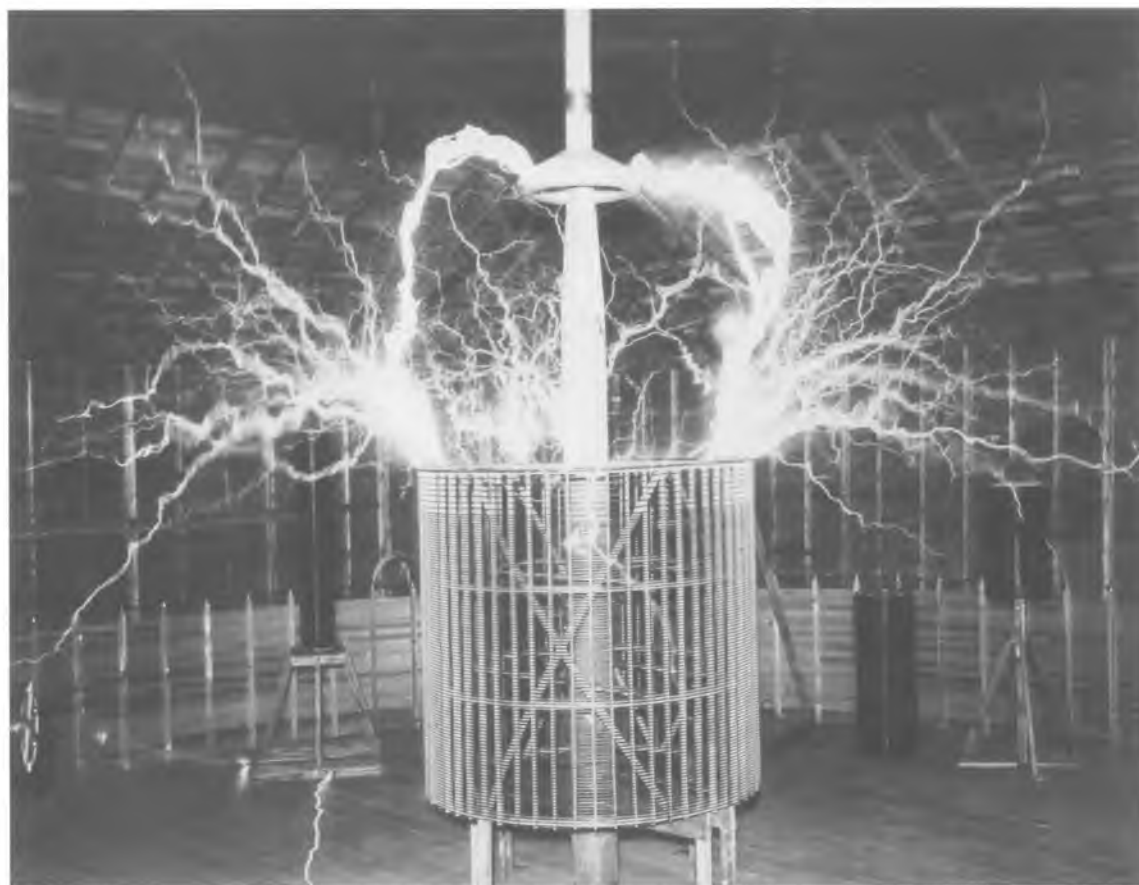


circuit, the ground connection being omitted. In this case the capacity was 3 tanks on each side or $1 \frac{1}{2}$ tanks total = 54 bottles = $54 \times 0.0009 = 0.0486$ mfd and the inductance 41,000 + 3 turns of the regulating coil = 41,000 + 10,000 = 51,000 cm, or $\frac{51}{10^6}$ H approx. This gives

$$T_p = \frac{2\pi}{10^3} \sqrt{0.0486 \times \frac{51}{10^6}} = \frac{2\pi \times 1.37}{10^6} = \frac{8.6}{10^6}$$

and $n = 116,300$ approx.

Note: Here the excitation of the primary circuit had to be strong, showing that the inductive action was feeble in comparison with action through the ground. The tuning was not quite exact in all these experiments described as time was pressing. In the last experiment n ought to have been just twice the value found in case XXVIII.



Phot. LIII. Produced under similar conditions as Phot. LII by a single closure of the circuit but of longer duration.

XXXI. This is a Roentgen photograph taken in a peculiar manner. It so happened that a workman who thought he had injured one of his figures desired to have a photograph taken and a tube was inserted between the ground plate and a coil, as illustrated in the diagram under XXII. It was doubtful whether the tube could be energized in this manner but the experiment proved that it could and a photograph was taken by flashing the tube a few times, after the adjustment of the vibration in the primary and excited circuit was completed and resonating condition in the latter secured. Nothing peculiarly interesting beyond the manner of taking the photograph was contemplated, nevertheless an inspection revealed that this photograph, probably owing to the high economy of the oscillating systems used in these experiments, or possibly on account of the frequency, was distinctly different from many others taken with different apparatus. The tube was *not strongly excited* and the exposure was scarcely more than a few seconds, yet much of detail was recorded. It is quite curious how plainly the nails are shown, much as in an ordinary photograph.

On this occasion I must point out a peculiar feature about the action of the currents developed by this apparatus upon Roentgen tubes. As might be expected, some experiments were carried on in this line also and possibly with greater pleasure than those in other directions, for my conviction is growing stronger every day that, with apparatus such as the present, wonderful results must be secured provided only that a tube is constructed capable of taking up any amount of energy. On my return this task will be a serious one. Many times tubes have been worked here from the secondary but curiously enough, for a reason which is to me not yet clear, they can only work for a *few seconds at the most* as, almost instantly, they become very highly rarefied and the sparks begin to dart over the glass, the tube becoming useless. No matter how the current was cut down the action took place, unless it was reduced to such an extent that the tube was scarcely excited at all. Already in New York with an apparatus similar to this, though much smaller, I observed that such an action always occurs, *in some degree*, when the vibrating system possesses a very *small resistance* and the electrical movement in the circuit connected to the tube is very large. This will be further investigated.

XXXII. This is a central view through the open entrance spoiled ...

Note: Plate XXXIII. is missing. One more photograph is to be made showing a lamp lighted without a coil, merely in series with a plate or object as capacity. If time permits a special coil will be constructed for *full power* of apparatus and all photographs, as far as practicable, taken *outside*. Taken in this manner they would be undoubtedly much more interesting to scientific men.

Colorado Springs

Jan. 3, 1900

Photographs taken with Mr. Alley from Dec. 17 to Dec. 31, 1899 and particulars relating to the same

In the photographs, which will be presently described, H"x14" Cramer plates were used, most of which were "instantaneous isochromatic".

XXXIII. View of the Pike's Peak Range taken from room through the window glass by moonlight, the night of an eclipse. A gale was blowing and it being impossible to place the camera outside, the photograph was taken in the above manner. As the building was trembling more or less during the sudden gusts of wind the picture is not as perfect as it might have been. The light was magnificent, the moon almost full and a good photograph might have been taken in 10–15 minutes. There was, of course, considerable loss in the transmission through the window glass though it was thoroughly cleansed, nevertheless the photograph is as good as if it had been taken in daylight. The exposure was much too long, *two hours*, from 9–11. Had the wind not been blowing a perfect picture would have been obtained



Phot. LIV. "Extra coil" discharging upwards from the brass ring on the top.

in a quarter of that time. The wonderful brightness of the moonlight was increased by the snow which was unusually heavy.

XXXIV. This photograph shows the laboratory viewed from behind with the mountain range from Pike's Peak to Cheyenne Mountain in the background. There was not much snow on the ground and little or none on the roof. The exposure was only 35 minutes, the moon nearly full. As the wind was blowing, the ball on top of the pole does not show well.

XXXV. This is another view of the laboratory from the rear with the Pike's Peak Range as background. Considerable snow on the ground. The exposure was *two hours*. It was again a windy night and the image of the upper part of the pole and ball is marred owing to swaying.

XXXVI. Again a view of the laboratory from the rear with the lower mountain range on the right side of Pike's Peak as background. There was snow on the ground. Extremely cold and very windy. Exposure 40 *minutes*.

XXXVII. Once more a view of the laboratory from the rear with the Pike's Peak Range as background. The moon was waning and a longer exposure – *three hours* – was made. It was found that the plate was somewhat over-exposed. Otherwise the conditions were not unfavourable. The wind was not strong and there was still considerable snow on the ground. The above photographs satisfied fully the novel phasure of taking pictures by the fascinating moonlight of Colorado and attention was then turned to less agreeable but more useful work.

XXXVIII. This is a view of the laboratory from the Pike's Peak side taken in the morning by sunlight, fresh fallen snow on ground.

XXXIX. A view of the laboratory from the rear taken under the same conditions.

XL. Illustrates discharge of "extra coil" laterally across the field from a pointed wire on the top of the coil to a ball 30" diam., provided with a point and a coil on a stand which supports the ball. Strong streamers and sparks, the latter passing to the floor; the coil mentioned and hood fastened to structure of iron pipes in the center of the building. Some sparks passed also to the roof causing, as usual, considerable concern, the fireproof paint notwithstanding. Some streamers in the same positions as others relative to the camera are very weak, this is probably due to their red color. Many streamers show clearly the phenomenon of splitting up or ramification and the sparks, where they strike the floor, develop increased luminosity. The feature of "splashing" on the floor upon striking the same is also well illustrated, particularly on one of the streamers which is thinner and sharper than most others. To give an idea of the magnitude of the discharge the experimenter is sitting slightly behind the "extra coil". I did not like this idea but some people find such photographs interesting. Of course, the discharge was not playing when the experimenter was photographed, as might be imagined! The streamers were first impressed upon the plate in dark or feeble light, then the experimenter placed himself on the chair and an exposure to arc light was made and, finally, to bring out the features and other detail, a small flash powder was set off. It was found necessary to sit in the chair during the exposure to arc light as, otherwise, the structure of the chair would show through the body of the person, if the same were exposed merely to the light of the flash powder. As the weather during these experiments, which were carried on late at night, was most generally far below zero, I tried to overcome the above necessity but neither I nor Mr. Alley could devise a practical remedy.

The simplest remedy would have been to employ a very powerful light enabling an instantaneous exposure, but this was not practicable with the arc light. On the other hand, the ball being very large, a great quantity of flash powder was required which it was not advisable to use because of danger and impairment of the quality of the photographs. In the instance described, the streamers shown were produced by 50 closures of the circuit energizing the Westinghouse transformer, each closure lasting approximately one half of one second, possibly less. The exposure to arc light lasted 5 minutes, about half of the full lens opening, and in flashing about one third of a large size Eastman powder was set off.



Phot. LV. "Extra coil"
discharging laterally
across the laboratory
from the tip of a
wire forming the free
terminal of the coil to
the floor and top wire
of the secondary.

XLI. This is a similar view of the discharge (fifty flashes, very short) of the extra coil from a pointed wire on top, or free terminal. The photograph shows, in an interesting manner, the splitting up of streamers or sparks near the floor. Another curious feature observable is the splitting and again uniting of a streamer or spark. I say "streamer or spark" because the former becomes a "spark" or perhaps stated better, an "arc" when it strikes some object which causes a strong current to pass through the path of the streamer, which then suddenly assumes the brilliancy and color characteristic of "sparks". I have seen at times a very strong discharge dart out from a point or surface in the form of a spark, continue for 6–10 feet or so and then split up in streamers. It is more than likely that this phenomenon will be found recorded in some of the photographs taken on closer inspection, as it is not unfrequent. At times, again, I have observed a small length of a streamer, anywhere along its path, assume a relatively very considerable luminosity and assume in this part the character of a spark. This I have, if I am not mistaken, already pointed out elsewhere. Some such luminous parts or points are to be seen plainly in this and other photographs.

When the action is very energetic, owing to the power of the streamer and other causes, the luminous portion of the same becomes a veritable "fireball". This observation which, to my greatest astonishment, I have frequently observed in experiments with this apparatus, shows now clearly how "fireballs" are produced in lightning discharges and their nature is now quite plain. I have heretofore always been inclined to believe this phenomenon to be merely a visual impression, similar to one which is experienced upon a violent blow on the eye, or some part of the head, or the spine, or which follows upon a sudden and very intense manifestation of light most generally. Although the vision of a moving ball of great luminosity is experienced only in the rarest instances, the person as a rule seeing luminous spots, "stars" or flaming tongues.

With the present experiences I am satisfied that the phenomenon of the "fireball" is produced by the sudden heating, to high incandescence, of a mass of air or other gas as the case may be, by the passage of a powerful discharge. There are many ways or less plausible in which a mass of air might be thus affected by the spark discharge, but I hold the following explanation of the mode of production of the "ball" as being, most likely of all others which I have considered, the true one. When sudden and very powerful discharges pass through the air, the tremendous expansion of some portions of the latter and subsequent rapid cooling and condensation gives rise to the creation of partial vacua in the places of greatest development of heat. These vacuous spaces, owing to the properties of the gas, are most likely to assume the shape of hollow spheres when, upon cooling, the air from all around rushes in to fill the "cavity" created by the explosive dilatation and subsequent contraction. Suppose now that this result would have been produced by one spark or streamer discharge and that now a second discharge, and possible many more, follows in the path of the first. What will happen? Before answering the question we must remember that, contrary to existing popular notions, the currents passing through the air have the strength of many hundreds and even thousands of amperes.

It was a revelation to myself to find that, even with the apparatus used in these experiments, a single powerful streamer, breaking out from a well insulated terminal, may easily convey a current of several hundred amperes! The general impression, if I am not mistaken, is that the current in such a streamer is small but this belief is due to the comparative unfamiliarity of the electrician with such apparatus as I am now using. As a matter of fact it is quite easy to consume in such streamers, as are illustrated in these photographs, most of the energy developed by the apparatus and the currents conveyed through the air may be, by suitable provisions, made as strong as those circulating in the wire or coil itself which produces them. No wonder then, that a small mass of air is "exploded" with an effect similar to that of a bombshell, as noted in many lightning discharges.

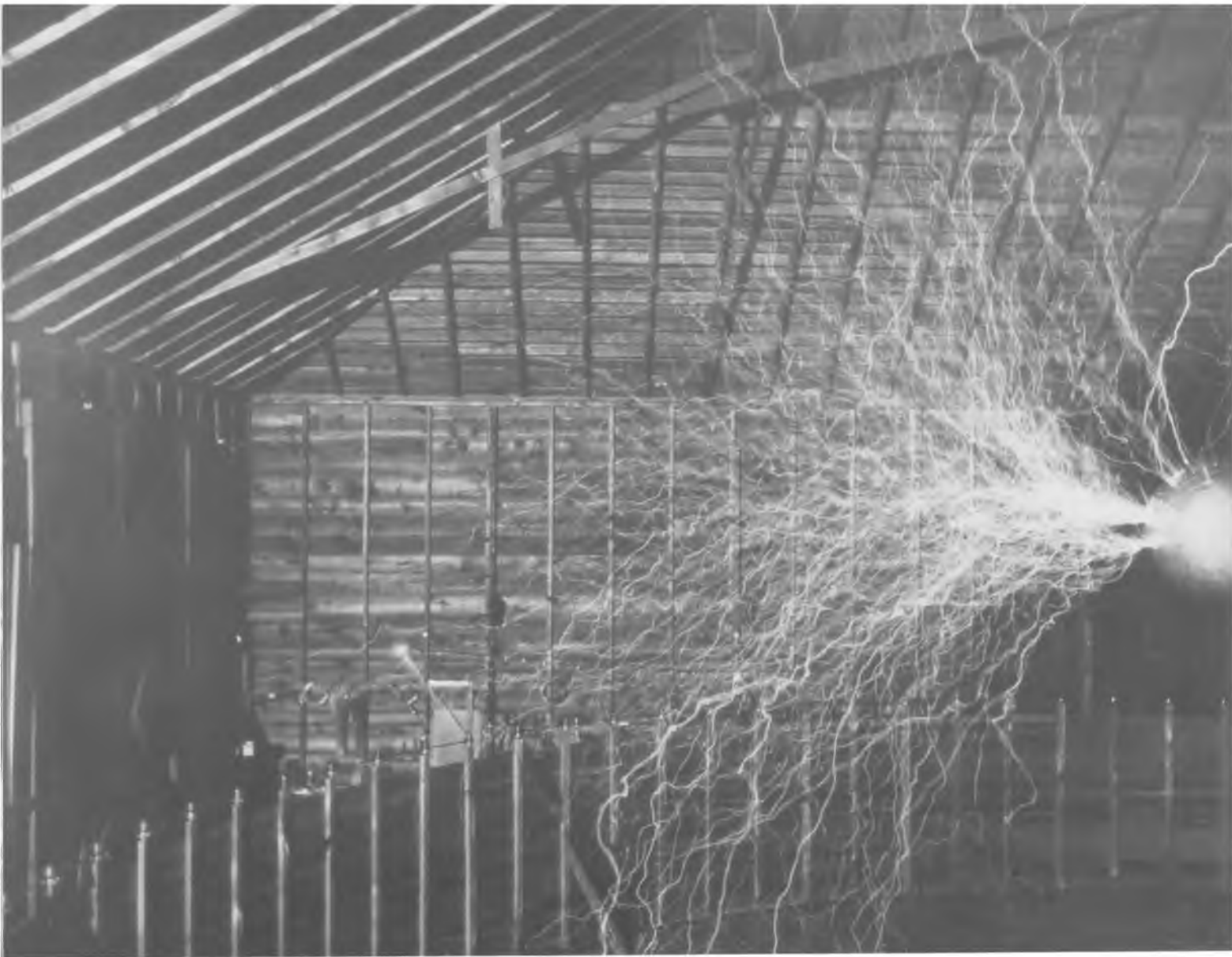
But to return now to the explanation of the "fireball", let us now assume that such a powerful streamer or spark discharge, in its passage through the air, happens to come upon a vacuous sphere or space formed in the manner described. This space, containing gas highly rarefied, may be just in the act of contracting, at any rate, the intense current, passing through the rarefied gas suddenly raises the



Phot. LVI. Discharge of "extra coil" issuing from a ball of 30" diam. forming the "free" terminal of the coil towards a coil on a stand.

same to an extremely high temperature, all the higher as the mass of the gas is very small. But although the gas may have been brought to vivid incandescence, yet its pressure may not be very great. If, upon the sudden passage of the discharge, the pressure of the heated air exceeds that of the air around, the luminous ball or space will expand, but most generally it may not do so. For assume, for instance, that the air in the "vacuous" space was at one hundredth say, of its normal pressure, which might well be the case, then, since the pressure in the space would be as the absolute temperature of the gas within, it would require a temperature which seems scarcely realizable, to raise the pressure of the rarefied gas to the normal air pressure. It is therefore reasonable to expect that, despite the high incandescence of the rarefied air, the space filled with the same will continue to contract, and here an important consideration presents itself. When, as before explained, the vacuous space was formed, the spark or streamer passed through the air *disruptively*, therefore the path was necessarily very thin, threadlike, and the minute quantity of the air which served as a conductor for the current was expanded with explosive violence to many thousand times its original volume. Owing to the fact, however, that the quantity of matter through which the current was conveyed was small, a great facility was offered for giving off the heat so that the highly expanded gas-owing to its expansion and to radiation and convection of heat-cooled instantly.

But how is it when the second discharge and possibly many subsequent ones pass through the rarefied gas? These discharges find the gas already expanded and in a condition to take up much more energy by reason of the properties it acquires through rarefaction. Evidently, the energy consumption in any given part of the path of the streamer or spark discharge is, under otherwise the same conditions, proportionate to the resistance of that part of the path; and since, after the gas has once broken down, the resistance of other parts of the path of the discharge is much smaller than that including the vacuous space, a comparatively very great energy consumption must necessarily take place in this portion of the current path. Here, then, is a mass of gas heated to high incandescence suddenly but not, as before, in a condition to give up heat rapidly. It can not cool down rapidly by expansion, as when the vacuous space was being formed, nor can it give off much heat by convection. To some extent even radiation is diminished. On the contrary, despite the high temperature, it is compelled to confinement in a limited space which is continuously shrinking instead of expanding. All these causes cooperate in maintaining, for a comparatively long period of time, the gas confined in this space at an elevated temperature, in a state of high incandescence, in the case under consideration. Thus, it is that the phenomenon of the "ball" is produced and the same made to persist for a perceptible fraction or interval of time. As might be expected, the incandescent mass of gas in a medium violently agitated, could not possibly remain in the same place but will be, as a rule, carried, in some direction or other, by the currents of the air. Upon little reflection, however, we are led to the conclusion that the ball or incandescent mass, of whatever shape it be, will always move from the place where an explosion occurred *first*, to some place where such an explosion occurred *later*. This will be most generally in the path of the discharge, from its origin to its end, but not necessarily always so. For example, it may so happen that a spark produced in some place strikes an object of a material which is evaporated or volatilized with difficulty, and that *later*, in another place, this same or other spark hits an object of a material more volatile. If so then the explosion on the later place will sooner occur, and the result will be that the current of air, when both the explosions have subsided, will move from the later to the former locality. But I believe that, in most cases, the current of air will take the opposite course, as before stated. In whatever direction the movement may occur, it is plain that the velocity can not be very great. In fact, all observers concur in the opinion that such a "fireball" moves slowly. If we interpret the nature of this wonderful phenomenon in this manner, we shall find it quite natural that when such a ball encounters in its course an object, as a piece of organic matter for instance, it will raise the same to a high temperature, thus liberating suddenly a great quantity of gas by evaporating or volatilizing the substance with the result of being itself dissipated or "exploded". Obviously, also, it may be expected that the conducting mass of the "ball" originated as described, and moving through a highly insulating medium, will be likely to be highly electrified, which accords with many of the observations made. A better knowledge of this phenomenon



Phot. LVIII. Discharge from "extra coil" issuing from two diametrically opposite wires, pointing upwards and fastened to the brass ring on the top of the coil.

will be obtained by following up experiments with still more powerful apparatus which is in a large measure already settled upon and will be constructed as soon as time and means will permit. There may be a way, however, of intensifying in this respect, the action of the present machine. A very important matter is to use better means of photographing the streamers exhibiting these phenomena. Much more sensitive plates ought to be prepared and experimented with. The coloring of the films before suggested might also be helpful in leading up to some valuable observation. It being a fact that this phenomenon may now be artificially produced, it will not be difficult to learn more of its nature. Photography will be, of course, the best means to investigate it and the first efforts ought to be in this direction. With the present plates, although the "balls" produced with the apparatus experimented with are probably up to 1 ½" diam. and possibly more, they leave only a small dark spot on the plate, only the nucleus or central portion impressing itself.

Colorado Springs

Jan. 4, 1900

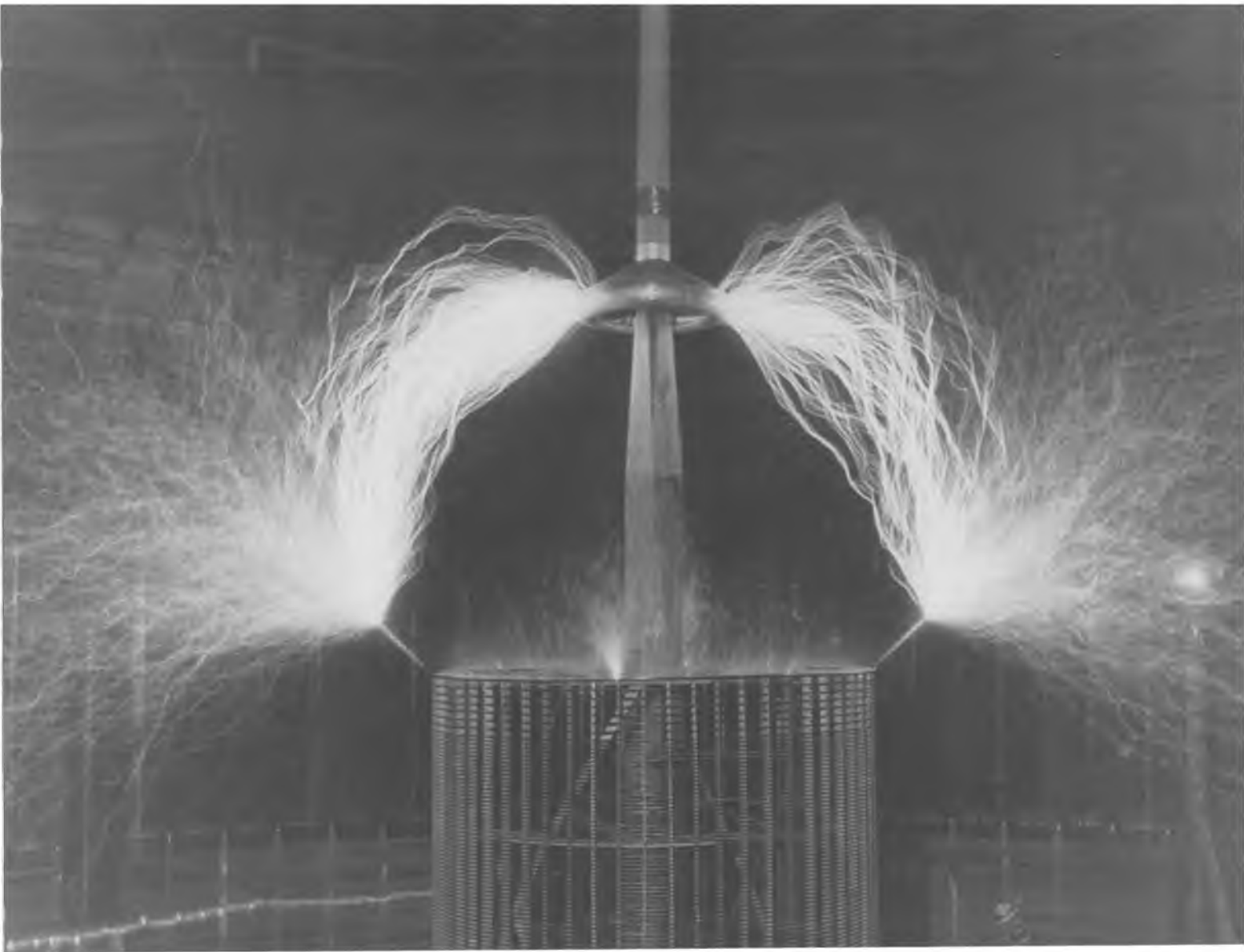
Photographs taken with Mr. Alley from Dec. 17 to Dec. 31, 1899 and particulars about the same

XLII. Illustrates a similar view of same apparatus in action. The streamers and sparks are produced by 25 short throws of the switch. The sparks pass to hood, floor and roof. The "splashing" on the floor is plainly visible. Many other features of interest, some of which have been already described, may be observed in the photograph. So, for instance, one or two streamers show clearly the phenomenon, which has been dwelt upon already, namely more luminous spots or "balls". The loss in luminosity of a streamer branching out is also illustrated. To give an idea of the magnitude of the display again a human figure is introduced, this time Mr. Alley sitting. The exposure to arc light was 5 minutes, about half opening of full lens and afterward about one half of the large Eastman powder was set off.

XLIII. This shows again the same discharge laterally across the shop, as before. The sparks are more powerful this time and there are more of them, fifty throws of the switch being made. The sparks and streamers are made to issue this time from a curved wire forming the terminal of the extra coil. The sparks to the hood and to the roof are particularly interesting. The point used before on the ball 30" diam. was taken off. The extra coil unfortunately broke through some places and also to the floor.

Some of the streamers form actual loops turning back upon themselves. A curious feature is presented by a long streamer striking the wooden support of the ball and splashing from there upon the ground wire leading from the ball. Some streamers are seen to pass along the wire without striking the same, lighting finally on the ball. This plainly illustrates that the path of such a discharge is accidental, dependent on the arrangement of particles floating in the air on the currents in the latter. Luminous points are again observed on some of the streamers, as in previous instances. In this experiment the other particulars were the same as before. Mr. Alley was photographed once more, a flash being used after the arc light exposure as in the preceding case.

XLIV. This plate shows the extra coil discharging laterally across the shop and to the floor, the streamers and sparks issuing from several thin wires tied together and spread apart on the end. In this experiment several discharges to the floor were so powerful as to actually inflame the wood on the spot where they struck the wood. Several instances of "splashing" on the wood are observed. The splitting or branching is nicely shown in one of the streamers. One of the sparks strikes the wood and disappears emerging again at some distance from the spot, having evidently followed a better conducting path through the wood. A powerful spark passes to the coil on the stand, jumps out and strikes the top wire of the secondary, instead of taking the shorter and easier route along the wire to the ground. Some very



Phot. LVIII. Discharge from "extra coil" issuing from two diametrically opposite wires, pointing upwards and fastened to the brass ring on the top of the coil.

curious curves and twists are observed on a number of the sparks and streamers. In the experiment, 100 throws of the switch were made and the particulars were in other respects the same as before, the vibration of the "extra coil" being the normal or nearly so.

XLV. This shows a slightly different view, the discharge of the extra coil taking a similar course laterally across the shop. Strong sparks pass to hood, floor, high coil on stand and also to roof. The photograph presents features of interest similar to the foregoing. One of the streamers behaves curiously, going for some distance away from the coil and then turning back upon the same. The feature of the thickening of some sparks and streamers on the lower end near the floor is well shown in a few instances, and unmistakably. The discharges are long as they are made to issue from the tip of a wire, mostly the leaks on other points being comparatively small. The glow of the top wire of the secondary is strong. Fifty throws of the switch were made in this instance, other particulars remaining substantially the same.

XLVI. In this case again the extra coil discharges laterally as in a number of instances just described. As there was a bad leak on a spot of the rubber cable forming the last two or top turns of the extra coil, a ball of 30" diam. was connected to the cable at that point, the object being to take up the pressure and prevent the leak. It was expected that the discharge from the end of the wire, from where it was intended to issue, would thus be strengthened. This proved to be the case decidedly, but the presence of the ball slowed down the vibration of the extra coil to some extent, thus destroying the best condition for resonance obtainable with the apparatus, for some inductance had to be inserted in series with the primary of the oscillator and this meant a slightly decreased economy. Some streamers, issuing from the large ball, despite the drain on the end of the wire, illustrate clearly the immense electromotive force and great quantity of electrical movement in the system. Many strong sparks pass to the high coil and still many more to the ground through the wooden floor, the latter showing some of the interesting phenomena described before. Particularly clear is the action of some sparks in inflaming or volatilizing the wood on the spot where they strike it. The splashing over the surface of the wood is also well shown in a number of instances. A portion of the floor struck by a number of sparks near together is considerably illuminated, chiefly by the increased light of the sparks on the surface of the floor and near the same. This additional light is, as may be seen during the experiment and also by an inspection of the photograph, due to the momentary ignition of the material to which also the thickening of the sparks near the floor might be ascribed, observable in some of the sparks. A curious screw movement is noticeable on some of the streamers. There were again 100 throws of the switch made in this experiment, the other particulars being, as nearly as practicable, the same as before.

XLVII. Once more a similar view was taken, illustrated on this plate, but the ball was not connected to the top of the extra coil and the vibration of the latter was very nearly the normal. There are some leaks on the cable on top, despite the most careful wrapping with mica and rubber, nevertheless some of the sparks and streamers issuing from the tip of the wire attain great length. A number of the sparks fly in curiously curved paths to the top wire of the secondary. These are about 22 feet or more in a straight line. There is a draught created by the discharge, as is evident from the splitting up of some sparks or streamers in individual discharges effected by the operation of the break wheel. Many interesting formations of the streamers and some phenomena before described are again noted in this case. Some sparks are seen to continue along the floor. The sparks to the hood show clearly and beautifully the effect of the draught created in consequence of the rapid heating of the air. A curious feature is afforded by some streamers actually doubling upon themselves. The secondary resonates very strongly but the strong streamers on the top wire are partially due to the reaction of the excited system. In the present instance also, 100 throws of the switch were made, the other conditions remaining practically the same as before.

XLVIII. This plate shows one of the strongest discharges viewed similarly, as in the previous cases just dwelt upon. The streamers and spark issue again from the tip of the "free terminal" wire of the extra coil. Some of the sparks pass again in winding paths, which are very long, much longer than the



Phot. LIX. Discharge of "extra coil" issuing from many wires fastened to the brass ring as on Phot. LVIII.

straight course which they should take, to the top of the secondary. These paths have easily a length of some fifty feet or so and are of extreme brilliancy. This is partially due to the capacity of the ball of 30" diam. connected to the top turn of the extra coil. Some very brilliant and thick sparks pass from the ball to the hood above and others much longer, though less brilliant, strike the high coil on the stand across the laboratory. One of the streamers is wonderfully interesting on account of the curiously twisted and curved appearance. It is hard to conceive how a discharge can pass through the air in this way when there exists a strong tendency to make it take the shortest route.

The curiously curved path clearly shows how extremely sensitive discharges of great length, and particularly those passing out into the air from a single terminal, are to currents of the air. This sensitiveness is still further increased when the streamer or spark is not compelled to issue always from the same point or points, as when the terminal is constituted by a pointed wire, but can issue with *equal facility* from other points as, for example, when the terminal is constituted by a large ball or disk. The slightest draught is, in such a case, sufficient to alter the position and shape of the streamer. In such an instance the discharge is also highly sensitive to other influences, as magnetic or electric actions, Roentgen rays, light and other forces or disturbances in the medium.

I now understand better why a "rotating brush", which I have described some years ago, is so wonderfully sensitive, many times more than any other sensitive device of which I have knowledge at present. It seems to me that a sensitive device in telegraphy on this principle will have to be ultimately adopted in preference to others. The trouble is that it is difficult, or at any rate inconvenient, to produce and maintain the phenomenon but this difficulty may be overcome in time. The photograph described shows very beautifully how a streamer falls apart and spatters after striking a wooden structure, owing to the sudden heat evolution and gas generation at that spot. The photograph conveys well the idea of the fierceness of the discharge produced by 100 throws of the switch, other particulars remaining.

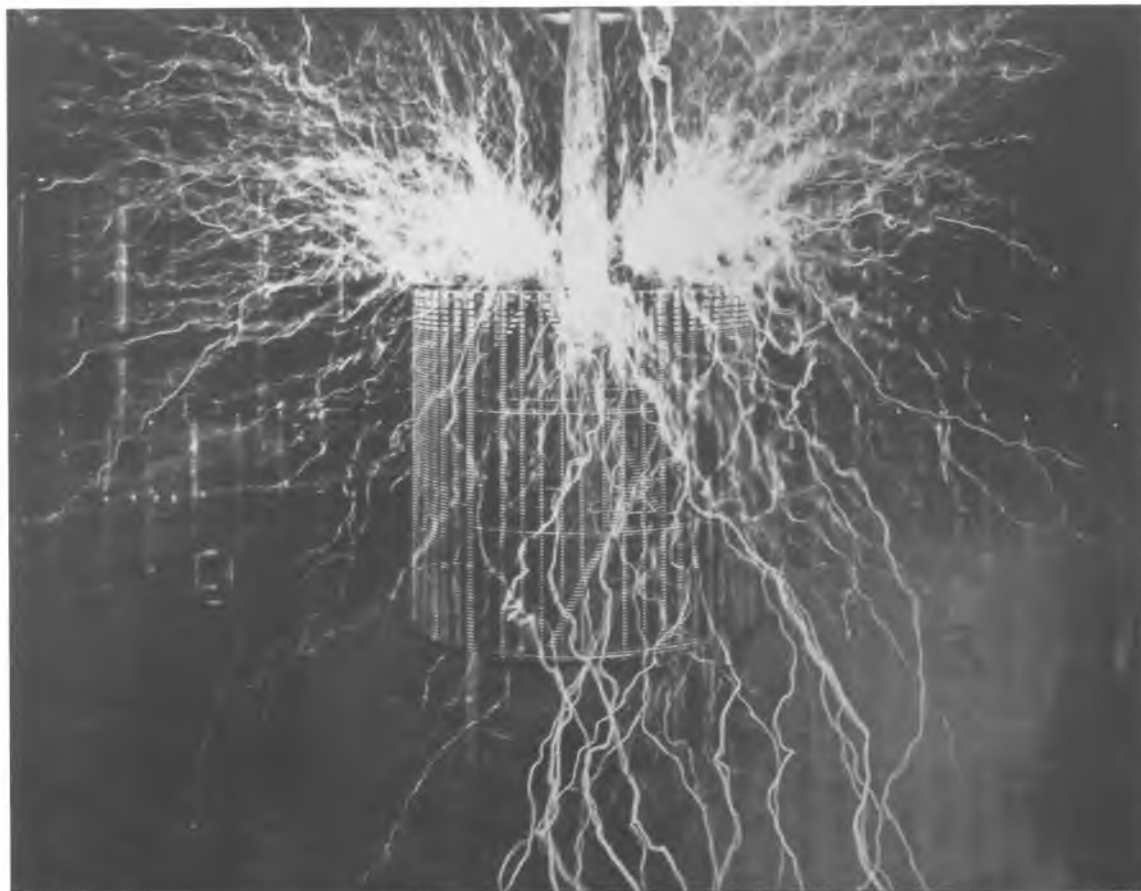
Colorado Springs

Jan. 5, 1900

Photographs taken with Mr. Alley from Dec. 17 to Dec. 31, 1899 and particulars about the same continued

XLIX. This plate shows again the extra coil viewed centrally and discharging from the brass ring on top, mentioned before, to which thin wires, pointing upwards, are fastened. As the streamers are made to issue from great many points at once, they are decidedly weaker than when, as in some previous cases, permitted to issue only from a few points. This is evident from the fineness of their texture, as shown in the photograph. But the total amount of energy spent upon the air is very great in this experiment and the coil in action produces the effect of a hot furnace, creating a strong current of air through the open roof which, rushing upward, takes effect upon the streamers as is plainly recorded on the plate, particularly on the upper streamers. A very interesting long spark passes to the wire leading from the secondary. It is evident that many streamers are split up to such an extent that they do not impress the film sufficiently. In the experiment also 100 throws of the switch were made and the other particulars were nearly the same as before. The e.m.f. at the terminals of the extra coil system is necessarily smaller because of the facility afforded for the escape of the streamers and great factional loss in the air, which causes the free oscillations of the system to die out more quickly than in some of the foregoing experiments.

L. This photograph represents a similar view of the extra coil discharging from the brass ring and wires fastened to same; in this case the wires being directed downwards. The streamers show much the same character as before and many are evidently not strong enough to record their path on the film,



Phot. LX. Discharge
from a ball 8" diam.
with two diametrically
opposite wires fastened
to the same.

on account of the great quantity of them. Most of them produce the effect of a strong glow only. Some strong sparks pass occasionally to the wire leading from the secondary. Again, the photograph was produced by 100 closures of the switch and normal excitation of the extra coil system.

LI. This is once more the extra coil discharging under similar conditions and viewed in the same manner. The wires fastened to the brass ring forming the last turn of extra coil are in this case pointed still more downwards. To strengthen the streamers somewhat the number of the discharging wires is reduced. The streamers on the top part of the picture are very beautiful, their paths being curiously curved. But the fine texture of the discharge again shows the weakening effect of the many wires or points of issue, though the individual discharges are evidently stronger than before. Some sparks passing to the hood and floor are interesting and show that the e.m.f. has been increased by reducing the number of the discharging wires. In fact some sparks and streamers attain great length and there are a number of instances of their splitting up in curious ways illustrated. A strong draught effect is also apparent. The photograph is rendered more beautiful by its symmetry. *All particulars* remained as before.

Colorado Springs

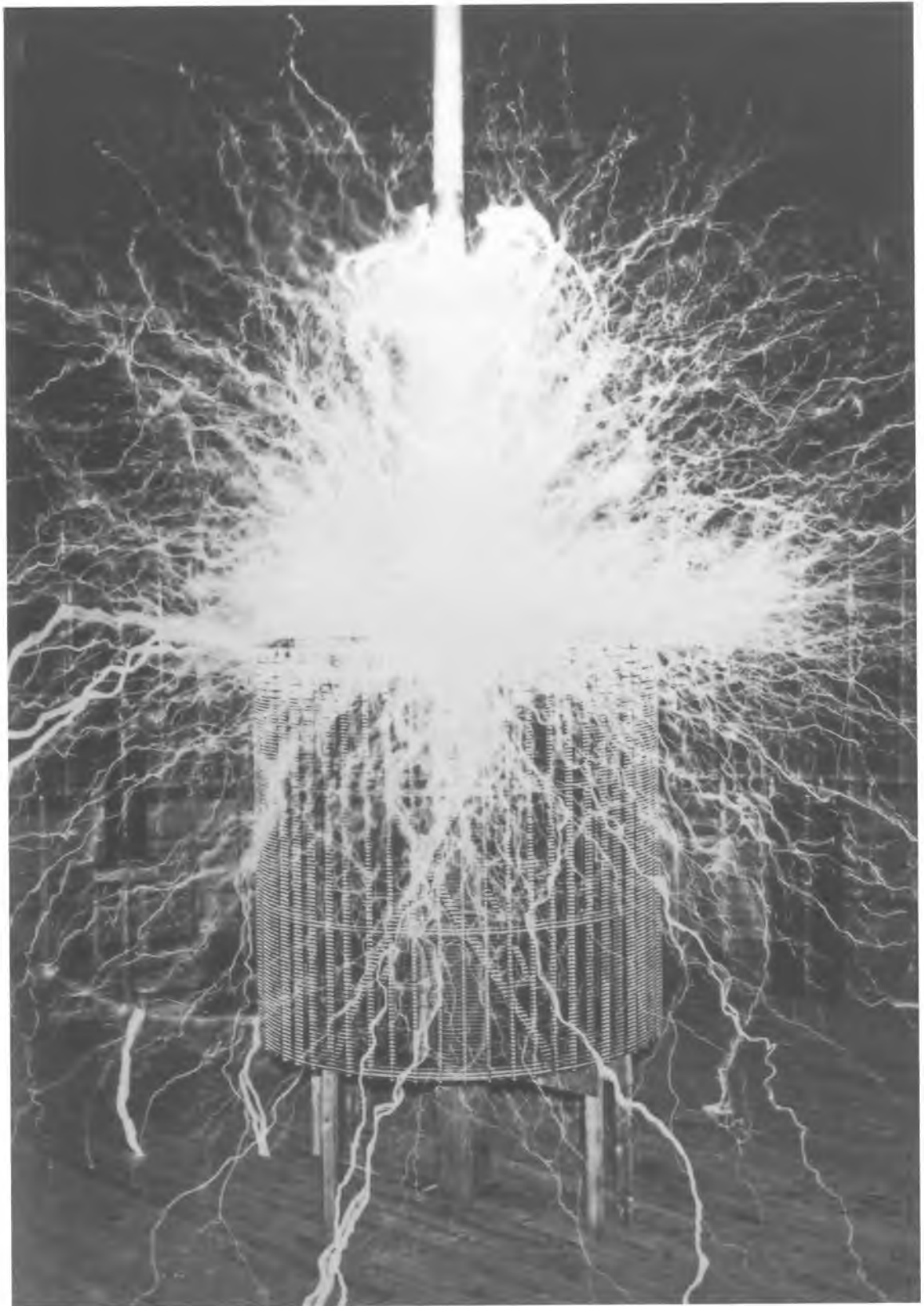
Jan. 6, 1900

Photographs taken with Mr. Alley from Dec. 17 to Dec. 31, 1899 and particulars relating to the same continued

LII. This plate shows a discharge from the top of the extra coil, produced by a single closure of the circuit or throw of the switch, of very short duration. The discharge issues again from the brass ring on the top of the extra coil, which is viewed centrally. Some streamers pass into the air and sparks dart to the hood above the coil. A curious spiral or screw motion in one or two streamers is noticeable. The light of the discharge, though lasting but one fraction of a second, is strong enough to reveal a part of the structure and the top of the coil. The current of air separates the sparks and streamers into the individual discharges produced by the break wheel. This effect is beautifully shown. The vibration of the coil and all other particulars are as in most previous instances recently described. *No* after illumination by arc or flash.

LIII. This illustrates again the discharge of the extra coil under similar conditions as produced by a single closure of the circuit through the switch, but of longer duration. This is a side piece to Photograph VI already described, only the door was not open as in that case and the draught was consequently much smaller. Some very interesting bending upon themselves and twisting of the streamers and sparks may be observed in the picture. In places, some streamers are actually interrupted. This singular phenomenon has already been described on a previous occasion. Some streamers again appear exceptionally thin though they ought to appear as thick as the others, judging from their position relative to the camera. This is evidently due to the smaller actinic power of these particular discharges, owing to which only the central and white portion impresses itself upon the film. A spark striking the floor shows the feature of "splashing", dwelt upon before very clearly. A few sparks reach the roof but do not continue along the same, being rather weak at that distance. The photograph is on the whole very beautiful. All the particulars were as normally or nearly so.

LIV. In this photograph the "extra coil" is again shown in central view discharging upwards from the brass ring or turn on the top, under conditions nearly normal. 100 throws of switch were made in the experiment. The plate is very interesting on account of the exceptional fineness of the streamers and perhaps still more so owing to the curious curves of the sparks. One of the latter is seen to pass quite close to the hood without striking it, preferring a point of the iron pole far above the hood. Another feature of interest is afforded by a streamer passing close to the iron pole and escaping through the



Phot. LXI. Streamers and sparks issuing from a disk facing the camera.

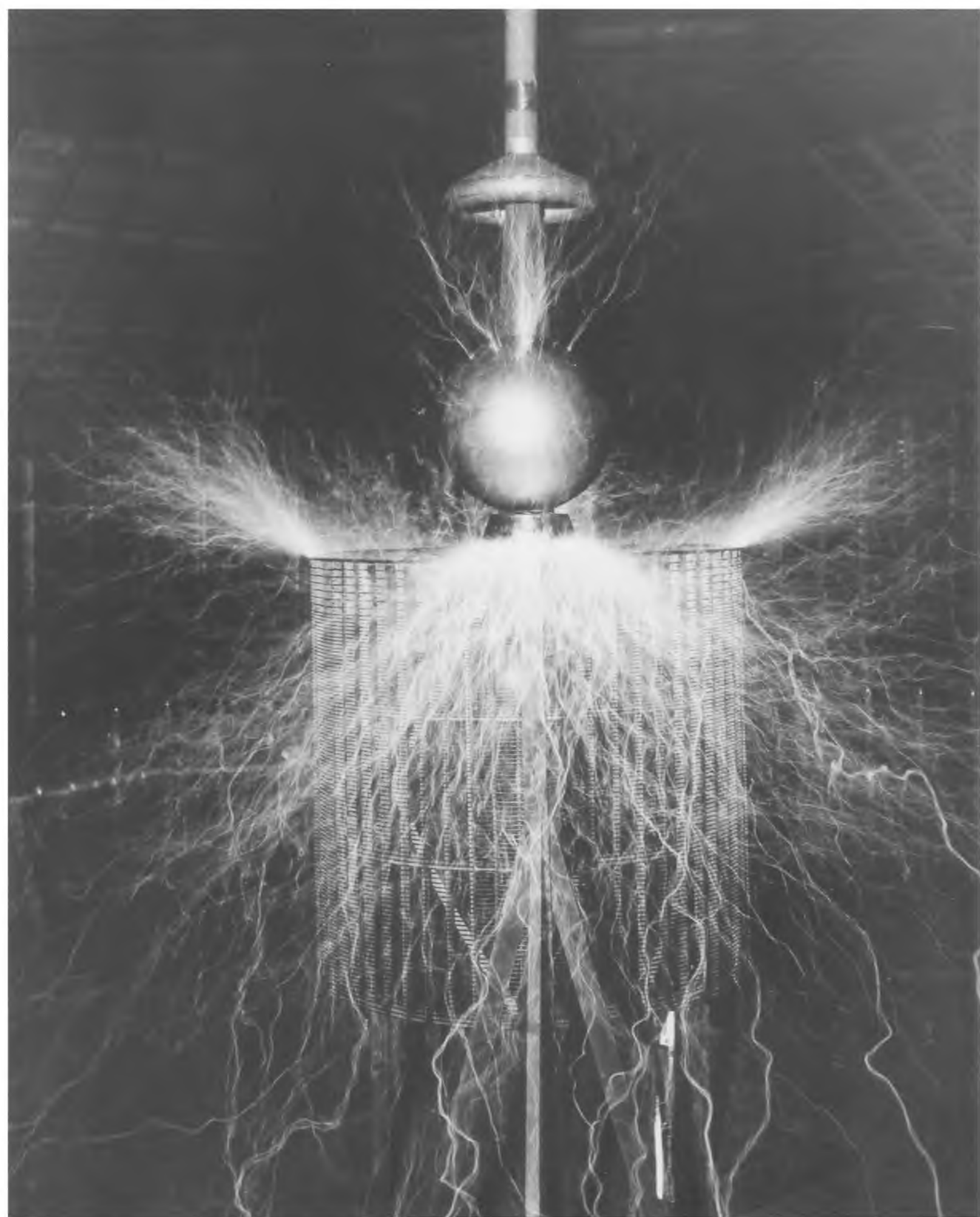
opening in the roof, seemingly not being affected by the presence of the pole. These two discharges are very long, the latter particularly. The photograph is very successful, the focusing being excellent.

LV. This plate illustrates the discharge passing laterally across the laboratory from the tip of a wire, forming the "free" terminal of the extra coil, chiefly to the floor and top wire of the secondary. The sparks and streamers are very powerful and long, exhibiting many of the phenomena described in some cases before. One spark passing from the terminal of the extra coil across the laboratory is of rare beauty showing the individual discharges effected by the break wheel exceptionally well. A few sparks and streamers show luminous points on some places which may be "fireballs". I have already dwelt at some length on this fascinating phenomenon and have explained what I consider to be its true nature. It may be of interest to state that such luminous points may be produced in other ways without partaking of the nature of the fireballs. One of these ways may be described here. It is well known—at least I assume so—that by causing two or more vibrations of different pitch to pass along a conductor, nodal points and points of maximum effect may be produced and caused to shift slowly along the conductor. Such a result I have frequently obtained with two vibrations of but slightly different period, the period of one of the vibrations being adjustable. If I recollect rightly I have described a result of this kind somewhere before this.

Substituting for a conductor of copper a vacuum tube of great length, I have also produced in the latter more or less luminous strips, striae or portions which would move along the tube with a velocity dependent on the relative wave length of both the vibrations, and which was at will adjustable by an adjustment of the wave length of one of the vibrations. The truth is, however, that I observed this phenomenon in vacuum tubes long before without being able to render myself an account of the nature of the same until I obtained the same effect on a wire in the manner stated. Now it is quite clear that, since a streamer is a conducting path comparable to a wire, the same phenomenon may take place on the streamer itself—being the result of two (or possibly more) vibrations of different wave length. This is all the more probable as in such an apparatus two vibrations of this kind may readily occur since the capacity, or the inductance of the circuit or both, may undergo variations as the discharge is playing, thus modifying the period to a slight extent—sufficient to cause the production of this phenomenon. In fact I have frequently observed such variations of the constants of the circuit which is oscillating, these variations being produced in various different ways. Thus it may happen that there is seen on such a long spark or streamer a point or portion of greater or smaller luminosity, or more such points, moving along the path of the discharge with a small velocity, without having anything to do with the occurrence of the fireballs, as before explained.

If the interruption of a discharge in some part of its course, which was noted before, would not have been actually and unmistakably observed, I would think it quite possible that this phenomenon might be due to a dark part or nodal portion formed on the streamer in the manner above set forth, this part being either stationary or slowly shifting along the path of the discharge, as the case may be. I think that I shall be able to settle this point in the following experiment which I propose to carry out. The idea is to provide a streamer which will be preferably straight and will pass continuously through the same path, thus enabling an effect propagated along the streamer to be observed just as on a wire. The streamer should be preferably also of very great length. This I am convinced I can realize as follows:

A glass tube of pieces joined together temporarily, of rather large diameter, and of a length of, say, 30 to 50 feet is to be provided. The end of a well insulated wire, forming the "free" terminal of a coil, as the extra coil here used, is to be led in one end of the glass tube, in the center of the same so that the streamer, when formed on the point of this wire, will have the tendency to pass along the tube on the inside of the same. In order, however, to keep the discharge away from the glass, suction is to be applied on the other end of the tube or else a current of air is to be forced through the tube—from the side of the discharging wire towards the other open end of the former, in any convenient way—so as to compel the streamer to pass along the axis of the glass tube. If the tube is of large diameter I do



not think that it will be difficult to carry out the experiment. Now this streamer is to be produced by oscillations or small wave length and under these conditions it will be quite easy to produce stationary or shifting, nodal or maximum points along the path of the streamer.

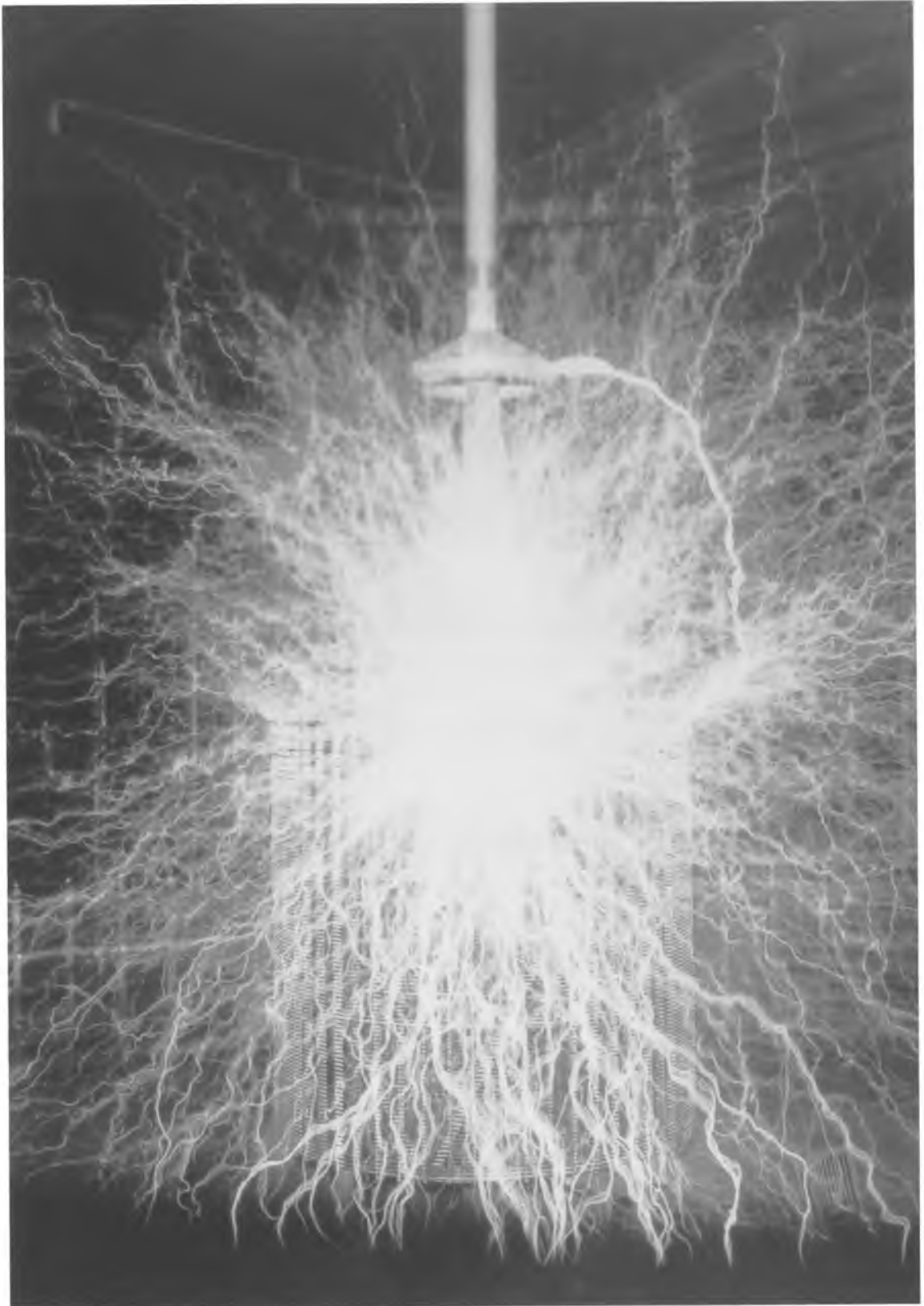
But, to return to the description of the present photograph, some of the paths described by the discharge are curious in the extreme. Many features dwelt upon before are again and even more clearly shown. So the "splashing", the splitting up and reuniting is plainly visible. Some streamers strike the roof and one particularly was dangerous, the plate showing that after hitting the roof it divided in three parts following the structure. *This will scarcely print.* An ignition of the roof would have been unavoidable had the switch been held on only a fraction of a second longer. But in manipulating the switch I always took care to throw off the handle instantly when, by chance, one of the discharges would dart to the roof. It is to be regretted that the building, although very large for ordinary experiments, did not allow the production of discharges still stronger than those before described, which would have been easily practicable with the present apparatus which – with more copper in the coils and particularly in the "extra coil", and possibly without any change – would have in all probability enabled me to reach twice or three times the length of the actual discharges. In the experiment a great many sparks were seen to pass to the top turn of the secondary. These discharges would, without adequate provision, infallibly injure the condensers and the Westinghouse transformer and also other apparatus connected with the circuits or at a small distance from the same, no matter how well insulated they might be. By grounding the circuits in proper ways this danger is in a large measure reduced. In the experiment just described there were again 100 closures, rather short, effected by the switch and the other particulars not dwelt upon were the same as before.

This statement repeatedly made in the description of these plates should be specified. The truth is, each experiment required a special adjustment as the size and form of the terminals and the character of the discharge affected, to some extent, the constants of the oscillating system or systems. But the departures from the conditions designated as normal were very slight, the inductance of the primary or exciting circuit being varied only by inserting a very few turns of the regulating coil.

LVI. In this photograph the discharge of the extra coil, issuing from a ball of 30" diameter forming the "free" terminal, passes across the laboratory to a wire turned toward and extending from the top of a coil on a stand. The discharge is made of smaller length for the purpose of heightening its brilliance. The shortest distance in a straight line from the ball to the wire is eleven feet. As the light of the sparks would produce a marring of the images, the photograph is taken through a diaphragm with a very small opening. The individual discharges corresponding to the closures of the circuit by the break wheel are very clearly shown. It is interesting to observe the curved paths of the sparks which are much longer than the shortest route open to them. Some of the sparks avoid the wire preferring to pass through fully twice the distance through the air. An interesting feature is afforded by one of the longest streamers which in a portion nearer to the wire, extending from the coil on the stand, changes from a *streamer* into a *spark*. It is also curious to observe its path passing far beyond the wire point and returning to the same. In this instance there were 50 throws of the switch made and the vibration was slightly slower than the normal on account of the large ball at the free terminal.

LVII. This plate shows the extra coil, with a ball of 30" diam. as "free" terminal, discharging laterally across the laboratory into the air. The discharges are much stronger when breaking out from the ball, requiring a much higher e.m.f. Capacity also adds to their volume and fierceness. Many streamers again show luminous points and attain great length, one in particular, which traverses the entire laboratory striking the wall. The end is probably too fine to print clearly. Many discharges again are carried to the roof by the draught they create. Once more 100 throws of the switch were made. The conditions were otherwise the same.

Phot. LXII. Discharge issuing from the base of a cone upon which a ball of 30" diam. is resting.



Phot. LXIII. Discharge
from a ball 30" diam.
supported on a vertical
coil.

Colorado Springs

Jan. 7, 1900

Photographs taken with Mr. Alley from Dec. 17 to Dec. 31, 1899 and particulars about the same continued

LVIII. This photograph shows the extra coil in central view with the discharge issuing from two diametrically opposite wires, pointing upwards, which are fastened to the brass ring or last turn on the top. The sparks, passing abundantly to the hood above the coil, produce a most beautiful symmetrical figure, which is rendered still more so by the fine texture and sharpness of the discharge paths. On the top of the coil from the brass ring delicate streamers rise producing the effect of a flame. The two wires from the ends of which the sparks and streamers sally forth *glow all along*. This is remarkable and indicates the great quantity of electrical movement. The glow of the top turn of the secondary and also that of the wire leading to the extra coil is strong, that of the latter wire being much stronger. Some exceptionally brilliant sparks occur occasionally. This happens when the discharge breaks out on one wire or point much earlier. In this case the spark continues along this path and practically all the energy supplied goes this way. In the experiment, as in most cases before, 100 throws of the switch were made, other particulars remaining unchanged.

LIX. In this plate the extra coil is again shown in central view, only the discharge is made to issue from many wires instead of only from two as before. The wires are fastened to the brass ring and are pointed upward as in the preceding case. This photograph is also symmetrical and extremely beautiful. Some stronger sparks and streamers occurring occasionally present many features of interest. A number of sparks starting from the back avoid the hood, though passing near the same, circle around and finally strike the hood on the front side. One streamer, extremely long, starts upward following the pole for some distance then turns, passing for a good distance horizontally, and finally darts upward through the opening in the roof, evidently carried by a sudden gust of the draught. Several sparks pass closely to the hood upward and return to the same after traversing a considerable distance. All the wires emitting the streamers glow. Again 100 throws of the switch were made and the vibration, as well as other particulars, remained nearly normal.

LX. This is a very interesting plate, the discharge taking place from a ball of 8" diam. and two diametrically opposite wires fastened to the same. The extra coil is again viewed centrally. Very strong sparks pass to the floor, some twisting and darting about curiously and exhibiting several phenomena described already. Sparks and streamers also pass to hood, roof and sides of the building. Some of the streamers attain great length being thirty feet, at least, in a straight line, while some sparks measure twenty feet or more. These latter are very brilliant and fierce. The upper streamers indicate the existence of a strong current of air created by the heat developed by the discharge. Again 100 throws of the switch were made, other particulars remaining the same.

LXI. This is another most beautiful photograph showing streamers and sparks issuing from a disk facing the camera. The extra coil is viewed centrally, as before, the disk forming the free terminal being on a point of the vertical axis of the coil. It seems that in some quick moving streamers the individual discharges are recorded, at least the texture appears far too fine for the break wheel period. Assume, for example, 4000 breaks per second and let the vibration be, say, 60,000 per second –then there would be 30 individual discharges in each break wheel period, understanding by this the time interval from one break to the next, or from one closure to the next. Since the break wheel effect is always seen, even when the streamer moves slowly, it would seem that the finer threads indicate the individual discharges. At any rate, with a stronger draught the latter can be evidently easily recorded and this might be a simple way of exactly determining the vibration of the system, certainly simpler than analysis by a revolving mirror.

This experiment I expect to perform on my return for it is indispensable to determine the vibration quite exactly. Up to the present this necessity was not imperative, the method used being satisfac-

tory so long as the chief purpose was to perfect the apparatus and make general observations. But now quantitative estimates have become important. To return to the description, the strong sparks to the hood are particularly curious. The strong current of air is evident from their behaviour and also from the appearance of the upper streamers. Some very strong sparks pass to the coil in series with the extra coil. One of the streamers striking the floor ignites the wood. Many streamers are carried through the opening in the roof. One, exceptionally long, passes to the photographer in the corner of the building. The shock is but slight as might be expected. A spark might be fatal, but there was no possibility of a spark taking that course without being stopped by conducting objects nearer to the origin. Some of the upper streamers are chopped up curiously indicating the presence of small whirls or eddies in the air current passing through the roof opening. The switch was here also closed 100 times; the closures were very short and the other particulars remained as before.

LXII. This is one of the most beautiful plates taken. It shows a discharge issuing from the base of a cone upon which a ball of 30" diameter is resting. Streamers, though a few only, issue also from the ball giving evidence of the immense electrical pressure and quantity of electric movement. It was indispensable to employ the metallic conical vessel for the purpose of preventing the discharge from following the wooden support, upon which the ball of 30" was supported, to the ground. This would unavoidable occur even if the support were of the most excellent material as regards insulation, as of glass for example, and no matter how high the support might be.

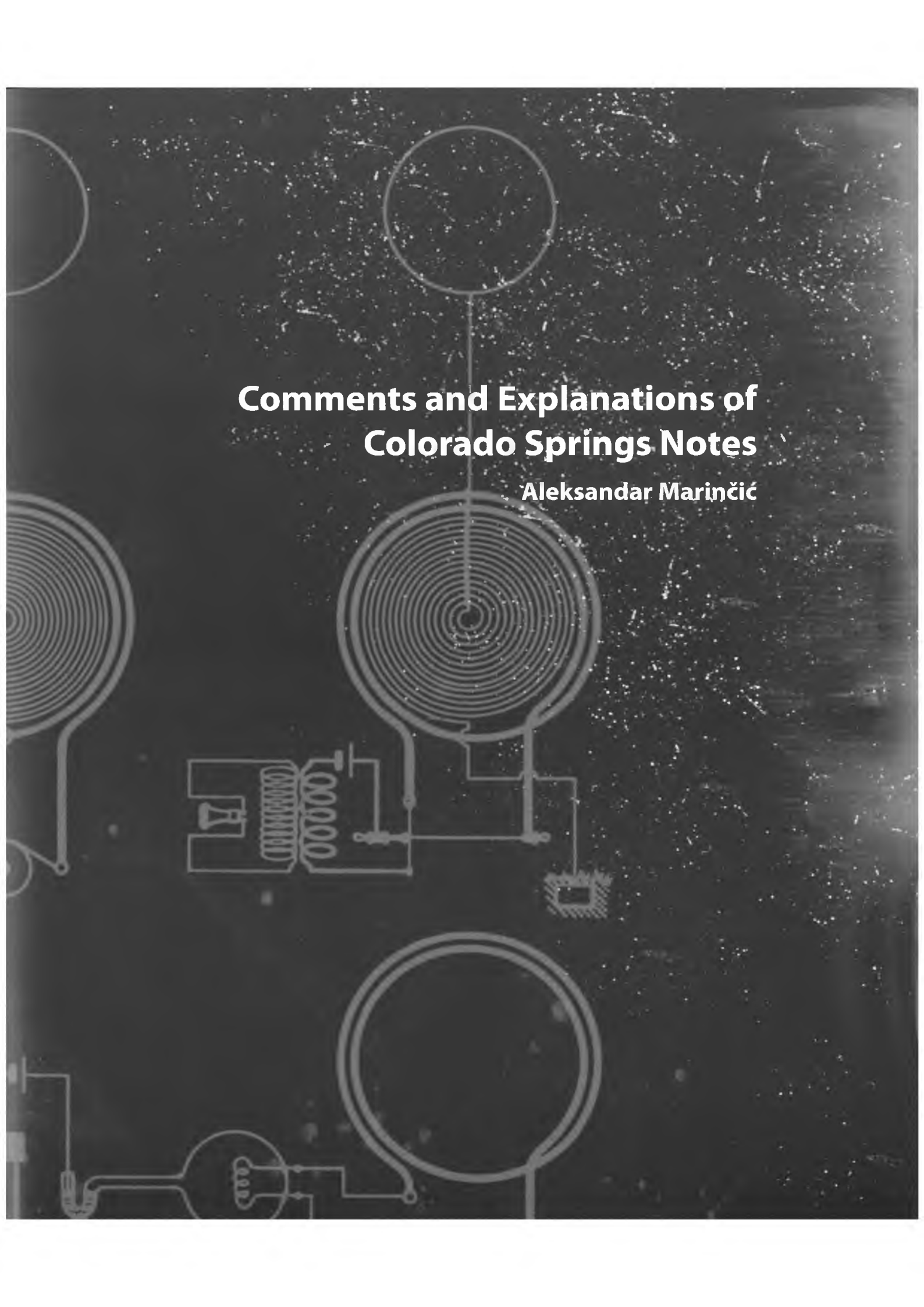
In fact, I have found from long experience with these discharges of extreme electromotive force, that it is almost impossible to insulate a terminal without some such provision as used in the present instance. The fundamental idea is to provide an arrangement such that the place of support, or that part of the terminal which rests upon the support, is guarded by the conductor projecting beyond. In other words the terminal must be resting on the support on points where there is *no electrical* pressure or, at any rate, a very small pressure. This amounts to screening the support statically. Another way to prevent the current from following the support is to place a coil, through which the current passes, beneath the support passing axially through the coil. The hood, referred to repeatedly in these descriptions, is used for the same purpose as without the same the current would pass along the pole to the ground. But the hood might be dispensed with by using an extra coil of much smaller diameter, axial with the wooden pole supporting the iron structure, but it would be necessary for insuring safety to let the coil finish very close to the bottom of the iron structure where it rests upon the insulating support. This has been one of the great difficulties encountered in the course of this work and it has required much time and trouble to overcome it successfully. For the same purposes also the large hood, above the cords keeping the iron pole in position, is employed. The rims of both these hoods are curved so as to enable a greater pressure to be reached by preventing the streamers to break out into the air easily and at a much smaller pressure. In a new apparatus, now under consideration, these improvements will be carried much further and I am confident to obtain results far beyond anything arrived at so far.

In the present experiment it is rather astonishing to see some streamers breaking out from the surface of the ball of such a large radius of curvature, when they can pass out so easily from the edge or base of the cone underneath. This shows the existence of violent surgings and a great quantity of electricity set in motion in the system. The photograph shows some luminous spots on a very powerful streamer passing to the floor. Many sparks are very curious on account of the curved paths they follow. The streamers here are also mostly of fine texture, this being due to the facility with which they break forth from the edge of the inverted pass and to their abundance. It may be seen from the plate that one of the supports of the extra coil caught fire. The particulars in this experiment were as in most cases before, 100 throws of the switch being made.

LXIII. This plate again illustrates a most beautiful discharge taking place from a ball of 30" diameter supported on a vertical coil. Owing to the abundance of the streamers the ball can not be seen. The streamers are of a peculiar character, probably due to the manner in which they were produced, which is different from that practiced in the instances before described. It so happened that when the

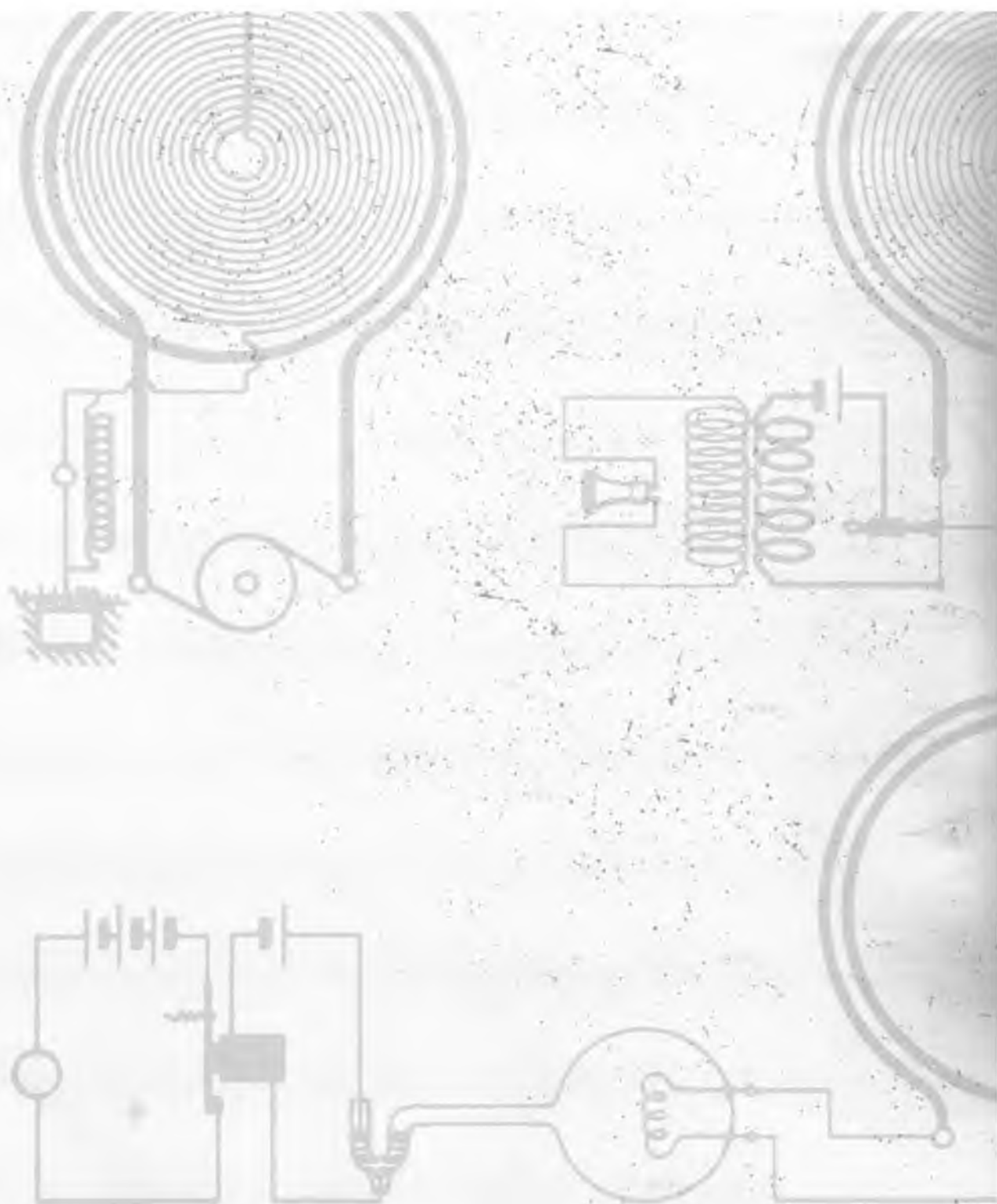
switch was thrown in the discharge from the ball always darted to the floor. Now, in order to make it pass upward also and so to produce a symmetrical figure, I held the switch on longer expecting that the heated air rising upward would carry the discharge towards the roof. Indeed this happened, the discharge always starting towards the floor and then gradually rising until it was vertical and passing out through the opening in the roof. The last and permanent position was attained in 3–4 seconds of time, this showing the great amount of energy spent in heating the air and rapid heating and rising of the latter. The air current exercises such a predominating influence that some streamers pass vertically upwards very close to the iron pole, without apparently being affected by the presence of the pole.

A peculiar feature of the present photograph is that the upper streamers are not sharp although the focusing was carefully done. This is evidently due to their fluttering motion caused by the sudden and changing gusts of the draught. This again forcibly illustrates the great sensitiveness of such streamers to air currents and I am once more impressed with the possibility of turning this property to some good use. The symmetry of the photograph is somewhat destroyed by a spark, which breaking the insulation of the top turn ($\frac{3}{8}$ " rubber), passes to the hood above the coil. All the particulars in this case remained nearly normal. There were again 100 throws of switch made.



Comments and Explanations of Colorado Springs Notes

Aleksandar Mariņćić



WITNESSES:

BY

June 1, 1899

Tesla envisaged the use of a tube with rarefied gas for the signal detection in the receiver shown. A suitable choice of battery voltage achieved the gas overstress, so that even a small voltage increase led to breakdown. The increase was supposed to create a signal getting to the tube via an antenna-ground system. The adjustment of the gas overstress would be performed by change of resistance R . A magnet M was to extinguish the tube right after the breakdown. Without it, the achieved gas breakdown of the incoming signals would be continued, and by doing so, it would prevent reception of the signals following. Tesla mentioned a similar application of a magnet for extinction of the arc in rarefied gas in his lecture to the IEE in London in 1892⁽⁵⁾. The initial idea for this type of detector may date from the time when he was intensively studying phenomena associated with currents in vacuum. Tesla informed scientific circles about these studies in his three famous lectures: in 1891 in the American Institute of Electrical Engineers⁽⁴⁾, in 1892 in London⁽⁵⁾, and in 1893 in the Franklin Institute⁽⁶⁾.

June 3, 1899

During the year 1899 Tesla filed applications for four patents⁽⁸⁻¹¹⁾, which made use of the principle of "accumulating energy of feeble impulses." It may be seen from these patents that the function of the capacitor was to store energy from the commutated (in fact rectified) HF current. The condenser is connected to the receiver (a relay) which periodically makes contact^(8,10) when the condenser charges up enough. Both these patents were filed June 24, 1899^(8, 10). The other two^(9,11) were filed August 1, 1899. They also refer to a method of accumulating energy but the way the incoming signal controls the charging of the condenser is different: here it causes variations in the resistance of a "sensitive device" which controls the current charging the condenser from a battery. The condenser discharges periodically through the receiver as in the previous case.

Tesla developed the magnet method while he was in Colorado Springs.

June 4, 1899

Tesla presented his principle ideas on wireless energy transmission in 1893⁽⁶⁾. Starting from his experimental results related to resonant phenomena in the circuits with high frequency currents and an energy transmission through one wire, he got the idea of wireless transmission of "signals, or maybe even power without use of wires." The design he showed consisted of the HF generator connected by one terminal to the ground and by the other one to an elevated metal conductor-antenna. Disturbance, which the transmitter caused, was emitted around it, being able to excite the resonant LC circuit at a certain distance. This plan of Tesla's established the foundations of telegraphy with continuous waves⁽¹²⁾ and his later experimental work made an important contribution in this field. Between 1893 and 1897 he was granted a number of patents for various types of high frequency generators. He filed applica-

tions for two particularly important patents related to wireless energy transmission on September 2, 1897^(13, 14). One of them (No. 645,576 titled *Electrical Energy Transmission System*), comprised a detailed explanation of the energy transmission principle at extraordinarily high voltages, "characteristics and level of which enable the current flow through high elevation atmosphere from the generating location to a remote place where the energy is received and used."⁽¹³⁾ Tesla repeated persistently that this energy transmission method was distinctly different from the other transmission methods since it could enable the atmosphere properties to be used as an excellent insulator. Through "other" methods, he considered, foremost, the electromagnetic radiation Hertz⁽⁸⁾ experimented upon.

June 5, 1899

Tesla does not state the origin of the formula he uses to calculate the power induced in the secondary, receiving coil, by a primary fed with a power of 4 kW (or 4×10^{10} erg/sec, not ergs). Although he himself expresses doubts about the calculation, the conclusion he draws is that this mode of transmission is greatly inferior to that which he calls the method of "disturbed charge of ground and air."

June 6, 1899

Working with a darkened Crooke's tube, on November 8, 1895, Röntgen noted luminescence of barium platino-cyanide crystals and discovered that it was due to some unknown radiation which he termed X-rays. Towards the end of that year he held a lecture on his discovery, and in amazingly short time the whole world knew about his work.⁽⁶⁶⁾

Tesla spent some time in intensive research on X-rays, publishing his results in ten articles in the period from March 11, 1896 to August 11, 1897.⁽⁷⁾ On April 6, 1897, he also gave a lecture on his X-ray studies⁽¹⁷⁾ and presented designs of a number of devices for generating powerful rays. During this lecture he reported interesting data from his earlier experiments with Crooke's tubes in 1894. He had then observed that some tubes that produced only feeble visible light had more effect on photographic plates than tubes which were brighter to the eye. As the goal of his research was to obtain true phosphorescence ("cold light"), he postponed further investigation of this phenomenon, and of the cause of various spots and hazing on photographic plates that had been kept in the laboratory for a period of time before use. When he finally did get around to it, a fire broke out in the laboratory, destroying practically everything (March 13, 1895). It was several months before he could resume his work, and in the meantime, Röntgen made his discovery. When Tesla heard about it, it was immediately plain to see what had been happening in his laboratory. He repeated Röntgen's experiments, which were rather cryptically described, and realized that he had been mistaken in not following up certain chance observations during his work with Crooke's tubes.

During 1896 and 1897 Tesla carried out many experiments with X-rays, also speculating about their nature. He thought "that the effects on the sensitive plate are due to projected particles, or else to vibration far beyond any frequency which we are able to obtain by means of condenser discharges." He immediately realized the importance of high voltages for producing powerful rays and suggested using his single-terminal tubes connected to the secondary of the disruptive discharge coil. It is interesting to note that Röntgen too, in a lecture to the Physical Medical Society of Wurzburg, in the same month as Tesla published his first article, also pointed out the great advantage of using Tesla's high frequency oscillator in generating X-rays.⁽⁶⁶⁾ Tesla measured the reflection and transmission of X-rays for several metals, lead glass, mica and ebonite. It is not clear, however, whether what he measured was true reflected radiation or secondary radiation. He also tried to detect refraction but did not succeed, for reasons which are today obvious. In papers and in a lecture before the New York Academy of Science he described a number of tubes for producing powerful X-rays, most of them resembling Lenard tubes (which he often mentions) but without the anode terminal.

Descriptions of the high frequency transformer are to be found in Tesla's publications and patents from 1891 onwards^(4, 15) but he did not patent it until 1897.⁽²⁶⁾ The invention protected by this patent is "A transformer for developing or converting currents of high potential, comprising a primary and secondary coil, one terminal of the secondary being electrically connected with the primary, and with earth when the transformer is in use, as set forth". It in particular protects the spiral form of the secondary, and a conical form is also mentioned. For ordinary uses a cylindrical secondary divided into two parts is proposed. A new feature is the specification that the length of the secondary should be approximately one quarter of the wavelength of the electrical disturbance in the secondary circuit, based on the velocity of propagation of the electrical disturbance through the coil itself, or, in general, so that at one terminal the potential would be zero and at the other maximum.

The primary coil of Tesla's HF transformer almost always has one to two turns. Even with their small number, the primary coil inductances are large enough regarding these coils' dimensions. For example, in his patent *Apparatus for Transmission of Electrical Energy*⁽¹³⁾ the primary diameter amounted to approximately 244 cm and its inductance to approximately 8,000 cm. He decided to use an even larger coil, which could be seen from the latest features (radius 762 cm!).

June 8, 1899

In his notes Tesla did not mention the preparations for his laboratory construction, and what he noted were the ideas and data necessary for the experimentation. For example, describing inductance measured by a balanced bridge he did not state the balance equation and therefore certain claims (and a scheme) could not be proven with assurance.

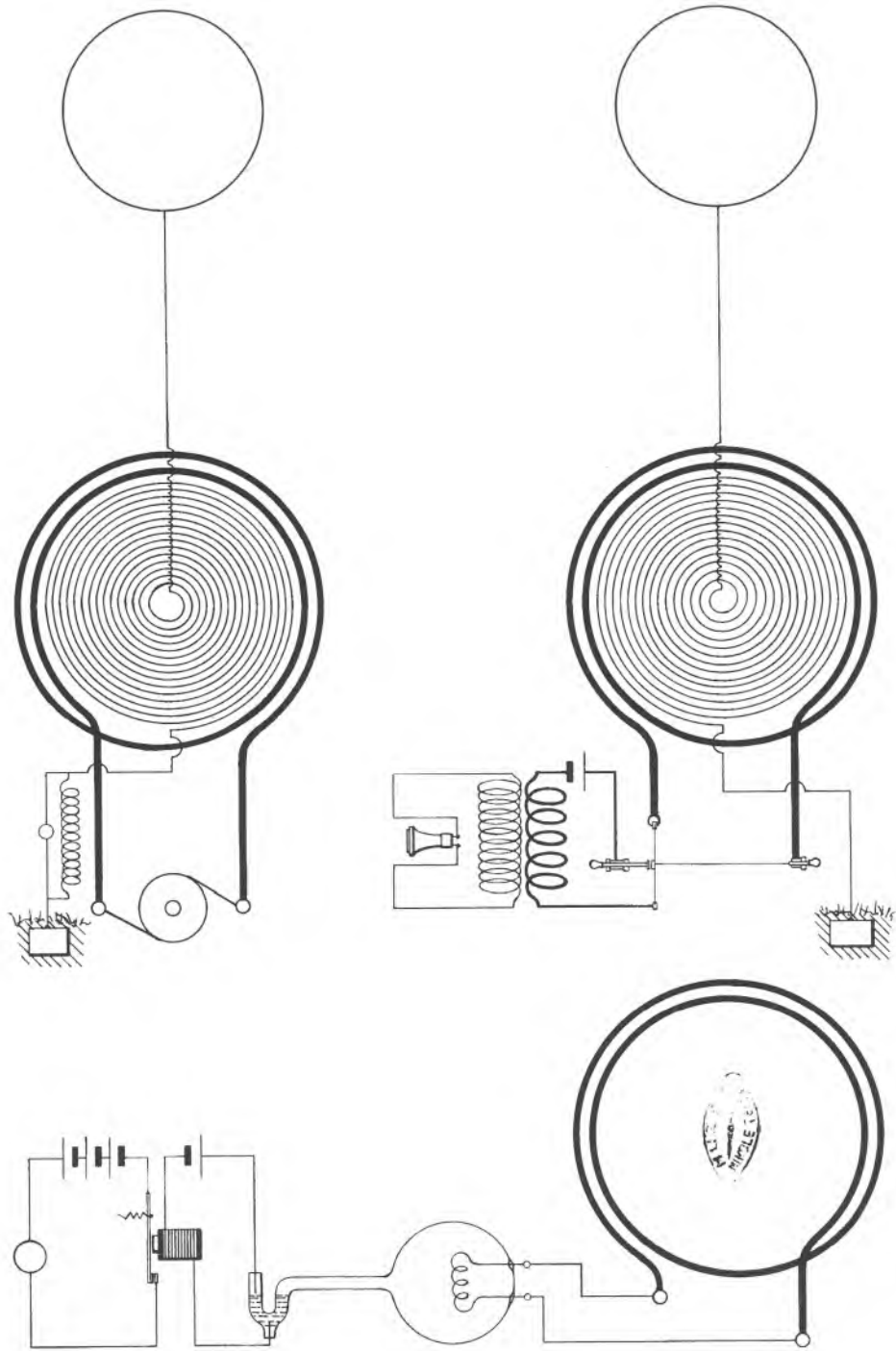
June 9-12, 1899

In his efforts to construct a sensitive detector for small signals, received by an antenna-earth system, Tesla worked out several designs making use of the thermal effect of high frequency current. Since the energies involved are very small (according to Tesla, on the order of 1 erg), receivers based on this principle would be extremely delicate.

In the first type of receiver the resistor is of a small mass. The current flows through it from an antenna to the ground, heating the gas in a container with reflective walls (in order to achieve the space which does not exchange the heat with its surroundings - adiabatic space). The heated gas expansion moves a liquid drop in a thin tube t towards the contacts ab (figure, June 9), through which the circuit for received signal registration is closed. In the archives of the Nikola Tesla Museum, Belgrade, a slide (shown on page 384) has been found which gives evidence that Tesla was probably preparing to file a patent on a similar receiver. It is not known whether he filed an application for the patent.

For another type of receiver (June 10) in place of a small mass resistor, Tesla proposes the use of a thin mercury cylinder. The received signal would be registered on the assumption of mercury expansion in the tube. According to mercury cylinder weight and the energy necessary for heating one gram of mercury to one degree Celsius, he finds that the required energy is considerably above the assumed signal energy. Therefore he concludes that the mercury cylinder should have to be much thinner.

With the receiver of the third type (June 11), HF current heats a small mass resistor and signals are registered by its resistance change. Previously Tesla established experimentally that a thin carbon layer resistance was reduced while a weak signal current was flowing from an antenna. The resistance reduction should be sufficient for the battery current to switch on the auxiliary relay. In the scheme given, the system is expected to be able to receive the subsequent signals as soon as the signal registra-



WITNESSES:

INVENTOR.

BY

ATTORNEY.

tion is completed. Tesla suggests the implementation of a bridge-form configuration but he does not explain how to use it.*

The receiver number 4 (June 12) is much more original than the previous ones. Looking for the small mass resistor, Tesla got the idea to use a thin steamed film on an insulator-made plate. It would be formed in a small jar with two terminals at temperatures and other conditions chosen suitably. It was expected to form and get destroyed (by the battery current) probably with each received impulse.

Out of these four receivers, two (June 9 and 11) were suggested to be followed up on experimentally. It is interesting that those were the receivers he had already worked on in his New York laboratory.

The basic principle of these detectors is of an earlier date. According to Fleming,⁽³³⁾ Gregory carried out measurements of radiation intensity by the extension of a thin wire in 1889, and Rubens and Ritter in 1890, using a bolometer (a bolometer is the instrument where the amount of heat it receives is measured according to its resistance change). The bolometer was made of iron wire 0.07 mm in diameter and its valuation resistance was measured by a Wheatstone bridge. Both the currents transmitted from an antenna to the ground and DC, feeding the bridge, flowed through bolometer. Antenna current in the device was adjusted to disturb the bridge balance.

The Rubens-Ritter method was applied in 1904 by Tissot⁽³³⁾ to carry out electrical oscillation measurement at a long distance from a transmitter. Tissot used a platinum wire, 10 to 20 microns thick instead of iron wire and in doing so, he detected signals at a distance of 50 km from the transmitter.

June 13, 1899

Tesla produced continuous currents with special alternators in about 1890⁽²⁾ and with dischargers having a resonant transformer starting from 1891 onwards.⁽¹⁵⁾ In 1893 he suggested a system for HF current use aiming at message transmission⁽⁶⁾. In comparison with the other researchers interested in radio technique, following the method suggested by Hertz,⁽²³⁾ already in 1893 Tesla clearly realized that it was not the best possible way for the radio future. Instead of dampened currents, Tesla proposed continuous currents that could use resonance efficiently, enabling so a selective signal reception. Instead of very short waves, emphasizing straight line propagation, Tesla suggested the application of long waves using the entire globe with its high conductive atmosphere layers for current transmission as if they were "ordinary" conductors. The advantage of continuous currents is particularly great toward the impulse and to dampened ones, particularly in the transmission of continuous signals, such as speech. The entries for the June 13 and 14 describe two modifications of the HF oscillator, which could be used for amplitude modulation. These two circuits were probably in fact the first modulators in the history of radio. It is not known whether Tesla carried out any experiments with this apparatus, but similar ideas were implemented later⁽¹⁹⁾ by other investigators.

In the scheme shown, of June 13, a carbon microphone *cc* was connected in parallel to a part of a HF transformer primary. Sound pressure variations change the carbon microphone resistance via funnel *f*, causing oscillation variations. Tesla's notes illustrate how carefully he studied the design, from the power supply to theoretical aspects such as the ratio of the maximum modulation frequency to the carrier frequency. Regarding the latter, Tesla considered that the number of primary circuit interruptions at the location of the discharger *d* has to be considerably higher than the voice "variation."

* On the backside of Tesla's writing on 11 June 1899, exists the seal of the U.S. Patent Office (Nov. 15, 1902).

June 14, 1899

The transmitter using “controlling arc” modulation of the oscillator power represents the “air” microphone variation. The oscillator diagram remained the same as the one of June 13. The remark on the advantage of DC power supply is repeated (probably due to parasitic modulation caused by an AC generator of low frequency). The transmitter output power modulation is now performed in a secondary – antenna circuit by an electric arc, the intensity of which varies with a sound pressure variation rhythm. The sound regulates the gas flow under the pressure of a special valve *v*, controlled by moving pipe *t*. This modulator also produces an amplitude-modulated wave by varying the carrier power about a mean value. The modulating signal can be of low power, so that the device as a whole can also be considered a frequency-shifting amplifier.

June 15, 1899

This trial run of the new oscillator was Tesla’s first step towards the implementation of the high power generator. The secondary of the HF transformer was made conical with 14 turns and with an average turn length of 40 meters. The primary consisted of one turn made of 37 braided wires 2.9 mm in diameter with rubber and cloth insulation.* Such a large transformer was dictated by the high voltage requirement. The secondary was conical in order to reduce the voltage between turns at the top of the coil. This feature is described as one of the alternatives in his *Electrical Transformer* patent⁽¹⁶⁾ (it seems that Tesla favored the secondary in the shape of a flat spiral with the primary at the outside of the spiral, so that the common terminal of primary and secondary was grounded).

Fast primary capacitor discharge was performed by a rotating interrupting device – 800 to 1200 times per second. The shape of oscillations was therefore close to the one on figure 2P.b (see Appendix: Tesla’s Oscillator). At this point, there is no sufficient data in order to consider the operation of the oscillator accurately and to understand all remarks on methods of lightning securing devices and grounding operation.

June 16, 1899

In these experiments Tesla investigates the influence of grounding on the HF oscillator. On the basis of a series of experiments and measurements of resistance between a water pipe and a grounding plate, in which wave intensity propagated around the oscillator and arcing on lightning arresters, Tesla concludes that grounding resistance is high. Besides this ground effect, he suggests that the induced currents in the ground (as a conductor) will influence the oscillator firstly and secondly.

The main point of interest for him was the propagation of electrical waves through the Earth. He had already put forward the hypothesis that the Earth could be used as one of the conductors in transmission of energy from a transmitting to a receiving aerial in 1893.⁽⁶⁾ He further developed this hypothesis in his patent application *Apparatus for Transmission of Electrical Energy* filed in 1897.⁽¹³⁾

June 17, 1899

The repeated measurement of ground resistance between the water pipe and the grounded plate shows clearly that the terrain around the laboratory was poorly conductive. After a long period of ground moistening, the resistance was reduced (probably the soil around the grounded plate was moistened). The obvious ground resistance instability led Tesla to think that grounding would cause difficulties in oscillator operation. The connection to the water pipe, as alternative grounding has, according to Tesla, disadvantages because this introduces an additional conductor in the oscillator circuit. Whether

* Tesla was the first who used braided wires in HF circuits instead of full conductors with the aim to reduce the effect of whirling currents (see e.g. lit. 46).

this was correct depends on a number of factors (e.g., the distance between the water pipe and the ground surface), but it is certain that the water pipe provided better grounding than the already mentioned grounding plate.*

Tesla measured the oscillator's primary and secondary inductance on the basis of an impedance module and the known resistance. He determined the impedance from the ratio between voltage and the current at a frequency of approximately 144 Hz. He indicated the coil resistances, but he did not explain whether they were determined by measurement or by calculation.

He determined the primary and secondary inductance from the ratio of no-load voltage in the secondary and excitation current in the primary, multiplied by the circular frequency at which he carried out the measurement.

The term "L-reduction" is not clear now. The term $L-M^2/N$ corresponds to the primary inductance when the secondary coil is in short circuit. Based on mutual inductance, and primary and secondary inductance, it is found that the transformer coupling coefficient was approximately 0.6, which indicated a very firm coupling.

June 18, 1899

So far Tesla did not present the method to determine the oscillation frequency, but it is clear that he already had some results. Looking for the mismatch reason of measured and calculated value, he tried out a new modification of the HF transformer. He made a new coil connected by its one terminal to the open secondary terminal, and then a considerable voltage increase at the other terminal of the new coil was achieved.

The secondary circuit was modified by the addition of another coil, altering its response to the primary and the spectrum of the oscillations. Tesla had already used it in experiments in New York. This coil was not inductively coupled to the HF transformer (some coupling probably existed, though weak).

The analysis of Tesla's oscillator with "extra coil" could not be performed according to Oberbeck theory because the secondary circuit was changed. Now the capacitance C_2 (see Appendix: Tesla's Oscillator) was replaced by the parasitic secondary coil capacitance to which is connected in parallel the series combination of "extra coil" with quite indefinite parasitic capacitances. When determining the secondary circuit, Tesla mentions as a guide, that the secondary wire length has to amount to one quarter of a wavelength. This requirement appears in his patents from 1897.^(13,14,26) Actually, the wire will be shorter because the current propagation velocity along the coil is lower than along the straight conductor.

He performs the measurement of oscillator circuit parameters on a rewound secondary. He gives the first capacitance measurements in a primary oscillator circuit.

June 19, 1899

Continuing his study of the receiver components referred to between June 9 and 11, Tesla describes a sensitive detector using the attractive force between the plates of a charged condenser. The plates of a charged condenser are two wires made of soft iron. Dielectric between these wires is under influence of a field from an auxiliary source - a battery, and that field is such that additional low voltage causes the wires' attraction. It is particularly interesting that the wires are in the coil field (that is why they are made of soft iron) so the device could be deactivated by current action through the coil. Deactivating current is obtained when contacts on wires touch one another. The magnetic field in the coil magnetizes the iron wires and they repel each other.

* At this time there was relatively little experience with grounding. He explains in this entry that grounding was made in "the usual way as here practiced", probably referring to lightning conductor grounding. Grounding for single-wire telegraphy dates from 1838, when Stinheil demonstrated that the Earth could be used as the return conductor. In 1893 Tesla described his system for energy transmission without wires⁽⁶⁾ where the alternating current source is connected "with one of this terminals to earth (conveniently to the water mains) and with other to a body of large surface P." Popov's receiver of 1895 also used grounding via a water pipe.⁽³²⁾ Around 1895 Marconi did some experiments with a Hertz apparatus grounding one terminal of the inductor and leaving the other connected to an elevated conductor with a terminal capacity. Exhaustive studies of the influence of the form of grounding and the nature of the ground were made around 1905 and later.⁽³⁰⁾

Descriptions of allied devices are to be found in several of Tesla's patents. In patents⁽⁸⁾ and this device⁽⁹⁾ is used to periodically make the receiver circuit when main condenser charges up sufficiently (there is no pre-excitation nor quenching, since the circuit quenches itself when all the stored energy gets discharged). A fuller description, where it is noted that the performance of the device is improved under reduced air pressure, may be found in various literature.^(35,36)

June 20, 1899

Tesla did not make strict theoretical analyses of the mode of operation of this oscillator, but determined all the main parameters by tests on a simplified representation of the oscillator circuit. For example, he estimated the power supply drain from the energy in the condenser of primary circuit multiplied by the rate of his discharge. This involves the assumption that the condenser charges up by the same amount before each discharge (which cannot be the case when it is charged from an AC supply) and that all the energy gets dissipated before the next charging.

The vibration, i.e. the resonant frequency of the primary circuit is calculated from the measured inductance of the primary with two turns (see June 17) and its capacitance. Since he was now using one turn, the inductance is divided by 4. The capacitance was somewhat greater than that measured on June 18 with the old jars. Using these L and C values he calculates the oscillation period of the primary using Thomson's formula for a lossless circuit.

He then finds the wavelength using the period of the primary oscillation circuit, and hence works out the number of turns the secondary must have so that its length is one quarter of a wavelength (see the commentary to June 18). With two primary turns, when the primary inductance is approximately four-fold and the period is doubled, he judges that 80 turns will be required. He estimates the inductance of a secondary with 80 turns on the basis of the known inductance of a secondary with 12 turns (see June 18), considering that the ratio of the inductances equals the one of squared number of corresponding turns. Tesla determines the secondary period from such an estimated inductance, assuming that the secondary does not have distributed capacitance and that the only capacitance in the secondary circuit originates from a metal sphere. Since the obtained secondary resonant frequency is high, he calculates the secondary inductance, which will produce the same period for primary and secondary circuits. He calculates the required secondary number of turns for such obtained inductance, but he does not comment on this result, although the wire-length in the secondary exceeds the length of a quarter of a wave.

It is interesting that, for the first time in his notes, Tesla mentioned expenditure, which leads him to think of other methods to reduce the secondary resonant frequency (applying a bigger sphere or disc).

June 21, 1899

Returning once more to the problem of the conversion of mains power into HF power, Tesla calculates the energy in each charging cycle of the condenser (see comments for June 20). Considering that all the energy in the charged condenser will at some instance be found in the condenser of the secondary circuit, he in fact works out the peak voltage on the secondary condenser. The energy equation for lossless coupled circuits has the general form

$$\frac{1}{2}C_p U_p^2 = \frac{1}{2}C_s U_s^2$$

where p refers to the primary, s to the secondary circuit, U is peak voltage. It should be noted that Oberbeck's theory (see Appendix: Tesla's oscillator) yields the same ratio between the voltage on the primary condenser just before discharge begins and the peak voltage on the secondary condenser.

June 22, 1899

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The circuit with two condensers, one being charged from the power supply and the second via a spark from the first, represents a modification of Tesla's classic oscillator.* Theory shows that protraction of the oscillation in the primary circuit lowers the efficiency of the oscillator because energy pulses back and forth between the primary and secondary. However, this circuit protraction of the spark does not have the same effect because while intensity lasts the primary capacitance is $C + C_1$, but when it stops the capacitance is only C_1 . Why the sparks in the secondary were stronger with $C = aC_1$, a being a whole number, is hard to say without a more exhaustive analysis.

* Drawings reproduced on p. 390, taken from Tesla's original slide, now in the Nikola Tesla Museum, Belgrade, show four modifications of the transmitter.

As a proof of better oscillator operation, Tesla accepts longer sparks at the secondary terminals. Sometimes he mentioned other spark characteristics but he assumed that the oscillator operated the best when the spark was the longest.

According to the diagram shown, Tesla already experimented with those circuits in New York. The scheme, with a special oscillating circuit, represents a system with three coupled oscillating circuits, and therefore the oscillation spectrum is more complex. Tesla's remark that the device operates better in such a layout when the number of discharging interruptions is low (the oscillator operation in two oscillating conditions being more emphasized in the classic schematics with two oscillating circuits) indicates a possibility of a new approach to an oscillator with a suitable spectrum, even at a relatively tight coupling between exciting and operating circuit.

From time to time Tesla puts special remarks at the end of the notes. Being obviously satisfied with the results, he felt it necessary to continue research in the same direction.

June 23, 1899

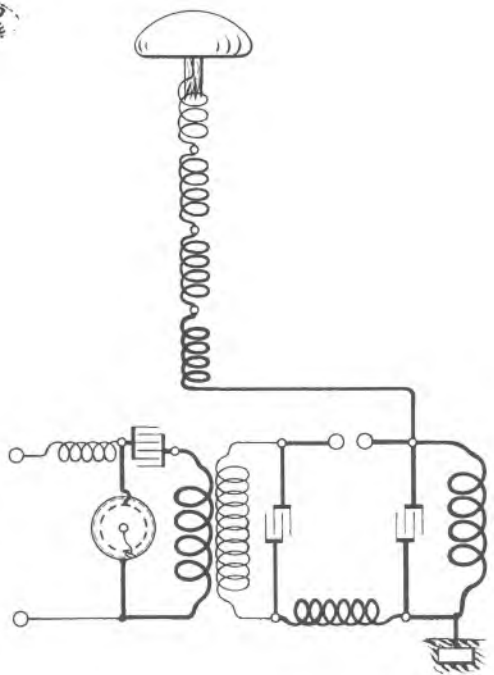
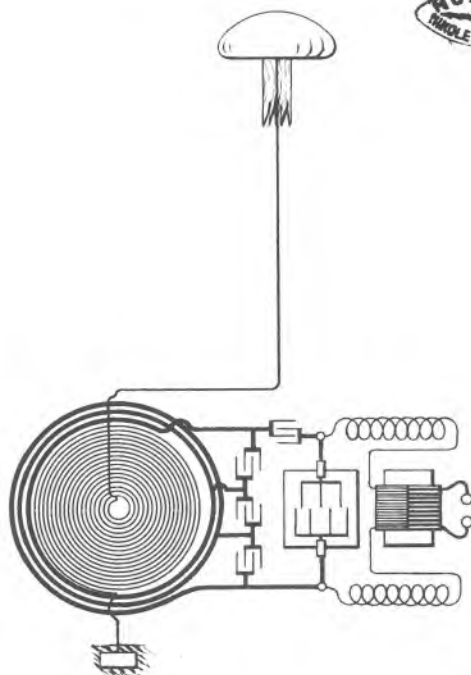
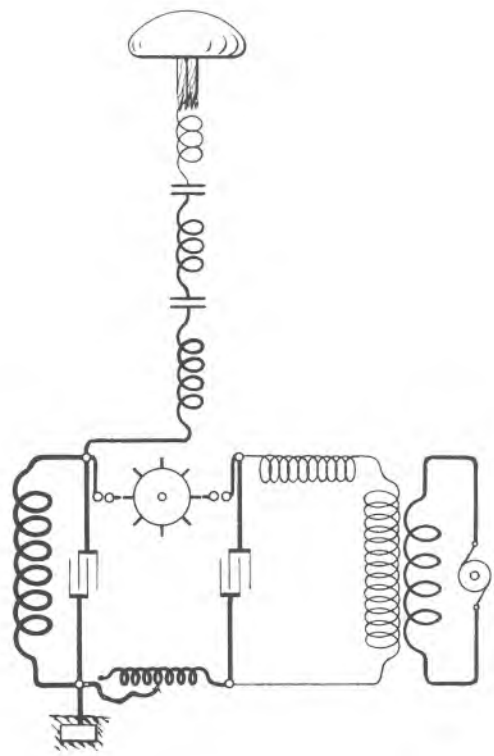
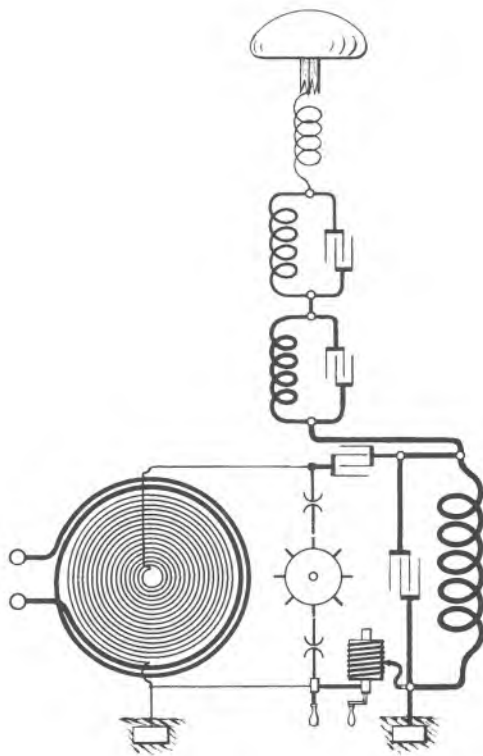
Tesla uses the variable inductance to adjust primary circuit resonant frequency. He determines the value of this inductance by calculation, using an equation for an infinitely long coil and another one, which he terms the Languine formula. The two formulae are in fact identical if the thickness of the wire is neglected, because then $L^2 = (2\pi rN)^2 = 4\pi SN^2$

In continuation of experiments with the oscillator from the previous day, he tests a new combination with auxiliary oscillating circuit formed from one portion of the primary inductance. With this connection Tesla expects the auxiliary circuit to influence the discharger oscillator efficiency. The oscillations in the primary last a short time, but oscillating is continued in the regime of coupled circuits L_1C_1 and secondary oscillating circuits. Damping being smaller in the L_1C_1 circuit than in the primary circuit with a spark is more suitable in respect of power balance, in case the spark lasts long. However, it is not certain that the short sparks in the primary are the only reason for better oscillator operation.

Regulating coil, probably connected in series in the primary circuit with the other components, is not shown in the diagram.

June 24, 1899

Rarefied gases had long interested Tesla, and his work on their conducting properties, especially at high frequencies, is well known, e.g. the patents on an electric lighting system and incandescent lamps with red-hot electrodes in vacuum.⁽³⁷⁾ He presented detailed analysis of the same problem in his famous lectures.^(4, 5, 6) Rarefied gas as a conductor is also referred to in his patent application *System of Transmission of Electrical Energy*.⁽¹³⁾ Now Tesla mentions the possibility of the use of gas in a tube instead of a metal conductor. Gas is heated from an auxiliary source to red-hot state, by which its resistance is reduced below the one the metal would have. So the coil with high quality factor, suitable for receiver circuit was obtained. Obviously, the system is not practical, but Tesla considers that the idea has to be developed in order to improve selectivity and sensitivity of a weak signal receiver.



WITNESSES:

INVENTOR.

BY

ATTORNEY.

June 25, 1899

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The device shown in the drawing was intended to amplify the vibrations, in the following way: some of the power-driving cylinder *A* is converted by friction of brush *b* against *A* into vibrations of *b*. Since the friction is a function of the current in the electromagnet, the longitudinal displacements of *b* have a variation similar to the time variations of the current. If the circuit of the electromagnet includes a microphone and a battery, then the device should amplify the speech signal, brush *b* vibrating in synchronization with the speech pressure but with much more intensity. This amplified signal could be used in a modulator (see June 13 and 14). The drawing shown on p. 392 (from Tesla's slide in Nikola Tesla Museum, Belgrade) illustrates how Tesla thought of implementing some of these ideas. *

* It is not yet been established whether Tesla patented or tried to patent this modulator. It appears that the slide is a copy of drawing intended for a patent application.

June 26, 1899

The principle of this device using high voltages to decompose gases would be based on separation of molecules (in fact ions) of the different mass/charge ratios. It is not known whether Tesla tried to verify this idea experimentally. In a later article⁽²⁸⁾ on electrical oscillators he mentions among the possible applications "formation of chemical compounds through fusion and combination; synthesis of gases; manufacture of ozone ..." but does not mention separation of gases, so that it may be true that he never went any further than this initial idea.

The described device consists of some components of so-called mass-spectrograph (a device for isotope separation according to mass/loading ratio, using combining action of electric and magnetic field) although, as Tesla described, it would probably not work as he expected.

June 27, 1899

The transmitter (figures 1, 2 and 3) and receiver (figure 4) having several tuned circuits, the transmitter generating several signals at different frequency and the receiver responding only when all these signals act at the same time, were the subject of two patent applications filed July 16, 1900.⁽³⁸⁾

This method allows much more selective reception than a single-frequency channel, and this is 449 times less sensitive to interference, and the signal can only be decoded by a special receiver. In this patent application Tesla links it to a lock that can only be opened when one knows the combination of numbers.**

** The back of the page bears the stamp "US Patent Office, Nov. 1902".

June 28, 1899

After four days he again continues the calculations related to the transmitter. He calculates the capacitance and inductance of the secondary transformer on a conical frame with 20 turns on the assumption of the known values for a coil with 36 turns.

Tesla considered that the self-capacitance of the secondary winding was proportional to the number of turns and inversely proportional to the spacing between turns, so that the ratio of the distributed capacities of the new and the old coil is $N_1 d / N d_1$ (N - number of turns, d - spacing between turns).

In the ratio of the inductance of the secondaries with different numbers of turns, he finds from the relation

$$\left(\frac{N_1}{N}\right)^2 \frac{l}{l_1} = \left(\frac{N_1}{N}\right)^2 \frac{N d}{N_1 d_1} = \frac{N_1 d}{N d_1}$$

derived from the expression for an infinitely long coil, and yielding the same ratio as in the case of capacitance of secondaries.

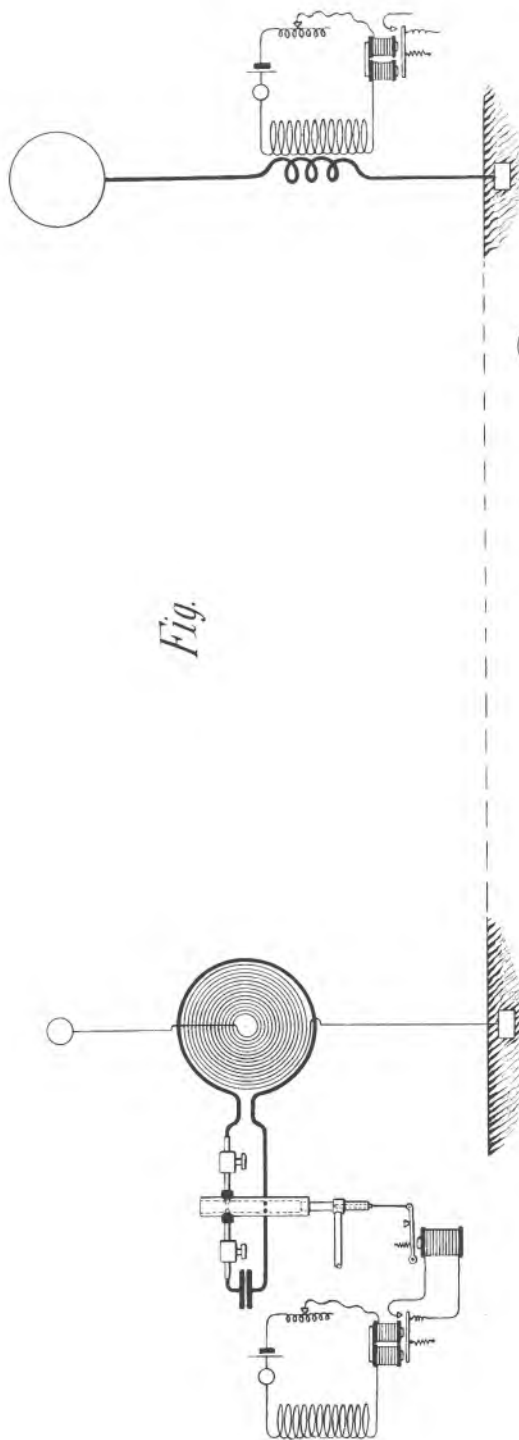
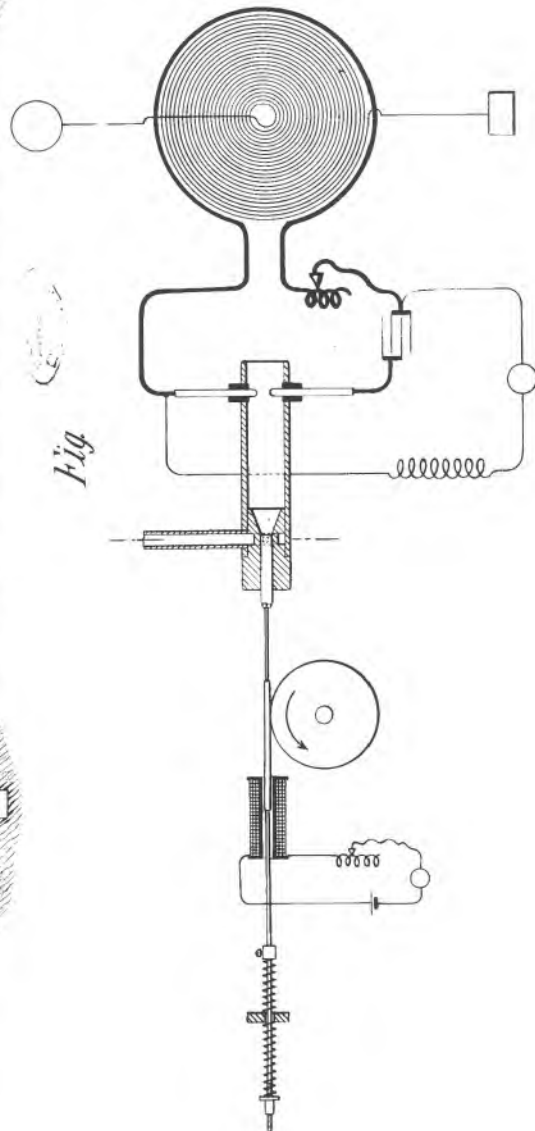


Fig. 2



Witnesses:

Nikola Tesla, Inventor

by

Attys

The numerical value for the capacitance of the old coil appears here, for the first time, without explanation. Tesla determined the oscillation period for the new secondary by the calculated distributed capacitance and inductance for a new coil. He compared this period (or its reciprocal value - frequency) with the value obtained, in case the wire-length in the secondary coil was equal to a quarter of a wavelength. Then he added the sphere capacitance to the secondary and he determined the reduction of resonant frequency. He concluded that vibration was high since the small capacitance in the primary circuit was required then. In that case the source could not operate at full power. At the end, he added "extra coil" in series with the secondary, put together all the capacitances (obviously incorrectly because they are not in parallel) and by not taking into account the inductance of "extra coil", he determined the change of secondary resonant frequency.

June 29, 1899

He did not use his calculations from the day before because he continued working with a 36-turn secondary. The first detailed tests of the oscillation operation did not provide expected results and Tesla attempted to determine the reasons by calculation. He implemented secondary inductance, calculated the "extra coil" inductance but he did not use these results; then he determined free secondary vibration from the condition that the total secondary wire length was equal to one quarter of wavelength. Being aware that the capacitance in the secondary circuit alters its wire-length, he neglected it in his calculation. He determined the required capacitance in primary circuit with an approximate value for secondary resonant frequency. Using small capacitances in the experiment, he concluded that his operation with higher harmonics was the reason for failure.

The receiver experiments were probably done in preparation for a patent application. Leonard E. Curtis appears, a number of times, as a witness to Tesla's patents (see for example refs.^{8,10}), or as one of the attorneys (on many patents from 1896 on).

June 30, 1899

Since Tesla used Thomson's equation for *LC* lossless circuit very frequently, he found it helpful to prepare suitable equations to obtain desirable values by minimal calculations.

Continuing his notes, he sorted out his impressions and results (maybe because that was the end of the month?). Description of electric circuits in terms of mechanical analogies was at one time very popular. The resonance of an electrical circuit was linked to the swinging of a pendulum, and coupled resonant circuits to two pendulums linked together.⁽³⁹⁾ Maxwell and his followers even tried for a long time to describe the electromagnetic field in terms of a mechanical model.⁽⁴⁰⁾ Tesla's comparison of his "additional coil" to a pendulum is not precisely formulated but rather intuitive. He makes discrimination between the excitation (initial conditions) and the Q-factor. He does not fully explain how he imagined that the vibrations of the three systems, the primary, the secondary and the "combined system", would be the same. By "freeing" the additional coil he means a weakening of the coupling between it and the secondary exciting it. He obviously had a clear understanding that a circuit can oscillate at its own resonant frequency if the coupling with an excitation circuit is loose. It is strange that he did not apply this logic to the secondary circuit, which he had intentionally designed to be tightly coupled with the oscillator primary circuit.

July 1, 1899

The parts of a receiver for registration of wireless signals are shown in the diagram. A complete receiver consists of two sensitive devices, out of which the one in the primary is not shown. There is also a capacitor in the primary, whose charging and discharging are controlled by a signal via sensitive device. Here Tesla neither studied the characteristics of these circuits, nor did he explain the role of capacitor C in the secondary circuit.

July 2, 1899

He finally formulated completely a method, up to then given in segments, as how to perform the approximate calculation on the oscillator in figure 1 (in Tesla's text of July 2). In order to clarify it, we shall repeat Tesla's calculation method:

- the oscillator wavelength is chosen;
- based on wavelength, the secondary coil wire length is determined to be a quarter of it;
- secondary inductance is determined according to the known wire length and a chosen coil form;
- for the most efficient operation the capacitance at the open secondary terminal has to be such that $C_s = 1/p^2 L_s$, neglecting the losses; the inductance and capacitance of oscillator primary circuit are determined if the condition of primary and secondary frequencies being equal is met: $L_p C_p = L_s C_s$. Normally L_p is much smaller than L_s , so that the winding ratio of primary and secondary N_p/N_s is much smaller than 1.

There was no mention about mutual link between primary and secondary in the procedure shown. Secondary distributed capacitance was neglected as well.

With the oscillator shown in figure 2, the discharger was outside the primary circuit $L_p C_p$ and, according to Tesla, it enabled the achievement of less dampened oscillations in the primary circuit and less current through the discharger. Under assumption that the circuit $L_p C_p$ was in resonance at the operation frequency, the current i was considerably smaller than current i_2 . Capacitance C_1 (appearing in figures 3 and 4 as well) was determined to store entire energy that could be transmitted from the network via the supply transformer. At discharge of C_1 accumulated energy was converted into HF currents." Additional condition for C_1 was given by equation II.

July 3, 1899

The distributed capacitance of the secondary windings is difficult to determine. It depends on the coil diameter, the dimensions of the wire and the insulation and the winding pattern. In a single-layer coil it is due mostly to the capacity between neighboring turns - this is the way in which Tesla calculated it. He considers a greatly simplified model in which it is taken that the parasitic capacity per turn is equal to $A/4\pi d$, where $A = \pi r l$, half the surface area of the wire in one turn, and d is the distance between turns. The capacitance is calculated as that of a plate condenser of area A and gap d with air between the plates. This model is open to a good number of criticisms, but it must not be forgotten that Tesla had to find some solution, whatever its shortcomings. It is also not correct that the total inductance and capacitance of the secondary circuit with the "additional coil" are additive, but Tesla was himself aware that this was guesswork, and often mentions the words "roughly," "estimate," etc.

In an earlier calculation (see June 20) he had started from the primary circuit and worked out the values for the secondary, whereas here he attacks it from the other end: from the resonant frequency of the secondary circuit and the known primary inductance (one turn) he finds the required capacitance

of the primary circuit. He then checks whether this capacitance can be used with an LF transformer of the given power. The formula is approximate, but gives a good rough guide for the power in the mains transformer. The peak power rating of the transformer must be even greater than the value found, because the condenser is not charging all the time but only in short pulses.

July 4, 1899

Tesla described and commented on discovery of “standing waves” created by natural discharges in his articles *The Problem of Increasing Human Energy* in 1900⁽⁴¹⁾ and *Electrical Energy Transmission without Wires* in 1904.⁽¹⁾ He did not write about these waves in the patent applications he filed a month later^(9,10) The phenomenon of “standing waves” was described with numerous details and data in his patent *Electrical Energy Transmission Method through Natural Media* filed May 16, 1900.⁽⁴²⁾ Tesla stated that, based on numerous data, he found out that wavelength was approximately between 25 and 70 km. From these results and some theoretical deductions he concluded that waves of this kind could propagate in all directions over the Earth and that their wavelength could be different, which in the final case depended on the Earth, its dimension and characteristics. Tesla described the globe as a “perfectly smooth conductor of negligible resistance with evenly distributed capacitance and inductance along the symmetrical axis of a propagating wave”. According to Tesla, in order to get such a conductor, i.e. the globe, in resonance, the following conditions should be met:

1. The Earth radius has to be an odd multiple of a quarter of the wavelength.
2. The oscillations applied have to be such that the energy radiation in the form of Hertz electromagnetic waves is small. Frequencies have to be below 20 kHz, minimal frequency at which the effect of standing waves is 6 Hz.
3. The most important condition is that oscillations last a certain period of time, not less than 0.08484 of a second, necessary for the wave to leave and return from the point on the opposite side of the globe from where the receiver is situated. Briefly described, the patent application was based on standing waves discovery and consisted of an improved method for obtaining and use of standing waves of various wavelengths on the globe, with a free choice of moving the locations of nodes and peak-amplitudes.

According to Tesla’s writing in 1904,⁽¹⁾ the event he described in his entry on July 4 actually took place on July 3. He was obviously very impressed by this discovery and therefore he devoted much attention to it. It appeared, however, that the other scientists did not share his enthusiasm but it is certain that his ideas had an impact. According to Eccles,⁽¹²⁾ in summer 1899 there was a rumor that “an American company will construct radio stations in New York and Ireland for the purpose of communication across the Atlantic.” These stories were probably based on Tesla’s preparations in the U.S. to establish communication over long distances by means of continuous waves instead of sparks. On one side, that caused the drop of cable dividend values on the stock market, and on the other side it stimulated the discussion on the wave propagation along the ground.” Eccles wrote about experiments Tesla carried out in 1899: “Tesla’s attempt in 1899 to send a signal over a long distance by very long continuous waves was not successful, although his method for producing the waves and wavelength choice of approximately 20,000 m proved to be extraordinary for ocean distances later on, when more sensitive receiving devices than his were invented. But his efforts to use long waves were helpful and the next step in improvement of arcing telegraphy was directed in that way.”

As far as the electrical discharges and the waves created by them, before Hertz’s research on electrical waves was published, Oliver Lodge, pointed to the possibility that the lightning discharge was of an oscillating nature similar to the one of a Leyden jar. In 1895, using his own type of the receiver, Popov detected the remote weather disturbances caused by the electrical discharge that followed⁽³²⁾ and showed that they created natural electromagnetic waves received by an antenna. Ferie registered

discharges at distances of approximately 150 km in 1901 and based on numerous observations, in 1903 Turpain showed that the notes on the discharges could be used for weather forecast.

Later on, the natural electrical discharges were used to determine certain parameters on wave propagation in the range of extremely low (6 to 3000 Hz) and very low frequencies (3 to 30 kHz), as well as for determining so called Schumann resonances. In the wave propagation analysis, it was supposed that the entire globe, together with a conductive ionosphere layer determined antenna an electromagnetic field as if they were located in a resonator. In some simplified models it was assumed that the Earth, as well as the ionosphere, was ideally conductive. The currents appeared on borderline surfaces of a spheric wave guide created by the globe and ionosphere, which could be, with some reserve, considered as Tesla's "conductive currents." Tesla's assumption on the Earth's resonance was proved by Koenig's and others' measurements in the 60's of the century. The resonance was found at approximately 8, 14, and 20 Hz and at higher frequencies.⁽³⁴⁾ The measurements of fading at propagation of extremely low frequencies (1 to 2 dB at 1 000 km at approximately 50 Hz) showed that Tesla was right when talking about small fading. The standing waves Tesla talked about, confirmed by measurements, were emphasized around anti-poles and not all over the Earth because the ground was not an ideal conductor, except at frequencies in the range of 1 Hz. It appears however that despite the obvious similarity of Tesla's ideas and experiments, his name was not related to the modern researches until 1974 when Wait⁽²¹⁾ wrote about it.

July 5, 1899

It is possible that Tesla was planning to construct a balloon to take an antenna to great height,^(13,14) and was therefore interested in the generation of hydrogen. He analyzed three variations and calculated it was best to decompose carbo-hydrogen C_2H_4 (non-saturated carbohydrogen-ethelene) by means of a red-hot wire. He does not give any indication, however, of whether he actually carried out any experiments in this direction, or of the grounds he had for expecting the desired decompositions to take place.

July 6, 1899

Returning again to the problem of coil capacitance Tesla attempted to calculate it using the equation for the capacitance of two parallel symmetrical conductors. He took the half of the coil length as a feeder length, the distance between the conductor centers being equal to the distance between centers of two neighboring coil turns. The value calculated for one coil convinced him it was not applicable since the difference between the calculated distributed capacitance and the one determined by an indirect method was too large.

July 7, 1899

From his notes on the experiences with HF oscillator it could be seen how deeply Tesla got into the operation of optimizing the device. He wanted to design the oscillator of high power and a very high voltage but he had to compromise, as far as the dimensions were concerned, because they were in direct relation with the voltage and in reciprocal ratio with the operating frequency. From the patents and the written works already mentioned (see comments for June 4) it was known why Tesla considered it necessary to achieve very high voltages. Explaining Tesla's ideas on wireless transmission Fleming wrote in 1944: "It appears that Tesla considered that the transmission mechanisms would be different if powers of sufficiently high level were achieved and he started the production of HF power of a very high level, probably hoping to cause by it disturbances comparable in magnitude with cosmic ones. The other ex-

perimenters of the time were satisfied with a power of several watts and they did not want anything else than to produce very weak signals at the distance... Tesla's vision was focused on an attempt to produce some important effects at long distances and he failed. In his efforts to do so he produced almost coincidentally a series of devices successfully used by other researchers with less ambitious goals."⁽²⁰⁾

From the standpoint of a high voltage production method, Tesla made a distinction between the transformation method in a transformer with a tight coupling (similar to the one in the low frequency transformer) and the method with a resonant transformer. The former was considered to be more applicable when power transmission was at a distance, and the latter was much better at low-level powers. The assumption that the application of the first method would cause reduction of the primary inductance due to the tight primary-secondary coupling (enabling, according to Tesla, primary circuit oscillation at a high frequency), was not generally correct. As far as the influence of the secondary capacitance was concerned, Tesla was right in considering it an obstacle in achieving high voltage levels, since the transformation ratio of the resonance transformer was proportional to the primary and secondary capacitance ratio (see Appendix: Tesla's Oscillator).

For the "resonance method" Tesla envisaged two possible types of resonant transformer: one with loose coupling between the primary and secondary, and the other with tight coupling but only with part of the secondary inductance.* This latter type he protected under the patent *Apparatus for Transmitting Electrical Energy*, for which he applied on January 1902;⁽⁴⁴⁾ a good deal of his time in Colorado Springs was spent in developing it.

His conclusions about various parameters of the oscillator indicate that he had by then gained sufficient experience to be able to design such devices with improved performance in the parameters he wanted. As the experiments proceeded, he gradually increased the voltage of the LF power supply. On June 20 he calculated with an excitation voltage of 20 kV, but he had assumed a much higher rate of charging of the condenser, so that he obtained then a greater power than when with 40 kV. The difference in the number of chargings per second is explained nowhere, nor had he very precisely described how it was calculated. The first time he had probably taken it as being equal to the number of breaks on the rotary discharger, and the second time as double the mains frequency. In this light, the accuracy of "the capacity of the condenser of which the transformer will be able to charging" is dubious. However, Tesla did not take the value he calculated as limiting the capacitance in the primary, noting that it did not take into account resonance and other factors that might enable the transformer to charge a much larger condenser.

* It is easy to demonstrate that these two methods are similar. If in the second case a part L'_2 of the secondary inductance is coupled to the primary with a coupling coefficient of k_2 , while in the first case the entire secondary inductance L_2 is coupled with coefficient of k_1 , then the response of the secondary to the primary will be the same if $k_1 = k_2 \sqrt{L'_2/L_2} < k_2$.

July 8, 1899

A detailed consideration of an HF transformer was actually a resumé of the experience obtained and theoretical thoughts. To achieve the goal, the machine of high power and voltage, Tesla looked for methods to optimize the oscillator details: discharger, primary and secondary inductances, mutual inductance and distributed secondary capacitance. In his analysis he made the distinction between a device to be used for high power transmission at a distance, and the one where small power was required, e.g. for message transmission. For the first type, a high frequency transformer would be made in a similar way as for low frequencies (therefore with a tight coupling) and for the other type, high secondary voltage would be achieved by the use of over-voltage on the secondary circuit, which is loosely coupled with the primary circuit. In the latter case, a maximum quality factor pL/R and a minimal secondary capacitance were required.

From observing the behavior of his oscillator, Tesla came to an interesting conclusion concerning the shape of the conductor of the primary winding, i.e. that a strip conductor was better than a wire of circular cross section because, all other conditions being the same, it did not get so hot. He believed that there was a special reason for this "not yet satisfactorily explained." Since the dimensions of the

strip conductor are not known we cannot work out the reduction in resistance relative to a circular section conductor due to the skin effect. The surface area of a strip will always be greater than that of a round conductor, the more so the flatter the strip: for a width to thickness ratio of 10:1 a strip will have about 1.8 times more surface area; this could effect a considerable reduction in resistance, which would explain, at least in part, the phenomenon Tesla discovered.

In connection with coils, a problem to which Tesla often returned was that of the velocity of phenomena through the circuit. In order to achieve the maximum voltage across the secondary terminals without the addition of capacitance, Tesla considered that the length of the windings should be equal to a quarter of the wavelength. This would be perfectly correct in the case of a straight conductor with one end grounded. Such a system, when excited, would certainly have the maximum voltage at the free end, but its magnitude would depend greatly on whether the conductor was horizontal (when radiation is small, so that the Q-factor of the resonant system is high) or vertical (when radiation is efficient so that the damping is high). With a helical conductor as in Tesla's oscillator, radiation is as low as with a horizontal conductor, so that high resonant voltages are possible unless they are reduced by parasitic capacity. In fact, helical winding increases the distributed inductance and capacitance so that the velocity of propagation of current through the coil is reduced, which means that the wire must be made shorter to achieve maximum voltage across the terminals. If the secondary is terminated with a capacitive load (e.g. a metal sphere) the winding length must be still further reduced in order to maintain the same resonance conditions. Tesla took both these effects into account in designing the secondary. Figures 1-8 illustrate several ways of reducing the distributed capacitance of the secondary. The solution of placing the turns apart (figure 6) is still used today when it is necessary to reduce parasitic capacitance.

July 9, 1899

In order to check the secondary distributed capacitance influence, Tesla prepared new experiments with secondary coils where a considerable reduction of undesirable capacitance could be expected. He worked out the operating frequency (calculation by a previously established method), using inductance and capacitance in the primary circuits. A new secondary was wound with a thinner wire (0.23 mm in diameter instead of 2.6 mm) and he established parameters of this coil according to the normal ones on the same core (for equation explanation see June 28) with factor D as a parameter. In calculating D (the ratio of the turn spacing of the old and new secondary) Tesla accidentally took the frequency instead of the period, so that he got $D = 83$ instead of $D = 2.45$. A second numerical error occurred by mistake in the formula relating D and C (38 omitted from under the square root) so that C came out to be 10000 cm instead of 227 cm. Since he never made use of these results, Tesla naturally never discovered his mistakes.

Tesla's method of measuring the oscillator frequency by means of an auxiliary coil is interesting. This coil, with its own distributed capacity, in fact constituted an absorptive resonator. The size of the spark across its terminal provided an indication of the amount of power it absorbed. (In some respects it resembled Hertz's resonator.) Tesla adjusted its resonance by varying the number of turns for the biggest spark. He then calculated the wavelength on the assumption that at resonance the length of the coil winding was one quarter of a wavelength. The wire length he determined by measuring the coil resistance, the resistivity per unit length of the wire being known. This method embodies a systematic error due to neglecting the reduction in speed of propagation through the coil⁽⁴⁵⁾ and it is applicable for oscillators of high power. However, it was the most reliable method Tesla had used to determine oscillation frequency up to that time.

For theoretical calculation of the oscillation period Tesla used two formulae: one which neglects the influence of the secondary (as for example at the beginning of this entry), the other taking this influence into account. In the latter case it is taken that the primary inductance is reduced by a factor $1 - M^2/NL$, which would be the case if the secondary was short-circuited. How far this is justified it is

difficult to say because an oscillator which discharges heavily does not satisfy the simple theory of the resonant transformer oscillator. The secondary is then heavily dampened and free oscillations in it decay rapidly, so one would have to apply a theoretical treatment for heavily dampened oscillations.

The same day Tesla returned to a problem of approximate calculations of distributed capacitance. This time he applied the Kelvin equation to establish the capacitance of a co-axial conductor. He considered an outside conductor consisting of two neighboring turns so that the capacitance calculated for the co-axial conductor was reduced by the ratio of wire radius and the spacing between two coil turns. Although not proving the applicability of such an approach (e.g. how this equation could be applied in the case when two turns were around the middle one at a different potential, shown in figure 2), he worked out the coil total distributed capacitance and provided a value that he said matched the measured one. So the capacitance determined was not equal to the ideal coil capacitance, presented in an equivalent coil scheme in parallel with a pure inductance.

July 10, 1899

Tesla considered the distributed capacitance to be the main obstacle limiting the voltage in the secondary. He checked his assumption regarding the influence of such capacitance by calculation on a coil model with an evenly distributed voltage and capacitances between the windings. In order to work out the active power (i.e. to simplify it) he assumed that all the energy received during one quarter of period by "capacitors" (representing the distributed capacitance), was used up in the second quarter of a period and so on. In the second half period a similar thing happened, only the charging was in an opposite direction. He took the number of charges and discharges to be equal to double the number of HF current periods.

After mentioning the damaging effect of the distributed capacitance, on the same day he continued the description of his thoughts on a secondary with a thin wire. He estimated that the induced secondary voltage would be approximately 40% smaller than the ratio between primary and secondary windings, which corresponded to the induced voltage in an open secondary. In real cases, however, a current in the secondary winding would appear, influencing the current in the primary and therefore the induced voltage would have another value.

By adjusting the capacitance in the primary and secondary circuits, he achieved the maximum secondary voltage. How well Tesla knew the physics of the process could be seen from the fact that he never lost sight of the effect of the secondary quality factor, as well as the magnitude of the primary capacitance, determining the amount of power provided by the source to the oscillator for conversion into HF current.

He achieved the voltage increase in the secondary by addition of a coil with 260 turns wound with wire 2.6 mm in diameter. Tesla added a third oscillatory circuit, thus obtaining an oscillator with three resonant circuits of which two are tightly coupled.* The third circuit will not necessarily be most strongly excited when its resonant frequency coincides with that of the primary and secondary (assuming these are the same) and the primary and secondary are tightly coupled. If the spark in the primary circuit lasts long, then the tightly coupled primary-secondary system will produce two distinct oscillations, and the third circuit will be most strongly excited if it is tuned to one (strictly speaking to near one) of these two frequencies. On the other hand, if the spark is of short duration, the tightly coupled system may oscillate strongest at the resonant frequency of the secondary, and then the third circuit will be excited the strongest when all three have the same resonant frequency. Tesla believed that his system of coupled circuits was producing a single vibration, which under certain conditions is in fact feasible.

For determination of additional coil inductance he applied the formula for an infinitely long coil. He estimated the coil's self-capacitance according to the known coil resonant frequency, assuming that

* Similar systems were analyzed in 1906 and 1907 by M. Wien, in 1907 by Fischer, and in 1909 by J. Kaiser.⁽⁴⁶⁾ From their papers it may be seen that the effective value of the current in the loosely coupled circuit will be a maximum if its resonant frequency is the same as the other two coupled circuits but if they were loosely coupled.

it was equal to the reciprocal period value of the primary circuit. When he found the required capacitance, by all these assumptions, it seemed to be small. When working out the Q-factor of the additional coil, he made approximations because he neglected the coil resistance increase with frequency and consequently he got an disproportionally high quality factor.

July 11, 1899

By introducing the additional coil in the oscillator circuit Tesla achieved a modification of his oscillator with resonance transformer that obtained higher voltages. When they exceeded several hundred thousand volts he had to lay out the components carefully and to choose very good insulators. Here the instructions are given on how to make terminals to provide the longest and the strongest spark along with delaying the flashover to the instant when maximum voltage (or some desired voltage) was reached. He proposed a procedure enabling the voltage measuring by means of the metal balls with different diameters. He discussed the disadvantages of this method because the spheres introduced additional capacitance disturbing the resonance conditions in HF circuits.

Tesla considered the additional coil to be extraordinarily suitable for the achievement of "any" voltage. He gave two wiring schematics of this coil for the secondary of an HF transformer oscillator. He claimed that this coil achieved considerably higher voltages than the secondary loosely coupled with the primary. Tesla explained this with the fact that the extra coil was not in an inductive link with the primary and that there was no such a reaction in the primary to dampen the oscillation. He did not explain how he imagined this coil would be excited without a response to the primary via the secondary, to which it was directly connected.

The description of the additional coil was very detailed. Tesla's wealth of experience in coil designs was obvious to its full extent. At the end of his considerations, he presented the formula for establishing the number of turns of the additional coil on the assumption of the operation frequency, wire diameter, spacing between the windings and a constant he determined experimentally. He checked out the formula through an example, providing a result very close to the experimental ones.

July 12, 1899

Early on in the diary, Tesla mentioned a method using a condenser to store energy from weak impulses arriving at a receiver. In the circuit drawn here, the condenser is charged by a battery via a self-inductance coil and a coherer shunted by the secondary of an oscillation transformer. In the absence of an external signal the resonance of the coherer is large so that the charging current is small. The circuit breaker periodically discharges the condenser through the primary of the transformer, generating alternating current in the secondary which biases the coherer. When an external signal is received the resistance of the coherer is reduced and the charging current rises rapidly, which in turn increases the additional voltage on the coherer and therefore soon gets to full conductivity (in fact there is a feedback loop).

July 13, 1899

Although short, the entry has several interesting features. The effect of a spark in the HF oscillator secondary circuit, reducing the system efficiency is considered but it has the advantage when it is desirable to produce short waves and high electromotive force.

The diagram shown indicates the oscillator with LC_1 circuit for the purpose of HF harmonic separation, which Tesla tested in his New York laboratory. He recommends this circuit as the solution for

generating the short waves without a spark in the secondary. The capacitor CC for “by-pass” of higher harmonic frequencies to the ground is envisaged in this drawing. A high Q -factor of the LC_1 circuit is required for the sake of good filtering.

July 14, 1899

Tesla had previously tested the schemes he provided, some of them for wireless boat control at a distance.* The circuit in figure 1 represents a “cascade” oscillator. The mercury breaker enables the production of impulses through the coil of the first transformer (S_1) which charges the capacitor C and the next is Tesla’s classic diagram of a resonant transformer with a discharger d . The circuit in figure 2 shows one of Tesla’s oscillator variations, planned for operations with a DC source supply. A dampening coil, preventing the source from short circuiting via a breaker when it is closed, and serving to store source energy supplied to the oscillator of this type. The capacitors get discharged, oscillating through the closed breaker and producing the HF current. When the breaker is open the oscillation in the primary circuit stops, capacitors being again charged from the source energy and the energy accumulated in the dampening coil. In these instances the secondary oscillates as dictated by its inductance and capacitance. The circuit in figure 3 is supposed to enable the use of a long wire in the secondary, when high frequencies corresponding to the vibrations of LC circuit are obtained. It is not clear how Tesla imagined to achieve the electromotive forces of any value by this method.

* See patent № 613.809 “Method of and apparatus for controlling mechanism of moving vessels or vehicles”, of November 8, 1898, application filled July 1, 1898, mentions the possibility of using electromagnetic resonance but does not give the circuit diagram of the transmitter referred to here.

July 15, 1899

Earlier on (see the entry for June 3) Tesla presented a general scheme in which the “dynamo principle” is referred to as one of the ways of accumulating energy from far, weak signals. The circuits given here illustrate how he implemented this principle. The sensitive device has a resonance that varies as a function of the antenna signal, and is connected so as to alter the excitation of a DC (figures 1, 2, 3) or AC (figure 4) dynamo.

Although he says that apparatus using this principle had already worked well in New York, none of these receivers, nor the principle they embody, appeared in any of his radio patents.

July 16, 1899

In order to achieve the oscillator secondary resonant circuit at relatively low frequency Tesla looked for a method to produce large capacitance, but not by means of a large sphere since that would not be practical. As a possibility, he suggested the use of a coil with large self-capacitance wound by a special technique (therefore completely opposite from the goal in his previous researches when he was looking for a method to reduce the coil self-capacitance - e.g. July 9, 10) or by winding a conductive layer of wire around the insulation to enable “maximum energy concentration” in the coil.

Another method was interesting as an idea, whose essence was the use of rarefied gas instead of a metal sphere. The third method has not been sufficiently explained and the fourth one was based on the use of high voltage capacitor, shunting one part of the secondary coil.

July 17-18, 1899

This is a continuation of the work described in the entry of June 12th, with different combinations of the same components plus relay R for registering the signals received. In all the circuits the sensitive device has an accumulating function. He experimented with different modifications trying to optimize

sensitivity and reliability. The circuit in figure 1 of July 18 has two batteries, and that in figure 5 an autotransformer instead of the usual transformer with a primary and secondary.

July 19, 1899

This is the first mention of a device that functions either as a transmitter or, with certain modifications of the power supply and antenna circuits, as a receiver. The transmitter is powered from the mains, the receiver from two batteries, B_1 biasing the sensitive device a with AC pulses obtained by discharge of condenser C through the primary of an HF transformer when the mercury switch closes.

The modification in figure 2, in which the relay is the secondary of the oscillator transformer, is simpler, but cannot be used as a transmitter.

July 20, 1899

For the instrument (galvanometer) that he obtained from Colorado College he established the sensitivity constant in amperes per deflection step and he checked the scale linearity. He assumed that the battery was a source of the known and a continuous electromotive force of 1.43 V with negligible inner resistance.

July 21, 1899

In continuation of his work relative to the receivers for continuous HF currents, he widened the researches on the assemblies with two sensitive devices. He lays the sensitive devices out so that they are sensitive to impulses of one direction, which enables the alternating current commutation. In figures 1 and 2, relay coils are connected so that the actions through both sensitive devices are added together. In this set-up a small excitation of one sensitive device is rapidly amplified by a feedback loop which acts via a transformer on the other sensitive device. Figure 10 shows how the receiver was excited by an aerial (elevated metal ball C or C_1) – earth system.

July 22, 1899

With the same components as on the previous day, he continued the experiments with the receiver. He looked for methods to reduce the resistance for currents through sensitive devices and to increase the operation regularity. In figure 4 he introduced the scheme in the shape of a bridge with battery, relay and transformer secondary in the diagonal. Figure 8 shows the circuit of a receiver obtained by modification of the transmitter Tesla was experimenting with. When functioning as a transmitter, it is powered from the mains and is in fact a standard Tesla's oscillator with a mercury interrupter between the condenser C and the primary P . The relay, sensitive device a , and battery B_1 are omitted and the secondary is connected to the antenna and ground. It may be noted that Tesla did not use the best receiver modification (as in figure 6), probably to simplify reconnection as a transmitter.

July 23, 1899

The "sensitive device" Tesla used for detecting electrical waves is usually known as a coherer.⁽⁴⁷⁾ It consists of a tube of some insulator with contacts at either end and metal powder (chips) inside. Its resistance is normally high, but drops rapidly when a large EMF is applied. Munk of Rosenschoeld described

the permanent increase of conductivity of a mixture of metal chips and carbon after a Layden jar was discharged through it in 1835. In 1856, Varley noted that the resistance of metal powder was reduced during natural electrical discharges. A major advance was Branly's observation in 1890 that a spark changed the conductivity of a metal powder at a distance. He carried out many experiments with metal powders, determining their change in resistance by connecting them in series with a galvanometer and battery. In 1894 Lodge* showed that the conductivity of a metal powder could be altered by an electromagnetic wave; this was the final step that preceded the widespread introduction of coherers for the detection of radio waves. From the period 1895-1896 the coherers used by Popov and Marconi are well known.⁽⁴⁷⁾

* The term "coherer" is attributable to Lodge, and denotes a device containing particles of metal such that its resistance is normally high, but is reduced under the influence of electromagnetic radiation.

Once activated, a coherer remains in the conducting state. To reestablish the high-resistance state it has to be shaken. The strength and timing of the shaking have to be properly adjusted. A novel method of de-coherence of powders was invented by Popov, and used by him in his receiver and later by others. In 1898 Rupp⁽⁴⁸⁾ found that constant slow rotation of the coherer keeps it sensitive. The de-cohering effect of rotation had been discovered earlier, in 1884, by Calzecchi-Onesti.⁽⁴⁹⁾

Tesla mentions that he had worked with a rotating coherer in the New York laboratory, so it is possible that he used de-coherence by rotation before Rupp. He finds it superior to other methods of de-coherence, because then the sensitive device behaves like a selenium cell, conducting only when radiation acts upon it. Also, its sensitivity can be controlled by changing the rate of rotation. As an illustration Tesla gives data on maximum and minimum resistance of a sensitive device, one mega-ohm for the former and 300-50 ohms or less for the latter value. The maximum value is related to non-excited and minimum to an excited device.

At the end he says that the device reacts to sound from a distance when the receiver is adjusted to its maximum sensitivity.

The experiments with the oscillator: in the meantime, starting from July 16, Tesla was preparing new experiments with the transmitter. He started the testing the day before and continued on July 23. Oscillator adjustment consists of a capacitance choice in the primary circuit and variation of regulating coil inductance, being a part of inductance in the primary. The oscillation period is worked out from the inductance and capacitance of the primary circuit "without taking the secondary reaction into account" and that would be approximately accurate in the extraordinary cases we have discussed previously.

In the description of sparks which appear at the points under high voltage stress, there are several interesting observations, such as, for example, the one on the current streamers that appears at voltages lower than expected. Tesla considers that it is due to the sphere being not sufficiently polished (and he does not doubt the assumption that it was the consequence of some short impulses, the voltage of which could be considerably higher than the effective voltage in the secondary). Through the observation of spark paths, he remarks that some of them deflect and "follow" wooden beams. He checks the various points of the apparatus where sparks appear (regulating coil, lightning arresters and so on), and studies the causes and possible consequences. He also establishes difficulties due to the oscillator action to the light bulbs at distances of 40 ft from the open secondary terminal. Quite unexpectedly he mentions strange behavior of horses in the field nearby during oscillator operation and gives a possible explanation. Almost not interrupting his thought, Tesla returns to the question of secondary circuit oscillation method and discharge rate in the primary. He envisages the possibility of use of a rotating mirror by which the nature of spark discharge could be established.

July 24, 1899

From the pagination of the manuscript it may be seen that the entry for this day was divided into three parts (the previous day two parts). The first part, three pages, refers to experiments with a 35-turn secondary on the oscillator, the second part, five pages, to a resumption of these experiments, and the third, three pages, to the determination of the capacitance of the 35-turn secondary.

* For the primary to oscillate at half the frequency the capacity would have to be quadrupled. It is possible that instead of connecting the banks of 8-9 jars in series, equivalent to the capacitance of 4-4½ jars, Tesla connected the previously series connected jars in parallel, achieving an equivalent of 16-18 jars, i.e. four times the capacitance of the series configuration.

Tesla adjusted the regulating coil in the primary to obtain the maximum secondary voltage (judged by the size of streamers). He connected an "extra coil" to the free terminal of the secondary. He investigated the operation of the transformer at harmonic frequencies by doubling the primary capacitance* and making fine adjustments of the primary frequency by varying the inductance in order to get maximum response of the secondary to the harmonic of the primary. He did not obtain the expected results and continued the experiment relative to the secondary circuit changes of capacitive loading and looked for the most suitable components in the primary circuit. He considered that he provided the best result when sparks in the secondary were the strongest.

On resuming the experiments, Tesla sought an explanation for the occurrence of the largest streamers from the secondary when the regulating inductance in primary circuit was practically cut out. He found it confusing that the highest voltage at the free terminal of the extra coil (connected to the secondary like in figure 2 of July 11) was not obtained when the frequency of the excitation was equal to the natural resonant frequency of the coil. After an extensive analysis he came to the correct conclusion (unlike that of June 30, which was valid only for a special case), that when free oscillation of the secondary becomes influential, the parameters of the primary have to be adjusted to get maximum voltage across the secondary, and resonant frequency of the extra coil has to be equal to the resonant frequency of the coupled primary-secondary system. It seems that it did not occur to Tesla that when the coupling was tight the combined system produced different spectra during and after the spark. It would seem therefore, all the more significant that he was able to reach this correct conclusion, through a combination of empirical results, simple theory and intuition.

Tesla notes that, during discharge in the secondary, sparks went across the lightning arresters. Since the arresters were connected to the power line, Tesla thought that the HF voltage came from a wave propagating through the earth and getting into the line somewhere else. We have no evidence that would support this statement or establish whether it was not due to coupling between the oscillator and the mains via the power transformer.

The third part of this entry refers to measurement of the capacitance to the ground of the secondary coil as a whole. Tesla does not explain how he performed the comparison with a standard capacitor nor at what frequency. Using several methods he calculates the wire capacitance of the same length as coil wire (C_1) according to the equation for capacitance of a single ellipsoid of which the longer axis was considerably longer than the short one and C_2 by the equation for conductor capacitance above an ideally conductive plane under the condition that the distance from it was considerably larger than wire radius). Expanding his consideration of capacitances, he describes the methods for achieving the largest capacitances and moves further and further away from his initial topic. He ends the entry with a discussion on the spheres filled with hydrogen, which were supposed to have maximum capacitance for given dimensions and therefore would be used for wireless telegraphy.

July 25, 1899

Continuing his work with the secondary, Tesla attempted to match the theoretical calculations with experimental results. As he did in the past, he adjusted the capacitance and inductance in the primary circuit so that the oscillator operated the best. Under these operating conditions he determined the primary circuit parameters and based on it he found natural resonant frequency of the primary circuit. He considered that as the oscillator operating frequency (measured on the previous day) as well determined the secondary inductance, taking in account the capacitance of secondary. It appears Tesla made this rough estimation, which he considered incorrect, only to convince himself that static coil capacitance was not the component showing up in the oscillator dynamic operation regime. He did some checking and by reducing the oscillator operating frequency in half (he introduced a primary with two turns instead of one which increased the primary inductance four times), he concluded that the secondary coil capacitance had probably a lower value than the one which he found by previous measurements in another operating regime.

July 26, 1899

405

This entry is concerned with much the same topics as that of June 30. He investigated the influence of the HF transformer primary-secondary coupling on July 8.

July 27, 1899

In his first condenser discharge oscillator for generating high frequency currents in 1891,^(4,15) Tesla used a simple "air gap" for regulating the charging and discharging of the condenser. However, a year later he had already described several improvements on simple spark gaps using a magnetic field or an air current for rapid extinction of the arc thereby reducing the period of the charge-discharge cycle. He also described the advantages of a "splitted arc" across several smaller air gaps; with the same total gap length the breakdown voltage is higher,* so that smaller gaps can be used and the losses are less. A fourth form of improvement which he invented was the use of various rotary interrupters.⁽⁵⁾

* The total resistance of a series of air gaps is less than the resistance of a single air gap with the same breakdown voltage.

In the period from 1893 through 1898 Tesla patented several types of interrupter, or "electric circuit controllers". It is interesting that all these patents referring to various types of rotary interrupter (with air gap or without it) were protected within patents for high-frequency generators, including the following:

- the combination with discharge points immersed in oil. The turbine whose blades make and break the condenser circuit is driven by oil under pressure⁽⁵⁰⁾
- mechanical make-break controller for DC⁽⁵¹⁾
- synchronous controllers with and without regulation of the interrupting timing, for use with AC sources⁽⁵²⁾
- commutators for alternate switching between two condensers in the primary circuit of a Tesla oscillator.⁽⁵³⁾

In 1897 and 1898 Tesla was granted a number of patents for "electric circuit controllers," The principle requirement was that they should make and break a circuit at the highest possible rate, i.e. that they should perform a large number of operations per unit of time. In eight patents⁽²⁷⁾ Tesla gives designs for rotary interrupters with conducting and insulating fluids, usually mercury and oil, respectively. In some designs the interruption takes place in an inert gas under pressure. He gives ingenious designs for using a mercury jet playing on a toothed metal rotor, and for producing two mercury jets (fluid contact).

The rotary interrupter with two auxiliary air gaps shown in the figure was a new idea. One of the reasons Tesla added these air gaps was probably the high voltage with which he was working, since it allowed him to regulate the excitation. That this could be done may be seen from the statement that by adjusting these gaps the period of charging from the secondary of the mains transformer could be shortened. At the end of the entry he records that the best results were obtained with two rotary interrupters (with toothed disks) rotating in opposite directions. He does not explain how he chose the "tooth ratio" so that the number of interruptions was equal to the product of the numbers of teeth.

July 28, 1899

This entry provides one of the most detailed descriptions of the receiver with two rotating coherers and a condenser for accumulating the energy from weak signals. At point *b* the circuit *C*—*P* is periodically made and broken and the resulting AC pulses bias the sensitive device *A'* in the secondary. Sensitive device *A* is still poorly conducting* so the charging current of *C* via dampening coil *L* is small*. When an arriving electromagnetic wave reduces the resistance of *A*, *C* charges much faster and the voltage induced in secondary *S* also rises rapidly. The resistance of *A'* drops rapidly and current from

* Up to a certain degree of coupling, Tesla's oscillator produced a single

frequency. According to Fleming and Dyke,⁽³¹⁾ with an ordinary spark gap the maximum coupling coefficient for monochromatic oscillation is around 0.05 (certainly less than 0.1), while with a rotary break producing pulse excitation a coefficient of up to 0.2 gives good results. With higher coupling coefficient three components are obtained, even if the primary and secondary circuits by themselves have the same resonant frequency.

battery B' activates relay R . Judging by Tesla's report, the receiver was very sensitive to distant electrical discharges.

July 29, 1899

To check out his theoretical conclusions about the free oscillations of the "extra coil" (see June 30 and July 26), Tesla made a new coil with a higher inductance. With this new "extra coil" he puts the oscillator in operation. As usual, he changes the inductance in the primary circuit (with the regulating coil) and a number of jars (i.e. capacitance) so as to provide the maximum voltage in the secondary. He obtained the rough estimation of operating frequency in terms of inductance and capacitance in the primary.

When adjusting sparking oscillator (see July 27) he observed that the light bulb on the mains power line gave a brighter light when there was no spark on the sparking oscillator. He was not sure whether the reason was capacitive loading of the Westinghouse transformer (mains transformer), which could cause resonant over-voltage. He suspected "electrostatic action" and gave his opinion on that phenomenon.

While looking for conditions for the best oscillator operations, Tesla checked out the circuit parameters. He matched the primary capacitance according to supply transformer power. By capacitance increase in the primary he provided a larger energy transfer, but the best results were obtained when the system operated at a suitable frequency. The operating system he applied here could be named "trial and error method" which was understandable with regards to his first experiment with the new "extra coil".

"Extra coil" described on June 29 was wound on the same core as the one he was using now but with approximately half the turns. Tesla expected the new coil's natural resonant frequency to be approximately two times lower. That was why, when testing the oscillator, he reduced its frequency by increasing the primary capacitance. When that did not provide the expected results, he reduced the inductance (by connecting two primary turns in parallel instead of in series) and when he produced good sparks, he stopped at that. From the description of the sparks, some kind of enthusiasm is evident, and the writing style is such that one almost forgets the description of a physical event is in question.

Gradually increasing the excitation voltage of the mains transformer (he came up to 22500 V), Tesla achieved the withstand limit of the capacitor (made of glass jars). In order to avoid the numerous jars connected in series for high voltage achievement, he tested another kind of jar with thicker walls. Tesla's ingenuity found full expression in the simple way in which he developed condensers for high voltages. He filed a patent application on his design for a fluid electrodes condenser on June 17, 1896.⁽⁶⁷⁾

July 30, 1899

Along with the application of a new "additional coil", Tesla repeated the experiments with his oscillator and after the usual matching procedure he achieved better results than in previous cases. He obtained sparks approximately 2.5 meters long. He considered the conductor curve radius influence on the streamer appearance phenomenon. On this occasion he emphasized the importance of elimination of streamers, which created the losses and reduced the system efficiency for wireless transmission. The conclusion on streamers was justified, which could not be said for the explanation of the advantage of having an elevated wire with capacitive loading in comparison with the same wire without it. Considering transient phenomena in oscillator circuits, he again separated the coil Q-factor influence from the excitation influence (sudden current changes) at the instance of the spark appearance and interruption in an oscillator discharger.

Commenting on the non-existence of sparks on lightning arresters, he estimated that the reason for this was the high harmonics blocked by appropriate coils in such a way that they did not react to the ground. To try and verify his presumption, Tesla changed the connection of his "extra coil" as shown in figure 4. Unfortunately, the experiment description was not complete and it was not known whether he made some changes in the primary circuit in order to achieve the maximum oscillator effect, as shown in figures 3 and 4. The difference between connections in figures 4 and 5 was that in the first one, the sphere grounded via "additional coil" was excited, and in the second one only the grounded sphere was excited. It is possible that the sphere system without an additional coil oscillated at a higher frequency but one cannot draw reliable conclusions without a deeper analysis.

The same day he devoted some time to a design and calculation of a high frequency transformer for a new receiver. He intended to use it for the operation with a "fast vibrating" system (probably the same as the one in figure 5). As far as the design was concerned, the receiver was probably similar to the one of July 28.

As on many previous days, Tesla studied several problems this time as well. He also found time to consider the voltage variation on supply transformer primary at various capacitive loadings. He found out the voltage variation that pointed to the transformer impedance increase, although the secondary reactive impedance was reduced.

July 31, 1899

Tesla made the condensers for the primary circuit out of mineral water bottles filled with a saturated solution of rock salt, and placing them in a metal tank of the same solution, thus creating a condenser bank with one common plate. The other plates (the electrolyte in the bottles) could be connected in parallel as desired. The smallest capacity adjustment possible was equal to the capacitance of one bottle. After various tests of what voltage the glass dielectric of the bottles could stand, at a frequency of 144 Hz he concluded that they would stand it up to 30,000 volts when two series of them were connected serially. Solving the capacitor problems in the primary circuit that way, Tesla returned to the secondary of the oscillator. He had not yet solved the problem of coil distributed capacitance in the secondary, which seemed to be the main obstacle towards the achievement of desirable high voltage. Tesla's analysis, somewhat strange for today's reader (sometimes even incorrect) impressed with its breadth being based on a limited number of facts. Tesla deeply penetrated into physical processes and attempted to understand what happened and how it happened. His experiments provided him with proofs for the conclusions he drew, considering and analyzing his previous experiments.

Having a desire to design the secondary coil with minimal self-capacitance, able to operate at extraordinarily high voltages, Tesla devoted his time, more than anybody else before him, to the study of coils. The results were not lacking (coil shapes, winding methods), but they did not satisfy him. He was thinking what would happen if he added a series capacitors, or if he changed the spacing between windings or the wire diameter, etc.

Aug. 1, 1899

The extraordinary atmospherics in the vicinity of his laboratory made Tesla devote some time to the phenomena that were the consequence of a clean environment, dry air and low pressure. In such an atmosphere sunshine and moonlight were more intense than usual, the visibility was better and even sounds propagated with less dampening. The air was highly electrically charged and according to Tesla, that might be one among other reasons for these phenomena.

Although the surrounding itself was not particularly attractive, Tesla was impressed by the clouds, sunrises and sunsets. His descriptions of these events were extraordinary, and they did not lack scien-

tific preciseness and a systematical approach. This particularly pertained to descriptions of cloud types and of the brightness of some of them, being brighter than the Sun itself. Radiation and its transformation into another kind and similar effects were topics Tesla was familiar with and he used his knowledge to explain the events around him. In his considerations he even grasped the biological aspects of sun rays and the atmosphere, and he also mentioned X-rays related with sun radiation, expressing his hope to produce these rays of such an intensity to be able to cure tuberculosis!

Aug. 2, 1899

A receiver of this type is mentioned in the entries of July 12 (the principle), July 28 (circuit diagram with two sensitive devices and relay), July 30 (in connection with earth waves). The transformer here has a frame similar to that of July 28 but with somewhat more turns. The sensitive device was described on July 21.

Tesla often worked on several problems in parallel. Here, for example, we have entries concerning the receivers, the development of condensers for the primary of the big oscillator, and the power balance for a new configuration of the oscillator primary circuit. The condenser C_1 in figure 2 protects the mains transformer against overload but has the drawback that it reduces the initial voltage on C_2 . Tesla's analysis refers to the case of two condensers in series, neglecting all transient phenomena. It may be that he was induced to think about protecting the mains transformer because of his doubts about the ability of the dielectric to stand the voltages he intended to use.

Aug. 3-14, 1899

These experiments are a continuation of some earlier research. Here Tesla investigates various modifications of his "condenser method of magnifying effects." All the circuit diagrams of receivers, over 50, include at least one battery, sensitive device, condenser, rotary interrupter and HF transformer. Some of them show a relay for registering the signal received, while in others its presence is understood. Likewise, in all except one case (August 5, figure 1) the plates that bring the excitation to the sensitive device are not shown. Tesla says that these plates can be in one or two media, meaning that both can be in the air, both in the ground, or one in the air and the other in the ground, preferably elevated. In the patent ⁽⁸⁾ referring to these plates, he also says: "... they may be connected to conductors extending to some distance or to the terminals of any kind of apparatus supplying electrical energy that is obtained from the energy of impulses or disturbance through the natural media."

Regarding the mode of operation, the various receivers have in common that the sensitive device is biased by a battery. They also include Tesla's oscillator (clockwork rotary interrupter), which creates an additional bias on the sensitive device (or devices). This AC pulse bias acts as positive feedback, avalanching the sensitive device as soon as an arriving signal starts to cause some change. In the receivers with two sensitive devices the one that receives the external signal is usually on the primary side and the other, which activates the relay, on the secondary side. When there is only one sensitive device, it usually shunts the transformer secondary (which has a high impedance so as not to reduce the performance of the device), thus creating an efficient feedback loop.

In two cases (figures 4 and 5, August 3), instead of a sensitive device with metal powder, the use of a dielectric, exposed to an electrical field of such an intensity very close to breakdown, was assumed.

A number of schemes contained two sensitive devices and two batteries (August 5). On August 6 Tesla described three schemes of a mobile apparatus in various phases of improvements. These receivers were operating with only one dry-cell of a Leclanche battery!

On August 7 he switched to the description of a group of receivers in which the sensitive device was positioned in the secondary circuit. From the previous experiments Tesla concluded that some schemes with a similar component layout gave good results. The reason for that could be found in the position of the sensitive device, which was situated in the circuit of high impedance before the excitation. So even a weak signal from the high impedance source (antenna-ground circuit) excited it easily. Tesla observed that the increased sensitivity of the sensitive device was obtained by an indirect excitation from the secondary. Such a circuit was shown in figure 5. The excitation was performed by the induction (probably via an electrical field). Since he stopped with this diagram, there must have been some bad characteristics due to which he did not continue the tests.

A general feature of all Tesla's receivers is their delicacy. Very careful adjustment was necessary to get the sensitive device as the threshold of avalanching. Most of the sensitive devices were rotated (see June 23) so that they were only good conductors during the action of a signal. In some cases, however, this did not achieve satisfactory deactivation of the coherer. Then he used an electromagnetic buzzer to periodically interrupt the excitation of the sensitive device (see figure 2 of August 8). Probably the circuit in figure 2 gave him the idea for that in figure 3, where the rotary interrupter is replaced by a buzzer as an electromagnetic interrupter. He then used a buzzer in various other configurations (figures 5 and 6 of August 8), with the aim of reliably biasing the condenser, and hence also the sensitive device, to threshold.

Tesla did not measure the sensitivity of his receivers by any definite method, but there is no doubt that he did compare them in some way. From his notes very little can be deduced about their sensitivity, i.e. the power required to activate them. A rough idea is given by data from July 4, when he used similar receivers to register electrical discharges. He estimated the registered waves produced by lightning at least 200 miles away, and continued to receive signals (at periodic intervals) later when the weather had already cleared. He records that with the receiver shown in the figure of July 28, he was in one instance able to register lightning discharges at a distance of 500 miles. He estimated the distance from the periodicity of the signals as the storm moved away.

In figure 6 (August 8) and figures 2, 3, 4 (August 9) the schemes with two primary coils on the HF transformer were shown. One of the two batteries produced the periodical pre-excitation and the second one (probably) produced the impulse excitation. It is possible that Tesla desired to achieve automatic deactivation.

In the receiver operation, there was a possibility for the contact d (rotating breaker) to bypass the capacitor C . In figures 2, 3, and 4 (August 10), Tesla showed several diagrams with two capacitors, where this complication was avoided. On August 11 he considered several schematic variations for achieving the initial excitation (figures 1, 2, 3). On the same day he again returned to the schemes already used in figure 4 (the only difference in the schemes shown in figure 1 on August 3 and figure 1 on August 6 was that they had L for the battery current control) and he made a note that it was necessary to develop this further.

On August 12 he again tested the possibility of the initial excitation of the sensitive device via high inductance (figures 1, 2, 3 and 4). In figures 5 and 6 he returned to the transformer with two primaries and in figures 7, 8 and 9 he presented several configurations with two batteries, out of which one served for initial excitation.

On August 14 Tesla experimented with circuits that contained two sensitive devices (figures 1, 2 and 3) and he improved the receiver's reaction timing. He concluded that it was probably possible to achieve higher sensitivity with two sensitive devices, since they might influence each other subsequently. He planned his further work with such dispositions. Other schemes of August 14 had only one sensitive device. Several possibilities of connection between the secondary and a sensitive device, as well as pre-excitation achievement were shown. The way the aerial and ground were connected could be seen in figures 6 and 7. The circuit in figure 6 contained inductance L_1 which, together with C_1 (aerial

* Tesla suggested the use of resonance at the signal reception in his lecture at the Franklin Institute already in 1893. He protected his synchronous receiver by the patent application in 1897.⁽¹⁴⁾ The receiver (actually the whole two-way system, same as in the previous patent) with two resonant circuits for the reception of the coded signals was described on June 27 in these notes and protected by his patent⁽³⁸⁾ in 1900.

capacitance), formed a resonant circuit adjusted to the oscillator frequency and in figure 7, secondary S was adjusted to it.*

The last experiments with the oscillator were described on July 31 with numerous comments and the remark "this to follow up." Probably he had prepared a new condenser bank in the meantime for work with higher voltages. He measured the capacitance of the new bottles on August 11, and tried them out with the highest voltage so far from the power supply transformer. After the usual checking and various adjustments to the capacitance in the primary and secondary circuit of the oscillator, he registered sparks almost three meters long. Even better results were achieved with one turn in the primary by adding the "additional coil" in the secondary. Comments on "lots of capacitance and a bit of inductance" in the secondary are an illustration of Tesla's estimation of resonance conditions in the oscillator circuits.

Aug. 15-26, 1899

With the new condenser bank the secondary had to be modified, and on August 15 he worked out the length of wire required. He calculated the period of the primary from the capacity of the new bottles and the inductance of one turn of the primary found earlier (mentioned on June 20 as 7×10^4 cm, probably one quarter of the value measured for two turns on June 17). It was also his intention to adjust the oscillator to the "extra coil".

On August 16 and 17 he considered a new connection of the supply transformer with a central tap. The experiment goal was the achievement of larger spark interruptions in the discharger, the reduction of the spark resistance influence and better use of the supply transformer. In order to reduce the short circuit of the mains transformer secondary winding he planned the use of two dampening coils (see diagram of August 17).

On August 18 Tesla performed the approximate calculation of an oscillation period by connecting condenser banks in series. This should enable operation of supply voltages up to 45 kV. He estimated quite approximately the change of the oscillation period due to the secondary influence. He assumed the secondary with a reduced number of turns (29 instead of previous $36\frac{1}{2}$), estimating that the coupling would be looser than previously and therefore, the reduction of the primary inductance would be percentage-wise smaller (see July 9).

On August 19 he carried out the experiments with the oscillator and came to the important information that, together with a voltage increase of the mains transformer, changes in oscillator operation will occur. At 22.5 kV the overload, as well as a voltage drop on primary side of the mains transformer was performed. ** At 15 kV, the mains voltage did even increase with the same oscillator. Later on, he increased the primary inductance (which was achieved easily by reconnecting two available primary turns), he reduced the capacitance in the primary and achieved reliable operation at higher voltage.

On August 20 he continued the experiments with the oscillator that had 29 turns in the secondary. The excitation voltage was increased to 30 kV and he used four capacitor groups connected in series. It was observed that with the bulbs lit brightest on the supply side, there were no sparks jumping on the sparking oscillator. He concluded that at that time, the minimum electromotive force was on the secondary side of the Westinghouse transformer. Tesla did not comment on this unusual conclusion, which at first glance seemed to be unbelievable. (This could be explained because he was too busy with other problems.)

The attempt of discharger location change, as shown in the figure, did not give any improvement.

On August 21 he experimented with three oscillator connection circuits with a double number of sparks on the discharger, but except for some minor improvements he did not achieve acceptable results. The main difficulties were secondary overloading of the mains transformer and the restriction of oscillator maximum power.

** Tesla mentioned the increase of EMF during the oscillator operation when the mains overload was eliminated. He did not explain where he measured this increase or drop, but it could be said that he drew the conclusion based on the lamp light intensity. The lamps were probably at a low voltage, so that he estimated the voltage measuring was performed at the mains transformer primary.

In this entry (August 22) he returns once again to the receivers. He tried out two receiver circuits using one battery and one sensitive device. He changed the capacitance in the primary circuit over a wide range, but it is not clear why 1 μF proved best. It remains unexplained what was the relationship between the frequency of the incoming signal and that generated by the receiver itself. Could it perhaps be, if the rotating coherer behaved as a nonlinear component, that the signal was amplified as in a heterodyne receiver?⁽⁵⁵⁾

On August 23 Tesla returned to the experiments with the oscillator. He put the "extra coil" in the center of the primary. Already the first experiment demonstrated successfully the efficiency and power of the oscillator. After connecting the secondary with "extra coil" (which he considered to have the same resonant frequencies) he stopped the experiment as soon as the fire danger appeared. After positioning the grounded metal ball in the vicinity of the one at the top of the "extra coil", the security increased. He easily achieved sparks from the coil top towards a grounded ball at a distance of more than two meters.

According to his estimation, Tesla expected the oscillator with one turn in the primary to operate at half the frequency, in comparison with secondary and "extra coil" resonant frequency. That was why he carried out the experiment with two primary turns in series, but the result disappointed him. He left any further experiments with harmonics and returned to a scheme that had previously achieved good results. Now he performed sparks more than four meters long, fast, explosive and very white. It appears that the capacitance adjustment in the primary was not critical. The currents wandered around and they could be observed at a certain distance from the oscillator (as e.g. the sparks from the water pipes).

The next day as well (August 24) he continued his successful experiments. Studying the occurrence of streamers, he concluded that it was necessary to use either a faster or synchronous discharge breaker. He created streamers by removing metal ball from the "extra coil" top and positioning a bare copper wire around the upper edge of the coil.

On August 25 he carried out various experiments with "extra coil". He put the open loops in the vicinity of upper and lower part of the coil. He observed that the streamers had a tendency to channel upwards, despite the grounded lower conductor.

On August 26 Tesla experimented with twice the interruption rate. The oscillator worked better and there was heavy sparking across the lightning arresters (figure 4). Investigating the cause of this sparking he inserted a coil in the lead of the metal sphere (figure 1) to reject high frequency currents. In an earlier experiment (see July 30), inserting such a choke coil in the ground line he had stopped sparking across the arresters. This time it did not, so Tesla tried the circuit in figure 2. Still there was no marked change, the sparking across the arresters was only slightly reduced. After this experiment he began to wonder whether the grounding point of the secondary was not perhaps a peak rather than a node of the standing wave. It must be understood that Tesla thought that standing waves were set up around the transmitter (like waves on an open transmitter line). With shorter waves the rate of change of amplitude with distance would be faster (i.e. maxima and minima would occur at shorter distance intervals), so he thought that a large potential difference could be obtained with a shorter distance between the grounding of the secondary and that of the lightning arrester.

In order to explain what happened when the sphere was not grounded (which would mean that there were no short waves) but the sparking across the arrester did not stop, Tesla found it necessary to formulate a new hypothesis: "Could the sparks be produced by static induction upon wire through air and not, in general, through earth by induction?" The experiment with which he tried to verify this hypothesis did not yield any definite answer.

Aug. 27, 1899

He returns to the question of how to deactivate the receiver's sensitive device. Although he has noted several times already that good results were obtained with various techniques (rotation, interruption of the excitation current), this reexamination of his old ideas shows that Tesla is still seeking a more reliable solution. One of the ideas he was gathering together for further investigation is illustrated by the diagram in figure 4, in which a rotary interrupter, condenser, choke and battery provide bias for the sensitive device. When interrupter d breaks, the voltage on C can be higher than the battery voltage. With proper choice of all values the interrupter can be biased to threshold, making it very sensitive.

Aug. 28, 1899

He continues the experiments with a transmitter with slight changes of secondary circuit. He alters the primary frequency to change the node points (for the explanation see patent 42), sparking on lightning arrester and generally, sparks and streamers. In the meantime, a change of weather occurred and Tesla devoted himself to electrical discharges and to the reaction of a receiver on them.

Continuing the experiment with the oscillator, it appeared that after stormy weather some operating conditions were changed. When the oscillator was switched on, the sparks on lightning arrester did not occur. His first assumption regarding the influence of a wet roof proved wrong the next day. The sparks did not show up any more, although the weather was nice and the humidity evaporated from the roof.

Aug. 29, 1899

He describes the receiver with the oscillator and two sensitive devices. This time, instead of a clockwork rotary interrupter, he uses a fast mercury rotary interrupter, and instead of circuit components of the standard receivers, he takes the transmitter circuit. The transformer of the oscillator serves as an excitation amplifier. Tesla's idea of a receiver with a "magnifying effect" could be easily understood through this example. Sensitive device a is excited by signal. The slightest change of device resistance alters the excitation of the oscillator with the mercury interrupter. This excitation causes the rise of HF voltage in the secondary for the higher absolute amount (due to voltage transformation upwards) and therefore the sensitive device a_1 being more excited than a . Although the circuit looks simple enough, an analysis of Tesla's receiver with a "magnifying effect" is rather complicated, because transient phenomena have to be taken into account and the resistance law of the sensitive devices as a function of voltage has to be known. It was not easy to adjust a receiver like this to work properly.

Apparently there was an earphone T in the secondary circuit of the transformer, but it is not mentioned in the notes. The sensitivity of an earphone would normally be much greater than that of a relay, so it would be interesting to find out how this apparatus performed. Unfortunately, earphones are practically not mentioned anywhere in the diary.

Tesla at last makes a few remarks here about how the sensitivity of receivers was estimated. To test its response he put a "small capacitor" across sensitive device a , but of what value, and whether it was charged or not he does not say.

Aug. 30, 1899

He experiments with the "resonant coil" he intends to use in a receiver. This coil requires the capacitance of 506 picofarads to achieve resonance at 50 kHz. With a small capacitance, which appears to be added by Tesla, the spark could have been due to a harmonic oscillator frequency.

Aug. 31, 1899

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Again he works with the oscillator, "extra coil" and capacitive loadings in the old layout. The aerial with the ball was going through the laboratory roof opening (see the laboratory photographs). Due to humidity, he performed short tests. In a few cases he checked the lightning arrester, but there were no sparks on it. The test of the power lines indicated that one of them had a good connection with the ground. It is assumed that he finally found the cause of the non-existence of sparks on the lightning arrester.

During the experiments he noticed that the small insects got killed when they were within the strong electromagnetic field of the oscillator.

When streamers were non-existent, the tendency of capacitor breakdown appeared in the primary circuit. The explanation is simple: the streamers represent the secondary load and when they do not exist, voltages in both oscillator circuits rise.

Sept. 1-2, 1899

Returning to the receiver problems, Tesla begins the analysis of the scheme shown in figure 1. With this circuit he had already achieved good results regarding sensitivity by an efficient feedback loop, for "high increase of the initial excitation." In respect of battery connection in series and the sensitive device, the pre-excitation created by circuit p - C and acting on sensitive device via secondary s , is not sufficient. That is why one more battery, improving the situation in this respect, was added in figure 2. The pulsating current appeared through the relay R , which was therefore relocated to the branch of the secondary s and of the sensitive device. Figure 4 indicated an even better scheme by which the relay self-inductance influence was reduced by an adjusted secondary circuit s .

Figure 5 shows the best alternative with an aerial that Tesla calls "air line and capacitance", and with the grounding by which the electromagnetic field performed the excitation of the sensitive device. On September 2 he presented one more diagram and experimented with various voltages of batteries B and B_1 . He concluded that full sensitive device excitation was achieved quickly (even at small excitation) if the batteries B and B_1 were connected so that their influences on capacitor C were additive and the excitation being interrupted in case of an opposite battery connection.

Sept. 3-8, 1899

The aim of these experiments is not explained, but it was probably associated with the "experimental" coil with which he examined currents in the water pipe. This was a resonant coil that in the receiver played a part analogous to that of the "extra" coil in the transmitter. Its purpose was to maximize the received signal. Since Tesla connected one terminal to ground, it appears that he wanted to pick up electrical vibrations from the earth. In this case too he found that it was not sufficient just to increase the Q -factor pL/R , but also that it was necessary to keep the coil's distributed capacitance as low as possible. This conclusion was consistent with what he had earlier found out about the distributed capacitance of the coils made with same wire, but with different numbers of turns.

On September 4 he tests the experimental coil to establish the distributed capacitance effect to the amount of resonant voltage at the coil terminals. The coil is excited via a water pipe, to which one lead of the oscillator secondary and one lead of the experimental coil are connected. Coils are mutually positioned so that between them there is no inductive coupling (figure 1). The voltage on the "experimental" coils, measured according to spark lengths, not only between the terminals of this coil but also from each terminal to the body of the experimenter (the body capacitance is added in such a way to change resonant conditions). He changes the number of turns of the coil from 448 to 168, then he

changes coil connection method (to increase excitation) as per figure 2 and performs further measurements reducing the number of turns up to 19. This conclusion was consistent with what he had earlier found about the influence of distributed capacitance of the coil upon the wire length needed to achieve resonance. The conclusion is interesting in that it shows Tesla was aware that the secondary and the extra coil (although excited by the same primary) would each oscillate at its own resonant frequency, and if these were not the same, they would “beat.” Their sum could be considered as vibration at frequency $(f_1+f_2)/2$ with a variable amplitude at frequency $(f_1-f_2)/2$.

On September 5 he performs tests with a new “experimental coil” and changes the measurement method. The spark length is not measured from the terminal to the body, but to various metal balls installed on insulators. The Q-factor is estimated according to the spark lengths at two coil terminals. Judging on the basis that with these experiments the sparks did not appear between the oscillator balls (figure 1), the oscillator operated with small power. Tesla gave particular attention to avoiding the direct coupling between the “experimental coil” and oscillator primary coil. Since he was convinced the coupling was loose, he continued similar experiments outside, always holding one coil’s terminal connected to a water pipe. Even at the distance of approximately 120 meters from the open end of the oscillator circuit to the body, he achieved sparks of more than 1 cm in length.

After a number of these experiments, Tesla once more concludes that parasitic capacitance is very harmful, so he decides to try winding a coil to have minimum capacitance. Unfortunately, he does not describe how this was done. In his desire to get the maximum possible voltage on the coil, he went as far as thinking that it was best to have no capacitance at the free terminal. From one aspect he was right (theoretically a coil gives the highest Q-factor with the least capacitance in the resonant circuit), but without the “elevated” metal sphere the received signal was much weaker because the free terminal of the coil no longer had a monopole antenna. In the practical circuit (September 5, figure 3), which he in fact used, he did not, however, go to such extremes. He added the “experimental” coil but left the metal sphere (aerial capacity) connected to one end of the sensitive device.

On September 6 he puts additional oscillating circuit in the vicinity of the oscillator secondary, by which he wants to produce short waves (see the figure). When calculating the wavelength of the cable vibrations with a ball, an error snuck in. Since T value was worked out, wavelength has to be approximately ten times shorter and the coil he wants to wind has to have 33 turns. The next day he wound a 400-turn coil. After the experimental checking of resonant frequency, he found out an approximate value, twelve times smaller than the one he calculated on September 6. In order to make sure that it is not a question of harmonic frequency he was reducing the coil’s number of turns. He concluded that after reducing the number of turns to less than 270, the spark length was continuously reducing as well. Then he made the coil with the thicker wire and achieved somewhat longer sparks. Next he unwound the coil again and achieved the longest spark with approximately the same number of turns as in the first experiment with thinner wire. The experiments were completed that day without definite conclusions. On September 8 he again wound a new coil, but this time he performed the calculations and inductance measurements and he found the agreement between theory and experiments.

Sept. 11, 1899

He continued the experiments started two days ago with the intention to find the nodes in the ground waves. He adjusted the oscillator to produce waves of somewhat higher frequencies than common ones, probably with an intention to get nodes of “standing” waves in the ground, closer to the laboratory. He measured the electromagnetic field with the apparatus in figure 2, very slightly changed in comparison with the previous one (see September 5, figure 3). Although he registered a signal at one-mile’s distance from the laboratory, he does not mention how the signal varied regarding the distance.

Sept. 12, 1899

He reduces the number of turns of HF transformer secondary from 29 to 26. After additional adjusting of the primary, secondary and "additional coil", he performs almost the same natural oscillating period in all three circuits. He achieved a voltage of more than three million volts on the metal sphere connected to the oscillator.

Sept. 13, 1899

From a document found in the archives of the Nikola Tesla Museum in Belgrade it may be seen that Westinghouse Corp. sent Tesla a 50 kW power transformer for a primary voltage of 200/220 V and secondary voltages of 40, 50 and 60 kV. This is probably the "Westinghouse transformer" he often mentions.

Sept. 14, 1899

He lifts the metal ball connected to the oscillator into the highest position (not providing the information about the actual height). With the series connection of an oscillator secondary and an "additional coil" (similar to figure 1 of September 11) he achieved streamers approximately 4 meters long.

Sept. 15-17, 1899

The receivers described on September 5, figure 3, and September 11, figure 2, include "tuned" coils whose function is similar to that of the "synchronizing" coils shown in the diagrams of September 15. Tesla did not make a detailed analysis of these receivers, nor do any of his patents on receivers refer to similar circuits. It therefore seems that we do not have sufficient information to draw any reliable conclusions about their sensitivity or their ultimate purpose (for example it is not clear whether they are just for registering or for receiving signals).

Sept. 18-19, 1899

As already remarked, oscillators like those he was working here with are not the classical Tesla oscillator with resonant transformer. The "additional coil" essentially changes the loading of the secondary circuit, and this alters the mode of oscillation. Also, shunting the secondary with capacitance (as in the diagrams of September 18 and September 19, figures 2, 3 and 4) alters the spectrum of the oscillation in comparison with that yielded by an oscillator with two oscillatory circuits. Configurations such as those shown in figures 5 and 6 of September 19 can be considered as typical Tesla oscillators with a loosely coupled third circuit consisting of the additional coil and capacitive load. Then the greatest voltage at the free terminal of the additional coil is obtained when the natural resonant frequency of this circuit (together with the ball antenna) is the same as that of the strongest component in the spectrum of the oscillator.

Sept. 20, 1899

He calculated the oscillator with an electrolytic breaker and a damping coil in the power line of the oscillator, assuming that the entire kinetic energy of the coil was converted into electrostatic capacitor energy, which happened when the voltage in the capacitor reached the source voltage. However,

in the circuit shown, the voltage in the capacitor could reach even higher levels depending on the quality factor of the coil and the breaker speed, but Tesla did not consider such a case here.

The breaker which Tesla describes operates on the principle of a fine fluid stream evaporation under the influence of current through the device d (see the figure), and he studied it in relation to the oscillator design switched on by disconnects.

Sept. 21, 1899

Tesla prepared a pole construction that carried a metal sphere approximately 75 cm in diameter at the top, total height of more than 42 meters. This was the aerial of Tesla's transmitter seen on the photographs of an outside view of his laboratory.

Sept. 22-23, 1899

Having investigated the tapering secondary, Tesla started making a new, 15m diameter cylindrical secondary. He planned the use of two primary turns and number of secondary turns amounting to 48. He makes the primary winding from 37 wires 2.9 mm in diameter and the secondary winding from a wire 2.6 mm in diameter (see September 23). The criterion that the weight of copper in the primary and secondary should be the same follows from the requirement of equal losses in the two windings (losses in the copper). This way of calculating the gauge of the primary and secondary conductors is applied in designing LF transformers, but for HF transformers it only provides a rough guide, for a number of reasons, e.g.: the current ratio may differ considerably from the turns ratio, skin effect is not taken into account, etc.

Sept. 25, 1899

Tesla measured the inductance of the primary and the regulation coil that he usually used as an added, adjustable primary inductance. The value he obtained for L_{2p} differs from that found earlier (see July 17) by the same method.

Sept. 26, 1899

By this method Tesla found the frequency of an oscillator with a help of a coupled resonant circuit of known parameters. When its resonant frequency is adjusted to coincide with the frequency of the oscillator, the voltage across its terminals, estimated by the strength of the spark across an "analyzing gap", is a maximum. Tesla says that the excitation must be "convenient". Since he introduced regulation of the excitation by means of the small gap b , it is clear that "convenient" excitation was obtained with loose coupling. Loose coupling between the primary and secondary circuits of a spark oscillator insures that the two frequencies that such an oscillator normally produces are equal or very close.* Tesla does not give any data on the method accuracy here, but judging by the conclusion that the excited circuit frequency is somewhat lower than the primary circuit frequency (by approximately 0.4%), it is likely he assumes a high accuracy.

Sept. 27, 1899

He measures the auxiliary coil inductance by the same method he applied on September 25, except that now he takes into account the coil resistance as well (measured probably by DC, neglecting the skin effect). True to the principle that measurements should be checked by calculation, Tesla

* According to Fleming and Dyke,⁽³¹⁾ with an ordinary spark gap the maximum coupling coefficient for monochromatic oscillation is around 0.05 (certainly less than 0.1), while with a rotary break producing pulse excitation a coefficient of up to 0.2 gives good results. With higher coupling

calculates the inductance of the same coil using the formula for a coil of greater length, but does not obtain agreement. In a short review of the disagreement reasons he mentioned the possibility that the distributed coil capacitance influenced the measured value. This is difficult to believe since distributed capacitance increases the effective inductance at frequencies below the natural resonance of the coil. The second possible reason which he mentions (inexactness of the coil dimensions) could have some influence, but the main reason is the poor approximation provided by the formula when applied to a coil with this big length: diameter ratio.

coefficients three components are obtained, even if the primary and secondary circuits by themselves have the same resonant frequency.

Sept. 28, 1899

Tesla displays new ideas about aerial excitation. The circuit diagrams are of great interest, because they illustrate a new approach to feeding the antenna (now known as shunt feed), which obviates the problem of insulating the aerial stand. Tesla's idea was that by such an aerial feeding he would avoid discharge when supplying energy to the aerial. Unfortunately, the explanations Tesla gives are too vague to be fully comprehensible. The figures do not clearly show whether the lower terminal of the antenna is grounded or insulated. Tesla's conclusions that a standing wave is set up along the antenna and that the distance between points of equal potential is half a wavelength are correct. It appears that Tesla did not take into account the aerial reduction due to the final capacitance when considering the events on the aerial. Remarks could be made on the chosen aerial length as well as the voltage distribution (or current?) along the aerial. The frequencies he was using were not high enough for his antennas to work in the manner shown by the figures, so that this contribution to the theory of wire antennas was not properly formulated.

Sept. 29, 1899

Three wiring diagrams are shown with terminal capacities connected to isolated secondary terminals C and C_1 . Tesla says that he experimented with the antennas shown in the drawings, but he does not compare them with a grounded antenna. The shortness of the antennas relative to the wavelength made them inefficient radiators. The configuration shown in figure 3 was best probably because it had the greatest terminal capacity, providing the most favorable current distribution on the antenna. Lack of coil and ball dimensions makes it impossible to get into any more detailed analysis of these antennas.

Oct. 1-2, 1899

Tesla designs and tests a new 22-turn secondary. Coil turns are positioned so that the distance amongst them is changed, starting from the grounded terminal. He chooses the secondary that enables approximately the same resonant frequencies as the previous ones (see September 22). The new secondary had less turns and it was shorter. He finally chose 18 turns.

Oct. 3, 1899

The drawing of several of the coils that Tesla often used offers some interesting information about the laboratory that cannot be seen from the numerous photographs. One sees that there was a wooden floor raised 30 cm above ground level, and the drawing shows the dimensions of the coils and how the HF transformer of the oscillator was wound.

Oct. 4, 1899

He performs the experiments to determine the variations of capacitance of an isolated metal frame at various distances from the ground surface. He designs the "special coil" connected between the secondary and the ball. He particularly makes efforts to reduce the natural coil capacitance.

The oscillator frequency is changed as usual by regulating coil and capacitor in the primary circuit. The maximum voltage, i.e. the longest spark between the terminals of special coil, is the indication of the adjusted oscillator. Regarding the secondary, he enters a note on the drawing that it does not "vibrate freely".

Tesla was primarily interested in the change of capacitance of a ball with height, so he measured the primary capacity for two elevations of the ball. In both cases he tuned to resonance of a "special coil". In the first measurement he had $L_p C_{p1} = L_{sc} C_{k1} = \frac{1}{\omega_1^2}$, and in the second $L_p C_{p2} = L_{sc} C_{k2} = \frac{1}{\omega_2^2}$. These equations neglect the effect of interaction between the primary and secondary on the work of oscillator. They readily yield Tesla's equation

$$\frac{C_{p1}}{C_{p2}} = \frac{C_{k1}}{C_{k2}}$$

The inductance of the primary L_p and of the "special coil" L_{sc} do not figure in the capacity ratio equation. In deriving this equation all distributed capacitance in the secondary and the secondary coil itself are neglected.

Oct. 5, 1899

Tesla checks out the secondary coil adjustment by the standard procedure. He adjusts the capacitance and inductance in the primary (with a coil of variable inductance connected in series) until he achieves the maximum spark at the secondary terminals. Operating frequency is calculated approximately, based on total inductance and capacitance in the primary. The influence of the secondary adjustment to the oscillation is checked by an addition of a sphere of 38.1 cm in diameter and since it had very little influence, he draws the conclusion that the distributed secondary capacitance is large.

The same day he continues the notes about the sources of possible errors when determining the ball capacitance variations due to height alteration. He gives the table of precise measurement results where, applying the method of October 4, the desired capacitance variations can be found. Starting from a certain height, he had to change the primary coil (reconnecting parallel turns into a series connection) due to the small maximum capacitance value in the primary.

Oct. 6, 1899

From the measured inductance of the new secondary and mutual inductance of the primary and secondary, and the primary inductance measured earlier (see September 25), it follows that the coupling coefficient was 0.58, i.e. tight coupling.* An oscillator with such coupling will probably produce three pronounced components, even with very rapid interruption of the spark in the primary. This is indicated by the results Tesla obtained with spark oscillators with looser coupling (see the commentary on September 26).

* The regulating coil in series with the primary reduced the coupling. The new coupling coefficient is found to be $k' = k \sqrt{L_p / (L_p + L_{rc})} < k$.

He adjusts the "additional coil" with the intention to adjust the same resonant frequencies of the secondary circuit and this coil. The coil resonant frequency is adjusted by the variation of the position of the metal ball, connected to the coil. When he achieves the longest sparks on the "additional coil," he considers that the coil is in resonance, but he does not say the way it is connected during this test. From the rest of the text it could be seen that he connected the "additional coil" to the open secondary terminal and he continued the experiment applying the system of three resonant circuits. By repeated adjustment of regulating coil inductance he performed better oscillator operation and the streamers approximately 5 meters long. When he removed the ball, he used to put a special coil to maintain the same resonant state in the oscillator.

As before, Tesla determined the wavelength of the oscillator from the period of the primary circuit (see, e.g., June 20). He compares one-quarter wavelength with the total length of wire in the secondary, special coil and additional coil (when no other coils were used, he considered that the length of the secondary windings should be one-quarter wavelength). Since there is no full agreement, he thought the differences were due to errors in measuring the inductance, capacitance and length.

Oct. 9, 1899

He continuously improved the method for variable capacitance measurement of a ball at different heights. He made the last measurements of the change of capacitance of a sphere with height on October 5, but did not give the calculation results. He subsequently improved the apparatus as a whole and in the present entry describes a different way of connecting the "special coil", the chief good effect of which was to loosen the coupling, which immediately proved its advantages. With weaker excitation of "special coil" it was easier to adjust it to resonance, because there were no streamers. Parasitic capacities were reduced, mainly limited to the distributed capacitance of the "special coil."

Tesla first determined the distributed capacitance of the "special coil." He assumed that the circuit with ball resonated at codetermined by the primary circuit, so that one can write:

$$L_{p1}C_p = L_{sc}(c + C),$$

where L_{p1} and C_p are the total inductance (including the regulating coil) and capacitance of the primary circuit, L_{sc} is the inductance of the "special coil" (including connecting wires), C is the distributed or parasitic capacity of the "special coil", and c the capacitance of the ball.

Subsequent changes in the height of the ball changed the capacitance in the circuit of the "special coil." To bring again the system into resonance with the signal from oscillator, Tesla changed the inductance in the primary circuit. When resonance is achieved, according to Tesla, one can write:

$$L_{p2}C_p = L_{sc}(c' + C).$$

Dividing this by the proceeding equation yields:

$$c' = \frac{L_{p2}}{L_{p1}}(c + C) - C,$$

which is in fact the equation Tesla uses to find c' . Because of an arithmetical error in calculating C , Tesla's numerical results for the ball capacity are about 10% higher than they should be, but this does not essentially affect the conclusions. To calculate the distributed capacity of the coil* he uses the relation $L_p C_p = L_{sc}(c + C)$ for the ball at a height such that he could consider its capacitance close to the theoretical capacitance of an isolated sphere.

* By distributed capacity Tesla used to mean the total capacity between turns of the coil. Here he uses a different definition of "internal capacity" similar to that normally used today.

Oct. 11, 1899

Tesla obviously did not sleep much the previous night, since he was photographing the oscillator in operation both late at night and early in the morning. The Nikola Tesla Museum in Belgrade possesses several photographs that date from this period, but they are too faded to be worth showing. One of the better-preserved photos is shown on p. 232.

Oct. 12-13, 1899

Tesla measures the impedance of the "special coil", "additional coil" and oscillator secondary. He performs measurements at the frequency of approximately 140 Hz as per method used to determine the impedance module based on voltage and current ratio. He does not explain how he measured resistance (on October 10). He compares the value found for "special coils" with the theoretical value determined by an equation for an infinitely long coil. The matching of these two values is poor but this is not surprising since the ratio l/d is small.

Oct. 14, 1899

He continues coil testing with parameters he measured during two previous days. He performs measurements at high frequencies and he couples loosely the measuring circuits with the exciting circuit (oscillator primary). The goal is to find the circuit resonant frequencies with the three mentioned coils at various capacitive loadings.

Oct. 15, 1899

He continues the measurements from October 9 with corrections in parameters according to the results of October 12. Because of the arithmetical error made on October 9, he mistakenly concludes that the capacitances of the ball are now somewhat less than before. Had he used the correct values, his conclusions would have been just the opposite.

Oct. 17, 1899

The 122 ft metal pole bearing the 30" ball is the antenna to be seen in the middle of the laboratory on many photographs. The bottom end of the antenna is insulated by a wooden pole. This is a single-pole antenna of small electrical length. Around the highest frequencies that Tesla used, the h/λ ratio was about 0.015. The terminal capacitance made the effective height somewhat greater than $h/2$, but it still remained an electrically short antenna. The main reason for the construction of this antenna is the testing of the "ground vibrations".

Oct. 18, 1899

He calculates a new coil by which he wants to continue the tests of the ball capacitance variation with relation to its elevation height. It is certain that he was not satisfied yet with the results achieved and he prepared the new components for the more perfect experiments.

Oct. 19, 1899

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He rewinds the “experimental coil” by which he tested the wave propagation through the ground at the beginning of September. Now the rewound coil is to be used for the measuring of the ball capacitance variation due to elevation height alteration. He calculates the rewound coil inductance (by the equation for an infinitely long coil, regularly used by him) and the system period applying a sphere of a certain diameter. Here he neglects the distributed capacitance of the coil.

At the end he carries out the experiment with one oscillator but it seems he only used the standard primary capacitors (*jars*), the primary being made of several turns of thick wire. That is why the primary inductance appears as an unknown value.

Oct. 20, 1899

He describes the measuring method for determination of the coil distributed capacitance. Tesla was measuring on the coil he had used for determining the change of capacitance of a sphere with height (up until October 9 he had called it a “special coil”). He excites the coil with additional short wire without having a galvanic connection with the oscillator circuit. Considering the dimensions of the primary (coil diameter 15 m) and the coil being tested (diameter 64 cm, length 145 cm), the coupling between them was obviously loose, so that the frequency, found from the parameters of the primary circuit (provided that the main secondary of the oscillator did not influence the oscillation of the primary), could be considered as exact. It is not stated how resonance was determined, but it was probably from the sparks at the terminals of the test coil.*

One is under impression that Tesla was suspicious of the found values of the coil-distributed capacitances. He worked persistently to prove further the measured values, searching for new methods for their determination.

Oct. 21, 1899

In a thorough analysis of all details of his measuring apparatus, Tesla did not omit a determination of the parasitic inductance of the connections, by an interesting method he says he used often in the New York laboratory. Varying the primary inductance and capacitance, but keeping a constant frequency of the oscillator (as determined with an auxiliary resonant circuit), one has:

$$C_{p1} (L_{p1} + L_{con}) = C_{p2} (L_{p2} + L_{con})$$

where C_{p1} , L_{p1} are the first and C_{p2} , L_{p2} the second capacitance-inductance pair in the primary giving the same frequency. From this equation one can find the parasitic inductance of the connections L_{con} , which Tesla denotes by x . In the measuring circuit the resonant coil plays the role of frequency indicator.

Tesla comes up with the first measured value of the ball capacitance. First he finds the value of the coil capacitance and supply connection capacitance, and then the capacitance of the coil, supply connections and the ball. The measuring method is similar to the one of October 9.

Oct. 22, 1899

He applies the same measuring method as on the previous day and finds a number of values for the primary inductance and capacitance (aiming at determination of connection inductance). The oscillator frequency is determined from the maximum spark at terminals of the coil with 689 turns (see the figure). Continuing the measurements, he adds a high power transformer primary coil in the oscillator spark circuit. He uses only some measuring data for finding the connection inductance.

* The similar resonance method is being mentioned nowadays in the books on electrical measurements.⁽⁵⁶⁾ It is remarked upon, however, that the determination of the coil distributed capacitance, based on the coil self-resonance is not reliable since it depends on the way of excitation and it always gives lower values. That is why it is proposed to measure this capacitance in cases where there is an addition of capacitance in the circuit.

Oct. 23-24, 1899

In further experiments to determine change of capacitance of the ball with height, Tesla uses an apparatus similar to that of the previous day. As far as can be judged, the coupling between the oscillator and the measuring circuit (coil with elevated ball) was loose. The lower terminal of the latter was connected with a condenser of the oscillator circuit. Loose coupling is evidenced by the relatively weak sparks obtained across the air gap of coil L (see figure) in comparison with the sparks obtained when a similar coil was excited by the secondary of the oscillator, tightly coupled to the primary (as for example on October 4 and 5). Under these conditions the spark oscillator would generate a single frequency, determined by the parameters of the oscillatory circuit with the spark.

In parallel with the coil L , a vertical wire is connected with the ball C . The ball is capable of moving along the wire and supported in the way shown in the drawing. The resonant state of coil L is estimated by the spark on the adjustable spark gap. This method of resonant state estimation has its shortcomings, because it requires relatively strong excitation, leading to streamers, which, in turn, change the circuit parameters. Tesla claims that streamers change the capacitance of a thin wire, causing the effects comparable with those created by large capacitance. That is why he took precautions to reduce the streamers when designing the apparatus. He paid particular attention to the sparker for resonance registration, introducing minimal capacitance in the coil circuit.

He adjusts the oscillator frequency step by step, connecting a certain number of capacitor jars (each jar had a capacitance of approximately 800 cm). The fine frequency adjustment was performed by variation of turn numbers of the regulating coil.

The ball capacitance was measured indirectly. First, the resonant frequency of the coil L was determined by means of the sparker for resonance registration. Then a vertical wire w , along which the sphere C slides, was connected. This way the second resonant frequency was determined. Finally, the resonant frequency was determined when the measuring circuit consisted of coil L , vertical wire w and a ball C (at various heights). From the values of three frequencies and coil L inductance being known, the ball capacitance values are determined at various elevations. Tesla performed a number of measurements, checking one value of primary circuit capacitance after another, but he did not do any calculations.

Oct. 25, 1899

He measures the capacitance of the thin N°10 wire positioned vertically above the measuring resonant coil (see figures of October 23). The method is the same as on previous days. He gives the measuring data in tabular form, but again he does not perform the calculation.

Oct. 26, 1899

Tesla had already been using the 689-turn coil for several days in experiments to determine change of capacitance with height of a ball. On October 18 he calculated its inductance using the formula for an infinitely long coil. Now he determines it by measuring the current and voltage at a frequency of about 140 Hz, knowing the resistance. He gives the results of two sets of measurements. He is convinced that the second set, for which he used a small dynamometer, gave low values, and this was probably so. The first set gave an inductance slightly less than calculated, but a correction of the theoretical value for the finite D/l ratio gives a value of about 6% less than that measured.* Thus the calculated value ought to have been 0.023 H, while the experimental result was 0.024 H. The accuracy of the measurement method cannot be verified but, in view of the small difference between impedance and resistance, it is doubtful whether it could be of the order of a few percent.

* Russel (57) gives the inductance of a coil at very low frequencies as:

$$L = (\pi D n)^2 l [1 - 0,424 (D/l) + 0,215 (D/l)^2 - 0,0156 (D/l)^4]$$

Oct. 27, 1899

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He tests the condensers of the oscillator primary circuit. Tesla does not explain how he made the comparison with a standard $0.5\ \mu\text{F}$ condenser. The number of bottles used in the condenser bank is indeed impressive. He did not carry out measurements of individual bottles to determine what kind of tolerance they had. Since he only measured complete banks, i.e. rather large capacities, and mentions "readings with 7 cells battery," he probably made the comparison in terms of measurement of quantity of electricity.

Substituting $\pi D^2 = 4S$ (D is the mean diameter of the coil), and $n = N/l$ (number of turns per cm), the first term in the above equation yields the expression Tesla used. l is coil length. When all quantities are expressed in units of cm, L is also obtained in cm.

Oct. 28, 1899

After several days gathering data and making further measurements of inductance and capacitance, he finally proceeds to the calculation of the unknown capacitance of the sphere, using the readings of October 23 and 26. Consistent with his general principle, he checked the measured values by (usually approximate) calculations.

He calculates the capacitance of the vertical wire by the formula for an isolated ellipsoid of high eccentricity. It is not known whether Tesla first had the idea of using this formula, but it was used later for a similar purpose.⁽⁵⁸⁾ All things considered, the agreement between the calculated and measured values is very good. Tesla then calculated the ratio of the capacitance in the lowest and highest positions. In the lowest position the sphere makes little difference to the total capacitance. In the highest position it increases the capacitance in the coil circuit L by 18.7 cm. This is less than the theoretical value for an isolated sphere having 18" in diameter, which does not agree with some of his earlier measurements (see the results of October 21 for a 30" ball). However, if a comparison is to be made, it must be noted that the new results are probably better, because the apparatus had been modified and the parameters checked.

Oct. 29, 1899

It contains a new measuring series with a larger sphere and somewhat changed excitation of the measuring circuit. Now the excitation is regulated by an adjustable spark gap between the lower coil L , terminal and grounding (for other details of the scheme see October 23). His remark about eddy currents in the sphere is interesting. To prevent their formation, he slit the tinfoil with a knife. Did he assume that in the vicinity of the coil the sphere would behave like a short-circuited turn? It is readily shown that if this effect is pronounced (and not taken into account), the measured capacitance of the sphere will be too low. This might be an explanation for the reduction of the effective capacitance of the sphere in the lowest position (see the calculation of October 28 for an 18" sphere in the lowest position).

In some cases Tesla finds that the resonance adjustment is not sharp. He checks the coil validity factor by calculation. The actual Q-factor is certainly smaller because Tesla takes the coil resistance at direct current.

Oct. 30-31, 1899

He continues with measurements that involve the primary coil of a big HF transformer, a regulating coil and the inductance of the connections. The wiring scheme was shown on October 30, the short-circuit being established via a rotary discharger and a capacitor. That way, only the above-mentioned inductances remain in the circuit. The measuring method has been explained several times so far. As a new item, it was explained how the signal of frequency of approximately 140 Hz was produced and how the frequency measuring was carried out.

On October 31 he determined the new coil parameters by measuring. This coil was made by re-winding the 689-turn coil mentioned on October 22. He took a thicker wire to improve the quality factor and he compared the measured values with the calculated ones.

Nov. 1-2, 1899

The new "additional coil" was larger in diameter but shorter than the previous one (see August 23). He performed the calculation again following the formula for an infinite coil. When he compared these results with the measured value, he experienced a large mismatch. He suspected the reason were windings, big and far apart. On November 2 he repeated the measurements but the measured value was similar. He drew the conclusion that the applied formula was incorrect in this case, being less and less applicable as turns were at greater spacing from each other. He considered that in the case when turns were very much separated, it was better to calculate the inductance of each turn separately and to multiply this value by the turn number. He suggested that if all of them were not the same (probably thinking if the spacing was not always the same as was frequently the case with his coils), then the mutual inductance has to be incorporated.

When he performs the coil calculation with the correction referred to in the commentary to October 26, the agreement with the experimental results is good.

The correction terms are significant, because the ratio D/l is even greater than unity, and the correction is more than 30%. The correction value is 0.0198 H, 2-3% less than the measured values.

Nov. 3, 1899

A repeated measurement of the capacitance of the vertical wire and the 30" sphere by the method of October 29 but with a new coil L (see October 31). A new feature is Tesla's attempt to eliminate the wires of the spark gap, estimating the excitation solely from the streamers.

Nov. 4-5, 1899

He measures the oscillator primary inductance again with a new supply source. He compares the result obtained with the previous ones, probably those of September 25 and draws the conclusion that it is more reliable.

Photographs of the Colorado Springs laboratory always show the pole rising from the center of the building. Its dimensions are given in the entry of October 17. Now Tesla calculates the capacity of the pole as the sum of the capacities of its parts of different thickness, using the formula first cited on October 28. His final remark indicates that he had thoroughly understood the physical essence of the phenomenon.

Nov. 6, 1899

Tesla carefully measured the capacitance of the aerial pole by the resonance method, from the known inductance of the 550-turn coil (see September 8) and known frequency of the oscillator, with two measurements, one with and the other without the annexed structure. He determines the resonance from the maximum spark, and the frequency from the inductance and capacitance of the oscillator circuit. In a series of separate measurements, he determines the inductance value of a regulating coil and connections, following a new procedure. The primary coil, and the regulating coil with connections as in

the measuring circuit are connected to an LF source (most probably 140 Hz, as previously) and he measures the voltage ratios, as shown in the figure. From the previously determined primary coil inductance and the voltage ratio, the total inductance of the connections and regulating coil is obtained. He did not make use of his earlier results for the inductance of the regulating coil and connections from October 30, although he could. A calculation check shows that the results of October 30 were rather high (by as much as 10% for 2 1/8 turns of the regulating coil), but Tesla probably thought that the new procedure was better and so did not use the old results. An analysis shows that if the old values had been used the final result would not have been essentially affected, so that Tesla's conclusion that the measured capacitance of the pole was less than the theoretical value of November 5 remains valid.

From the relatively lengthy discussion following the measurements, it may be seen that Tesla expected just the opposite. As usual when his expectations were not fulfilled, he considers ways for getting more reliable results.

He measures the capacitance of the structure with two coils, one being a new "additional coil" (November 1), and the other an "experimental coil" (see October 31). The results are similar to those of November 6. Measurement of the capacitance of the structure at two frequencies was intended to demonstrate the reduction of effective capacitance with increasing frequency. Tesla did in fact obtain a small difference, but it is dubious proof considering the accuracy of the measurements. The change of frequency was quite large, from 50 kHz to nearly 250 kHz (using "additional" and "experimental" coils).

Nov. 8, 1899

He gives the table of calculated inductances of primary and regulating coil and connection inductance, in terms of number of turns. The cited primary inductance values are from November 5. The other values given in the table do not agree with those derived from the measurements of October 30. Also, earlier data do not include values for half a turn of the regulating coil. It must therefore be concluded that the measurements from which the tabulated values were calculated are not described in the diary.

It seems that, in measuring inductance from voltage, current, frequency and resistance, Tesla had difficulty because of unreliability of the frequency determination. He therefore used the voltage ratio only when it was necessary for the frequency to be constant. By this method he measured the inductance of the regulating coil plus connections, for various numbers of turns.

Nov. 9, 1899

The measurements of mutual inductance, in terms of the inductance of the primary when the secondary is open and short-circuited, are noteworthy. They were made at constant current and frequency, simplifying the calculation. He compared the obtained mutual inductance with the inductance determined previously by an induced voltage under no load conditions. Tesla thinks that the difference originates from the influence of the secondary on the primary when the former is open.

To reduce the oscillator frequency, in some cases Tesla used two special coils, which he refers to only by wire gauge number. He compares the calculated and measured values for these coils. The values measured by the voltage ratio method are about 2% less than those found from voltage, current and frequency. The calculated values are lower than either. Correction of the measured values as described in the commentary on October 26 does not make much difference (about -5%), because D/l ratio is relatively small.

Nov. 10, 1899

He winds a new 1314-turn coil on the same core on which he used to wind 689 (see October 18), and later 346 turns (see October 31). With this coil he measures the metal sphere capacitance again and achieves a value similar to the one on November 7 with "additional coil." At the end of these measurements and calculations, he established that the method of resonance determination by the spark length in the spark gap is not quite satisfactory. In the next experiments he changed the resonant determination procedure. He returned to a method he applied earlier in the New York laboratory. The method comprised use of an auxiliary secondary coil in a weak inductive coupling with the excitation system, at whose terminals was the instrument for registration of current or voltage change in the secondary. Usually a small light bulb for the indication of these changes was used. The variation of the method, when the small light bulb was preheated by a DC current (see figure 2), was particularly interesting. It could indicate very small excitation changes from the HF current circuit, which are applied to heat up additionally already preheated filament in order to produce luminance.

Using the newly applied method of resonance indication, he performs some measurements again, working out the capacitance of a vertical wire 50 ft long. After that he switches over to determine the capacitance of 1314-turn coil. He compared the measured result with the calculated one for the capacitance of a metal cylinder of the same shape as the coil. According to Tesla, this attitude serves only as a rough estimation. When in the first calculation he obtained a higher value with the total coil length than the measured one, he took the effective coil length based on the bare wire. It is obvious that Tesla looked upon the theoretical equation as a rough guide to estimate parameters, but the experiment was the most effective factor for him. As far as the problem of determination the coil self-capacitance, it is present all the time from his first entries onwards (e.g., see June 20, July 3, etc.).

Nov. 11, 1899

In measuring the capacitance of a sphere at different heights, Tesla here uses a loosely coupled circuit containing a lamp to determine resonance. The results for a 50 ft wire differ somewhat from those of October 28, but are within the limits of error of the method. The values for capacitance of the sphere are somewhat higher than before, but not in proportion to the diameter of the sphere.

Nov. 12-13, 1899

He repeated measurements of the pole capacitance, like those of November 7th, but now using a coil with 1314 turns. Resonance was determined by means of a small lamp loosely coupled to the measuring circuit. The value obtained was again similar, so Tesla concludes that it is near the true value of the effective capacitance. On November 13 Tesla uses an improved method for determining the resonance point (with a light bulb in a dark box for more precise detection of luminance) and determines the capacitance of the structure of iron piping once more. The change of oscillator frequency is achieved by inductance variation, thus obtaining a value about 10% less than in earlier measurements (see November 7 and 12).

Nov. 14, 1899

He measures the 1314-turn coil, the coil halves being connected in parallel. He expects the connection of two halves in parallel to provide one quarter of total coil inductance, which he approximately does obtain in this case, since the ratio l/D of the tested coil is fairly large (see November 10). He carried out the measurement at the frequency of 140 Hz, similar to the one on November 10, when he measured

the total coil inductance. The measured value is four times larger now, amounting to 83,524,000 cm and the previous total coil measurement amounted to 85,000,000 cm. The small difference proves Tesla's claim that the inductance is almost four times larger.

Nov. 15, 1899

Tesla again measures the capacitance of the sphere on top of the metal pole as on November 7 and 12, but with the secondary coil of the oscillator instead of the earlier "supplementary" coils. The results did not agree with those obtained earlier. Tesla puts this down to the large distributed capacity of this coil, but it would seem that other factors influenced the accuracy as well. Because of the tight coupling between the primary and secondary of the oscillator, it was possible that the spectrum became more complex, which can influence the results of measurements.

Nov. 16-20, 1899

He makes a new auxiliary coil on a core 35.5 in diameter and 244 cm long with 344 turns of wire 2.6 mm in diameter. As per the already described method, he measures the capacitance of a vertical wire of various lengths, the sphere capacitance at various elevations above the ground, the capacitance of metal cylinders of various lengths using this coil and he compares the capacitance of a horizontal and a vertical wire of the same length. Capacitance measurements, made during the period 16-22 November, agree on the whole with those made earlier. Tesla does not explain why he repeated similar measurements, e.g. those of November 16 and 18 when he determined the distributed capacity of the supplementary coil and the vertical wire. Nor does he explain why he repeated the measurements of the change of capacitance of the sphere with elevation (see November 18 and 20). He may only have wanted to confirm the earlier results.

On November 17 and 19 he measured the capacitance of a vertical wire of various lengths and gauges. From his comments on November 17 it may be seen that at greater lengths he expected some inductive effect. A check of the wavelength, however, reveals that all Tesla's antennas were short in comparison to wavelength (h/λ of the order of 0.01), so that divergence between the theoretical and measured values cannot be ascribed to an inductive effect.

Nov. 21, 1899

Tesla was interested in the capacitance of the same wire when vertical and horizontal, which he measured by the usual resonance method, repeating it with two different capacitances in the primary as a check. Although the results from the two sets of measurements differ appreciably, the value obtained with the wire horizontal was somewhat higher in both cases. The formulae which Tesla used July 24 here yield 54.37 cm for the vertical wire and 58.43 cm for the horizontal. These values agree well with his measurements, especially the first set.*

Nov. 22-23, 1899

Tesla performs the measurement of small capacitances of the order of centimeters. These experiments illustrate the high level of the resonant method perfection in the form described on November 10. The abbreviation E.R. pertains to the magazine *Electrical Review* in which Tesla published a series of articles on X-rays in 1896 and 1897 (see comment of June 6, 1899).

* Tesla calculated the capacitance of conductor alone using the formula:

$$C_v = \frac{L}{2 \ln \frac{L}{R}} \text{ [cm]},$$

L being the length of the conductor in terms of cm and R being the diameter of the conductor in terms of cm.

Nov. 24, 1899

The capacitance of the thin conductor above the metal plain at the height of h cm, the other dimensions being the same as the above mentioned is given by the equation:

$$C_h = \frac{L}{2 \ln \frac{R}{h}} [\text{cm}]$$

To check the values for the inductance in the primary circuit (of the oscillator), which he had earlier measured by the voltage, current and frequency method (see October 30), Tesla repeats these measurements using the resonance method. He described the procedure on October 21 and made some measurements but did not follow them up with calculations. This time he made both measurements and calculates, but only for one $L_p C_p$ combination. He compares them with values derived from the table given November 8 using linear interpolation. He was probably satisfied with the agreement, and did not make further checks.

Nov. 25, 1899

He performs one more experiment to determine the capacitance of a vertical conductor with various current distributions. The experiment was uniquely thought up and the innovation comprised the adjustment with a harmonic frequency.

Nov. 26, 1899

He gives the description of some details of the structure with a metal sphere on top. He measures the capacitance of this system combined with a 344-turn coil and with a new "additional coil." He had measured the capacitance of the same structure, but without the protective cap and using the "additional" and "experimental" coils, on November 7. On November 12 he had made similar measurements using the 1314-turn coil. In the November 26 entry he refers to the result of November 7 with a new "additional" coil. There is also one more result obtained with an "additional coil", using the best method he had developed for detecting resonance (see November 13). This result, which differs appreciably from the others, is not mentioned on November 26.

The remark closing this entry suggests the possibility of a systematic error in the determination of resonance, and Tesla emphasizes that it has to be checked.

Dec. 2, 1899

Tesla provides a review of the methods for the purpose of experimental determination of the resonant state in the coil C (see figures 1-5). He connected the measurement circuit with the maximum coil excitation indicator in three ways: in the auxiliary circuit with the weak inductive coupling (figures 1 and 2); to a part of the coil (figure 3), and in series with the coil (figures 4 and 5). For the first time in the notes he also mentions here the series of possible indicator types, such as a microscopic spark, vacuum tube (the indicator of gas luminescence), any instrument with a heating filament (e.g. a bulb), or Cardew voltmeter.* He presented several ways to adjust the resonance indication sensitivity: by mutual coupling regulation (figures 1 and 2), by an adjustable resistor in an indicator circuit (figure 4) and by means of an autotransformer coupling (figures 3 and 5).

* Thermic instrument of the maximum current of 0.33 A. It was considered to be very successful at Tesla's time.

Dec. 3-4, 1899

He returns to the experiments with an oscillator and an "additional coil". As earlier, he calculates the resonant frequency by a simplified procedure.

In the measurement performed on December 4 he excluded the "additional coil". He measured the frequency by a resonant coil (i.e. the coil which becomes resonant with its own distributed capacitance). He determines "reduced" primary inductance by means of an interchange method.

Dec. 5, 1899

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He continues similar measurements as on the previous day but the secondary self-frequency is closer to operating frequency. This measurement, same as previous ones, finds "primary inductance reduced due to secondary reaction."

Excluding for the moment the "additional coil," the three frequencies which a Tesla oscillator with tight inductive coupling⁽³¹⁾ and equal natural resonant frequencies of the coupled circuits can be expected to produce are:

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad \omega_1 = \frac{1}{\sqrt{LC(1-k)}} \quad \omega_2 = \frac{1}{\sqrt{LC(1+k)}}$$

where k is the coupling coefficient. Thus ω_1 can be interpreted as the natural frequency of a circuit with capacitance C and inductance $L(1-k)$. For the primary inductance of Tesla's oscillator (see November 9) one obtains the "reduced" L , i.e. $L(1-k) = 23.094$ cm; Tesla measured $L = 24.063$ cm.

Dec. 6, 1899

On December 6 Tesla continues further measurements of "reduced primary inductance" with a changed circuit for resonance indication. Instead of a 344-turn coil, he puts the "additional coil" with 100 turns of significantly bigger dimensions. The photographs of the inside of the laboratory show the 100-turn "additional coil" raised above the floor in the center. With this coil Tesla again got similar results for the "reduced" inductance of the primary. However, aware of the indeterminacy of this "reduction," and hence also of the working oscillation frequency, he notes that the secondary should be broken at more points when the primary is used as a measuring inductance. This would ensure monochromatic oscillation of the oscillator by reducing the coupling of the primary and secondary (i.e. the circuit of the "additional coil"). The measurements with the secondary eliminated are more reliable, and the accuracy with which the values thought are determined depends mainly on the accuracy to which the inductance and capacitance in the exciting circuit of the oscillator are known.

Dec. 7-10, 1899

Tesla wants to determine the influence of the ground as a conductor, upon the resonant oscillator of the transformer. He performs the measurements on a circuit in the shape of the rectangular frame and its position is adjustable in relation to the ground surface. The rectangular frame is wound with 14 turns and connected in series with the 344-turn coil and one terminal of the coil frame is grounded. He does not give complete information how these coils are coupled with the oscillator. He determines the oscillator frequency change of the coil frame due to the varied height above the ground. He draws the conclusion that the resonant frequency of the tested circuit is increased with the increased height of the rectangular coil. Based on it, his conclusions are following: a) The ground does not act as a good conductor (coil in the vicinity of a conductive plane has smaller inductance due to induced currents); b) The capacitance of the coil towards the ground is a significant factor. The conclusions that Tesla develops on December 8 and 9 are justified, because it is a question of relative determination of the values, even if there would be a secondary influence, not allowing reliable oscillator frequency determination. On December 9 Tesla attempted to calculate the coil capacitance in the tested circuit as per previously described method (see June 28), but very soon he ended the discussion without giving a complete answer to the problem as a whole.

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Dec. 11-13, 1899

431

According to a note at the beginning of the month, he was working on patent applications relative to decomposing of gas mixtures by high voltages of HF current. Tesla wrote about this separation in his notes of June 26, 1899.

Doc. 14, 1899

He tests a new "additional coil" using previously described resonant method (see December 3). He includes the resonant transformer, and the "additional coil" excited via secondary terminals in the oscillator circuit. He obtains the estimation of the operating frequency by calculation on the assumption of "reduced primary inductance" and capacitance in the primary circuit. In respect of the undefined "reduction of primary inductance" (see the remark along with the comment on December 5), all the results are, as Tesla himself says, rough approximations of exact results.

Dec. 16, 1899

Tesla applies the formula developed previously for the determination of the resonant frequency coil on the rectangular frame (see the notes of July 11, 1899). As the formula was developed for a circular coil, he performs the correction of the results obtained for the square coil.* The correction contains multiplication of the achieved resonant frequency with a ratio of wire length in coils of rectangular and circular cross-section. At the end of the same day, there was a note that the experimental result approximately agreed with the theoretical one, but there was no description of the experiment.

During the period of December 17 to 31, Tesla and the photographer, Mr. Alley (this being the only full name mentioned in his notes) took 14 photographs, which he sent through the photographer to his friends, probably associates of the Century Magazine.**

In the archives of the Nikola Tesla Museum in Belgrade, a certain number of original negative plates were found (approximately the total of 63 photographs mentioned in the notes) and some of their contact-copies. Several so far not published but identified photographs are attached to Tesla's description of their contents. The photographs were copied and published (a total of 12 of them in articles^(1, 41)) for the purpose of completion. Except in one case when it was not established for which photograph out of four described corresponded to the found one, all photographs were designated by Roman numbers as in Tesla's notes.

Viewed as a whole, the photographs impress by their composition, content and technique. Undoubtedly the photographer, Mr. Alley and Tesla himself contributed to this effect. There are unusual photographs taken in moonlight and the photographs of the laboratory inside taken at the electrical discharge light. The photo transpositions were also made with a flashlight, as to see the contours of the devices (sometimes the human figure being incorporated "to reconcile the dimensions") and the artificial lightning was photographed, too. The electrical discharge at the oscillator secondary terminals of various coils was photographed with the devices being switched on and off several times in course of one shot. Many photos were made in this way, with very rich streamers and sparks, which made them nicer, but less realistic. Sometimes a hundred device switchings on and off were necessary to get only one photo.

Since the description of numerous photographs is such that no further comments are required, the attention would only be paid to some of them to point at facts or data, helping a reader to fully understand them.

Photo:
Main entrance to Colorado Springs Laboratory in the early phase of development. Tesla is looking through the door (Tesla's own photograph now at the Nikola Tesla Museum, Belgrade)

* By "circular" and "square" he considered the shape of cross section of the coil core.

** This magazine published Tesla's famous article The Problem of Increasing Human Energy in June 1900. Several photographs (a total of nine) of Tesla's laboratory in Colorado Springs were presented in the article. The experiments with a big oscillator were also mentioned, but the writing style was completely different from the one in the notes. While, for instance, the details of the apparatus were precisely described and its function commented on in the notes, in the article the events and the experiments were taken as proof of some of Tesla's hypotheses.

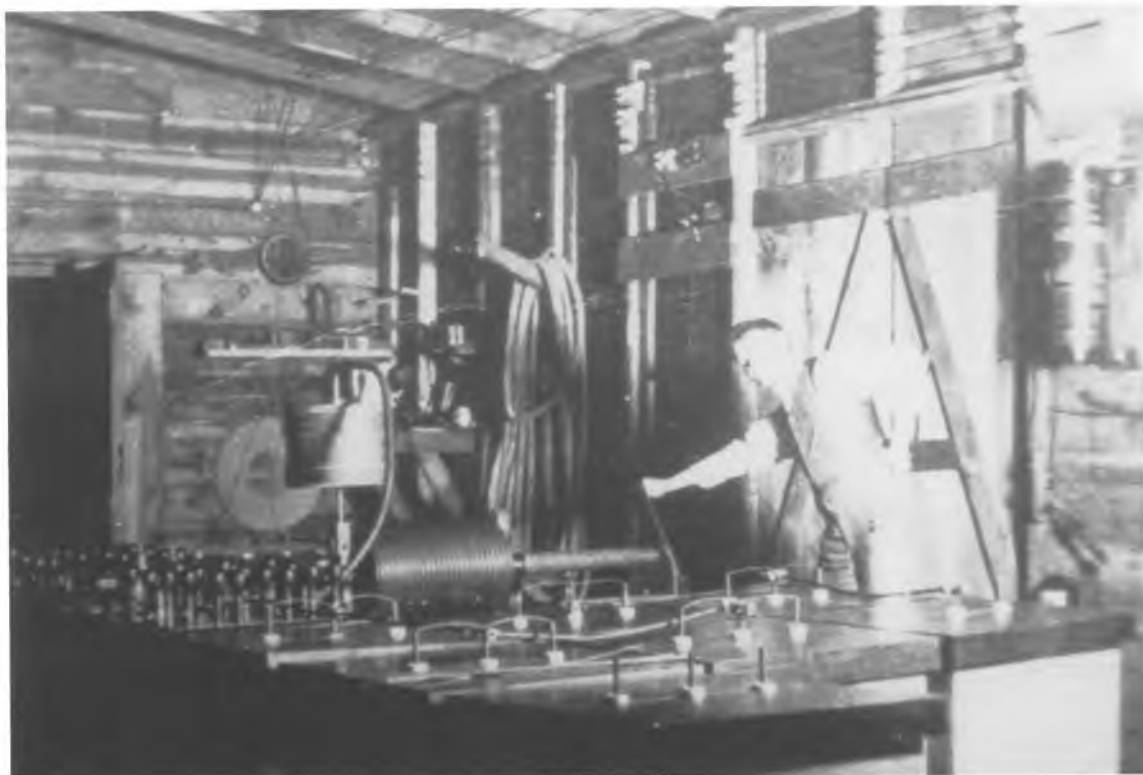


Photo:
Interior of Colorado
Springs Laboratory

Jan. 1, 1900

Photograph XVII shows lamps connected into a resonant circuit consisting of one square turn. According to the data Tesla gives, one side of the square was about 1.3 m away from the secondary coil of the oscillator. The capacitance of the oscillator circuit consisted of two parallel condensers. With the lamps paralleled.

Tesla calculates the inductance of the square turn from the formula for the inductance of two parallel conductors, as if there were two such pairs connected in series. The formula for a square coil (Fleming, p. 155):

$$L = 8l \left(\ln \frac{d}{r} - 0,774 \right),$$

yields a value 12.6% less than Tesla found. The calculated resonant frequency is therefore somewhat higher than it should be, so that the inductance of the oscillator primary, as Tesla calculates it, is still less. In fact, because of the tight coupling of the secondary, the oscillator must have been producing a complex spectrum, probably with its strongest component at the resonant frequency of the oscillatory circuit of the square coil.

In connection with photographs XVIII-XXI showing the secondary producing intense discharges, Tesla makes an interesting remark about signaling over great distances. Comparing this with other inductance apparatuses he had constructed, he concludes that one could expect signals to be picked up at distances of a thousand miles or more, even on the Earth's surface. The diary does not mention any measurements at great distances, but in an article⁽⁴⁴⁾ he published soon after finishing work at Colorado Springs, he states that he observed effects at a distance of about 600 miles.

Jan. 2, 1900

In this entry of 21 pages (the longest in the Notes) Tesla describes 11 photographs.

The explanation to photograph XXII concerning the transmission of energy from the excited primary circuit to the "additional coil" via the earth is similar to that he gave in 1893.⁽⁶⁾ The experiment to which the photographs refer to was made with the aim of estimating the power of the oscillator from the thermal effect of the HF currents. What Tesla calls the "total energy set in movement" would correspond to the total energy transferred to the condenser in the secondary (i.e. the power) if an energy of $\frac{1}{2}CV^2$ is transferred in each half-cycle. It can be shown that the active power dissipated in the circuit is much less than this and is inversely proportional to the Q-factor of the oscillating circuit.

The next photographs show a movable coil that lights up the bulbs by means of the high-frequency energy that it picks up. One end of the coil is grounded, the other free or just connected to a short piece of wire. The bulbs are inductively coupled to the resonant coil via the auxiliary secondary. Tesla gives no data about the distance of the resonant coil from the oscillator coil.

Tesla's commentary on photograph XXVII illustrates that he still retained a lively interest in the problem of electric lighting, even after a period of over ten years. His earlier discovery of the luminescence of the gas and not only the filament with HF currents was here again confirmed.⁽⁵⁾

In photograph XXVIII the bulb is connected in series with the terminal capacitive load. In the calculation Tesla does not use the "total energy set in movement" but assumes that $1/2CV^2$ of electrostatic energy is consumed in the bulb in each half-cycle. A similar comment applies to photograph XXIX.

Several times Tesla remarks that the principle energy transfer from the oscillating to the receiving coil takes place via the earth. He finds confirmation for this in the experiment described in photograph XXX. He found that the voltage induced in the receiving coil was greatly reduced if the ground connection was broken.

Photograph XXXI is an X-ray picture of a finger. Tesla's comments on this experiment illustrate his interest in this type of radiation, already referred to (see the commentary to June 6, 1899).

Jan. 3, 1900

After describing some photographs of the laboratory, in the commentary to photograph XLI Tesla explains some transformations of streamers. He mentions the splitting of streamers near the floor, splitting and reuniting, the phenomenon of more luminous parts on the streamers (which he then refers to as sparks), and the breaking up of sparks into streamers and fireballs. His remarks concerning the genesis of "fireballs" are particularly noteworthy. This phenomenon has been a source of interest since ancient times. Some references to it can be found on Etrurian monuments, in the works of Aristotle, Lucretius and the others.⁽⁶³⁾ Fireballs are considered to be a form of electrical discharge generated during thunderstorms. They are rare in nature, but a fair-sized body of observations has nevertheless been assembled upon which several theories of their origin have been formulated. Some hypotheses maintain that fireballs are an optical illusion (an opinion shared by Tesla until he produced them himself), others that they are the traces of meteors. The first genuine scientific approach to the problem was Arago's analysis of some twenty occurrences of fireballs in 1838. After the publication of his work they became a legitimate subject of scientific interest, but to this day have remained something of an enigma.

A fireball is a luminous sphere occurring during a thunderstorm. Fireballs are usually red, but other colors have also been observed: yellow, green, white and blue. Their dimensions vary, a main diameter being about 25 cm. Unlike ordinary lightning, fireballs move slowly, almost parallel to the ground. They sometimes stop and change their direction of motion. They can last for up to 5 seconds. Their properties vary greatly from case to case, so that it is believed that there are various types. According to Singer⁽⁶³⁾ it can be stated that as yet no single theory can explain the occurrence of fireballs in nature.

Despite numerous attempts, only a few types of fireballs have been created, and not entirely successfully, in the laboratory. These include the weakly luminescent fireballs generated when ordinary lightning strikes some object. Tesla mentions phenomena of this type several times as the result of sparks or streamers striking wooden objects (see e.g. photograph XL). According to recent theories, fireballs consist of a plasma zone created by electrical discharge. The latest research and calculations by Kapitsa⁽⁶⁴⁾ show that the lifetime of a fireball cannot be explained by the energy it receives at the time of genesis, but that it must receive energy from its surroundings. Kapitsa theorizes that this external energy is produced by a naturally created electromagnetic field. The small zone of ionized gas, created by the initial lightning or other electrical phenomenon during the storm, subsequently expands at the expense of the external electromagnetic field. The diameter of the plasma sphere is determined by the frequency of the external field, so that a resonance occurs. The usual dimensions of fireballs would require that the electromagnetic field have a wavelength of between 35 and 100 cm. According to this theory, standing waves created by the reflection of natural electromagnetic waves from the earth would play a certain role. The theory has obtained partial experimental confirmation, but there are still many points for which it is unable to give a satisfactory explanation. It has been found that to maintain a lump of plasma in air requires a power of the electromagnetic field of about 500 W, which is much less than power that can be produced by an electrical discharge. However, too little is known about natural electromagnetic waves to allow any reliable conclusions to be drawn.

Tesla's hypothesis on the origin and maintenance of fireballs includes some points that are also to be found in the most recent theories, but it also bears the stamp of the time. For instance, like Kapitsa, Tesla considers that the initial energy of the nucleus is not sufficient to maintain the fireball, but that there must be an external source of energy. According to Tesla this energy comes from other lightning passing through the nucleus, and the concentration of energy occurs because of the resistance of the nucleus, i.e. the greater energy-absorbing capacity of the rarefied gas than the surrounding gas through which the discharge passes. In nature the probability of other discharge passing through the nucleus of

a fireball is small, so Kapitsa's hypothesis that act via electromagnetic standing waves is more logical. It is possible that in Tesla's experiment the "passage" of a number of later discharge through the same nucleus was more frequent.

Jan. 6, 1900

In his comment on the photograph LV, Tesla explained another possible way of generating luminous spots in streamers. He predicted that a sort of a moving standing wave was formed along the streamer by two (or more) waves of different frequency. He had even described how two waves of close frequencies can be generated due to variations of parameters of the constants of the oscillator at different momentum of operation. Tesla referred to some earlier experiments but failed to provide sufficient explanation for complete understanding. Led by his thoughts, he described a future experiment with a "tamed" streamer in a large glass tube, which should confirm the existence of luminous spots in a streamer - two waves of close frequencies traveling along it.

Jan. 7, 1900

This is the last entry in Notes. On the last day (January 7, 1900) he spoke, apart from his usual description of photographs, about future experiments on his return (where to?). He said that the experiments, performed thus far, were satisfactory in view of his aim to "perfect the appliances and create a whole picture." The future appliance, of which he had been thinking already at that time, should be an advanced oscillator that would yield results superior to anything obtained earlier. It is known that Tesla, as soon as he returned to New York (according to the press he was there in February 1900), proceeded with the implementation of his idea of the "World Radio Station" starting the construction in 1900 on Long Island near New York City. Tesla was short of funds and neither his financier's Morgan assistance was sufficient nor that of the others; Tesla was compelled to give up further building of the station in 1905.



Theoretical foundation of operation of Tesla's oscillator was provided in 1895 by Oberbeck.⁽²⁹⁾ Here we shall present some of the results of the author mentioned, which can help the reader to comprehend the phenomena in Tesla's oscillator.

According to Oberbeck's theory the model of Tesla's oscillator was composed of two inductively coupled resonant circuits with a sparker in the primary circuit (figure 1P). The primary circuit consisted of inductance of the primary L_1 and capacitance C_1 . The secondary circuit was made by the secondary of transformer L_2 and capacitance C_2 . Mutual inductance of coils was marked M and sparker v in the primary circuit. High voltage is charged to condenser C_1 from a source of direct current or alternate current of low frequency.

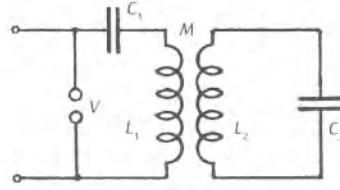


Fig. 1P. Model of Tesla's Oscillator.

Unlike the discharges from condenser in a simple oscillatory circuit analyzed by Lord Kelvin, discharge in the circuit of Tesla's oscillator was more complex due to the effect of the secondary oscillatory circuit. Had losses been neglected in oscillatory circuits, the current from the discharge would consist of two sinusoidal currents that were determined from the equation:

$$\omega_{a,b}^2 = \frac{L_1 C_1 + L_2 C_2 \mp \sqrt{(L_1 C_1 - L_2 C_2)^2 + 4k^2 L_1 L_2 C_1 C_2}}{2(1 - k^2) L_1 L_2 C_1 C_2}$$

where k stands for coefficient of coupling of transformer equal to $M/\sqrt{L_1 L_2}$. The above stated equation is obtained when differential equations are resolved for currents in the circuit presented in figure 1P in case of discharge from condenser C_1 through a short connected sparker.

Frequencies ω_a and ω_b are not equal even if oscillations of the primary and secondary circuits were the same. Then there are $L_1 C_1 = L_2 C_2 = 1/\omega_0^2$, giving:

$$\omega_a^2 = \frac{1}{(1+k)L_1 C_1} \quad \omega_b^2 = \frac{1}{(1-k)L_1 C_1}$$

For $k=0$, ω_a and ω_b are the same and equal to ω_0 . If k goes up, ω_a drops down and ω_b goes up. For $k=1$ (the biggest possible coupling), $\omega_a^2 = 0,5\omega_0^2$, and ω_b tends to become endless!

When $L_1 C_1 \neq L_2 C_2$, the flow of ω_a and ω_b with k is similar as in the quoted example, but no ω_a and ω_b are any longer the same for $k=0$. In case of $k=1$ only one solution is obtained:

$$\omega^2 = \frac{1}{L_1 C_1 + L_2 C_2}$$

To make Tesla's oscillator generate current of the same frequency, k should be selected so as to equal either zero or one. For a successfully operating transformer in the domain of high frequencies, it is practically impossible to achieve k to be one, so another possibility should be chosen - to make k zero. However, in spite of a theoretical solution, this is obviously senseless, because the primary circuit remains alone thus no oscillations can be excited in the secondary. For small values of k and in cases of equal individual resonant frequencies of the primary and the secondary two currents in Tesla's transformers shall have mutually close frequencies. Approximate values of these frequencies are:

$$\omega_a = \omega_0(1 - k/2) \quad \omega_b = \omega_0(1 + k/2)$$

The preceding discussion was concerned with the case of oscillation caused by charging condenser C_1 with a shortcut at place v . In the real situation, energy of the condenser would be quickly spent and oscillations would end in a short while. That is why energy must be added externally and at the time intervals when the primary circuit breaks down at place v . Breakdown of the circuit occurs when the spark dies in the primary circuit. From the moment of breakdown of the primary circuit, the secondary circuit remains alone and oscillations therein continue, determined by the parameters of the secondary circuit. Frequency of oscillation was given as $\omega_s^2 = 1/L_2C_2$, and in general differs from the frequency of the two components during the life of a spark in the primary circuit.

Depending on the duration of a spark in primary circuit, the form of the primary and secondary current shall change in Tesla's oscillator. The form of those currents is presented in figure 2P for a real oscillator, where subdued oscillations occur. In case of a long spark, multiple passage of energy from the circuit of the primary to the secondary shall occur and consequently the subdued oscillations are affected by losses in both circuits. Once spark terminated, the oscillations continue in the secondary circuit and are determined by the parameters of the secondary circuit. During sparking, the currents in the primary and secondary circuits consist of two components (similar as in the system without losses) with various factors of subductance.

The shape of currents presented in figure 2P.b is typical for the system of quick spark termination. Such a system of operation enables more efficient work of the oscillator, because there will be no passage of energy from one circuit into the other and no additional losses in the primary circuit either. Also, time interval in which the oscillator produces two oscillations is shorter and the one where the frequency of the oscillator is determined by the secondary circuit alone is longer.

According to Oberbeck's theory, the relation between the voltage in the condenser C_1 before the start of discharge U_1 and maximum voltage in the condenser C_2 for the circuits without losses and with the same resonant frequency is equal to $\sqrt{C_2/C_1}$. The momentary value of voltage in the condenser C_2 is:

$$u_2(t) = \frac{U_1}{2} \sqrt{C_1/C_2} (\cos \omega_a t - \cos \omega_b t)$$

The momentary value of current through C_2 is:

$$i_2(t) = \frac{U_1}{2} \sqrt{C_1C_2} (\sin \omega_b t - \omega_a \sin \omega_a t)$$

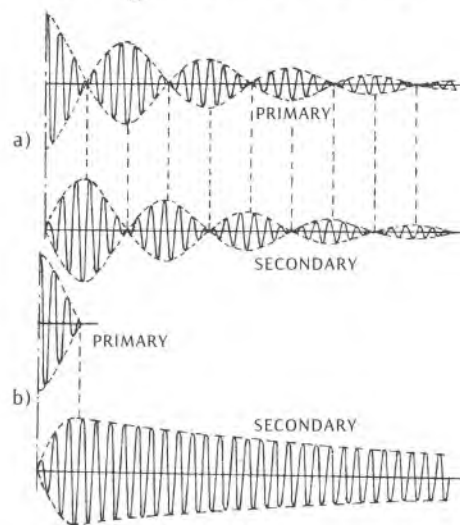


Fig. 2P. Voltages in the primary and secondary circuits of the Tesla Oscillator: a) long spark, b) quickly subdued spark.

Amplitude of higher frequency current is bigger. Real circuits require considerably more complex analysis and several authors have been undertaking it. Drude's analysis⁽⁶²⁾ showed that in case of circuits with losses terms for $u_2(t)$ and $i_2(t)$ were changed so far as the ratio of transformation in the primary and the secondary was somewhat decreased and each component of voltage or current was multiplied with a term of form e^{-at} (namely it exponentially decreases in time). Fleming and Dyke⁽³¹⁾ measured the resonant curves of the Tesla oscillator operating at the ordinary and subdued sparks. They showed that with the ordinary sparker k it must be less than 0.1, namely k less than 0.3 in case of subdued spark to prevent oscillation on two (or even three) frequencies. Numerous values for k should change with the selected parameters of the circuit, but stronger coupling should always be available with subdued spark, causing no multi-frequency operation of the oscillator. The Tesla oscillator with the third oscillatory circuit, which Tesla called the "additional coil" was theoretically analyzed only years later.⁽⁴⁶⁾

Appendix II: The Tesla Oscillator with additional coil(75)

The classical Tesla transformer with adjusted primary circuit and self-oscillating secondary coil, particularly when so fitted to achieve the highest possible secondary voltage with minimal capacitance load, cannot be exactly calculated on the basis of theory of circuits with concentrated parameters. Resonant frequency of a free secondary greatly depends on the position of that coil relative to the objects surrounding it (particularly metal ones) so that calculation of inductance and capacitance of the coil based on quasi-static analysis is not particularly successful. As of late a new approach was developed for the calculation of the secondary circuit based on the theory of helicoidal transmission line with a slow electromagnetic wave. In this case current wave is considered traveling along the coil at a speed close to light speed in free space and electromagnetic wave traveling along the axis of helicoid at a considerably lower speed.

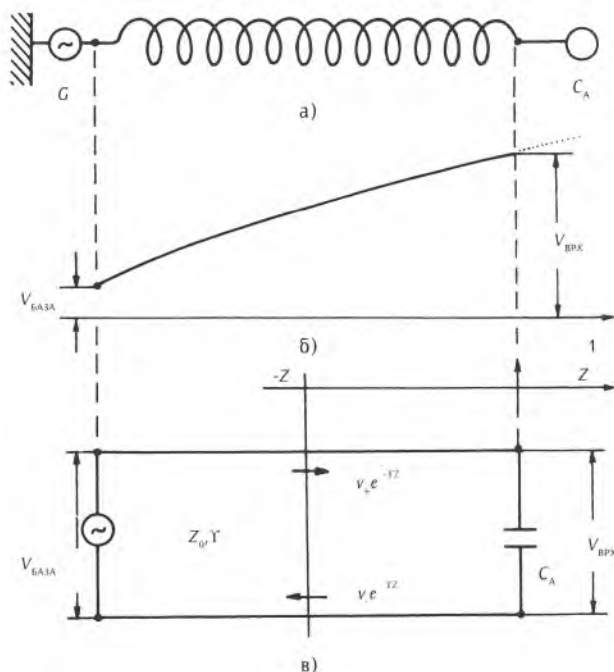


Figure 3P

Voltage at a cross section of excited helicoidal line (cf. figure 3P) is a sum of direct and reflected wave of voltage, which is analytically expressed by the known relation:



Photo:
In Colorado Springs
memorial Park,
near site of Tesla's
experimental station,
an historic marker notes
the operation.

$$V(z) = V_+ e^{-\gamma z} + V_- e^{+\gamma z}$$

Where $\gamma = \alpha + j\beta$, complex coefficient of propagation along helicoid. A component of direct wave at the line end is V_+ , while component of reflected wave is V_- . Distance is measured from the line end. The complex coefficient of reflection at the line end is a relation of reflected and direct voltage at the line end and expressed depending on the closing impedance Z_L and characteristic impedance Z_0 via relation:

$$\Gamma_2 = \frac{V_-}{V_+} = \frac{Z_L + Z_0}{Z_L - Z_0} = |\Gamma_2| e^{j\varphi_2}$$

On the excited side of the line, the complex coefficient of reflection is a relation between direct and reflected voltage at the beginning of the line:

$$\Gamma_1 = \frac{V_- e^{-\gamma l}}{V_+ e^{+\gamma l}} = |\Gamma_2| e^{-2\alpha l} e^{j\varphi_2 - 2\beta l}$$

The degree of standing waves at the line end is found from the relation:

$$S_2 = \frac{|V_+| + |V_-|}{|V_+| - |V_-|} = \frac{1 + |\Gamma_2|}{1 - |\Gamma_2|}$$

On the conductor without losses the degree of standing waves is not changing along the line and remains the same as at the beginning of the line. On the line with losses it depends on the input impedance and characteristic impedance, namely on the module of the coefficient of reflection at the line input:

$$S_1 = \frac{1 + |\Gamma_1|}{1 - |\Gamma_1|} = \tanh \left[\alpha l + \tanh^{-1} \left(\frac{1}{S_2} \right) \right]$$

for standing waves greater than 6, the preceding equation can be simplified:

$$1/S_1 = 1/S_2 + \alpha l$$

with an error less than 1%. In case when the end of line is capacitance loaded and without loss $S_2 \rightarrow \infty$, so that $S_1 = 1/\alpha l$.

To obtain maximum voltage at the open end of the secondary, the parameters of a helicoidal line are chosen so that it behaves at the working frequency as a quarter-wave line. If at the input of the line of l length the input voltage is then the voltage at the end line is expressed by relation:

$$V_{basis} = V_+ [e^{(\alpha + j\beta)l} + \Gamma_2 e^{-(\alpha + j\beta)l}]$$

length of the input voltage is then the voltage at the end line expressed by relation:

$$V_{top} = V_+ (1 + \Gamma_2).$$

By eliminating V_+ from the two preceding equations the ratio of excited voltage and voltage at the end of line is obtained.

$$V_{top} / V_{basis} = \frac{1 + \Gamma_2}{e^{(\alpha + j\beta)l} + \Gamma_2 e^{-(\alpha + j\beta)l}}$$

To obtain maximum voltage at the line, output it is necessary that the nominator of the above equation at the right side be the least possible. For further calculations, the coefficient of weakening and phase coefficient of helicoidal line are expressed in parameters of the units of length of lines: resistance, conductance, capacitance and inductance (r, g, l, c). In cases when weakening is not great, as can be considered in the observed case, the coefficient of weakening is found from the relation:

$$\alpha = \frac{r}{2Z_0} + \frac{gZ_0}{2} \approx \frac{r}{2Z_0}$$

because, usually conductance per unit of length is significantly lower than resistance per unit of length of the conductor. For the calculation of voltage at the end and beginning of the line it is necessary to know αl , namely rl , which in the case considered represents total resistance of conductor of helicoidal line. Phase coefficient depends on the factors of reduction of phase velocity of propagation of the phase of the wave along the axis of helicoid V_f and is calculated from the relation:

$$\beta = \frac{2\pi}{\lambda_g} = \frac{2\pi}{V_f \lambda_0}$$

To calculate coupling with other elements of the transformer it is necessary to know input impedance of the helicoidal transmission line and it is calculated based on the relation:

$$Z_{in} = Z_0 \frac{1 + \Gamma_2 e^{-2\gamma l}}{1 - \Gamma_2 e^{-2\gamma l}} = Z_0 \frac{1 + \Gamma_1}{1 - \Gamma_1}$$

For practical application of the above theory it is necessary to connect physical parameters of Tesla's transformer and parameters figuring in theoretical formulae. A physical helicoidal line is characterized by the diameter of the coil, thickness of wire, distance between conductors, length of turns and material from which the wire was made. On the basis of the mentioned data, the following is determined:

Factor of reduction of phase velocity V_f which figures in the term for the phase coefficient

$$V_f = \frac{v}{c} = \left[1 + 20 \left(\frac{D}{S} \right)^{5/2} \left(\frac{D}{\lambda_0} \right)^{1/2} \right]^{-1/2}$$

where λ_0 is wave length in free space, D is diameter of helicoid, S is the distance between two neighboring turns. All the values should have the same dimensions.

Weakening of helicoidal transmission line is calculated from the relation (for copper conductors):

$$\alpha l = \frac{198,44 \left(\frac{H}{D} \right)^{1/5}}{d_{mm} Z_0 \sqrt{f_{MHz}}}$$

where d_{mm} is diameter of wire in millimeters, f_{MHz} is frequency in mega Hertz, H is the length of the coil in the same unit as D . The third parameter is *effective characteristic impedance*:

$$Z_0 = \frac{60}{V_f} \left[\ln \left(\frac{4H}{D} \right) - 1 \right]$$

With the above theory it is possible to calculate two types of Tesla's transformers. One is the classical type with resonant primary of small inductance and the secondary in the shape of long coil that is calculated as a helicoidal line. The primary circuit excites helicoidal line and at the end of the line maximum voltage is achieved when electric length of helicoidal line is $\lambda_g/4$. If closing capacitance is located at the end of the line then the line must be shortened to achieve the maximum voltage.

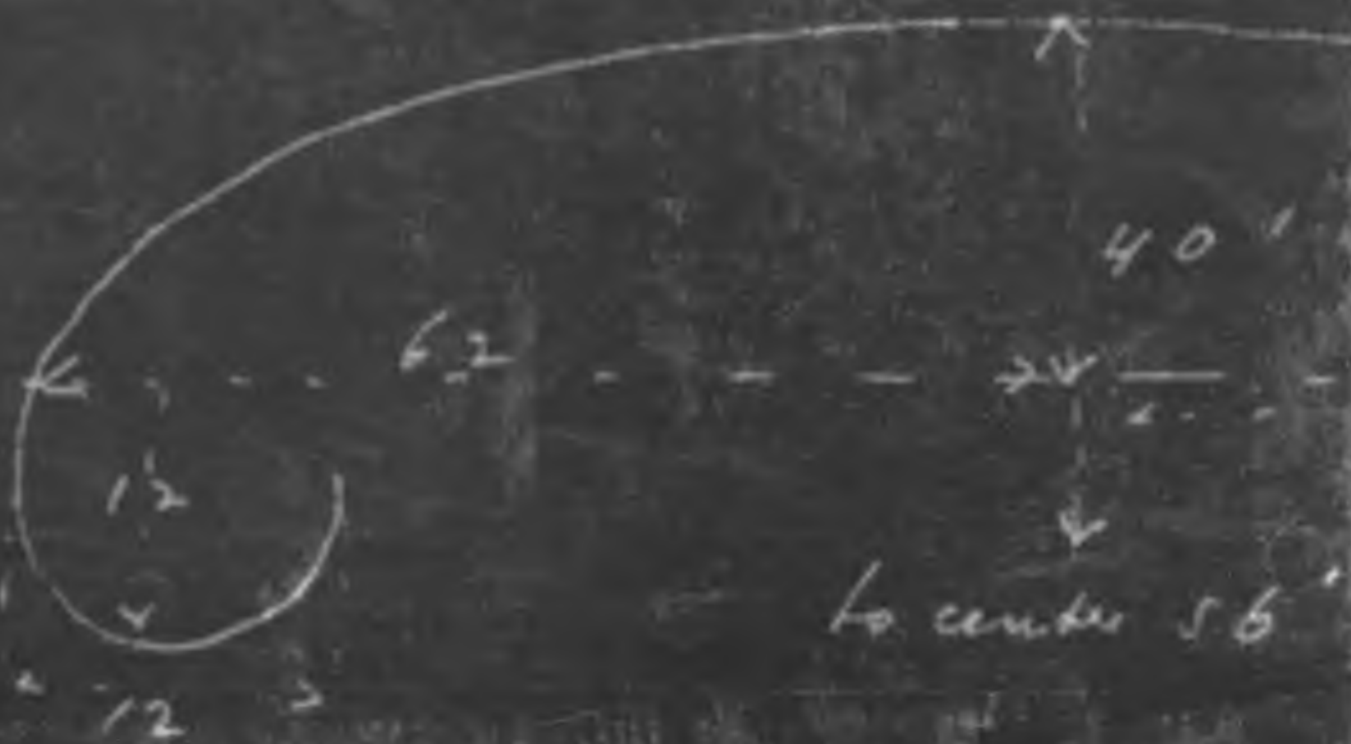
Another type of high voltage transformer, developed by Tesla in Colorado Springs, has three coils: primary and secondary coils are in a relatively strong inductive coupling and the third, extra coil is not practically inductively coupled with the first two. We may consider that the third coil practically behaves as a helicoidal line that achieves a high degree of multiplication of voltage if properly dimensioned and charged from a source of low impedance. Such a coil was connected by Tesla to the secondary of the transformer of high diameter (see, for instance, data about transformer, provided in

his Notes on October 2, 1899) and achieved voltages of the magnitude of 10 million volts. In doing so, he started from the voltage of the magnitude of 20 kV/133 Hz and achieved the increase of voltage by some 45 times. The increase in voltage of that magnitude in the domain of high frequency currents with which Tesla worked is not at all simple. In this case a simple Tesla transformer with two coupled oscillating coils requires ratio of capacitance of the primary and secondary of some 2,000. For such a ratio and capacitance of the secondary of 200 pF the primary capacitance should be above 0.4 microfarad, which is at least three times bigger than that which was sufficient for Tesla.

Tesla's theory of an additional coil was ultimately simple. He calculated (and then measured at 133 Hz) inductance of the additional coil starting from a simple formula of inductance of an endlessly long coil and connected it to the free end of the coil of the antenna pole so obtaining the third oscillating circuit in a weak inductance coupling with the other two coupled circuits. He experimentally established that considerably higher voltage is achieved than with only two coupled circuits, namely considerably stronger antenna current. He made no attempt at more complex analytical calculations, since experimental perfection for him was a pathfinder and inspiration for new variations. When the operation of Tesla's transformer with sparker is studied today, computer technique may be resorted to in scaling variations and after considerable trouble arrived at a series of replies that Tesla obtained with his simple theory and capability of experimenting and extraordinary successfully interpreting and applying of the results on his further investigations.

The operation of Tesla's transformer with two oscillating circuits excited by sparks is possible to describe by an analytical model based on the above described Oberbeck's model, but at considerable widening thanks to the computer.

Nikola Tesla
Research Notes
New York 1900-1901



Aug. 26. 1901

Transcriptionist's Comments

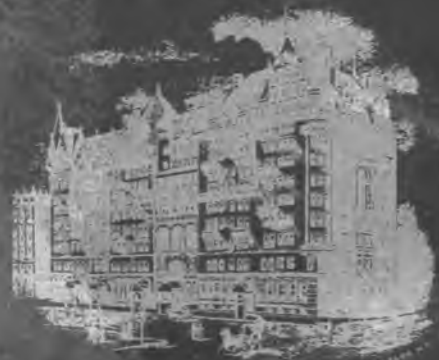
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THE WALDORF

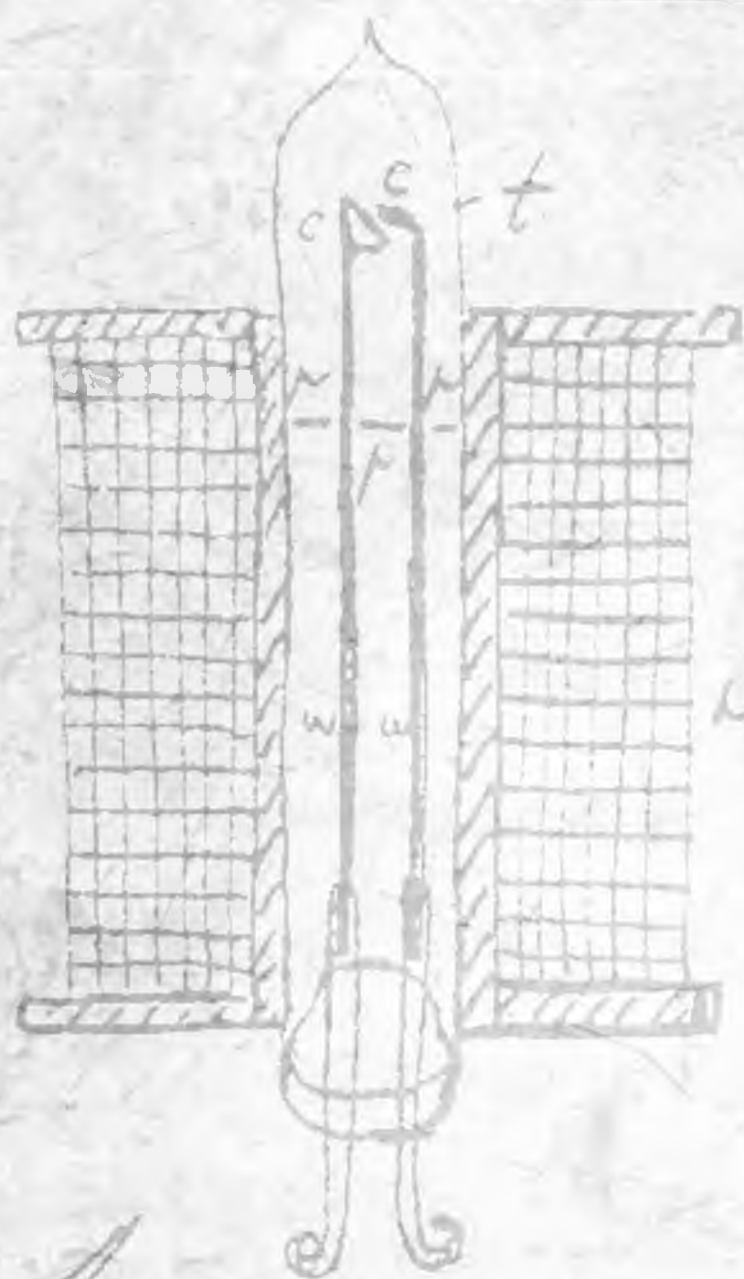
THE WALDORF-ASTORIA, New York
HOTEL BELLEVUE, PHILADELPHIA

The Waldorf-Astoria,

Fifth Avenue, 370 and 34th Streets
and Astor Court,



THE ASTORIA



Luna

19

During his eight month stay at Colorado Springs Tesla carried out a series of experiments with his spark-discharge oscillator. From the results obtained he came to the conclusion that the waves of his provisory transmitter spread through earth as concentric circles with the ground plate of the oscillator at the center and, accordingly, their intensity decreases linearly with the distance and not in proportion to the square of distance like the Hertzian waves. He became aware of the possibility of producing stationary waves of certain exactly defined wave-lengths. In September 1899 he succeeded in lighting a lamp of approximately 10 W "placed far out into the field," the exact distance from the ground plate being indicated in the Colorado Springs Notes, in the introductory comment for that month. Encouraged by these results he probably at that time began to consider the construction of a similar but more powerful transmitter which would not only enable reception of its telegraphic signals throughout the world but also the wireless transfer of power required for operation of industrial plants.

After his return to New York in January 1900 he began looking for a financier interested in the realization of such a venture. At the end of November 1900 he established the first contact with J. P. Morgan, the famous financial magnate, and on March 1, 1901 signed a letter of agreement that seemed to him extremely favorable for the realization of his aim in life. For \$150,000, which was a great sum of money at that time, he sold to Morgan 51% of interest in all the patents "having relation to or being useful in any way in connection with electric lighting and wireless telegraphy or telephony" already issued to him and to be secured by him later on, "for putting his discoveries and inventions into practical use."

At that time, immediately before signing the agreement and several months later on, Tesla continued rewriting some of his Colorado notes. Apart from this, in his laboratory in New York he performed a series of additional experiments in order to ascertain the effect of arrangement of coils in the oscillatory circuit on the inductivity and tuning. Reconsidering the phenomenon of stationary waves he came to a significant conclusion that the waves of his transmitter will be most effectively received at the opposite point of the terrestrial globe. He analyzed the feasibility of wireless transfer of energy to great distances not only with a view of sending Morse code but also with the intention to transmit printed text and images. He considered all of that to be attainable by his spark-discharge oscillator, however with some additional devices and improvements.

In the analysis of the possibility of wireless transfer of energy in the quantities and rates required for industrial purposes his estimates were very conservative. Finally, he ascertained that it could be feasible only by a successful use of resonant effects.

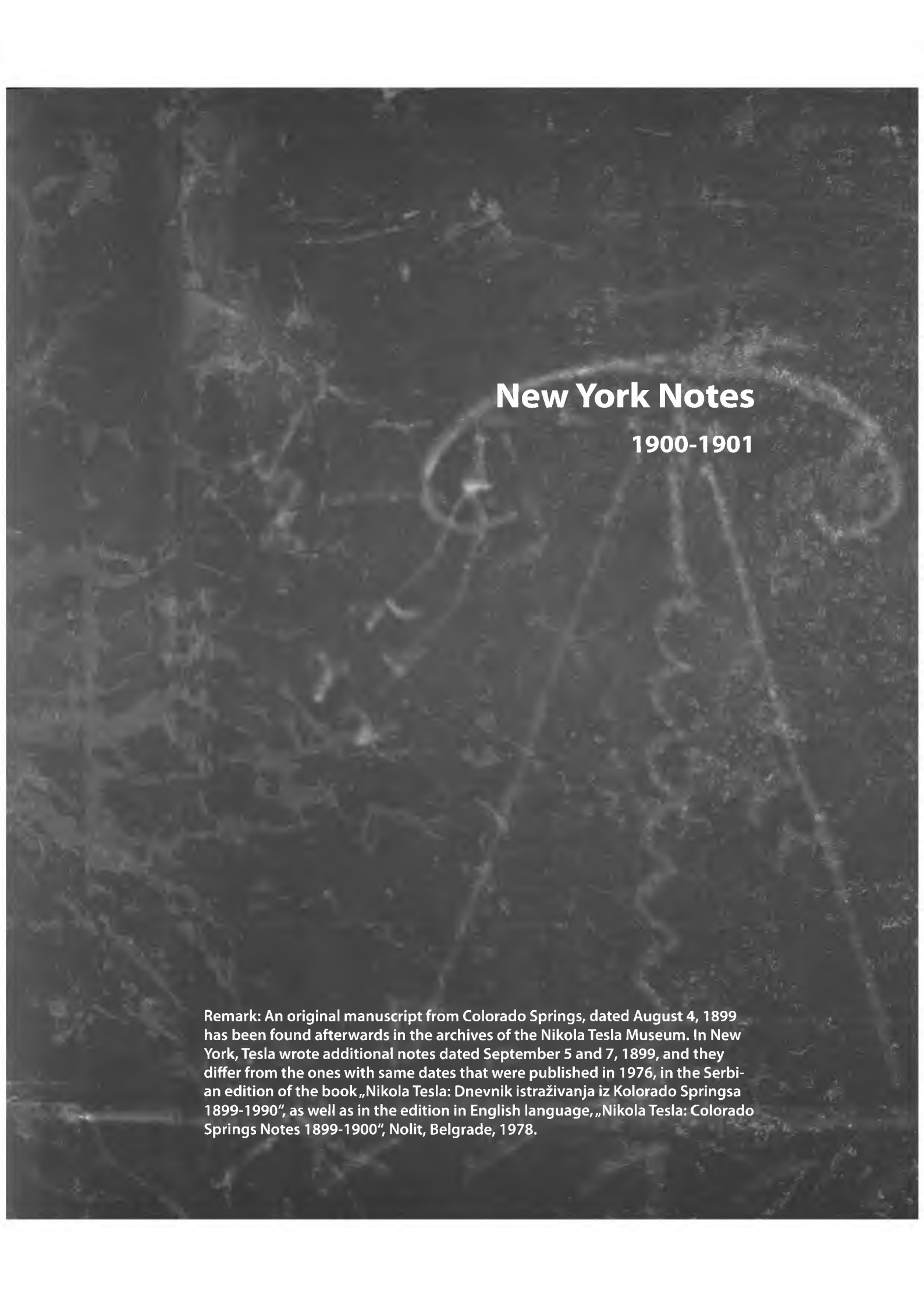
A general conclusion drawn from all these considerations was that for the attainment of this goal a powerful "magnifying transmitter" would be required, the terminal of which could be operated at extremely high tensions of several million volts. Aware of the fact that such a terminal would be the most expensive part of the transmitter, i.e. of the whole project, he considered various possibilities relating to its height (from 60 to 200 m approximately) and optimal geometry of its top. It is interesting to follow the development of the idea of the famous tower on Long Island through preserved calculations of capacitances and inductances and of the maximum possible tension at the top of the terminal and sketches of various hemispheres and spherical segments with toroidal appendends.

* In the preparation of these notes for publishing only a few orthographic errors (e.g. *chocking* instead of *choking*) as well as the units for capacitance (c.m. and M.F. instead of cm and μ F resp.), which could cause some ambiguities, have been corrected. Other errors have been retained.

All these considerations can be traced through these notes kept in New York, for the most part from May to August 1901. Some of them are arranged like the Colorado Springs Notes, as if he had intended to publish them at a proper time. The majority of them, however, are hardly legible drafts with orthographic errors* and lapses in usual arithmetic operations as if they had been written in great haste, just to keep in mind a new idea deserving further elaboration.

Despite their imperfectness these notes are significant for the history of science. Together with the preserved documents from Long Island i.e. from Wardencliff, they will surely contribute to better and more complete comprehension of Tesla's greatest, though unfinished project.

Milan Ćirić, PhD



New York Notes

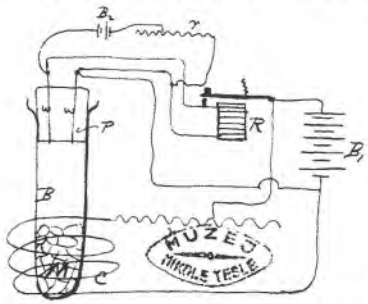
1900-1901

Remark: An original manuscript from Colorado Springs, dated August 4, 1899 has been found afterwards in the archives of the Nikola Tesla Museum. In New York, Tesla wrote additional notes dated September 5 and 7, 1899, and they differ from the ones with same dates that were published in 1976, in the Serbian edition of the book „Nikola Tesla: Dnevnik istraživanja iz Kolorado Springsa 1899-1900“, as well as in the edition in English language, „Nikola Tesla: Colorado Springs Notes 1899-1900“, Nolit, Belgrade, 1978.

Colorado Springs Aug. 4. 1898.

Sensitive receiver for detecting feeble disturbances.

This device is based on a principle briefly described on a previous occasion that formed the subject of experiments about two years ago. Time was prevented further investigation but I was convinced that a good device possessing certain advantages over those usually employed may be developed on this principle. Work is now to be resumed and plan outlined below is to be adopted.



Referring to the diagram B is a bottle containing volatile or evaporable (easily) material M closed by a plug P through which pass two wires w . The two wires are connected to a battery B_2 in series with an adjustable resistance

x . To the wires is also connected a relay R of extremely high resistance. By means of an adjustable resistance x , that is connected in series with a coil C surrounding the bottle, to another stronger battery B , the current of the latter through the convolutions of coil C may be so graduated that the material M is evaporated or volatilized at the required rate. Now the material is such that a minute film of it deposited between wires w will make a path of a high resistance, but sufficiently low to shunt the relay more or less. When this film is deposited, the resistance x is so adjusted that the relay is just balanced

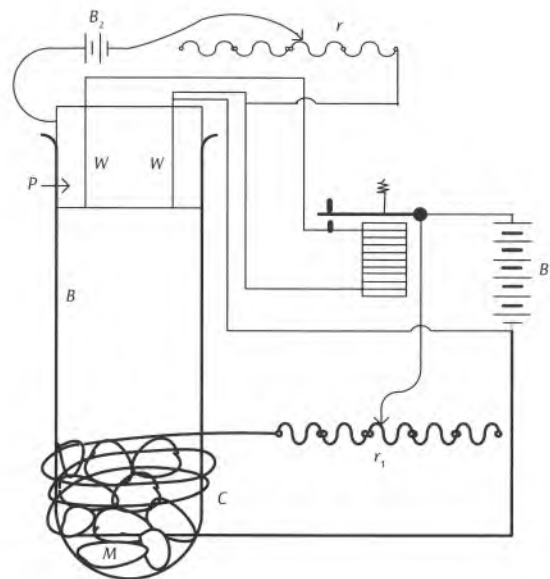
Aug. 4, 1899

Sensitive receiver for detecting feeble disturbances

This device is based on a principle briefly described on a previous occasion which formed the subject of experiments about two years ago. Pressing work prevented further investigation but I was convinced that a good device possessing certain advantages over those usually employed may be developed on this principle. Work is now to be resumed and plan outlined below is to be adopted.

Referring to the diagram B is a bottle containing volatilisable or evaporable (easily) material M closed by a plug P through which pass the wires $w w$. The two wires are connected to a battery B_2 in series with an adjustable resistance r . To the wires is also connected a relay R of extremely *high* resistance.

By means of an adjustable resistance r_1 that is connected in series with a coil C surrounding the bottle, to an other stronger battery B_1 , the current of the latter through the convolutions of coil C may be so graduated that the material M is evaporated or volatilised at the required rate. Now the material is such that a minute film of it deposited between wires $w w$ will make a path of a high resistance, but sufficiently low to shunt the relay more or less. When this film is deposited, the resistance r is so adjusted that the relay is just balanced.



Sept. 5, 1899
From old notebook
Colorado Springs

The large ball was elevated until the secondary of oscillator was in resonance with the primary there being 7 turns on each side and 13 turns of Regulator in the primary circuit.

An old coil was taken and its vibration determined. The coil was wound in one layer with two kinds of wire: Wire No 22 about $\frac{3}{5}$ of the layer from one end; wire No 18 the rest of the layer. The drum was $25\frac{1}{4}$ " diam. When connected with the thick wire to the ground with this wire free resonance was obtained with 6 turns on each side and 7 turns of Regulator; when turned upside down, that is, with the thin wire connected to the ground and the thick free, resonance was with 6 turns on each side and 10 turns of Regulator in circuit. In the former case, when the coil was connected to the water main about 300 feet away from the shop it gave a 3" spark to the body of an assistant; when turned the other way spark was much smaller but thicker. Experience shows that in coils for receiving the last turns should be of thinner wire. The receiving circuit should be in fact thickest on ground connection and the conductor ought to taper down towards the free end. The section at any point may be calculated from data which give the current. A telephone connected in shunt gives strong sound when a wire added to the free terminal and placed in a certain position, so as to slow down the vibration and bring it in resonance with the secondary system of oscillator in shop. The sound in the telephone was chiefly due to the low frequency break – about 3000 per second but a very high note was barely audible between the breaks. The sound in the telephone ceased as soon as wire was slightly displaced and resonating condition disturbed.

Note: no spark in secondary oscillating system.

Sept. 7, 1899
From old notebook
Colorado Springs

The wire No 22 on coil experimented with on Sept. 5, was taken down and wire No. 18 wound up. The total number of turns was now 495. The secondary oscillatory system was used as before and the coil was connected to the water pipe with one end the other end free **straight up**. In the succeeding test turns were gradually cut off from the bottom. Spark length was noted in the way described.

Results:

Number of turns	Spark to body no capacity on terminal	Spark with small terminal sphere
495	$\frac{3}{8}$ "	smaller
470	$\frac{7}{16}$ "	"
460	$\frac{7}{16} + \frac{1}{64}$ "	"
450	$\frac{7}{16} + \frac{1}{37}$ "	"
440	$\frac{9}{16}$ "	almost same
435	shade more	rather less
430	almost $1\frac{1}{16}$ "	$\frac{1}{2}$ "
425	$\frac{3}{4}$ "	$\frac{1}{2}$ "
420	$\frac{3}{4}$ " full	"
415	$\frac{7}{8}$ "	"
410	1"	$\frac{9}{16}$ "

Number of turns	Spark to body no capacity on terminal	Spark with small terminal sphere
405	1 $\frac{3}{16}$ "	$\frac{5}{8}$ "
400	1 $\frac{1}{4}$ "	$\frac{5}{8}$ "
395	1 $\frac{1}{4}$ "	$\frac{5}{8}$ " full
390	1 $\frac{1}{4}$ "	$\frac{5}{8}$ "
385	"	"

By further reduction of turns the spark continuously diminished. The true tone was obtained with from 85 – 400 turns. The experiment shows bad effect of coils of comparatively large diameter. It also shows increase of effect of wire № 18 over wire № 22. It is evident that small resistance, great self-induction small capacity are the requirements for sharp and strong response in these circuits.

June 2, 1900

Note about method of insulating conditions by freezing:

Insulating effected by cooling $\left\{ \begin{array}{l} \text{both ways} \\ \text{one way} \end{array} \right\}$ in conductor

Continuously maintaining frozen

Insulating and fastening?

Continuously maintaining fastened

Diminution of resistance considered

Cheap conductors to consider

Heat supplied at rate computed

Cooling agents {gas, fluid liquid}

Special care when air is used

Special provision for desiccating?

Conveyance of material to be utilized individually

Iron as sheet metal considered

Consideration as to pressure and temperature, curves

Chart of curves including all considerations and showing most economical relations of all.

Utilization of river beds, channels natural or artificial

Underground and deep sea conditions specially considered

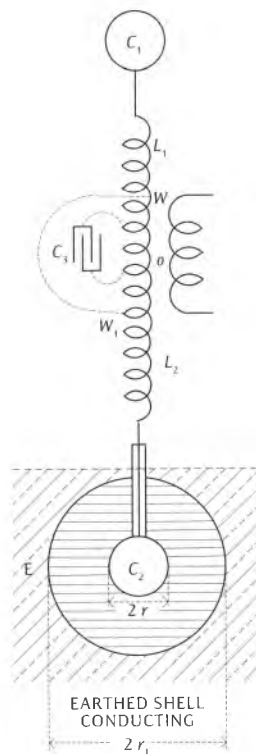
Particular case of insulating in places, the rest of conductor being otherwise protected as by air.

Plans and designs special cases: Niagara

July 23, 1900
From old notes

In my system of transmission through Earth by conduction for exciting tuned circuits the maximum pressure should be at C_1 . This is always the case when the length of conductor from ground to loop is $\frac{1}{4}\lambda$ or $\frac{n}{4}\lambda$, n being uneven number. But the condition may be satisfied also by making the conductor $\frac{1}{2}\lambda$ or an even number of wavelengths. This can be done by arrangement illustrated when $C_1 = C_2$, it being understood that C_1 is the capacity of the sphere or terminal C , while the capacity of C_2 is taken with reference to the conducting enclosure* E . Expressed in symbols, $C_2 = K \frac{r r_1}{r_1 - r} = C_1$.

* Inclosure in the manuscript - Ed.



If we use oil K will be about $= 2$. The same arrangement lends itself also to greater lengths of wire than $\frac{1}{2}$ wave for evidently so long as the capacities are equal the system will have the neutral point in middle as in ordinary coil and the potentials on top and bottom will be both respectively plus and minus maximum.

The conductor $L_1 L_2$ may be excited in any way as through primary P . A condenser C_1 may be advantageously employed to shunt. The more the capacity C_2 gets preponderating over C_1 the more the neutral point o will shift lower and finally when C_2 practically infinite then the vibration will be one half as fast and the conductor $L_1 L_2$ will be $\frac{\lambda}{4}$ or $\frac{n}{4}\lambda$ as explained above. The adjustment can be made by taking two points connecting and shifting up and down along $L_1 L_2$. There will be a maximum in middle position ww_1 . With fine spark gap to Earth also easy to investigate. No sparking at neutral point.

Aug. 5, 1900

1 lb. water 1°C, 1390 ft lbs

To carry 1 H.P. we have $\frac{33000}{1390} = 24$ lb (about) 1°C.

Now 1 lbs. air has specific heat in ratio $\frac{23}{100}$ smaller hence we want for carrying 1 H.P. $\frac{100}{23} \cdot 24$ lbs air 1°C.

If the air be -200° less than in closure we have $\frac{100}{23} \cdot \frac{24}{100} = \frac{12}{23} = 0.52$ lbs. for each H.P. to carry off.

Now 1 lbs. of water is $\frac{1}{62}$ of a cub. foot.

Since air is 776 times lighter we shall have $\frac{776}{62} = 12.5$ cub. feet per lb. or 0.52 lbs of air will have volume of $0.52 \times 12.5 = 6.5$ cub. feet.

But as air is 200° colder its volume for the above weight will be much less about $6.5 \left(1 - \frac{200}{273}\right) = 6.5 \times 0.27 = 1.755$ cub. feet.

This will carry off 1 H.P. (per minute). Therefore to carry off at the rate of 1 H.P. we have $\frac{1.755}{60} = 0.03$ lbs cub. feet (nearly) per second.

Assume hollow pipe 1" square. There would go through this pipe at the velocity of feet per sec. a volume of $12v$ cub. inches or $\frac{12v}{1728}$ cub. feet. Hence $\frac{12}{1728} \cdot v = 0.03$ this gives for $v = 144 \times 0.03 = 4.32$ feet.

Otherwise stated we want to carry off 1 H.P. in velocity of 4.32 feet per second in a pipe of 1 square inch section with air. Now it is easy to have 1000 feet. This would be competent to carry off $\frac{1000}{4.32} = 230$ H.P. with return pipe 460 H.P.

If same copper used loss in Buffalo would be $1/5$ of 20% that is 4%. Therefore total power 11500 H.P.!

O.K.

Sept. 3, 1900

According to Hensel's 162 gram Cellulose require 176 Litres CO_2 and 352 Litres oxygen free furthermore 100 grams leaves ... 1 Litre N.

From this take for instance a tree of ordinary size. The weight may be 4000 lbs. = $4000 \times 450 = 1\,800\,000$ grams approx. This tree will take up more than $\frac{1800000}{162} \cdot 176 = 1900000$ librae CO_2 and will give off more than 3,8000000 librae O. Not to speak of the N of the leaves. A square mile may have 10000 trees. This would want 19,000,000,000 CO_2 and free 38,000,000,000 Litres O!

1 cub. foot has about 60 librae this would make $\frac{19000000000}{60} = 300,000,000$ cub. feet CO_2 bound and 600,000,000 cub. feet O.

A cubic mile has roughly 5300×5300 cub. feet hence $\frac{600000000}{53 \times 53 \times 53 \times 10^6} = \frac{600}{53 \times 53 \times 53} = \frac{6}{1489}$ cub. miles of oxygen free and $\frac{3}{1489}$ cub. CO_2 bound for every mile square of forest. Or 496 square mile forest binds one cub. mile of CO_2 and free 2 cub. miles Oxygen.

Say roughly

1000 square mile forest binds 2 cub. miles of CO_2 and free 4 cub. m. O.

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THE WALDORF
THE WALDORF-ASTORIA, NEW YORK
HOTEL BELLEVUE, PHILADELPHIA
THE STRATFORD, PHILADELPHIA
BULLITT BUILDING RESTAURANT, PHILADELPHIA



THE ASTORIA

New York July 23 1900

from old note



In my system of transmission through earth by conduction for existing lines creates the maximum pressure should be at C_1 . This is always the case when the length of conductor from ground to top is $\frac{1}{4}\lambda$ or $\frac{3}{4}\lambda$ & being uneven numbers. But the condition may be satisfied also by making the conductor $\frac{1}{2}\lambda$ or an even number of wavelengths. This can be done by arrangement illustrated when $C_1 = C_2$ & being understood that C_1 is the capacity of the space or terminal C_1 while the capacity of C_2 is taken with reference to the conducting surface E . Expressed in symbols

$$C_2 = K \frac{\pi r_1^2}{r_1 - r_2} C_1 \text{ If } r_1 \text{ is an oil } k \text{ will be about } = 2.$$

The same arrangement lends itself also to greater lengths of wire than the same for evidently as long as the capacities are equal the system will have the neutral point in the middle as an ordinary cord and the potentials on top and bottom will be both respectively plus and minus maximum. The conductor L_1 may be excited in any way as through primary P . A condenser C_2 may be advantageously employed to shield. The more the capacity C_2 gets proportionately over C_1 the more the neutral point o will shift back and finally when C_2 practically infinite then the vibration will be one half in fact and the conductor L_1 will be $\frac{1}{4}\lambda$ or $\frac{3}{4}\lambda$ as explained above. The adjustment can be made by taking two points connecting and shifting up and down along L_1 . There will be a maximum in middle position o . & fine sparks to earth also easy to investigate. neutral point.

Nov. 24, 1900

459

Consider Earth as straight conductor of length $l = 8000$ miles and mean diameter $r = 4000$ miles. That is $l = 5280 \times 8000 \times 12 \times 2.54 = 1278 \times 10^6$ cm.

$r =$ accordingly $r = 639 \times 10^6$ cm. This would give for inductance of Earth

$$L = 2 \times 1278 \times 10^6 [\log_e 4 - 0.75] = 2 \times 1278 \times 10^6 \times 0.6363$$

$$L = 1.63 \text{ Henry}$$

Capacity say $710 \mu\text{F}$.

$$\text{Hence period roughly } T = \frac{2\pi}{1000} \sqrt{1.63 \times \frac{700}{9 \times 10^5}}$$

$$T = \frac{6,28 \times 10.7}{3 \times 10^5} = 0.00022 \text{ roughly.}$$

That is to say the Earth will vibrate 454 times per sec.

$$\text{The wave would be } \frac{186000}{454} = 410 \text{ miles.}$$

Nov. 28, 1900

Take one of the experiments in Colorado with a comparatively small movement. A sphere 20 sq. feet surface is charged to a pressure of 3 million Volts. Say the wavelength is 4 miles. That means the half 2 miles. The density if uniformly distributed would be reduced in the ratio $\frac{20}{x}$ where x is the area of a cut out circle 2 miles wide. Suppose this circle to progress up to the equator it would be cylindrical and x would be

$$X = 2\pi D \text{ sq. miles} \quad D = 8000 \text{ miles}$$

$$= 6.28 \times 8000 = 6280 \times 8 = 50240.$$

Roughly say $X = 50000$ sq. miles or say

$$50000 \times 30\,000\,000 \text{ sq. feet.}$$

(over)

Hence the density would be $\frac{20}{15 \times 10^{11}} = \frac{2}{15 \times 10^{10}}$ smaller than on sphere. Since pressure and density are proportionate this would mean that the portion of ground would be charged to a pressure of $\frac{2 \times 3 \times 10^6}{15 \times 10^{10}} = \frac{6}{15 \times 10^4}$ Volts.

$$\text{The maximum will be about } \frac{3}{2} \cdot \frac{6}{15 \times 10^4} = \frac{9}{15 \times 10^4} = \frac{3}{5 \times 10^4} \text{ Volts.}$$

If a synchronized circuit be placed with a magnifying factor of 10^6 (which is easy) we would be able to charge a sphere like the one on the sending station with a pressure of $\frac{3}{5}$ Volt.

Capacity is say 40 cm. Energy would be per charge

$$\frac{1}{2} \times \frac{9}{25} \times \frac{40}{9 \times 10^{11}} = \frac{1}{50} \times \frac{40}{10^{11}} = \frac{4}{5 \times 10^{11}} \text{ Watts.}$$

THE WALDORE

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THE STRATFORD, PHILADELPHIA
BOLDT'S RESTAURANT, PHILADELPHIA

SEE C POINT BACK

MUZEO
MIKOLETESLE

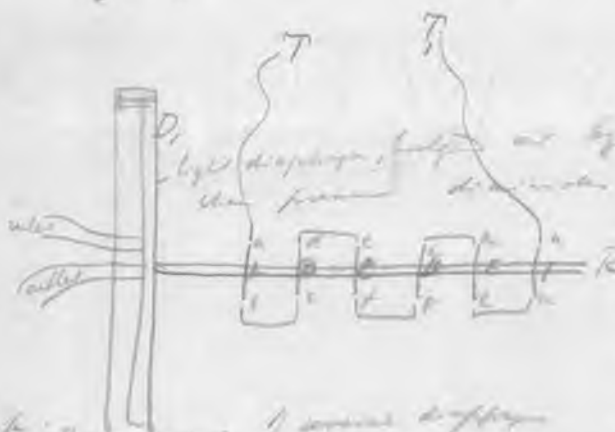
Fifth Avenue, 33rd and 34th Streets
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THE ASTORIA

New York Nov 24 1901

Measured method from controlling waves of pulse
determining by waves or impulses of small intervals.



At the [4]
XXXX-1111

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and *Fig. 301* and *Fig. 302* and *Fig. 303* and *Fig. 304*
and *Fig. 305* and *Fig. 30*

The diaphy D_1 is related by entering rules of plan
(iii) for previous or entering the outlet. The
small vibration of diaphy are multiplied in a
all signs in relation to first relation in current P.P. are
of diaphy. Difference There is very few
of both of both of both

Now with 100,000 charges per sec we have total energy movement $\frac{10^5 \times 4}{5 \times 10^{11}} = \frac{4}{5 \times 10^6}$ Watts. But this can be in the most intense action of Colorado apparatus $\frac{4}{5 \times 10^5}$ Watts.

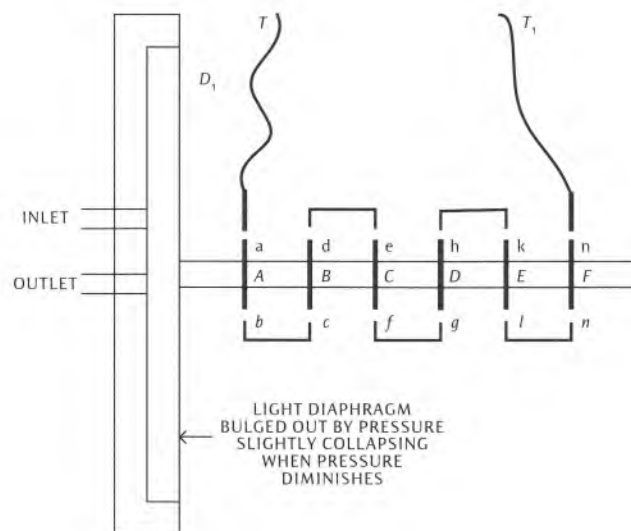
Note. As observed in Colorado Experiments the effect on the opposite side of Earth will be much stronger, hence with plate or roof on building and capacity a little over 100 meter diam. we would get about 200 times that is $\frac{4 \times 200}{5 \times 10^6} = \frac{8}{5 \times 10^4}$ Watts which is far more than necessary.

P.S. Increase sphere or capacity 2000 times we have $\frac{4}{5 \times 10^6} \times 2 \times 10^3 = \frac{8}{5 \times 10^2}$ roughly $\frac{1}{50}$ Watt perfectly sufficient. In the * more easy. * Illegible

— . —

Means and method for controlling waves of great intensity by waves or impulses of small intensity

Light diaphragm, bulged out by pressure, slightly collapsing when pressure diminishes



Note. This arrangement of several diaphragms to lengthen stroke.

$a - n$ small gaps through which arc discharge passes. $A - F$ wires of aluminium or plates (any other metal). Very light, preferably on insulating rod R fastened to diaphragm D_1

The diaphragm D_1 is vibrated by controlling inlet of fluid (air) under pressure or controlling the outlet. The small vibrations of diaphragm are multiplied since all gaps in series and great variations in circuit TT_1 are obtained.

P.S. Pressure may be on both sides of diaphragm. Differential control of both spaces. This is very good.

How much capacity is it practicable to use? A wire about 200 feet high will have say 300 cm. Hence to have 300 000 we have 1000 such wires!

Jan. 24, 1901

Motor windings for new oscillator light plant small, 2 mica condensers, primary with secondary winding about 300 V on latter. Break mercury on mercury.

Take wire N^o 19 as before calculated we shall have 24 turns per inch, on little core 1 $\frac{5}{8}$ " clear, 39 turns per layer. This allowing for paper between layers will give 10 layers. Space clear is $\frac{5}{8}$ ". Consequently we shall have total $39 \times 10 \times 2 = 780$ turns.

We have assumed before 10,000 lines per sq. cm. Now determine Ampere-turns on armature. Now length of conductor is as follows:

1 conductor 1" or 2.54 cm. Call N number of turns. We shall have sizes of 18 holes, 4 holes are not included on each side seven holes. Say that x is number of turns in each hole we shall have total $7 \times x$. Total length of active conductor: 7×2.54 cm.

Velocity v will be as follows:

Mean diam. 47 cm. 2400 per minute gives 40 per second or $47 \times 40 = 1880$ cm per sec = v .

We shall have now e.m.f. counter on motor for that speed:

Now we shall have in air lines as follows.

Sect. of armature total is 8.875 sq. cm. Section of air gap total 47.60 cm sq. As there are 10000 lines per sq. cm in armature there will be through the air per sq. cm $\frac{8.875}{47.60} 10000$, or per sq. cm 1864 lines.

$$\text{Hence } E = 220 \times 10^8 = 7x \times 2.54 \times 1864 \times 1880;$$

$$x = \frac{22 \times 10^9}{17.78 \times 1864 \times 1880} = \frac{22 \times 10^9}{623 \times 10^4} = \frac{22 \times 10^4}{623} = 353 \text{ turns.}$$

* Illegible

Conclusion: wind ten layers N^o 19 wire * series

Arm. $\left\{ \begin{array}{l} \text{N}^{\circ} 24 \text{ if possible} \\ \text{N}^{\circ} 26 \text{ probably} \end{array} \right\}$

Second estimate lees

Take 12 layers N^o 20 wire about 43 turns on layer

Arm. N^o 26 wire turns in each groove: 300 turns.

Approximate theoretical estimate of constant determining wavelength of electrical disturbance through Earth

Taking Clarke spheroid of 1878 the average radius of Earth is:

$$\left. \begin{array}{l} 6,378,301 \text{ Equatorial} \\ 6,356,515 \text{ polar} \\ \hline 12,734,816 : 2 = \end{array} \right\} \text{average radius } r = 6,367,400 \text{ cm}$$

This may be adopted as the electrostatic capacity or in farads:

$$\frac{63674 \times 10^4}{9 \times 10^{11}} = \frac{63674}{9 \times 10^7} = \frac{7075}{10^7} = 0.0007075 \text{ farad.}$$

In miles, being convenient to calculate in larger numbers,

$$\left. \begin{array}{l} \text{equatorial radius is } 3963.296 \text{ miles} \\ \text{polar} \quad \quad \quad 3950.738 \text{ " } \end{array} \right\} \text{average radius } 3957 \text{ miles approx.}$$

The diameter is thus 7914 miles.

Let us now suppose that there would be n waves, then the Earth's surface will be divided in $2n$ parts and the average capacity of each part will be $\frac{1}{2n}$ th of the whole capacity of the globe. Similarly the inductance of each part on the average may be assumed to be $\frac{1}{2n}$ th of the whole inductance.

Determination of approximate inductance and capacity per mile.

For the present purposes it will be sufficient to consider the Earth as a cylindrical conductor of same capacity. Call R capacity of the globe = r . The capacity of cylindrical conductor of same length would be $\frac{l}{2 \log_e \frac{l}{r_1}} = r$. Now $l = 2r$. Hence $\frac{2r}{2 \log_e \frac{l}{r_1}} = r$, or $\log_e \frac{l}{r_1} = 1$ or nat log $\times 2.3025851 = 1$, $\log \frac{l}{r_1} = \frac{1}{2.3025851} = 0.43429$. Hence $\frac{l}{r_1} = 2.72$ approx. $r_1 = \frac{2r}{2.72} =$ approx. 2910 miles = r_1 . A cylinder of

same length as Earth and radius about 2910 miles would have same capacity.

Inductance of cylinder of such dimensions should be ignoring magnetic influence (considering $\mu = 1$)

$$L = 2l \left(\log_e \frac{2l}{r_1} - 0.75 \right) \frac{2l}{r_1} = 5.44$$

$$\log_e \frac{2l}{r_1} = 1.69378$$

$$L = 2 \times 2 \times 63674 \times 10^4 (1.69378 - 0.75) = 4 \times 63674 \times 9437.8 = 2,403,770,000 \text{ cm}$$

$$\text{or } L = 2.40377 \text{ Henry.}$$

To sum up: Capacity of cylinder 0.0007075 farad

Inductance " 2.40377 Henry

Note. The Earth being magnetic this inductance will be no doubt greater. This is to be followed up.

Now average inductance and capacity per mile will be

$$\text{Capacity per mile } \frac{0.0007075}{7914} = C$$

$$\text{Inductance per mile } \frac{2.40377}{7914} = L$$

For vanishing resistance we have $\alpha = p\sqrt{LC}$,

$$\begin{aligned}\sqrt{LC} &= \frac{1}{7914} \sqrt{0.0007075 \times 2.40377} = \frac{1}{7914 \times 10^6} \sqrt{7075 \times 240377} = \frac{41240}{7914 \times 10^6} = \frac{4124}{7914 \times 10^5} = \\ &= \frac{0.521}{10^5} \approx \text{roughly } \frac{0.52}{10^5} = \frac{52}{10^7}! \quad (\text{Curious!}) \quad \text{see Colorado experiments.} \\ \text{Hence } \alpha &= p \times \frac{52}{10^7} \quad \lambda = \frac{2\pi}{\alpha} = \frac{2\pi}{p \frac{52}{10^7}} = \frac{2\pi 10^7}{52p} = \frac{1,204,000}{p} \\ \text{or } \lambda &= \frac{2\pi}{2\pi n \times \frac{52}{10^7}} = \frac{10^7}{52n} = \frac{192,308}{n} \quad \text{this is } \frac{v}{n}.\end{aligned}$$

Long Island apparatus

* M.F. in the manuscript – Ed.

Let the capacity of Earth be $707 \mu\text{F}^*$ and suppose frequency of 200 000 per sec. employed. The wave length will be not far from $\frac{186000}{200000} = 0.93$ miles. We may say for the present 1 mile. This will give 12000 complete waves over globe. Now the capacity of each half wave region should be on average $\frac{707 \times 9 \times 10^5}{24000} = \frac{636300}{24} = 26500 \text{ cm} = C$. Hence if the potential on free terminal of capacity $c = 4000$ be p , the potential of Earth will be $p \frac{c}{C} = \frac{4000}{26500} = \frac{4}{26}$ roughly $\frac{1}{7}$. This would be hardly possible.

The law of density will be truer. Assume equatorial region belt for half wave is 24000 square miles.

Sphere of 4000 cm capacity would have area of

$$\pi \times 8000^2 \text{ cm square} = \pi \times 80^2 \text{ square meters} = 10.78 \times \pi \times 6400 \text{ square feet.}$$

If density on terminal be σ then density on ground will be

$$\frac{10.78 \times \pi \times 6400}{\pi \times 8000 \times 53 \times 53 \times 10^4} \sigma = \frac{86.24}{2809 \times 10^5} \sigma.$$

The pressure will be regulated by density as assumed to have pressure proportional to density. Hence if pressure on terminal be only 200000 volts we should get on equator:

$$\frac{86.24 \times 200000}{28.09 \times 10^5} = \frac{172.48}{2809} = \frac{6}{100} \text{ Volt roughly}$$

Notes, experimental records, arrangements of oscillatory apparatus etc. imp. Feb. to Sept. 1901

Feb. 2, 1901

From old notes

In many experiments with electrical oscillations of very high frequency curious spark discharges were observed which for long time could not be accounted for. Finally I found that they were due to exceptional rise by resonant action of the electromotive force. Further investigation led me to the discovery of fact that any conductor, say a straight wire telegraphic line cable etc. has a definite frequency at which the capacity just counteracts the inductance and when worked with currents of that frequency the conductor is capable of transmitting energy under conditions exceptionally favorable.

To get a rough idea suppose we use a concentric cable outside diam. R , inside diam. r .

The capacity $C = \frac{kl}{2 \log_e \frac{R}{r}}$. On the other hand the inductance $L = 2 \mu l \log_e \frac{R}{r}$. Now we should

have for series arrangement

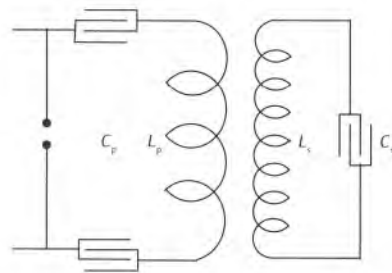
$$p = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{\frac{kl}{2 \log_e \frac{R}{r}} \cdot \frac{2 \mu l \log_e \frac{R}{r}}{9 \times 10^{11} \times 10^9}}} = \frac{1}{\sqrt{\frac{k \mu}{3 \times 10^{10}}}} = \frac{3 \times 10^{10}}{l \sqrt{k \mu}}$$

Now $p = 6 \times 10^4$ say, $\mu = 1$. Taking $\sqrt{k} = 1.5$ we have $p = \frac{2 \times 10^{10}}{l}$ (in centimeter). $l = \frac{2 \times 10^{10}}{6 \times 10^4} = \frac{10^6}{3} = 330$ meters. From this it would seem that such concentric cable worked with currents of above frequency would satisfy condition for every 330 meters of its length. But it should be remembered that in this case capacity and inductance can not be taken in series. When considered in multiple there ought to be a number of values. To follow up.

Feb. 24, 1901

Relations of primary and secondary

Consider a primary which is periodically closed and opened as in my coil with a resonating secondary in inductive but not too close relation as otherwise the free vibration would not properly assert itself. I shall first assume there is no ground connection and in general no cause to produce asymmetrical distribution. Diagram 1 below illustrates arrangement of the circuits which is familiar.



Calling combined capacity of the two condensers in primary circuit C_p , inductance of primary L_p , and C_s and L_s respectively the capacity and inductance of secondary circuit, and lastly M the mutual induction coefficient, we shall have during the time when the primary circuit is closed the inductance of the same reduced from L_p to a value $L_p \left(1 - \frac{M^2}{L_p L_s}\right)$. The period of the primary circuit when it is closed will thus be $T_p = \frac{2\pi}{10^3} \sqrt{C_p L_p \left(1 - \frac{M^2}{L_p L_s}\right)}$. Evidently for the best resonating condition the period of secondary when primary is opened should be the same. Now period of secondary will be $T_s = \frac{2\pi}{10^3} \sqrt{C_s L_s}$. Hence $C_p L_p \left(1 - \frac{M^2}{L_p L_s}\right) = C_s L_s$

When the relation is satisfied we get one clear note in secondary. In practice C_s or L_s or C_p or L_p may be adjusted, also M in some instances when the secondary or primary are movable relative to each other. But in large apparatus this is obviously impracticable. A glance at the equation shows that if we seek values for L_p , L_s , or M we get more than one but there is only one value for either C_p or C_s . The above equation leads itself probably best for finding value of C_s which is

$$C_s = \frac{C_p L_p}{L_s} \left(1 - \frac{M^2}{L_s L_p} \right).$$

The above makes it clear that primary circuit when the secondary is removed should vibrate slower than the secondary alone. When they are linked together the primary vibrations must quicken up to the pitch of the secondary free vibrations. On the other hand there are two effects in the secondary produced by the primary which must exactly balance each other: There is a tendency created by the primary to slow down the free secondary vibrations because of the lower pitch and there is an other tendency of primary which is to quicken the free secondary vibrations by diminishing the self-induction coefficient L_s .

When the oscillations in the primary are arbitrary or forced as by a dynamo then the periods of secondary when primary closed and when opened must be equal. Putting it in symbols:

$$\frac{2\pi}{10^3} \sqrt{C_s L_s \left(1 - \frac{M^2}{L_s L_p} \right)} = \frac{2\pi}{10^3} \sqrt{C_s L_s}.$$

Hence $C_s L_s \left(1 - \frac{M^2}{L_s L_p} \right) = C_s L_s$ or $L_s L_p = M^2$. This means to say that the circuits are linked very closely as in ordinary transformers.

A few special cases are of interest. Suppose the ratio of conversion to be n , that is n times as many turns in the secondary as in primary. Assume the secondary turns bunched together then $L_s = n^2 L_p$ and in above equations C_s will then be

$$C_s = \frac{C_p L_p}{n^2 L_p} \left(1 - \frac{M^2}{L_p n^2 L_p} \right) = \frac{C_p}{n^2} \left[1 - \left(\frac{M}{L_p n} \right)^2 \right].$$

An other case is of interest. When $n = 1$ $L_p = L_s$. Then the equation becomes:

$$C_s = C_p \left[1 - \left(\frac{M}{L_p} \right)^2 \right],$$

from which either C_p or C_s may be found which ever it may be more suitable to adjust.

Note: From above relations the material coefficient may also be determined by resonance method.

It is easy by adjustment of one or the other of the quantities to produce two notes of distinct pitch such as will interfere least with one another. This is important in connection with my improvements in signaling and also in other respects.

$$\text{We have found that } T_s = \frac{2\pi}{10^3} \sqrt{C_s L_s} \quad \text{and} \quad T_p = \frac{2\pi}{10^3} \sqrt{C_p L_p \left(1 - \frac{M^2}{L_s L_p} \right)}.$$

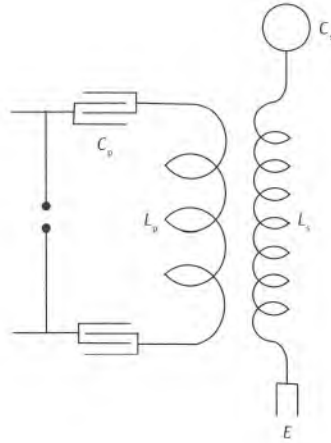
Now T_s and T_p should as I have found in practice be selected as primary (relative) numbers so as to get the greatest number of beats per unit of time. In this case the vibrations interfere least, because the periods when they cooperate and those when they work against each other follow in most rapid succession. At any rate in the receivers greatest safety against disturbance is seemed when the periods of the tuned circuits are so related. We may put

$$\frac{T_s}{T_p} = \frac{M}{n}.$$

Hence

$$\frac{C_s L_s}{C_p L_p \left(1 - \frac{M^2}{L_s L_p}\right)} = \frac{M^2}{n_2} = K \text{ and } C_s L_s = K C_p L_p \left(1 - \frac{M^2}{L_s L_p}\right).$$

From this later equation one or the other of the constants, which ever is found to be more convenient, may be calculated.



The above found relations are modified in case of earth connection or general asymmetry. In case of earth connection we have approximately (only secondary being connected to ground), since the secondary now will vibrate just half the period, if the quantities designated by letters have same values as before:

$$4 C_p L_p \left(1 - \frac{M^2}{L_s L_p}\right) = C_s L_s \text{ for one clear note}$$

and

$$4 K C_p L_p \left(1 - \frac{M^2}{L_s L_p}\right) = C_s L_s \text{ for two notes as above explained.}$$

Evidently to satisfy resonating conditions the capacity and induction in primary will each have to be doubled. Theoretically this is so, but in practice it is found that they need not be quite double. The reason is that capacity effect of coil \$L_s\$ is smaller relatively then when coil used without earth.

Various reflections to follow

NEW YORK CABLE ADDRESS, BOLDT, NEW YORK
PHILADELPHIA CABLE ADDRESS, BOLDT, PHILADELPHIA



THE WALDORF
THE WALDORF-ASTORIA, NEW YORK
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GEO. C. BOLDT, PROP.

The Waldorf-Astoria, Fifth Avenue, 33rd and 34th Streets and Astor Court.



THE ASTORIA



New York March 1 1901

from old note:

Considerations relative transmission to great distance through Earth by my system.

assume I use a terminal elevated at 300 feet. This height might be attained with three lengths of gal. pipe joined by steel pipes. For the first plant I would be better to resort to wood as other material expensive. Later some of the inconveniences with metal or masonry supports which I have devised may be avoided. Possibly a single chimney or center may be used if terminal small. Three chimneys at any rate will be sufficient. Let the insulated terminal be in the form of a roof flat, with broadened sides as in sketch. Surface of the roof will be



$$\text{length: } \frac{\pi}{4} D^2 + \frac{\pi}{2} d \cdot \pi (D+d) = S$$

Suppose $D = 700$ meter or say 300 ft
 $d = 10$ meter or say 30 feet

$$\text{Then } S = 0.7854 \times 90000 + 10 \cdot 30 \cdot 330 = \text{say } 170000 \text{ square feet}$$

The covering of roof or terminal will be not far from 4000 sq. ft. and at a height of 300 feet this ought to be about 10000 c.m. If the frequency

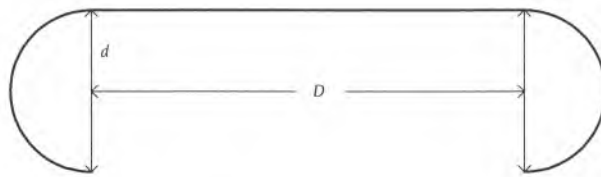
1)

March 1, 1901
From old notes

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Considerations relative transmission to great distance through Earth by my system

Assume I use a terminal elevated at 300 feet. This height* might have been attained with three lengths of Cal. pine joined by steel pipes. For the first plant it would be better to resort to wood as other material expensive. Later some of the arrangements with metal or masonry supports which I have devised may be used. Possibly a single chimney in center may be used if terminal small. Three chimneys at any rate will be sufficient. Let the insulated terminal be in the form of a roof flat, with toroidal rim as in sketch.



* Tesla's erroneous spelling of some english words in the manuscript (e.g. *accross*, *hight*, *chocking*, *inclosure*, and writing some compounds as one word (e.g. *sparkgap*, *watermain*, *groundwire*) has been corrected in this edition.

Surface of the roof will be roughly: $\frac{\pi}{4}D^2 + \frac{\pi}{2}d\pi(D+d) = S$.

Suppose $D = 100$ meter or say 300 feet, $d = 10$ meter or say 30 feet. Then $S = 0.7854 \times 90000 + 10 \cdot 30 \cdot 330 =$ say 170000 square feet. The capacity of roof or terminal will be not far from 4000 cm and at a height of 300 feet this ought to be about 10000 cm.

If the frequency be 50000 per sec. we have:

$$\frac{1}{50000} = \frac{2\pi}{10^3} \sqrt{\frac{10^4}{9 \times 10^5}} L \quad \text{and} \quad L = \frac{9}{10^4} \text{ Henry}$$

This might do but it will probably be preferable to match the length of wire 3 quarter of wave or $(n + 1)$ quarters where n even number. This will give more prolonged vibration on account of greater inductance associated with system.

It is interesting to see what would be attained with the ordinary frequency of alternator say 125 cycles. In this case $\frac{1}{125} = \frac{2\pi}{10^3} \sqrt{\frac{10^4}{9 \times 10^5}} L_1$ and $L_1 = 144$ Henry about. This inductance could scarcely be obtained without iron. For trial suppose drum 6 feet diam. $A = 24000$ cm square. Wound with wire N^o 20 and string equal thickness. Spool of 100 feet length would have about 12000 turns (120 turns per foot).

This would give the inductance of spool $L_2 = \frac{4\pi \times 24000 \times 144 \times 10^6}{100 \times 12 \times 2.5} = 14$ Henry approx. Evidently too little unless we use larger diameter. If the spool were about 20 feet it would be possible. The section or area of spool would then be more than 10 times and induction more than 10 times larger which would bring it to about the value required. The string between the turns might stand 5000 Volts. Hence it would be roughly considered possible to get a pressure of $5000 \times 12000 = 60 \times 10^6$ Volts. This is evidently exaggerated estimate probably only 1000 Volts between each turn would be practicable and all that could be reached would be scarcely more than $1000 \times 12000 = 12$ million Volts. Of course this could imply an enormous magnifying factor which could not be attained. For the length of wire N^o 20 would be about $60 \times 12000 = 720000$ feet and resistance about 7200 Ohms. p being $= 2\pi \cdot 125 = 800$ approx. and $L_2 = 140$ Henry the magnifying factor would be $\frac{140 \times 800}{7200} = 140:9 = 16$ approx. The supply transformer might give 50000 Volts and this would only rise to $16 \times 50000 = 8,000,000$ Volts.

Suppose we have to charge roof to one million Volts. What would be effect at equator?

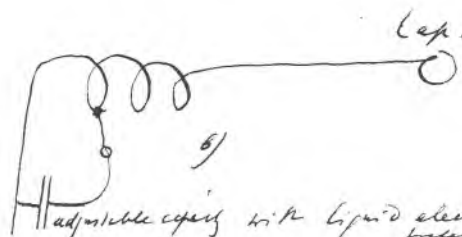
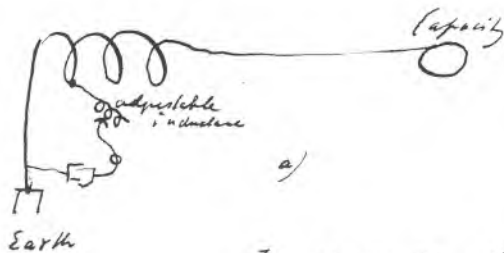
March 24 1901.



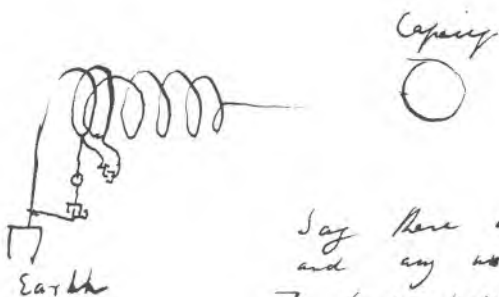
Some of the preferred arrangements for getting the secondary circuit in tune with primary when latter is closed and also when opened. Furthermore for getting any desired relation between the rates of vibration when closed and when opened.



In this case a point is found along the conductor when Synchronism exists or else when the desired relation is obtained.



In a) & b) by adjustment with fixed length of primary & secondary.
 Adjustable cap. with liquid electrolyte Condenser preferably.



This is very good for prolonging vibrations and exciting better the reel system (secondary).

Say there are two fluxes which are the primary and any number of secondary turns. All in series. The first primary turn gets the condenser discharges - that is the turn nearest to ground (connected to Earth). The second primary turn is very close inductive relation to first and shunted with a condenser and tuned to primary. When first turn interrupted second turn vibrates long.

When using secondary in close relation and series with primary the latter may be off or in resonance or in specific results.

$$\text{Density } D = \frac{p}{S} = \frac{10^6}{17000 \times 144 \times 6.5} \text{ on roof}$$

Surface of equatorial belt 1 mile wide (two miles or one half wave reduced to uniform electric field)

$$\text{Surface of equatorial belt } S_1 = 8000 \times \pi \times 5300 \times 5300 \times 144 \times 6.5$$

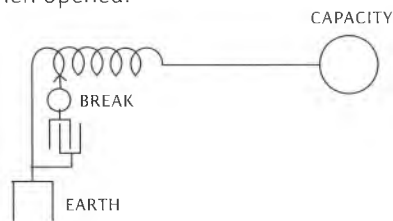
$$\text{Hence density } d = \frac{10^6}{17000 \times 144 \times 6.5 \times 8000 \times \pi \times 53 \times 53 \times 10^4 \times 144 \times 6.5} . \text{ If same kind of roof or terminal}$$

$$\text{be used on equator the pressure initial would be } p = \frac{1}{8 \times 65 \times 144 \times 53^2 \times \pi} \text{ roughly } \frac{1}{6 \times 10^8} \text{ Volt. Assume}$$

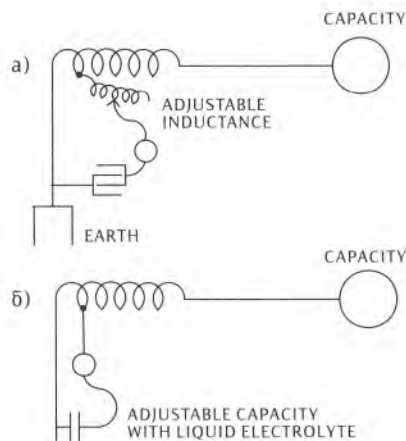
$$\text{magnifying factor 10000 the volts would be } \frac{1}{6 \times 10^4} . \text{ Apparent energy: } \frac{1}{2} \cdot \frac{1}{36 \times 10^8} \cdot 10^5 \cdot 10^4 = \frac{5}{36} \text{ Watts. Plenty.}$$

March 24, 1901

Some of the preferred arrangements for getting the secondary circuit in tune with primary when latter is closed and also when opened. Furthermore for getting any derived relation between the rates of vibration when closed and when opened.



In this case a point is formed along the conductor when synchronism exists or else when the desired relation is attained adjustable capacity with liquid electrolyte condenser preferably.

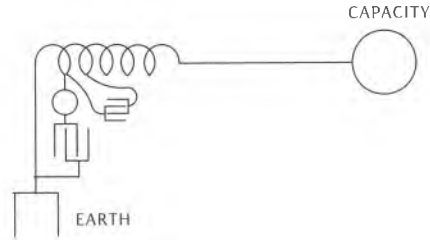


In a) and b) by adjustment with fixed length of primary and secondary

This is very good for prolonging vibrations and exciting better the real system (secondary)

Say there are two turns which are the primary and any number of secondary turns. All in series. The first primary turn gets the condenser discharges – that is the turn nearest to ground (connected to Earth). The second primary turn in very close inductive relation to first and shunted with a condenser and tuned to primary. When first turn interrupted second turn vibrates long

When using secondary in close relation and series with primary the latter may be oppositely wound or in same direction. Specific results.



April 1, 1901

From old notes

Transmission without wires to great distances considered

Suppose my insulated terminal be a metallic roof as proposed before. It is easy to get 6000 cm. Let the capacity be charged to one million Volts we have

$$Q = \frac{6000}{9 \times 10^{11}} \cdot 10^6 = \frac{2}{300} \text{ Coulomb. Estimated surface in centimeter of roof approximately } 26 \times 10^7 \text{ cm square.}$$

I shall assume that the waves used be four miles long. Then belt on equator of Earth (taken with reference to transmission station as a pole) will be: $2 \times \pi \times 8000$ square miles. Taking for the present the electric density of ground charged by the wave uniform we may take about $\frac{2}{3}$ of above value in estimate to follow. This gives about 32000 square miles of uniformly charged surface. Or $5300 \times 5300 \times 32000 \times 144 \times 6.5$ centim. square approximately. The electric densities on roof and equatorial belt will be as $\frac{26 \times 10^7}{53 \times 53 \times 32 \times 10^4 \times 144 \times 6.5} = \frac{1}{220000 \times 144} = \frac{1}{3 \times 10^7}$, since densities must be inversely as the areas charged. Now density on roof or terminal when charged to one million Volts will be $\frac{2}{3 \times 100 \times 26 \times 10^7} = \frac{1}{39 \times 10^9}$ that is approx. $\frac{1}{4 \times 10^{10}}$.

$$\text{Hence density on equatorial belt will be } \frac{1}{4 \times 10^{10} \times 3 \times 10^7} = \frac{1}{12 \times 10^{17}}.$$

Suppose now at the receiving station a similar roof or terminal it will get a minimum quantity of electricity $26 \times 10^7 \times \frac{1}{12 \times 10^{17}} = \frac{26}{12 \times 10^{10}}$ or approx. $\frac{2}{10^{10}}$ Coulombs. From this we shall get the pressure $p = \frac{q}{C} = \frac{\frac{2}{10^{10}}}{\frac{6000}{9 \times 10^{11}}} = \frac{3}{100}$ Volt.

Now, if we would not magnify at all we would get energy:

$$E = \frac{1}{2} \times 100000 \times \left(\frac{3}{100} \right)^2 \frac{6000}{9 \times 10^{11}} = \frac{3}{10^7} \text{ Watts under the conditions assumed.}$$

But if a magnifying factor of only 10000 which is quite practicable be used taken with reference to one second then if one signal needed $\frac{1}{100}$ second we should still magnify 100 times and would get apparent energy of $\frac{3}{10^5}$ Watts. Taking transmission across the diameter of Earth to a distance of 8000

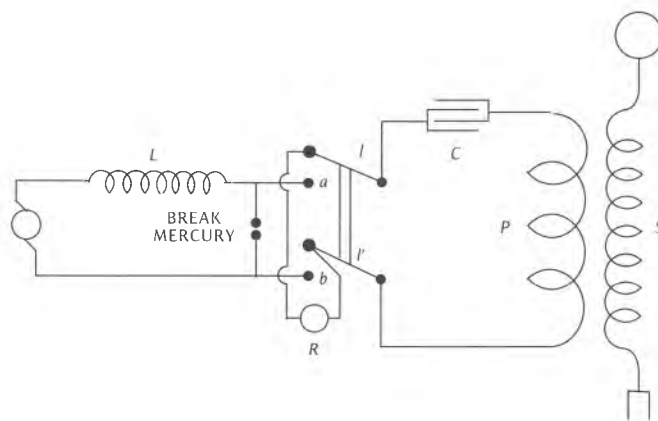
miles straight line the density would be at the pole about $\frac{32000}{24} = \frac{4000}{3}$ times greater. Since excitation is proportionate to density (important fact!) we would get apparent energy $\left(\frac{4000}{3}\right)^2$ times more energy because e.m.f. would be $\frac{4000}{3}$ times greater. Or apparent energy gathered in a station at the pole would be $\frac{16 \times 10^6}{9} \times \frac{3}{10^5} = \frac{480^3}{9} = 53 \text{ Watts!! approx. Great!}$

P.S. It would be easy to get by surfaces of small curvature **larger** capacity.

We could light a lamp at the pole no doubt.

From old notes

Following arrangement with ordinary form of oscillator and as used on supply circuits in the laboratory has been found convenient for use in signaling. The idea is to use the apparatus alternately as transmitter and receiver by simply changing its connection with a switch which may be automatic in returning to the position of receiving.



L induction for primary raising pressure of supply circuit as used. C and P condenser and primary. S secondary which may be either directly used in the transmission to a distance or for exciting of other circuit, R is the receiving circuit with the sensitive receiver in any suitable way arranged. I are the arms of switch. In position indicated the apparatus is ready to receive. The secondary S being in tune with vibrations from distanced transmitter is excited and induces currents in primary circuit. P C R likewise tuned.

When switch placed in position ab then the receiving circuit R is disconnected and the apparatus transmits. The arrangement is very simple and suitable particularly for transmissions to small distances. It can be arranged in a small compass.

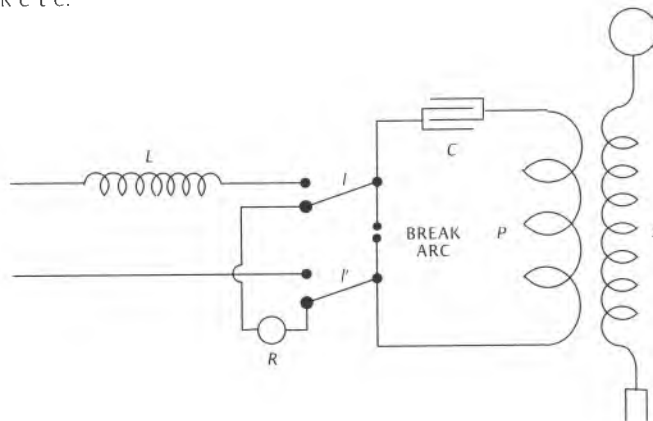
— . —

Following modified disposition is adopted as suitable when break is an arc and hot mercury an other contact making device.

The letters signify corresponding parts as on sheet preceding. This same arrangement I find can be used for determining resistance of arc in following manner.

First, coil S adjusted to be in resonance with primary excited system with the arc playing, then the coil is excited from an other source and resistance R is varied until again resonance attained in primary system. The switch I may be operated by hand or be made automatic as in ordinary key. A controlling magnet also may be used for shifting, the levers I and the magnet may be controlled by a key as usual.

The above arrangement is not practicable with the mercury break unless the same be stopped when receiving. This of course can be done. At any rate useful data may be gained in experiments to ascertain resist. actual of break e t c.



To follow up.

April 15, 1901

Considerations relative to terminal in transmitter for transoceanic plant in process of construction

Compare insulated roof disk form rounded on ends in form of tore with condenser comprising two plates. The roof should be at some distance from Earth's surface that the capacity relative to Earth is small under which condition most of charge will be "free".

We have for condenser of two disks $C = \frac{\pi r^2}{4\pi b} = \frac{r^2}{4b}$ where b = distance from Earth's surface, r = radius of disk.

At present it will be sufficient to assume roof as straight disk.

For one disk (roof) alone, $C_1 = \frac{2r}{\pi}$, k assumed = 1, C = capacity of roof on Earth's conducting surface, C_1 = capacity far removed from Earth's conducting surface.

From this
$$\frac{C}{C_1} = \frac{\pi r^2}{2r \times 4b} = \frac{\pi r}{8b}$$

For
$$b = r \quad \frac{C}{C_1} = \frac{\pi}{8}$$

$$b = 2r \quad \frac{C}{C_1} = \frac{\pi}{16}$$

$$b = \pi r \quad \frac{C}{C_1} = \frac{1}{8}$$

This last means to say that if the conducting disk or roof be say of radius $r = 200$ feet the elevation should be 300 feet to have say $\frac{1}{8}$ of effectiveness or effective capacity. But now there is an increase of capacity as I find of about $\frac{1}{2}\%$ per foot of elevation. This means 150% for 300 feet. Consequently the actual ratio $\frac{C}{C_1}$ will be instead of $\frac{1}{8}$ $\frac{1}{8 \times 2.5} = \frac{1}{20}$. From this it would seem that 200 feet would be all that is needed to work with fair economy.

Inductance coils to be placed in series with closed iron circuit Westinghouse transformer for the purpose of raising pressure, preventing short-circuiting by break and increasing economy. Two spools 19" outside diam. 5" inside are made. They are 2½" wide but space for wire available will be only 2". There will be about necessary wire as follows:

Average diam. 12". The inductance of one turn will be approximately $\frac{1}{64} \times 8000 = 125$ cm. (8000 cm being inductance of loop 8 feet diam.)

As found before for resonating condition we shall want $\frac{10}{6}$ Henry in each coil.

$$\text{Now } \frac{10}{6} \times 10^9 : 125 = N^2 : 1 \quad N^2 = \frac{10^{10}}{750} = \frac{10^9}{75}$$

$$N = 10^4 \sqrt{\frac{10}{75}} = 3700 \text{ turns approx.}$$

With № 16 wire we get 32 turns per 2". This would require 3700:32 = 120 layers (about). This would need 8" space wound. We have only 7". Wire № 16 will want 3" width. This per layer gives 48 turns and 80 layers would be sufficient. The space needed 80 : 16 = 5" fully enough. In as much as Nr. 16 wire has an unnecessarily large section we may take Nr. 18 double covered, fiber between layers ¼" (final).

April 28, 1901

Considerations relative to elevated terminal

It is for practical reasons desirable to get along with the smallest height and also with the least surface because these two influence largely the cost.

As to elevation it ought to be such that most of the charge is free. In other words – the capacity with reference to Earth should be much smaller than that of the surface of terminal itself considered as far remote from other conducting bodies.

Regarding the form I have found that for many reasons it would be best to employ a sphere with the lower part less than one half open, but it may be difficult to construct such a terminal. A plane roof or surface with rounded circumference (of large radius of curvature) would seem easiest to construct and also appears to be the cheapest. A sphere, it is true, might be made smaller than any other terminal because it would allow the charging to the highest pressure. Next to sphere a cylinder with half spherical ends seems best. To get an idea suppose the terminal to be in the shape of a disk or plane with rounded edge (in the shape of a tore if the radius be r the capacity would be $\frac{2r}{\pi}$. Taking value assumed in above estimates $\frac{2r}{\pi} = 10000$. Hence $r = 15700$ cm or 157 meter.

Now the disk would have to be at a height such that its capacity with reference to an other surface on the ground would be much smaller. Suppose an other disk of the same dimensions were on the ground then the capacity of the condenser so formed would be $\frac{S}{4\pi b} = \frac{\pi r^2}{4\pi b} = \frac{r^2}{4b}$. The ratio of both the capacities is $\frac{2r}{\pi} : \frac{r^2}{4b} = \frac{4b \times 2r}{r^2 \pi} = \frac{8b}{r\pi}$. Here b is the height. Suppose we take this ratio = 10, we have for b value $\frac{8b}{r\pi} = 10$, $b = \frac{10r\pi}{8} = \frac{1570\pi}{8} = 616$ approx. This shows that under the above conditions the height would have to be very large. It is clear that the larger the plane conducting surface the greater will have to be the height to satisfy above relation. For $b = \frac{r\pi k}{8}$, where k is the number expressing ratio. As it is



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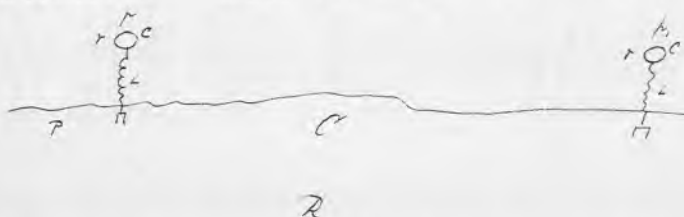
The Waldorf-Astoria.

Fifth Avenue, 73rd and 74th Streets
and Astor Court.



New York April 28 1901

Signalling through the earth with open synchronous circuits
Theoretical considerations: for frequency impulses.



Capacity of isolated
thermal system to
be a sphere at some
distance from the Earth's
surface that most of
its charge is "free".
Capacity of earth
R radius of
" " of sphere.
L oscillating coil.

A certain quantity of Electricity being conveyed to the sphere a corresponding quantity will be abstracted from the tube and the potential on the tube will accordingly rise and fall according to the sign of electricity conveyed to the sphere.

Let the quantity of electricity at each alternation be q and the quantity of electricity in the Earth then there will be a variation of $(E+q) - (E-q) = 2q$ coulombs during one complete cycle in the Earth.

the complete cycle in the Earth.
Line $q = pC$ p being the potential of sphere charged w.r.t
 $a = pC$ p " " " Earth
the variation of potential will be $(PC + pc) - (PC - pc) = 2pc$ per cycle

2.

seen b is proportionate to r . If therefore instead of having 157 meter radius the conducting surface is only 15.7 meter radius the height required would be only 61.6 meter which is reasonable.

This shows the importance of having the terminal small to avoid great expense in the construction of same. Evidently the same electrical movement as before could be attained with a small terminal charged to a corresponding higher pressure.

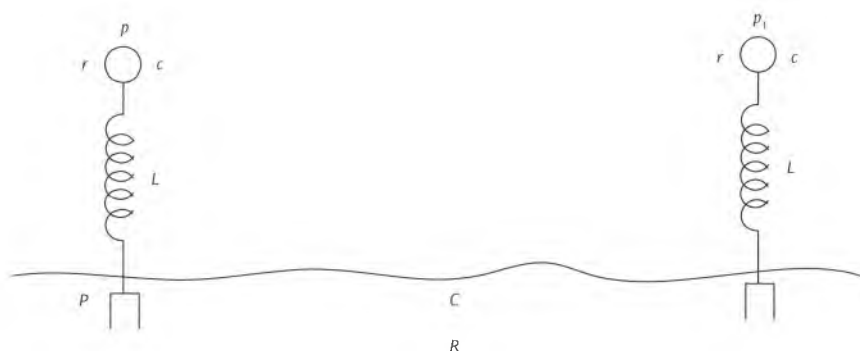
We have assumed before 10000 cm capacity charged to 288000 which would give at any point of the globe a pressure of $\frac{7}{10^5}$ Volt for exciting the receiving circuit. But since Q the quantity of electricity stored $= p' C' = p'' C'' = p''' C'''$ etc. the capacity may be made smaller in the same ratio as the pressure is increased. Now how far can the pressure be carried is important to ascertain.

Suppose first that the frequency of the dynamo say 60 cycles be used and by a step up transformer of the type I employ in wireless transmission the e.m.f. raised. For closed iron core transformers (unless supplied from insulated, independent sources) the e.m.f. of 288000 Volts is about as high as could be carried even with oil insulation. But with the above transformer properly constructed I think a ten times greater e.m.f. might be attained. This would mean that to produce same el. movement as previously considered with capacity 10000 cm we would want only a capacity of 1000 cm or the disk would have to be of 15.7 meter radius. But to charge a capacity of 1000 cm to a pressure 10 times greater would require 10 times as much energy as before ascertained since $\frac{1}{2} p^2 C : \frac{1}{2} p_1^2 C_1 = \frac{p^2 C}{p_1^2 C_1} \cdot p = 10 p_1 C$
 $= \frac{1}{10} C_1 \cdot \frac{p^2 C}{p_1^2 C_1} = \frac{100 p_1^2 C}{p_1^2 C_1}$ or 10.

To be continued

Signalling through the Earth with open syntonized circuits

Theoretical considerations in low frequency impulses



c capacity of insulated terminal assumed to be a sphere at such distance from the Earth's surface that most of its charge is "free".

C capacity of Earth,

R radius of "

r " of sphere

L oscillating coil

A certain quantity of electricity being conveyed to the sphere a corresponding quantity will be abstracted from the globe and the potential on the latter will alternately rise and fall according to the sign of electricity conveyed to the sphere.

Let the quantity at each alternation be q and Q the quantity of electricity in the Earth then there will be a variation of $(Q + q) - (Q - q) = 2q$ Coulombs during one complete cycle in the Earth.

Now

$$\left. \begin{aligned} s &= 4 \pi r^2 \\ S &= 4 \pi R^2 \end{aligned} \right\} \text{ therefore } \frac{s}{S} = \left(\frac{r}{R} \right)^2$$

Substituting the quantities found and assumed:

We have

$$p_1 = \left(\frac{100}{\frac{12700000}{2}} \right)^2 \cdot \frac{32}{10^4 \cdot \frac{10000}{9 \times 10^{11}}} = \left(\frac{1}{63500} \right)^2 \cdot 288000 = \frac{1}{(635)^2} \cdot 28.8 = 0.00007 = \frac{7}{10^5} \text{ Volt approx.}$$

The energy stored will be

$$\frac{1}{2} p_1^2 c = \frac{1}{2} \cdot \left(\frac{7}{10^5} \right)^2 \cdot \frac{10^4}{9 \times 10^{11}} = \frac{49}{18 \times 10^{17}} \text{ Watts.}$$

This energy would be available at each charge for operating a device at no matter what distance.

The quantity of electricity available will be as before found:

$$\begin{aligned} q_1 &= \frac{s}{S} \cdot \frac{32}{10^4} = \left(\frac{200}{12700000} \right)^2 \cdot \frac{32}{10^4} = \frac{1}{(63500)^2} \cdot \frac{32}{10^4} \\ &= \frac{1}{(635)^2} \cdot \frac{32}{10^8} = \frac{1}{126 \times 10^{10}} \text{ Coulomb.} \end{aligned}$$

Even one discharge would be sufficient to send a perceptible signal under the conditions assumed. (The special calculation to be added).

We may, however, without using any greater quantity of actual energy make available for the operation of a device a vastly greater amount energy. If one signal per second were required the energy available would be $8 \times \frac{49}{18 \times 10^{17}} \text{ Watts} = \frac{392}{18 \times 10^{17}} = \frac{21.7}{10^{17}}$ roughly $\frac{2}{10^{16}} \text{ Watt.}$

Per minute one signal we could make available by the process of storing as described in my patents:

$$\frac{120}{10^{16}} = \frac{12}{10^{15}} \text{ Watt.}$$

Evidently a signal can even under the above enormously unfavorable conditions be transmitted by such apparatus as I contemplate using.

The conditions could be greatly improved by raising the pressure say to 10 times the value in which case the effect at distance would be 100 times as great. The amount of power required would still not be prohibitory. In fact as the power is only intermittently used it might not be necessary to use a greater amount of actual power. The preceding considerations have been made without regard to the great advantages which can be secured in my tuned system.

In this case to begin with the generator we can raise the pressure at the terminal to a value greater in the proportion of $\frac{p'L}{R}$ than the one before found. In the case assumed p' would be $= 2\pi n$ roughly $= 24$. The ratio $\frac{L}{R}$ is merely a question of copper. If this ratio were but $= 1$ we still would have the e.m.f. at the transmitter end 24 times the value above assumed.

Suppose further that the receiver is equally proportioned. Then the electrical movement in the receiving circuit would be magnified $(24)^2$ times. We would thus have $\frac{(24)^2}{126 \times 10^{10}}$ Coulombs per second available for operating an instrument which should be one dependent on the quality of energy that is not requiring a great amount of actual energy. This gives $\frac{46}{10^{11}}$ Coulomb. Thus the current obtained in the receiving circuit would be $i = ec\omega = \frac{46}{10^{11}}$ Amperes. There are many instruments responding to a flow of $\frac{1}{10^{11}}$ Amperes. That signals can be transmitted to any distance by my system is therefore perfectly sure.

Higher frequencies considered

Experiments in Colorado have demonstrated that waves with crests and hollows can be made to pass over the globe when the intensities of the impulses are enormous. With such impulses the transmission to any distance is quite easy.

First I shall consider the frequency obtained with dynamo ordered for transatlantic plant, 60 cycles per second. The wavelength λ is $= \frac{320000000}{60} = 5333000$ meters or 5333 kilometers.

There will then be according to my experience belts of alternating high and low density $\frac{5333000}{2}$ meters wide. At the equator the density will be smallest – that is at the equator relative to which the transmitting point or station is a pole. Taking the more unfavorable case – the transmission to a point in the equatorial region we shall have: $s_1 = \pi d \times \frac{\lambda}{2}$ approximately. I assume for sake of simplicity that the curvature is ignored and the zone or belt considered cylindrical. It would be close enough for present purposes.

Evidently the density will now come out in the same ratio greater as the surface s_1 is smaller than the total Earth's surface. The latter is $S = \pi D^2$, hence density in present case will be

$$d_1 = \frac{\pi D^2}{\pi D \frac{\lambda}{2}} \cdot d = \frac{2D\pi d}{\lambda}, \text{ } d \text{ being the density before ascertained.}$$

$$\frac{2D}{\lambda} = \frac{12,700000 \times 2 \times 60 \times \pi}{320\,000\,000} = 4.76 \times \pi = 15d \text{ nearly.}^*$$

* Tesla's lapse, i.e.
 $2D/\lambda = 4.76$. - Ed.

As the density is 15 times that found before the pressure at the terminal of receiving station will be in same ratio greater and that means that the energy stored per one charge will be 15^2 times or 225 times greater. This would be the case if the impulses were of the same intensity as before assumed but we must consider that the energy if the dynamo is the same as before, consequently the energy of each impulse will be reduced in the ratio of their number. Taking 60 per sec. as compared with 4 per second the energy of each of the impulses of the higher frequency will be $\frac{1}{15}$. Therefore the energy at each change will be only 15 times greater at each half cycle. Nevertheless the advantage is very great as it is, for we can now accumulate in the same time interval a much greater electrical movement than it was possible with the frequency first assumed. Not considering the advantages of resonance we would get $\frac{60}{4} \cdot 15$ times or 15^2 times the energy before received per sec. That is, we would have for the operation of the receiving device an electrical movement 225 times greater at our disposal or in figures:

$$\frac{8 \times 225}{126 \times 10^{10}} = \frac{1800}{126 \times 10^{10}} = \frac{18}{126 \times 10^8} \text{ Coulombs of electricity per sec.}$$

The current would be $\frac{18}{126 \times 10^8}$ Amp evidently ample.

Suppose however we use carefully adjusted syntonized circuits, then the e.m.f. at transmitter could be raised in ratio $\frac{377}{1}$ approx. assuming again $\frac{L}{R} = 1$, and on receiver we would get an electrical movement

$$\frac{(377)^2}{126 \times 10^{10}} = \frac{142}{126 \times 10^7} \text{ approx. and a current of nearly } \frac{142}{126 \times 10^7} \text{ Amperes.}$$

This is many times larger than required.

Still higher frequencies will give greater amperage and in proportion to the square of the frequency. Hence if I use 100 000 per sec instead of 4 as first contemplated there would be per second available an electrical movement of rate equal to $\left(\frac{25000}{4}\right)^2 \cdot \frac{1}{126 \times 10^{10}} = \frac{625 \times 10^6}{16} \cdot \frac{1}{126 \times 10^{10}} = \frac{625}{16 \times 126 \times 10^{10}} = \frac{100}{31 \times 10^4} = \frac{1}{3100}$ Coul. and we would get current $\frac{1}{3100}$ Amperes. This would be amply sufficient for operating a rough instrument. At the poles or any other point not in the equatorial belt the figures would come out still more favorable to the transmission which as has been before recorded would be easiest effected to the opposite pole that is to the point diametrically opposite to the transmitting station, at least this is theoretically reasonable to assume.

For the last frequency we should now take correction. First of all I shall have instead of 500 H.P. only 150 H.P. available. Then there may be some limitations to the capacity. This latter limitation I do not feel as if the surface is smaller the potential may be correspondingly raised. It is fair to take correction only for power; this means that instead of above value the current will be only $\frac{150}{500} \cdot \frac{1}{3100}$ Amperes $= \frac{1}{10000}$ Amperes approx. But it still to be borne in mind, that this would mean only one signal per second. If we take 10 signals per sec then the amperes obtained would be only $\frac{1}{100}$ that is $\frac{1}{1,000,000}$ Amperes but even in this case it is ample for operating an instrument of the ordinary kind.

Consider further that I have assumed above $\frac{L}{R} = 1$. This is very insignificant. Usually $\frac{L}{R}$ will be large – at least = 10. All this will make the actual result ever so much better then would be inferred from this rough estimate. Evidently $\frac{L}{R}$ should be made as large as it can be made without great expense which would be prohibitory. Cooling the conductors may pay very well. Investigate further.

— . —

Following principle seems to me very good in connection with signaling.

At receiver station the energy is utilized to alter the pressure on a microphone contact and thus produces an action on any kind of receiver.

Scheme:

A receiving circuit

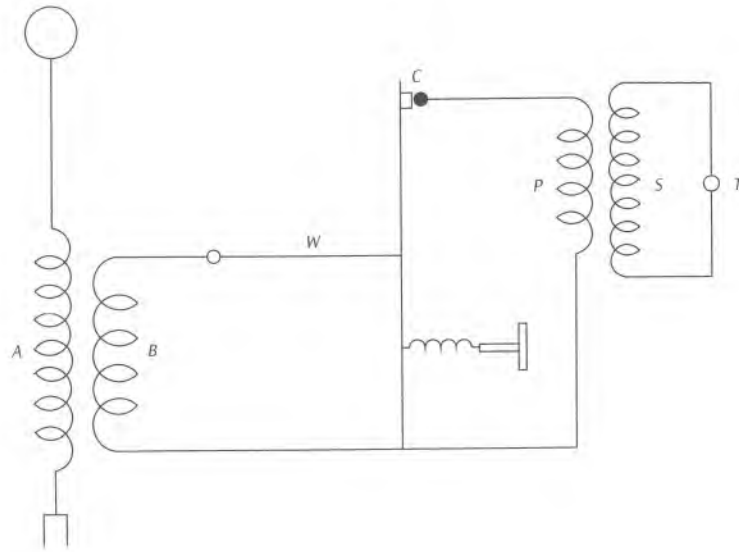
B secondary as in my system

w wire of small mass

c microphonic contact the pressure of which is adjusted by adjustable spring

p and s are the primary and secondary respectively of an induction coil

T is a telephone or other device



When the signal is sent, wire w is heated, elongates, and the pressure at C is increased. The stronger current passing through p induced current in S actuates T . The principle is capable of many modifications.

The movement may be magnified in many ways. This may be expanded and a liquid column moved altering the pressure etc.

May 1, 1901

From old notes

Considerations regarding transmission without wires to great distances by my system

Take following data:

Capacity of an elevated terminal (at some distance above ground, enough to have most of charge "free") to be 10^5 cm. Assume electrical movement to amount apparently to a rate of 5 (five) million Horse Power, 3 – 4 cycles per second the rate of vibration.

We have $5\,000\,000 \times 750 = \frac{1}{2} V^2 \frac{10^5}{9 \times 10^{11}} \cdot 40$; $p = 40$ approx. From this we get $V = 40,000\,000$ Volts approximately. This would be necessary to charge capacity with for producing movement assumed of 5×10^6 H.P.

Taking now capacity of Earth $9 \times 10^5 \times 720$ cm, each potential variation max. per half cycle will be $\frac{10^5}{9 \times 10^5 \times 720} \times 4 \times 10^7 = 6000$ Volts. Suppose now an other plate of 10^5 cm be used at distant station how much energy could be received? Energy will be $= \frac{1}{2} \times \frac{10^5}{9 \times 10^{11}} \cdot 36 \times 10^6 \times 40 = 80$ Watts. But the apparent energy could be magnified greatly by resonance at best 100 times. Hence 8000 apparent Watts could be obtained. From this clear that transmission of a signal even to a planet possible.

May 4, 1901

483

Readjustment of laboratory apparatus

Large coil № 16 Oconite wire in center of room.

Fundamental tone obtained with

4 jars in each condenser set

$2\frac{3}{4}$ turns in Selfind. Regul.

Green coil for physiological effects:

Fundamental tone

4 jars in each condenser set

$7\frac{1}{2}$ turns in Self. Regul.

Coil with handle brass for lighting tubes in hand etc.

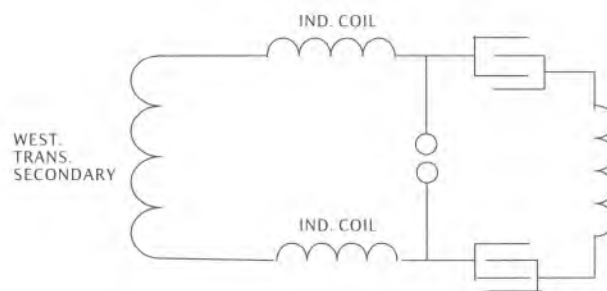
4 jars in each condenser set

20 turns in Self. Regul.

Note. A curious observation was made when cable around room was energized very shortly. The cable was bent into a circular loop to serve for room experiments. When a large loop with miniature incandescent lamp was held horizontally in the room the miniature lamp lightened up strongly. When holding the loop in a vertical plane, parallel to the plane of loop of cable and **not far** from same the lamp **did not light up** as strong although theoretically it should have received **much more** energy. This is **very curious** particularly because effect observable only with very strong excitation of cable or loop.

May 10, 1901

Approximate estimate of inductance coils to be used in series with Westinghouse transformer for charging the condensers in laboratory apparatus.



Two spools are made 19" outside diam.

5" smallest diam. (core)

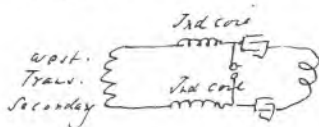
Width of coils $2\frac{1}{2}$ ".

Taking 1000 makes and breaks per sec. on spark wheel this would correspond to cycles $500 = n$. To work with, we should have the inductance of the two coils to satisfy relation $2\pi n = \frac{1}{\sqrt{LC}}$. We can take C approx. equal to capacity of 3 large jars = $0.03\mu\text{F}$. This would give for both coils inductance: $\frac{10}{3}$ Henry. Or each of the coils should have $\frac{10}{6}$ Henry = $\frac{10^{11}}{6}$ cm.

May. 10. 1901.



Approximate estimate of inductance coils to be used in series with Westinghouse transformer for charging the condensers in laboratory apparatus.



Two spools are made 19" outside diam.
5" smallest diam. (core)
width of coils $2\frac{1}{2}"$

Taking 1000 turns and breaks per sec. on spare steel this would correspond to cycles 500 = n . To work well we should have the inductance of the two coils L satisfy relation $2\pi n = \frac{1}{\sqrt{LC}}$. We can take C approx equal to capacity of 3 large jars = 0.03 m.f. . This would give for both coils inductance: $\frac{10}{3}$ Henry. Or each of coils should have $\frac{10}{6}$ Henry. = $\frac{10^{10}}{6}$ c.m.

Call length of each layer l , n_1 number of turns per layer n_2 number of layers, a smallest area, A largest area. Then inductance of smallest coil $L_1 = \frac{4\pi a n_1^2}{l}$

$$L_2 = \frac{4\pi a n_1^2}{l}$$

$$L_{n_2} = \frac{4\pi A n_1^2}{l}$$

$$\text{Total will be } L = \frac{4\pi n_1^2}{l} (a + a_2 + \dots + A) = \frac{4\pi n_1^2}{l} \cdot \frac{n_2}{2} (a + A) \\ = \frac{2\pi n_1^2 n_2 (a + A)}{l}$$

Since all the turns are superimposed the actual inductance - when all coils are instead of being separated together - will be approximately $\frac{1}{2}$ times greater. Hence the inductance (actual) will be not far from

$$L_1 = \frac{2\pi n_1^2 n_2 (a + A)}{l} \quad \text{from this formula}$$

we can now determine the number of turns and layers.

$$n_1 n_2 = \frac{L_1 l}{2\pi (a + A)}$$

$$\text{Here } L_1 = \frac{10}{6} \text{ H} = \frac{10^{10}}{6} \text{ c.m.}$$

$$l = 2\frac{1}{2}" - \frac{1}{2} - \frac{1}{2} = 2" = 5 \text{ c.m.}$$

Now n_2 is a fraction of n

$$a + A = 19.5 \text{ c.m.} \quad 2\pi (a + A) = 123.4$$

$$\text{Hence } n_1 n_2 = \frac{\frac{10^{10}}{6}}{123.4} = \frac{10^{10}}{73700} = \frac{10^6}{737} = 136 \times 10^3$$

1)

Call length of each layer l , n_1 number of turns per layer, n_2 number of layers, a smallest area, A largest area. Then inductance of smallest coil,

$$L_1 = \frac{4\pi a n_1^2}{l},$$

$$L_2 = \frac{4\pi a_1 n_1^2}{l},$$

$$L_{n_2} = \frac{4\pi A n_1^2}{l}.$$

$$\text{Total will be } L = \frac{4\pi n_1^2}{l}(a + a_1 + \dots + A) = \frac{4\pi n_1^2}{l} \cdot \frac{n_2}{2}(a + A) = \frac{2\pi n_1^2 n_2 (a + A)}{l}.$$

Since all the turns are superimposed the actual inductance – when all coils are instead of being separated together – will be approximately l times greater. Hence the inductance (actual) will be not far from

$$L_1 = 2\pi n_1^2 n_2 (a + A).$$

From this formula we can determine the number of turns and layers.

$$n_1^2 n_2 = \frac{L_1}{2\pi(a + A)}. \text{ Now } n_2 \text{ is a function of } n. a + A = 1956 \text{ cm}, 2\pi(a + A) = 12284$$

$$\text{Here } L_1 = \frac{10}{6} \text{ H} = \frac{10^{10}}{6} \text{ cm}, l = 2\frac{1}{2}'' - \frac{1}{4}'' - \frac{1}{4}'' = 2'' = 5 \text{ cm}.$$

$$\text{Hence } n_1^2 n_2 = \frac{10^{10}}{6} \cdot \frac{1}{12284} = \frac{10^{10}}{73700} = \frac{10^8}{737} = 136 \times 10^3.$$

To carry the current No 20 wire should be used. This will give 45 turns per layer. Take average insulation between layers $\frac{1}{32}''$.

$$\text{Now from above: } n_2 n_1^2 = 136 \times 10^3 \quad n_2 = \frac{136 \times 10^3}{n_1^2} = \frac{136 \times 10^3}{45^2} = \frac{136 \times 10^3}{2025}.$$

$$n_2 = \text{approx. 67 layers.}$$

Now we get for 2" 45 turns.

The outer diam. of spools is 19", inner diam. 5". Space for wire 7". Of this we must deduct say $\frac{68}{32} = 2.12''$ for insul. Would give more layers than necessary. Hence we may take wire thicker.

Assume No 18 wire. Comes out still too much.

With No 16 we get 31 turn per layer that is ... Take length 2". This would make

$$n_2 = \frac{136 \times 10^3}{31 \times 31} = 140 \text{ layers that is too much}$$

Take again wire No 18. For layer 42 turns. $n_2 = 136000 : 1764 = 77$ layers. As a matter of fact more layers ought to be put on. Therefore wire No 18 will probably suit. 96 layers can go on in space. By using insulation slightly thicker about 80 layers can be put on. This will do. This will make total turns 3360 turns. Length of wire approx. = over 10 000 feet in each coil. We want more than 20 000 feet for both or over 100 lbs. Order 120 lbs at once.

May 19, 1901

From old notes

In many instances when working with an oscillatory system transmitting its vibrations upon the ground I observed that the effects produced were stronger when the oscillating system was connected to earth through a condenser. This may have been due to some secondary causes but theoretically there are reasons for expecting such a result.

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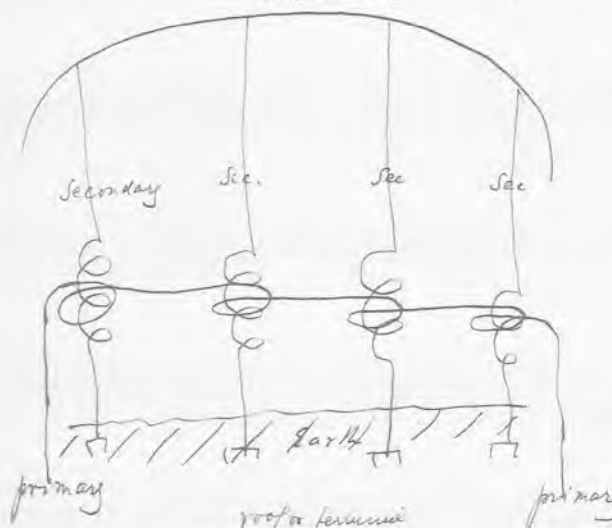
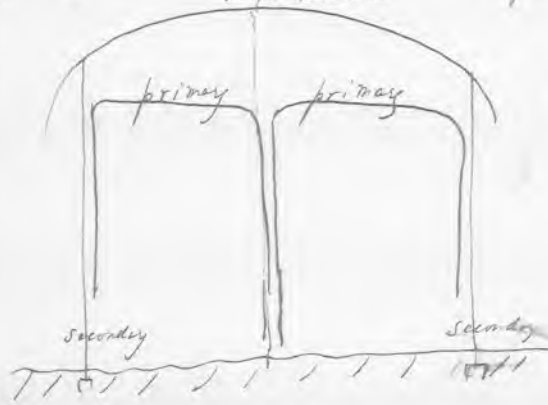
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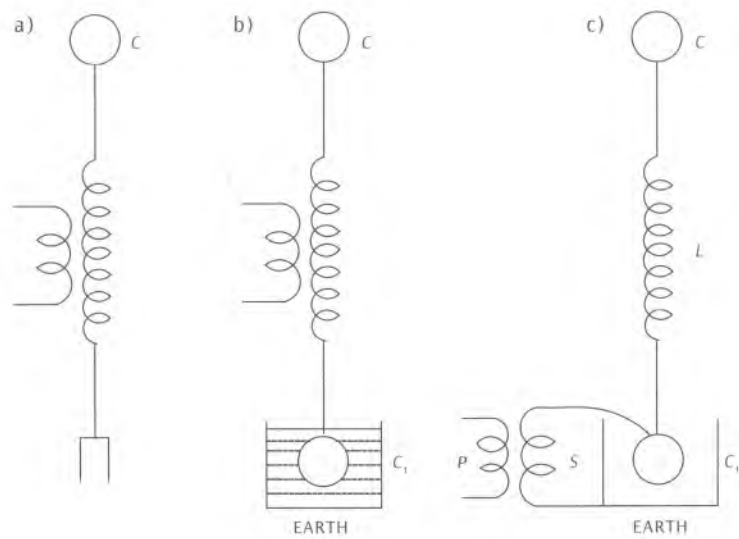
New York May 19 1901
from old notes

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This arrangement may be resorted to so as to make insulation of terminal in my system unnecessary. The support of a roof may be of metal and currents may be induced in them through primary discharges or currents.

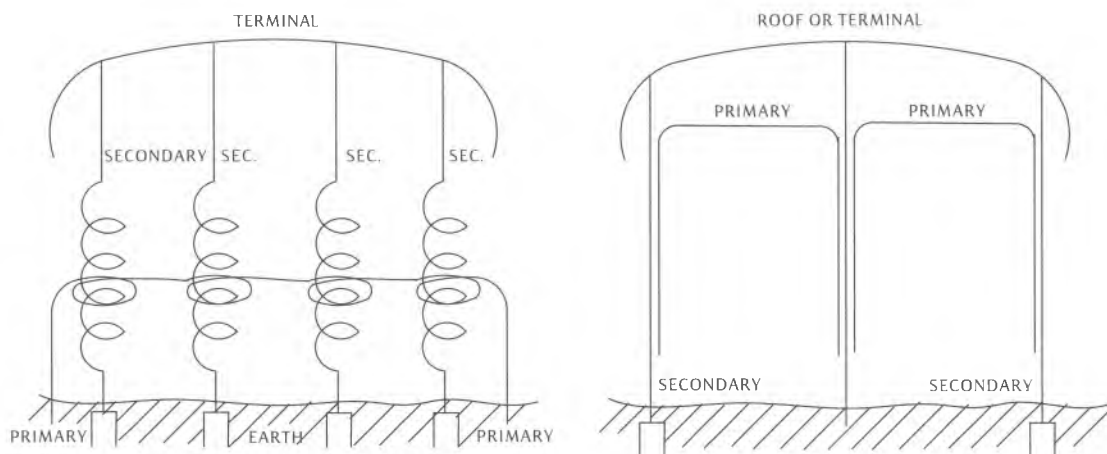
The second arrangement will permit the use of straight metallic supports. In some cases it may be practicable though not highly economical.



a illustrates the older arrangement, *b* the modified plan with condenser C_1 . It would seem that in case *b* a more vigorous vibration can take place in system because it is left to itself and not intimately connected to ground. The damping factor might be smaller in case *b*.

In fig. *c* the most effective plan is illustrated. Here the secondary *S* is joined to the condenser C_1 . When $C = C_1$ the length of oscillating condenser or coil *L* should be $\frac{1}{2}$ of the wave length.

From old notes



This arrangement may be resorted to so as to make insulation of terminal in my system unnecessary. The supports of a roof may be of metal and currents may be induced in them through primary discharges or currents.

The second arrangement will permit the use of straight metallic supports. In some cases it may be practicable, though not highly economical.

The following plan has been found convenient in the determination of capacities as that of an insulated terminal or of a coil by resonance method as described in Colorado Notes.

The coil L is excited in any of the ways previously described, for instance by connecting a point a to a source of the oscillations. When C is equal C_1 then the neutral point m is just at the middle of the coil. The capacity C_1 is easily calculated or determined. The greater C_1 as compared with C the more the point m shifts towards C_1 . Interesting measurements may be made in this manner. There are a number of ways of locating the point m . A minute spark gap is the simplest means. When C_1 is connected to earth then m falls together with one of the coatings of C_1 , at least practically so.



When a terminal is used in the form of a metallic surface on roof supported on metallic bars or pipes or any conducting supports the difficulty arises to get the vibration quick enough. Even if the roof be large owing to the small inductance of supports the vibration is still very quick and for many purposes as signalling without wires to great distances unsuitable.

Following plan may be very good:

I propose to construct a roof in the form of a spiral of metal sheet (copper) (or aluminium) so that it forms a solid structure but with turns insulated from each other. The insulation may be porcelain or glass. Blocks of such material may be cast in proper shapes so as to render construction of roof cheap and easy. The turns of the spiral roof would lay horizontally and would be wound around a larger central terminal and the whole supported on conducting supports buried with their lower ends in the ground. Into the terminal in center a resonating high tension circuit may discharge causing the system to oscillate.

Several constructions to follow.

— : —

Suppose we attempted to transmit a message to a planet as Mars by rhythmical variation of the potential of Earth through a powerful oscillator. Take area of one coating of the condenser constituted by the planet Earth and intervening dielectric $A = 32 \times 10^{16}$ sq. cm

Assume distance to be greatest 64×10^{11} cm.

The minimum capacity would be $C_{\min} = \frac{32 \times 10^{16}}{4\pi \times 64 \times 10^{11}} = 4000$ cm approximately.

If we now were to produce a variation of one volt 10 times per second the energy delivered per second would be

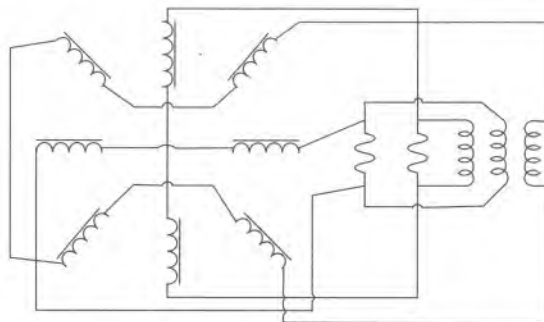
$$E = 10 \times \frac{1}{2} \cdot \frac{4000}{9 \times 10^{11}} = \frac{2}{9 \times 10^7} \text{ Watts. With 100 Volt we would have } \xi = \frac{2}{9000} \text{ Watts!}$$

Such a variation 10 times per second could be produced by my method easily.

— : —

Motor with great torque and no dead point

The following seems to be a very good way of constructing a motor of my system which will have advantages over the two phase as ordinarily constructed, also over three phase motor.



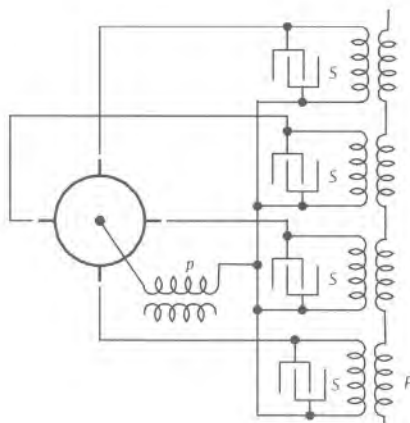
The general idea is to get the intermediate phases by cooperation of the two phase circuits. A transformer is used the secondary of which is energized by both the circuits. This gives 45 degrees for intermediate poles. The idea is applicable also to 3 phase motors.

May 24, 1901

Old arrangement with many spark gaps or make and breaks in multiple arc reconsidered.

By using instead of one n spark gaps or make and breaks the current in each is $\frac{1}{n}$ of the total. The loss in each is $\left(\frac{1}{n}\right)^2$ and the total loss $\frac{1}{n}$ of that which would occur if all the current were passed through one arc. Theoretically with this arrangement the loss could be reduced as far as desired by simply augmenting the number of arcs.

With alternating current it is easy to use a number of transformers or one with many separated windings insulated from each other at least at one end. The connections are in the simplest way as indicated on diagram below.



Suppose there are four arcs all made in same moment. The advantage is that the loss will be only $\frac{1}{4}$ of that taking place in usual arrangement. The primary p may serve for all condensers or independent primaries may be used. The sketch shows the idea applied to my system and it is generally applicable. Various dispositions to be shown.

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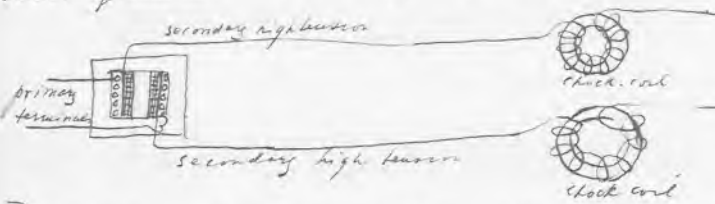
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New York May 26 1901

from old notes

Producing high e. m. f. from ordinary alternating current
in the transformers and checking coils.

Arrangement as a sketch is as follows:



Series of coils as here

Series of coils as here

Each terminal has capacity of 1000 p.f. or more. Say spheres or insulated by glass, rods e. l. c.

The current in each system will vary according to conditions maintained and large and therefore may be very great depending not on then 1000.

Now L of end of the checking coils

$L = \frac{4.5 \cdot X^2 \cdot A \cdot \mu}{l \cdot 10^9}$ The individual coils should be small so that they may be wound back through to the iron core.

If they are large the space would back through to the iron core.

Take $A = 10$ c.m.² $l = 10$ c.m. $X = 500$ Then $L = \frac{12.6 \times 20 \times 10^4 \times 10}{10^{10}} \cdot 10^3$

$= 0.126 \times 20 = 2.52$

Suppose we work with 180 cycles per sec.

Let capacity on each of each terminal be 1000 p.f. say $C = 1$ Henry.

Assume further secondary connected to ground in middle then there would be two circuits

and: $\frac{1}{100} = \frac{2.5}{10^3} \sqrt{A \cdot L \cdot C}$ A number of coils in each circuit or branch, C capacity on each terminal. Self-induction of secondary neglected also capacity of wire for present.

from this $n = 444$ coils.

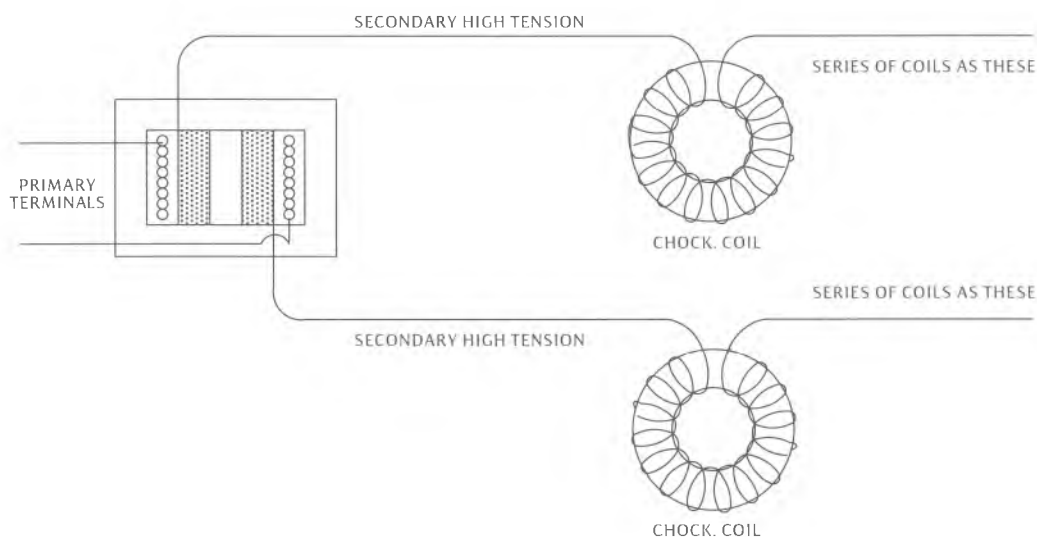
Several windings, sources or induction apparatus arranged to discharge through gaps or make and breaks. The oscillation started in one of them, spark or break bridged. Current now induced in an other element and spark in that element bridged and so on. This forms a direct current system. Oscillation may be started and the discharges will pass through the gaps or make and breaks automatically. Many ways of carrying out the idea obvious. Will be shown in subsequent sketches.

May 26, 1901

From old notes

Producing high e.m.f. from ordinary alternating circuits with transformers and choking coils.

Arrangement as in sketch or similar:



Each terminal has capacity large on end. Say spheres or insulated cylinders, roofs etc.

The currents in such a system with resonating conditions maintained are large and therefore μ may be very great, certainly not less than 1000

Now L of each of the choking coils $L = \frac{4\pi \cdot N^2 A}{l \times 10^9} \mu$. The individual choking coils should be small so that they may withstand the stress. If they were large the spark would break through to the iron core.

Take $A = 10$ cm sq. $l = 10$ cm, $N = 500$. Then $L = \frac{12.6 \times 25 \times 10^4 \times 10}{10^{10}} \cdot 10^3 = 0.126 \times 25 = 3.15$. Say $L = 3$ Henry

Suppose we work with 130 cycles per sec. Let capacity at end of each terminal be 1000 cm. Assume further secondary connected to ground in middle then there would be two circuits and: $\frac{1}{100} = \frac{2\pi}{10^3} \sqrt{nLC}$; n = number of coils in each circuit or branch, C = capacity on each terminal. Self-induction of secondary neglected, also capacity of wire for present.

If both branches constitute one circuit this would mean that there would be 444 coils in all or 222 in each leg.

The above estimate is rough but shows clearly that under above assumptions it would be hardly practicable to use such apparatus.

We should have higher frequency, more turns in each choking coil and greater capacity on end.

We may use as terminals horizontal roof with rounded ends (toroidal form) large radius of curvature to withstand high pressure. The capacity of such terminal if not at great altitude may be considerable. We can get very easily 10 000 cm. By using finer wire in coils we can have in each 1000 turns. Then the inductance of each will be above 12 Henry. For the same frequency as before we would then have n_1 number of coils:

$$\frac{1}{130} = \frac{2\pi}{10^3} \sqrt{n_1 \cdot 12 \times \frac{10000}{9 \times 10^5}} \quad n_1 = 11 \text{ coils nearly.}$$

This would be thoroughly practicable. The coils could be oil insulated. One terminal connected always to core and oil tank and only one terminal insulated and led to next tank core and terminal etc.

We may now consider what under above conditions might be expected from apparatus. To get 1000 turns in each coil we should have to use wire № 22 perhaps silk insulated.

1000 turns will have length approx. of: $1000 \times 8 = 8000$ inch = 750 feet.

Assume 6 coils in each leg, that is 12 coils total, we would then have total length of wire in choking coils: $12 \times 750 = 9000$ feet.

The resistance would be: 62 feet per Ohm $9000 : 62 = 145$ Ohm.

Suppose total resistance of circuit to be 200 Ohm. Neglecting for the moment hysteresis and other frictional losses we would have E at the terminals:

$$E = e \cdot \frac{Lp}{R}$$

e initial e.m.f. at the terminals of exciting transformer.

$L = 12 \times 12 = 144$ Henry.

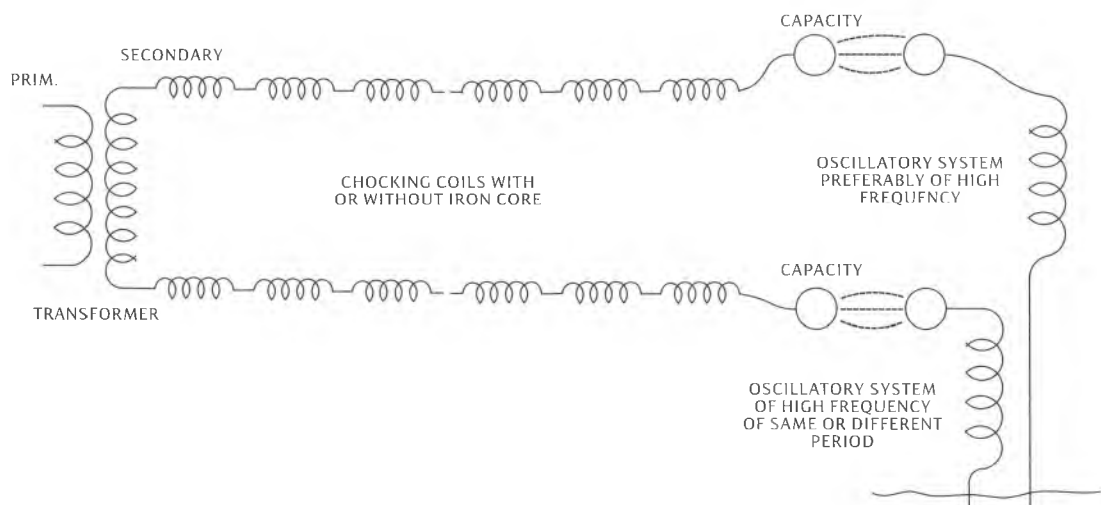
$p = 2\pi n = 820$ approx. $R = 200$.

$$E = e \cdot \frac{144 \times 820}{200} = 580 \cdot e$$

say approximately the e.m.f. initial will be raised to 500 times the value

Now e can be under above conditions easily 10000 Volts judging from the number of turns the secondary might have with resistance assumed. Hence $e = 500 \times 10000 = 5$ million Volts.

Summing up preceding results show that it is practicable to raise the e.m.f. in the manner for many purposes. For example in telegraphy without wires a high pressure may be in this way attained and by discharging the capacity or capacities at the terminal or terminals of the system into an other system strong effects may be secured without the necessity of converting to high frequency currents first. A scheme of this kind is illustrated below:



In this case the energy accumulated in the resonating circuit will be suddenly discharged and causes high frequency oscillations in the two system in accordance with my method. The both systems may be of same period or of different as described in my patent. At the receiving station the receiver may be operated by one vibration or two. In similar manner more circuits may be provided. This scheme is simple and good.

May 29, 1901

From old notes Oct. 1900

Various ways of controlling oscillators or vibrating currents in general. The chief question involved in the various plans is to control with the miniature effort great movements of electricity. This is a broad important idea and great triumphs will be achieved in many directions by delicate control of strong effects. This is practically important in connection with telephony without wires also in telegraphy over great distances as I soon contemplate to carry out.

Following ways of controlling oscillators have been experimented upon:

a) varying the intensity of oscillations produced; b) varying period and thereby destroying resonating conditions (very sensitive); c) shunting primary exciting current or circuit and varying resistance or impedance of shunt; d) double wound vibrating circuit employed and period in one of the windings varied (excellent results); e) various ways of utilizing heating effects of receiving station which are to be separately described. In some cases spark reproduced and an other transmitter set in action.

- f) Various electrodynamic effects to be separately described.
- g) Bridge arrangement with resistances excellent in its results.
- h) Bridge arrangement with condenser in secondary receiving circuit **very sensitive**.
- i) Various arrangements with condensers in transmitting and receiving circuit to be described.
- j) Arc of oscillator primary to secondary controlled by air compressed. Control of valve delicate.
- k) Auxiliary small arc controlled at transmitting end. Arc to ground controlled **excellent**.
- l) Condenser connection controlled impedance or resistance of same in many ways.
- m) Several dead beat arrangements when condenser method used at receiving end.
- n) Various ways of using batteries with condensers for control etc.

A very excellent idea is to cause a shifting of maxima and minima points along a conductor and effect control of other useful performances in this way. There are great many ways in which this idea may be applied. A condenser may be charged from the circuit by tapering same at one or more (two) points and great sensitiveness can be secured by using the energy of the condenser in receiving circuit. Slight displacements of the maxima and minima will cause great variations in the energy and in this way also a transmitter can be controlled by slight effort. This is to be separately treated.

A good way is to use a spark gap which is so arranged that by any change in its points of maximum and minimum are shifted. The arc may be controlled by voice. This is capable of great sensitiveness. In this way Roentgen rays and ultraviolet rays and similar radiations may be controlled or utilized. These rays themselves enable the control. This to be separately dealt with.

In telephony as well as telegraphy through media natural it is very good to have independent oscillating circuit connected to ground through a condenser and effect variations of capacity of latter. Also very good to alter period of impressed vibrations or otherwise destroy harmony thus varying effect. The freely vibrating circuit may be of low period and tuned to average of voice undulation. A very

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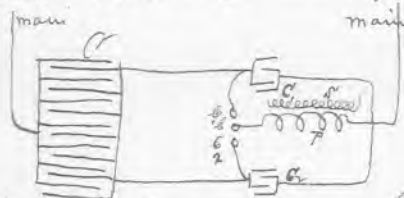


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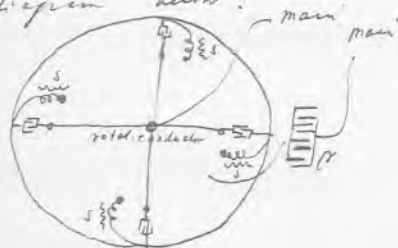
from old notes of experiments.

In order to improve oscillating apparatus arrangements as below illustrated were experimented with:



found in this arrangement break points can be close, no arcing. The condenser prevents short-circuit effects. For many purposes this scheme is excellent. An improvement was effected by using great many small condensers $C_1, C_2, \dots, C_n$. In one case 24 condensers were used. The condensers are discharged successively through the same primary. The apparatus worked very well but output is comparatively small.

The machine was subsequently modified and instead of one many primaries were used, one for each condenser. The secondary were connected in series. Also in multiple they may be connected under certain conditions. The scheme of connections is shown in diagram below:



Or a large condenser supplied from direct current generator of 220-500 volts. Higher tension would have been preferred. Or, or smaller condensers, e.g., break points effects of making as in my breaks. It was no arcing. The condenser can be close. For arcing. The condenser is excellent.

For many purposes this scheme is excellent. An improvement was effected by using great many small condensers $C_1, C_2, \dots, C_n$. In one case 24 condensers were used. The condensers are discharged successively through the same primary. The apparatus worked very well but output is comparatively small.

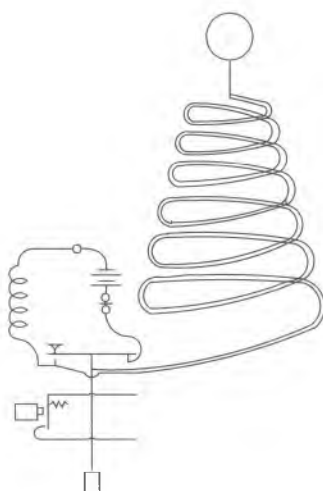
The machine was subsequently modified and instead of one many primaries were used, one for each condenser. The secondary were connected in series. Also in multiple they may be connected under certain conditions. The scheme of connections is shown in diagram below:

Only four condensers in primaries are shown. The secondaries SSSS may be used separately or any number of them connected together. The condenser C_1 must be always large as it is charged and discharged completely only once by one complete revolution of rotating discharge of conductors.

long lever light moved by diaphragm seems very good. Continue to investigate. Two primary windings oppositely wound and one shunted. By controlling impedance of shunt small variations are made to produce great changes. Very good.

From old notes

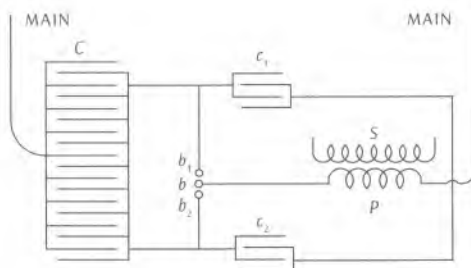
Following was found to be an excellent arrangement in signalling without wires suitable both for transmitter and receiver circuit. In the former great variations of intensity should be produced by small variations in the action of controlling device. This is particularly important in telephony. In the receiver, however, when using a secondary it is difficult to utilize economically the energy received in primary from distant transmitter. The scheme illustrated offers in this connection great advantages. The diagram shows connections as have been used sometimes in telegraphy.



The idea is as before illustrated to use two circuits placed close together and effect variation by disturbing resonating balance. When one of the circuits is but slightly quickened or retarded great changes in the intensity of signals transmitted are produced because chiefly of large capacity effect of adjacent turns. So at least I explain great sensitiveness. This makes evident the effectiveness of transmitter. On the receiver station one of the conductors is used as secondary that is only one of the circuits or conductors receives effectively the oscillations through the ground. As the circuits are very close throughout their extent the transformation is economical. Particularly good is in this connection a concentric cable the inner wire serving as secondary being very thin so as not to impair resonant rise. Various arrangements of this kind with telegraphic and telephonic apparatus are to be shown.

From old notes of experiments

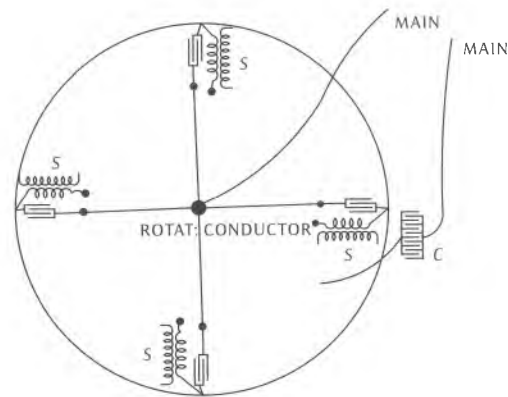
In order to improve oscillatory apparatus arrangements as below illustrated were experimented with:



C a large condenser supplied from direct current generator of 220–500 Volts. Higher tension would have been preferable. C_1, C_2 smaller condensers. b, b_1, b_2 break generation effected by mercury as in my breaks.

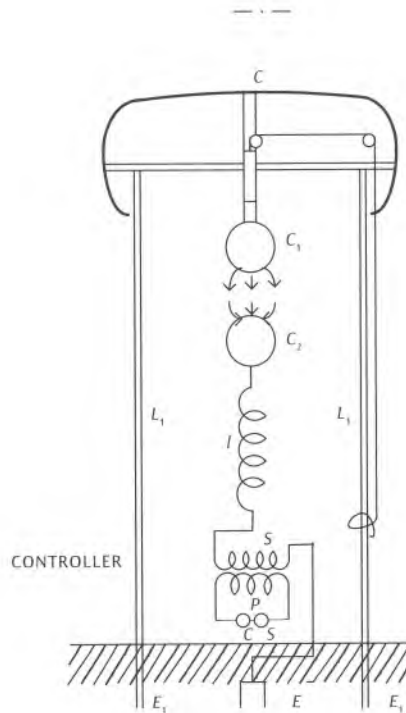
It was found in this arrangement break points can be close. No arcing. The condenser C prevents short-circuit effects. For many purposes this scheme is excellent. An improvement was effected by using great many small condensers, $C_1, C_2, \dots, C_n$. In one case 24 condensers were used. The condensers are discharged successively through the same primary. The apparatus worked very well but output is comparatively small.

The machine was subsequently modified and instead of one many primaries used, one for each condenser. The secondaries were connected in series. Also in multiple they may be connected under certain conditions. The scheme of connections is obvious in diagram below:



Only four condensers and primaries are shown. The secondaries ssss may be used separately or any number of them connected together. The condenser C must be always large as it is charged and discharged completely only twice by one complete revolution of rotating discharging conductor.

From old notes



In annexed sketch a terminal C in form of a roof is supported on conducting supports L_1L_1 . Terminal C_1 is adjustable and in contact with structure of roof or terminal C . A resonating system C_2IsE discharges into C_1 and produces oscillations in system $CL_1L_1E_1E_1$. This arrangement obviates necessity to support roof or terminal C on insulated supports.

Now in a sketch the difficulty will be probably to get the oscillations of the free system $CL_1L_1E_1E_1$ slow enough to be very effective in transmission through Earth as in my system. The length of conductors in the free system should be $\frac{\lambda}{4}$, and the length of the discharging circuit should be $\frac{3}{4}\lambda$ or $\frac{n}{4}\lambda$ eventually, n being uneven number. Suppose to get an idea we take $C = 10000$ cm. This is realizable. Then we have $\frac{2\pi}{10^3} \sqrt{L \times \frac{10000}{9 \times 10^5}}$ the period of system. We should have vibration not much quicker than 100 000 and to satisfy this L would have to be: $\frac{1}{100000} = \frac{2\pi}{10^3} \sqrt{\frac{L}{90}}$; $L = \frac{9 \times 10^5}{4} = 225000C$.

Calculated it would appear that the supports L would have to be about 600 feet. The arrangement would be o.k. with quick oscillations. The self-induction of a straight conductor is $L' = r l' (\log_e \frac{2l'}{r} - 0.75)$. Now, take $L' = 300$ feet = 9000 cm. If we have to use iron pipes 4" diam. $r = 5$ cm. Then $\frac{2l'}{r} = 3600$ and from this I find $L' = 134000$ cm. Again taking the length 600 feet we would get inductance probably 268 000 cm. To get lower frequencies evidently in above scheme self-induction must be increased. The charging and discharge circuit may also be of different period and both vibrations used to excite receiver.

May 30, 1901

Previous calculation decidedly shows that we can expect 1) to store 1000 Watts in condenser primary per charge 2) that condenser can be charged and discharged 5000 times per second. This ignores all losses so far. Primary rate would be limited to one discharge and so also secondary rate without further provision. But if discharges fall together and are all added up, then secondary rate determined by 1) duration 2) by Ohmic etc. loss.

Suppose then 1000 Watts stored charges and discharges 5000 times.

The rate will have to be reduced first of all to one half because of intermissions necessary for charging. This might be overcome by a number of condensers 2 or more which are charged and discharged alternately. But with one condenser evidently primary rate can not be more than 2,500,000 Watt rate during the intervals of charges while the break is working. This too is by far too high.

The losses in the arc etc. must bring this rate down to one half. Conservatively estimated we can not transfer to the secondary more than 1,000,000 Watt rate. The mechanical system does not limit, nor the capacity of the condenser for storing and giving off. During signalling energy may be taken of for $\frac{1}{30}$ of a second if necessary. We may take $\frac{1}{5}$ of second then the total energy accumulated in secondary swinging system will be $\frac{1}{2}CP^2 = \frac{10^6}{50} = 20000$ Watt. Hence with $C = 1000$ cm, $p^2 = 40000 \times 9 \times 10^8$, $P = 6 \times 10^6$ Volts.

Transmission to a distance through wires or conductors of writing, print, pictures or images. Also "seeing by wire".

Method of and apparatus for same.

The broad idea underlying the invention is to enable a condition – similar in many respects to that existing in the eye and optic nerve – to be attained. There must be a definite relation as to order

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NEW YORK June 1, 1901

Determination of vibrations of Laboratory apparatus.

Large secondary spiral wound on frame 8x8 feet high H. & outer
turns coil H. & inner turns both ok with insulation thick.
arrangement:

Test: Resonance with:

Capacitance 6 jars in each condenser set
Inductance Connections + 6 1/16 turns }
Same test in each lamp & in secondary

Then I think preferable to former method with a gap one in apt
L are more easily.

Test shows Resonance with:

Capacitance 6 jars in each condenser set
Inductance Connections + 7 turns in selfed box.

There is an objectionable feature in both these methods
of testing although they are good. Namely, the system to
be tested should be connected to ground. The c.m.f. necessary
for excitation obtained by induction. I propose to employ small
coil of thick wire in ground connection and induce in the same the a.m.f.
necessary.

and intensity between numerous channels, fibres or nerves of the transmitter and receiver. I use for this purpose tuned circuits and by methods and apparatus already described it is easy to provide any number which may be required. Taking only a few fundamental notes a great number of combinational effects may be obtained, comparable to those involved in vision as to number. Now the eye receives rays and these propagating in straight lines necessarily retain their order and relation in space. But in transmitting impulses through a wire for example all currents will pass through same channels and not in fibres or bundles separated from each other. Nevertheless a result for all practical purposes the same as in the transmission of light images by rays can be obtained by arranging the transmitting and receiving circuits in the same order. Although the impulses will pass through the wire without preserving order yet inasmuch as they are again singled out and separated in the same order as sent from transmitter it is evident that by such means images pictures etc. in fact knowledge of forms can be conveyed.

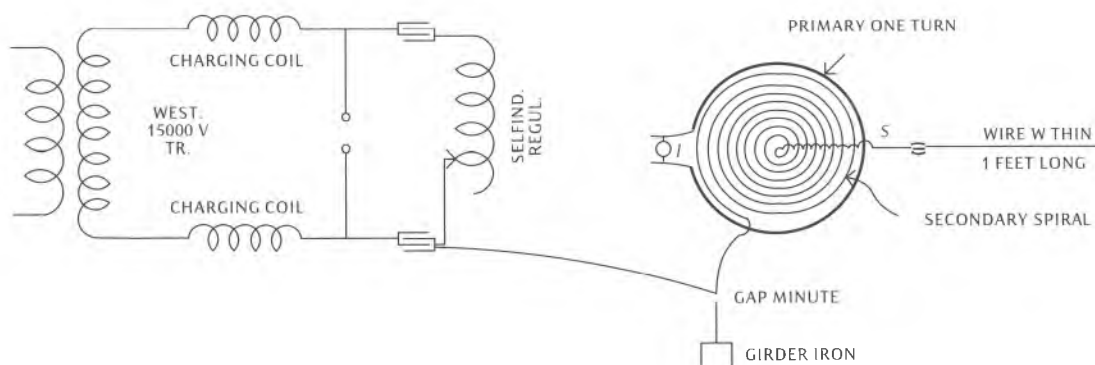
To this I referred in article in "Colliers weekly". The best way now known to me to carry out the invention is to provide a transmitting and a controlling plate comprising numerous separate and insulated points close together as to form a surface practically uniform. The separate elements of this surface or plate are to be cells of selenium in the picture transmission. The elements could form little squares or hexagons preferably. The individual cells of selenium will control such a transmitting circuit tuned or individualized by my methods. When an image is projected upon the surface consisting of these cells the corresponding transmitter will be set in action. The control by means of the cells of these transmitting circuits should be such as to produce variations of density in the oscillations proportionate to the action on the cells. At the receiving end there will be receiving circuits or elements each corresponding to one of the transmitting circuits. The receiving circuits will be in any way connected with an apparatus comprising elements similarly arranged as in transmitter to form a plate or surface. Now there are great many ways of producing on paper an impression or image from the plate so constituted. The image must resemble the picture projected on the transmitter plate because the receiver plate is composed of elements arranged in same manner. Effects of color will enable the production of an image. By this method and apparatus transmission of images is certainly practicable. As to transmission of characters it is easy. In this case the selenium cells are not necessary for the control of the transmitting elements can be effected by contact for instance. **No synchronous movement in this!!**

June 1, 1901.

Determination of vibrations of laboratory apparatus

Large secondary spiral wound on frame 8x8 feet, wire N^o 8 outer turns cord N^o 8 inner turns both Okonite insulation thick.

Arrangement:



Test: Resonance with:

Capacity 6 jars in each condenser set
Inductance Connections + $6\frac{5}{16}$ turns

} Spark to ground was very small, $\frac{1}{32}$ "
to wire w 1"
(should have been greater, I think)

Same but with small lamp / in secondary

This I think preferable to former method. With a spark one is apt to error more easily.

Test showed resonance with:

Capacity 6 jars in each condenser set

Inductance Connections + 7 turns in Selfind. box.

There is in objectionable feature in both these methods of testing although they are good. Namely, the system to be tested should be connected to ground. The e.m.f. necessary for excitation obtained by induction. I propose to employ small coil of thick wire in ground connection and induce in the same the e.m.f. necessary.

"Extra" coil used in connection with spiral secondary wound with Rubber wire.

Same test as with spiral coil with spark analyzer as before:

Resonance obtained with

Capacity 6 jars in each condenser set
Inductance Connections + 2 turns in Ind. Regul.

} Spark to ground a little
over $\frac{1}{32}$ " , strong;
Spark to wire w $\frac{5}{8}$ "

Test with miniature lamp connected to sparking rim of coil on bottom showed resonance with:

Capacity as before
Inductance Conn. + $2\frac{1}{8}$ * turns in Regulator

} * This shows also as above
that vibration slower in test
with lamp slightly

A test was now made with big spiral again but with a vibration such as would make the length of spiral $\frac{3}{4} \lambda$. Rough computation showed that only one jar in each condenser set could be used making vibrations 2-4 times quicker. By taking out self-induction resonance was obtained with lamp:

Capacity one jar in each set of condensers
Inductance Conn. + $1\frac{1}{16}$ turns in Self. Regul.

} spark to structure very small,
almost touching electrodes

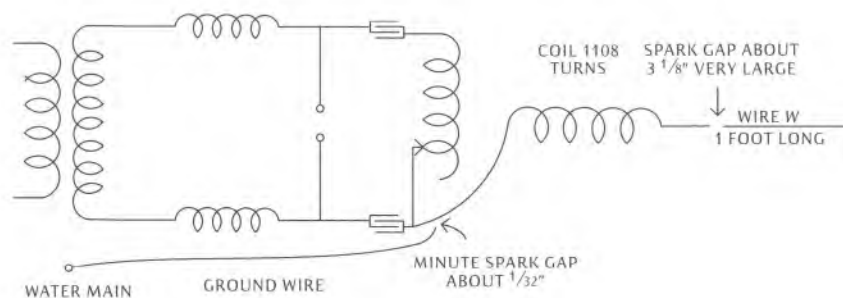
Test with spark analyzer showed resonance with about same turns in Regulator. An other tone was sought and resonance obtained with $5\frac{1}{2}$ turns in Regulator. The spark to iron girder was rather large: $\frac{3}{64}$ " about.

Effect of ground wire used in laboratory experiments ascertained:

For convenience in some experiments a ground wire No 8 cord is employed leading from apparatus along steam pipes to water main. The length of this wire is ... feet.

As this conductor adds to length of oscillatory system it has to be taken into consideration. To ascertain effect a coil was used of No 20 cotton covered bell wire, 1108 turns wound on wooden cylinder $3\frac{7}{8}$ " diam. $69\frac{3}{8}$ " long (wound part).

Arrangement first used:



Resonance was obtained with:
 4 jars in each set of condensers
 2⁵/₈ turns in Regul. Selfind.

In this test the ground wire added to the length of coil and made $\frac{1}{4}$ wave longer, hence system responded to slower vibration.

Test modified with ground wire omitted and the small spark gap arranged on one of the iron girders. As the building is an iron structure of very large capacity even if there would be no ground connection we would get practically $\frac{\lambda}{4}$ for the length from small spark gap to larger on end of coil.

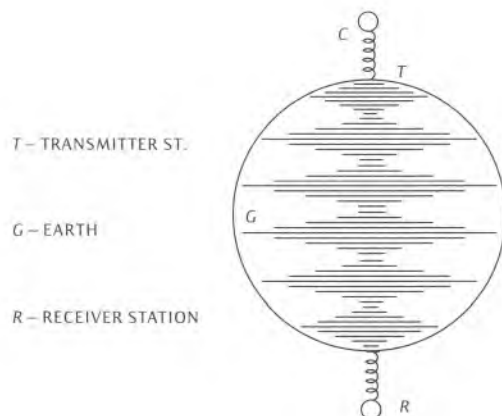
Test showed resonating conditions took place with:

4 jars in each condenser set
 2³/₁₆ turns in Regulating Selfind.

Note: In this experiment the coil had only 1100 turns which amounts for a slight quickening of the vibrations but not for the greater part of effect which was due to omission of ground wire.

June 2, 1901

Transmission of electrical energy by conduction through Earth with my open synchronized circuits considered with reference to discovery of law of density



The experiments in Colorado seem to be conclusive in their proof that no appreciable loss of energy results in transmission under the conditions as illustrated in diagram, hence if we have a quantity Q of electricity in terminal at the transmitting station T the same quantity will distribute itself at

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New York June 2 1901.

Transmission of electrical energy by conduction through Earth with my
open syndromed circuits considered with reference to discovery of laws of drawing



The experiments in Colorado seem to be conclusive in their proof that no appreciable loss of energy results in transmission under the conditions as illustrated in diagram. Hence if we have a quantity Q of electricity at terminal at the transmitting station T the same quantity will distribute itself at the opposite pole when receiving station is supposed to be located over an area covered by half of the world. An example will aid in giving an illustration of what can be reasonably expected in applying the principles for the above purpose. Suppose the capacity $C = 10,000$ k.f. This can be obtained by a roof insulated supports. If the roof be say in the shape of a sphere (this will serve in the present example) it would have to have a radius of 100 meters. But since as demonstrated in my tests the capacity of these insulated terminals increases with elevation about $1/2\%$ per foot, by elevating sphere 400 feet only 33 meters radius will be all that is needed.

Assume now that 100,000 per second is adopted as frequency and that we expend on the generator 100 H.P. How much under best conditions can we expect to get at receiving station? 100 H.P. roughly = 75,000 Watts. This enables us to get promise to which the insulated space or capacity C can be changed by the amount of energy

1)

the opposite pole when receiving station is supposed to be located over an area covered by half of the wave. An example will aid in giving an illustration of what can be reasonably expected in applying the principles for the above purpose. Suppose the capacity $C = 10,000$ cm. This can be obtained by a roof on insulated supports. If the roof be say in the shape of a sphere (this will serve in the present example) it would have to have a radius of 100 meters. But since as demonstrated in many tests the capacity of these insulated terminals increases with elevation about $\frac{1}{2}\%$ per foot, by elevating sphere 400 feet only 33 meters radius will be all that is needed.

Assume now that 100 000 per second to be adopted as frequency and that we expend on the generator 100 H.P. How much under best conditions can we expect to get at receiving station? 100 H.P. roughly = 75 000 Watts. This enables us to get pressure to which the insulated sphere or capacity C can be charged by this amount of energy.

Let the pressure be P then we have:

$$\frac{1}{2}P^2 \cdot \frac{10000}{9 \times 10^{11}} \cdot 200000 = 75000 \text{ and } P^2 = 67500000 = 6750 \times 10^4.$$

From this $P = 100 \sqrt{6750} = 8200$ Volts roughly. This means to say that we could charge the terminal periodically (200 000 times per second) up to a pressure of 8200 Volts.

Evidently with such small pressure the effect at distance would be qualitatively very small but we can, without using more power increase the pressure many times by resonating action.

For the moment it will be useful to consider what might be done by working with the above pressure of 8200 Volts only. According to law of density referred to before the charge distributes itself over the surface of Earth as illustrated and the density of each zone is inversely as the surface of the zone.

If we use 100 000 vibrations per second the wave length will be about 1.86 miles. Hence $\frac{1}{2}$ wave 0.93 miles. Taking for simplicity density uniformly distributed over the area or zone we may estimate it to be $\frac{2}{3}$ of the maximal.

Let a = area of sphere or terminal of transmitter,

A = area of zone – the last on opposite pole where density greater.

As above assumed the radius r of sphere may be 33 meters or about 100 feet. The radius of polar cap = 0.93 miles 4900 feet approx.

$$\frac{a}{A} = \frac{4r^2}{R^2} = 4 \left(\frac{r}{R} \right)^2 = 4 \left(\frac{100}{4900} \right)^2 = \frac{4}{49^2} = \frac{1}{600} \text{ about.}$$

Under the conditions and with reference to above law, since the quantity of electricity on polar cap is exactly equal to the quantity on sphere C the density of charge on the polar cap will be $\frac{1}{600}$ of that on sphere. From what has been said above, however only $\frac{2}{3}$ of this value or $\frac{1}{900}$ can be taken. If Q the quantity of electricity both on sphere and polar cap, D density on sphere, d density on cap we have: $D = \frac{Q}{a}$ $d = \frac{Q}{A}$ $\frac{D}{d} = \frac{A}{a}$. On the other hand $Q = CP = \frac{10000}{9 \times 10^{11}} \cdot 8200 = \frac{8}{10^5}$. Hence $D = \frac{8}{10^5 \cdot a}$. Here a should be taken in cm square. Now $a = 4\pi \times 3300^2 = 140 \times 10^6$ cm sq. approx.

Therefore $D = \frac{8}{10^5 \times 140 \times 10^6} = \frac{8}{144 \times 10^{12}} = \frac{4}{7 \times 10^{12}}$ and $d = \frac{4}{63 \times 10^{14}}$ as absolute values of D and d respectively.

From the law of density and obvious considerations it follows that the e.m.f. impressed at polar cap will be in the same ratio smaller as the density is smaller or it will be $\frac{8200}{900} = 8$ Volts*

* I.e. 9.1 Volts. - Ed.

As the polar cap gets all the energy of the transmitter less of course the frictional and medium losses which from my tests seem very insignificant, we could theoretically recover all the energy if we could utilize the whole of the successive charges of the cap. We could do so if we would utilize a large

capacity C_1 capable of taking up the whole charge. The capacity C_1 should be such that $C_1 p = CP$. Hence $C_1 = C \frac{P}{p} = 900C$. Undoubtedly this capacity could be obtained by vertical wires for instance, distributed over the polar cap at suitable distances. The currents passing into the wires could be converted to suitable tension as usually is in my system. The secondaries could however be connected to advantage only when the currents of same phase. This would probably necessitate the arrangement of the wires in concentric stations at which this condition would obtain. But this difficulty is not a serious one. A wire even then of say 200 feet height might have, with consideration of increase by elevation about 500 centimeter and to make up a capacity of 900×10000 cm as would be required we would want $\frac{900 \times 10000}{500} = 18000$ vertical wires or other kind of terminals. If wires were used about 680 miles would be needed, but they could be thin as the pressure would be small and the air loss consequently negligible*. In addition to this the secondaries would require about as much wire.

* Negligible in the manuscript.

The amount of copper seems large – too large in fact for practical purposes but it seems only so because we have assumed but 100 H.P. energy expenditure at transmitter.

Suppose we would install a plant with 10 000 H.P. that is one giving 100 times the energy before assumed. Then, since the e.m.f. at transmitter will be greater in proportion to the square root of the power we would get at transmitting station an e.m.f. of 82000 Volts instead of 8200 as before, and then the polar cap would be charged to 80 instead of 8 Volts.

Here I come to a momentous question: Can the transmitter convey all its energy to the polar cap or can it merely convey the same quantity of electricity?

To be sure the energy in a vibrating system as a wire is conserved but will the Earth behave identically? This is of enormous importance. For if all the energy is conserved then the polar cap will receive all the 10000 H.P. of the transmitting station and of the 18000 wires circuits or terminals each will receive $\frac{10000}{18000}$ H.P. = 416 Watts!!! But – if the transmitter can do no more than to convey the same quantity of electricity which it sets in movement to the polar cap then under the conditions presently considered the energy collected at the polar cap will be small. Namely we could only employ a capacity 900 times as great as that of the transmitter and could only charge it to 80 Volts. To use a greater capacity – even if we could – would seem of no avail since, the quantity of electricity being fixed, we would not be able to charge the capacity to 80 Volts. The maximum of energy we could collect then would be: $\frac{1}{2} \times \frac{900 \times 10000}{9 \times 10^{11}} \cdot 80^2 \times 200000 = \frac{516 \times 10^{13}}{9 \times 10^{11}} = \frac{51600}{9} = 5733$ Watts or we could get only $\frac{5733}{750} = 7.6$ H.P. approx.

Each wire or circuit will then receive only $\frac{5733}{18000} = 0.3$ Watts or a little more an amount of energy extravagantly large for operating automatic devices even such things as clocks but otherwise inadequate.

This seems discouraging but perhaps it can be helped. A consideration here presents itself. If instead of using 100 000 per sec. as assumed we use a frequency much higher, the conditions, all other factors remaining – will be improved. Suppose the same amount of energy is expended on the transmitter with a frequency n times the one before assumed then, since energy $e = \frac{1}{2} C P^2 \cdot 200000$ also $\frac{1}{2} C P_1^2 \cdot 200000 \cdot n$ where P_1 is the pressure in latter case, we have $P_1^2 n = P^2$ or $P_1 = \frac{P}{\sqrt{n}}$. This means, if a frequency four times the assumed were employed the pressure at transmitter would be $\frac{1}{2}$ of the former that is $\frac{82000}{2} = 41000$ Volts. At the polar cap we would then get, since its surface would be only $\frac{1}{4}$ of the cap on former instance, an e.m.f. of $\frac{80}{2} \times 4 = 160$ Volts, that is twice as much as with the frequency

first assumed and now we could with the same capacity collect 4 times the energy i.e. $7.6 \times 4 = 30.4$ H.P. = 22932 Watts and each wire or circuit would collect 1.2 Watts.

But from the preceding it is clear that, unless radically better conditions can be attained, even with frequencies much higher than the one last assumed, a transmission of energy for industrial uses would not be practicable in this way. Suppose the frequency were, instead of 400 000 per sec – $16 \times 400000 = 6,400,000$ per sec which is manifestly impracticable then even we could get only $16 \times 32 = 512$ H.P. roughly on the whole polar cap and this would hardly pay in power transmission for it would mean a loss of 95% of the power of the transmitter. It should be stated, however, that with such a high frequency the three kinds of losses would be not inconsiderable. Certainly the dielectric loss and radiation would begin to feel.

Returning now to the above important question we may ask: What is it that limits the amount of power transmitted? Surely, it is the small e.m.f. for to all evidence, experimental and theoretical, it ought to be possible to transmit through the earth all the energy of the transmitter to the polar cap as if Earth were a wire, with the exception, of course, of that comparatively small amount unavoidably lost through well known causes. The limitation in the amount of energy collectable on the polar cap is evidently of the same kind as that restricting the energy in a conductor in series with a condenser. The generator supplying the e.m.f. may have any desired amount of energy to deliver but if the e.m.f. is not high enough it is of no use.

This leads to the conclusion that what is necessary is to increase the e.m.f. of the polar cap in any way possible.

So far resonant conditions and advantages of same have been ignored. But by their observance I think the above drawbacks can be largely, if not wholly done away with. First of all it is evident that **without** expending more power on the transmitter the e.m.f. can be many times increased at the polar cap and conversely the same e.m.f. on the latter can be obtained with an incomparably smaller amount of actual expenditure of power on the transmitter. The same e.m.f. at the transmitter and cap could be certainly obtained with an expenditure of only $\frac{1}{100}$ of the power. This means to say that instead of using 10 000 H.P. we would need only 100 H.P. to get 80 Volts on polar cap. Taking 400 000 per sec on which bases 30 H.P. roughly could be collected we would have an efficiency of 33%! and if it be true this already is worth of very serious consideration.

But from my experiments with these transmitters I should say that much better results are possible. There should be no great difficulty of working with a magnifying factor of say 100 ($\frac{Lp}{R} = 100$). As much as that is easily predictable. The e.m.f. at the transmitter would then be 8,200,000 Volts and of the cap on pole instead of 80 Volts 8000 Volts. This I think would be perhaps too high because with 8000 Volts the frictional air loss would be probably of some consequence, if not serious. The points of structures, wet leaves etc. would at that pressure emit small streamers. This is to be seen later by computing the density. For the present I shall assume that 8000 Volts are obtained at the cap. With this e.m.f. we can now charge a capacity sufficiently large to take up all the energy of the transmitter. This capacity is C_2 and we find it from the equation: $\frac{1}{2} \cdot C_2 \cdot 8000^2 \times 800000 = 10000 \times 750$. $C_2 = \frac{75 \times 10^6}{64 \times 10^6 \times 400000}$ farad = 2640000 cm roughly. This is a capacity only 264 times greater than that of transmitting terminal and could be easily obtained. If the same kind of wires were used for collecting the energy as before each having 500 cm capacity we would want $\frac{2640000}{500} = 5280$ wires only and then figures are much better.

To sum up: it seems that we can get working with a magnifying factor of $\frac{Lp}{R} = 100$ and expending 10000 H.P. at transmitting station, terminal capacity of 10000 cm and voltage maximum of 8,200,000 Volts at the polar cap with frequency of 100 000 per sec. a voltage of 8000 V and can collect all energy

with vertical wires or other terminals 5280 in number each of a capacity of 500 cm and distributed judiciously over the area of polar cap. Each wire would be capable of collecting $\frac{10000}{5280}$ roughly say 2 H.P. The electrical movement would be, however, much greater since from this it would appear that capacity might be smaller, eventually 2000 wires might do.

The question of density. In the preceding estimated a pressure of 8,200,000 Volts has been assumed at the terminal of transmitter. This may be too high and streamers may impair the efficiency. From experience I know that with the frequency proposed before streamers will break out from a terminal of 1 cm radius of curvature with a pressure of 50000 Volts or thereabouts. In the absence of exact data I shall for the moment take this as the limiting figure. From this we may get an approximate idea of density. Say a spherical terminal of 1 cm radius is charged to a pressure of 50 000 Volts. The quantity of electricity is $q = 50000 \times \frac{1}{9 \times 10^{11}}$ Coulombs. The surface of sphere is $4\pi \cdot 1 = 12.57 \text{ cm sq.}$ Hence the density of charge: $\frac{50000}{9 \times 10^{11} \times 12.57} = \frac{1}{22626 \times 10^4}$ roughly $\frac{1}{226 \times 10^6}$.

At this density streamers will break out from terminal at any place of smaller radius of curvature.

Now, on the transmitting terminal we have as follows:

The quantity $D = 8200000 \times \frac{10000}{9 \times 10^{11}} = \frac{82}{900} = \frac{8}{100}$ Coulomb.*

The surface of terminal was found before: $a = 140 \times 10^6 \text{ cm sq.}$ Taken exactly as sphere it is about $1328 \times 10^5 \text{ cm sq.}$ but it will be generally larger. Hence it is preferable to take it at $140 \times 10^6 \text{ cm sq.}$ From this,

density $\frac{D}{a} = \frac{8}{14 \times 10^9}$, still far below the critical value.

Energy transmission through Earth with my apparatus and currents of low frequency considered on bases of estimates of June 2

The results were arrived at under tacit assumption of certain ideal conditions which could be only partially realized. But, allowing liberally for all drawbacks the calculations together with results of experiments in Colorado leave no room for doubt that on a large scale energy transmission for industrial purposes is practicable.

I find density in former case was $\frac{8}{14 \times 10^9}$ while the limiting density with 100 per sec was approx. $\frac{1}{226 \times 10^6}$. Making ratio we find $\frac{1}{226 \times 10^6} : \frac{8}{14 \times 10^9} = 8$ which means that we could have in case calculated June 2. employed density 8 times as large. This would mean e.m.f. of 8 200 000 Volts on capacity terminal of transmitter.

From previous considerations it is clear that if all other conditions remain the same and instead of 100 000 per sec 200 per sec currents are used which may still do well with motors we would get with 8,200,000 Volts at transmitter in lieu of 8000 Volts = E on polar cap a smaller e.m.f. $e = \frac{E}{\sqrt{n}}$ where $n = \frac{100000}{200} = 500$ and $\sqrt{n} = 22.4$ approx. from which $e = 360$ Volts only. This would give little energy to be collected by the small individual capacity terminals.

Assuming again 10000 H.P. expended at transmitter the energy at each capacity collected would be in ratio $\left(\frac{360}{8000}\right)^2 \cdot \frac{1}{500} = \left(\frac{9}{200}\right)^2 \cdot \frac{1}{500} = \frac{81}{40000 \times 500} = \frac{1}{500^2} = \frac{1}{25 \times 10^4}$ smaller. Evidently for such low frequency we would want e.m.f. ever so much greater. I think that 400 000 000 Volts would not be impossible with surfaces of large radius of curvature and this for same conditions would give energy in ratio $\left(\frac{400}{8}\right)^2 = 2500$ times greater than preceding value. Or energy collected with low frequency currents

* i.e. $\frac{9}{100}$
Coulomb, and
 $\frac{D}{a} = \frac{9}{14 \times 10^9}$
resp. - Ed.

200 cycles p. s. and 400×10^6 Volts would be $2500 \times \frac{1}{25 \times 10^4} = \frac{1}{100}$ of that obtainable with 100 000 per sec and 8,200,000 Volts. As regards transmission of power all these estimates show that high frequency currents are imperative to employ. But if they can be successfully directed or if, without conversion in direct current, motors can be run then a **great problem is successfully solved.**

June 4, 1901

Test to determine inductance of one of the cables in square frame $8 \times 8'$ in terms of turns of Regulating coil:

One of the cables was connected in series with spark gap and the spiral coil with primary was used to determine period. Across the terminals of primary a minute lamp was connected and the coil shifted to a distance of about 8 feet from square frame.

Resonance was obtained with	{ Turns in Self.Regulator $4\frac{1}{2}$ Capacity: jars in each set 4 }	A comparison of this with result previously recorded under similar conditions of tuning will give inductance. Calculate.
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* The inductance of both cables in square frame when connected in series will be four times as large.

Test to illustrate advantage of spiral coil with high pressure terminal in center instead of on the outside. The results give a general idea of the advantage of having the turns near the high pressure terminal or end small to reduce as much as possible effect of capacity. The drawbacks due to internal capacity increase with square of diameter. In telegraphy when a spark gap or metallic powder is used it is for this reason of greatest importance not to have capacity at the terminals of device as great capacity means smaller density. What is desired in working with sensitive microscopic gap or microscopic film of dielectric is great variation in electric density of terminal. The greater the density resulting from the action of transmitter the more sensitive is the receiver. Therein lies the advantage of spiral coil as I use them in such cases.

Test: a) Coil connected as ordinarily, outer end to ground wire

Turns in Regul. coil $5\frac{1}{4}$ Capacity: jars in each set 4	}	fundamental note
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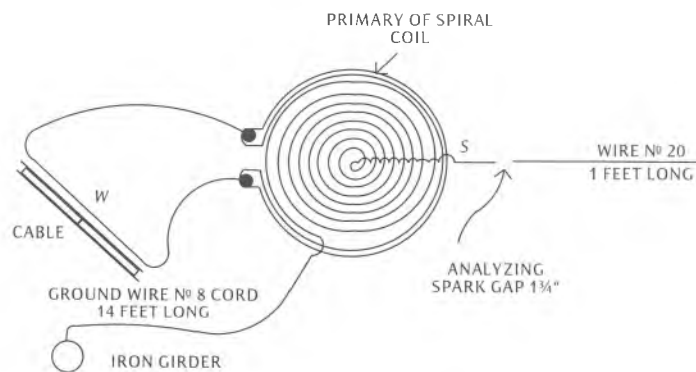
b) Coil connected oppositely, inner wire end to ground wire, outer wire end forming free or high pressure terminal.

Turns in Regul. coil 14 Capacity: jars in each set 4	}	fundamental note
---	---	------------------

* Here miniature lamp across primary of spiral coil was used as analyzer. The capacity of the primary no doubt is of considerable moment. In an other test for same purpose this will be eliminated

Observations made in tuning

The arrangement with wire w before described was used first to determine again the period of large spiral coil of № 8 Okonite wire and cord. Spark analysis to determine maxima and minima, connections as illustrated below.



The experiment was first tried to tune by exciting secondary spiral directly with wire w putting latter in series with ground wire and spiral coil but the e.m.f. so obtained was small. The method was then changed to that illustrated in which case the e.m.f. impressed was very high.

Results:

Turns in Self. Regulator $5\frac{1}{8}$
Capacity: jars in each set 6

} gave fundamental tone
under these conditions

Note: To see to what an extent the length of free terminal wire s might vitate result the wire was pulled out 1 foot. The vibration remained practically unaltered. This corroborates previous observations that when energy in the system small and pressure at terminal comparatively low the pulling out of the wire produces little change. But when the pressure at terminal very great then the every centimeter of increased capacity counts very much. It should be remembered that the energy stored increases with the square of pressure. The general conclusion arrived at is that while pressure itself does not alter the capacity yet for practical purposes it is as if it did.

The above test left room for a doubt that the primary might have considerably altered the period of the spiral coil. To investigate this, the primary was left open and the ends of wire w were connected to one of the cables in frame square 8 × 8 feet. Thus a primary for the excitation of the spiral coil was obtained, the distance of which could be raised. This gave an idea of influence of primary on period of spiral coil.

Resonance was now obtained with

Turns in Self Regulator $6\frac{3}{8}$
Capacity: jars in each set 6

} fundamental note

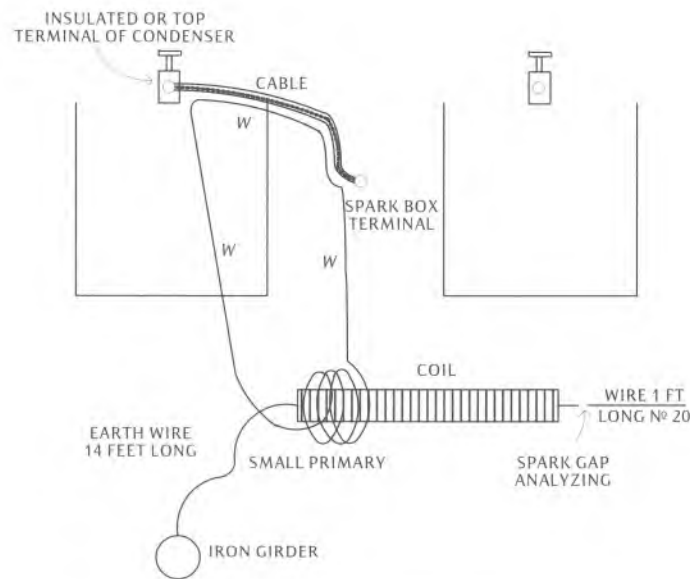
This showed that the primary in first test quickened the vibration appreciably. Obviously the tuning of the coil should be always made with regard to this fact.

To investigate further properties of complex transmitters and receivers and to ascertain best vibrations to be adopted in plant under construction four cores were wound on cylinders of wood of $3\frac{1}{2}$ " diam. and length.

Core A N° 23 wire	double cotton covered	1212 turns
" B " 24 "	"	1350 "
" C " 25 "	double but thinner	1489 "
" D " 26 "	insul. as the first two	1389 "

The periods were ascertained in the following manner:

A wire w was fastened with tape to one of the short thick cables connecting the insulated terminal of one of the condensers with the spark gap. The wire was Nr.8 Okonite covered and the portion close to the thick cable was about two feet long. The wire w was left longer and the ends were joined and wound to form three turns, thus giving a primary of sufficient energy to serve the purpose of the tests and one which would have only a negligible influence upon the period of the coil to be experimented with (arrangement is illustrated).



Results:

Turns in Selfind. Regul.		Capacity
Coil A	3 1/8 turns	4 jars (each set series)
" B	4 1/8 "	"
" C	4 3/4 "	"
" D	4 1/4 "	"

Now coils C and D were connected in series. Result was:

Coil C + D	1 5/8 "	4 "
------------	---------	-----

This was octave evidently.

" C + D	6 1/4 "	4 in one set which corresponds to 8 in each set series.
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To get the fundamental vibration corresponding to the two coils in series one condenser set was short circuited and resonance was obtained with

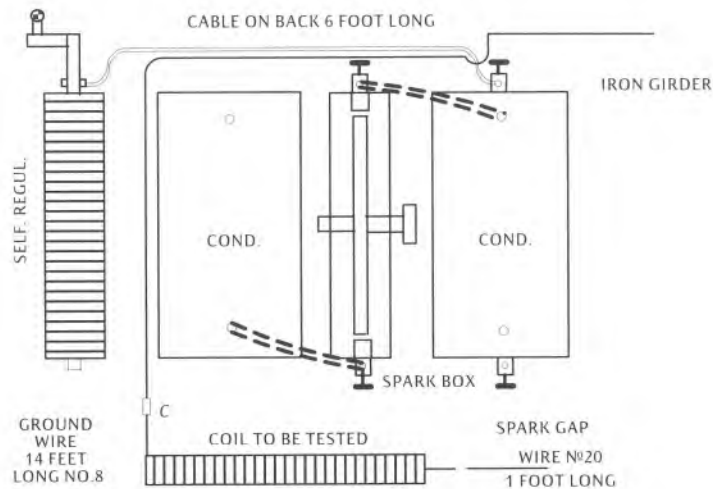
Note. Tuning sharp but must be made much more so

June 5, 1901

Further observations in tuning

In order to eliminate as much as possible influence of source impressing the oscillations upon the freely vibrating circuit the method of inducing a small e.m.f. in ground wire was again resorted to. When tried before the e.m.f. induced was small because the cable from insulated or upper terminal of one of the condensers to terminal of spark box was short. To get higher induced e.m.f. the ground wire was fastened with tape along the longer cable (about 6 feet) on the back of both condenser sets this giving e.m.f. required.

The condensers and positions of the several apparatus are indicated in sketch below viewed from top.



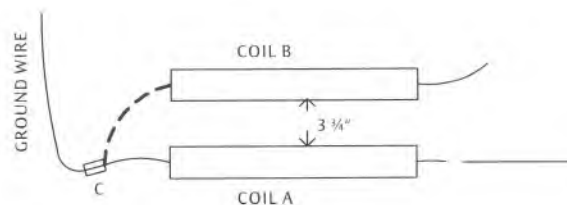
With coil before designated A wound with No 23 wire 1212 turns resonance was obtained with:

3 $\frac{3}{8}$ turns in Self-induction Regulator	} Analyzing spark barely capable of jumping $\frac{3}{4}$ "
4 jars in each condenser set as capacity	

The record of yesterday shows that the vibration was quicker in previous test. The small primary used to induce e.m.f. undoubtedly was the cause of it.

This shows that in exact tuning the present method is preferable.

Now the coil B was placed on two chairs parallel to coil A at a distance of 3 $\frac{3}{4}$ ". Coil B, however, was not connected to ground wire.



The excitation of coil A was exactly the same nevertheless the presence of coil B though not connected in circuit reduced the spark at free end of A very much to $\frac{1}{16}$ ".

The resonating condition was attained with

3 $\frac{3}{4}$ turns in Self. Regul.	} Coil B slowed the vibration in A down as is evident from comparison with preceding result
4 jars in each cond. set capacity	

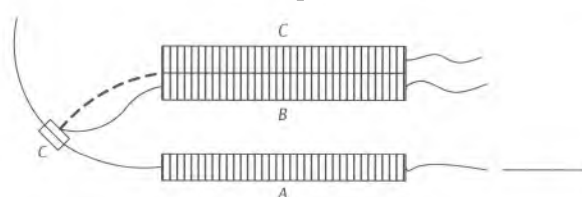
Coil *B* was now connected to ground wire, coil *A* remaining as before. Resonance was presently reached with $2\frac{1}{2}$ turns in Self regulator and 4 jars in each condenser set as before. It was at once observed that the spark at free of coil *A* was **stronger**, jumping easily over $\frac{3}{8}$ ". It was also decidedly thicker.

This effect was to be expected from previous experiments chiefly in Colorado. When the coil *B* was disconnected again and the end left close to connector *c* the strengthening of spark at free terminal of *A* was still perceptible.

In the experiment which follows an other coil *C* was placed close to coil *B*, coils *A* and *B* being connected to ground wire as in previous test. Resonance of coil *A* was now obtained with

Turns in Self. Regulator $1\frac{7}{8}$
Capacity: jars in each set 4

} The spark at analyzing gap was now weaker



Presently coil *C* was likewise connected to ground wire as indicated by dotted line and vibration of coil *A* was found exactly the same as before, $1\frac{7}{8}$ turns, 4 jars. But spark of coil *A* was **stronger** and very much so. It jumped over $\frac{7}{16}$ ". It was also perceptibly thicker.

Conclusions: The above seemingly inexplicable phenomena are due to a simple cause and the experiments further confirm theory that excitation of a coil connected to ground as in my system is in proportion to electrical density of ground or ground connection. When coil *B* was placed near coil *A* the former not being connected to exciting ground wire the e.m.f. at free terminal of *A* was reduced both by capacity and to some extent also by induced currents in *B*. The chief cause however was the increased capacity since the coil *B* slowed down vibration in *A*. The induced currents in *B* would have quickened the vibration of *A*, at least this would be reasonable to expect.

When coil *B* was connected to ground wire effect was **increased** in *A* because of greater density at condenser *C*. The vibration in *A* was **quickened** probably by inductive action the currents in *B* passing presumably in opposite direction. This I regret to say was overlooked but it will be ascertained on next occasion. When end of *B* was close to connector *c* the strengthening effect was due to similar cause. The same theory explains also the influence of coil *C* above noted.

June 6, 1901

Modified method of determining constants of circuits and ph. quantities

Take a coil wound on long cylinder of length *l*. The inductance will be

$$L = \frac{4\pi N^2 A}{l \times 10^9} \text{ Henry, } A = \text{area.}$$

Determining vibration of coil it will be found

$$T = \frac{2\pi}{10^3} \sqrt{\frac{4\pi N^2 A}{l} \cdot c}$$

The capacity expressed in μF is here that capacity which would have to be added in circuit with coil if the latter had **no** capacity whatever. *c* is therefore an ideal quantity which can be determined

from T as in Colorado experiments. Adding to terminals of coil an other capacity C which for the present is assumed as known we would get

$$T_1 = \frac{2\pi}{10^3} \sqrt{\frac{4\pi N^2 A}{l \times 10^9} (C + c)} .$$

Knowing T_1 and T we can then determine C .

Winding an other coil exactly alike to first in all respects except that it is longer we can so adjust it that it has period T_1 without capacity C . Call c_1 the "ideal" capacity of this coil and l_1 the length of the same we have

$$T_1 = \frac{2\pi}{10^3} \sqrt{\frac{4\pi N_1^2 A}{l_1 10^9} \cdot c_1} .$$

But as shown in Colorado we shall have $c_1 = \frac{l_1}{l} c$

$$\text{Hence: } T_1 = \frac{2\pi}{10^3} \sqrt{\frac{4\pi N_1^2 A l_1}{l_1 10^9 l} \cdot c} = \frac{2\pi}{10^9} \sqrt{\frac{4\pi N^2 A}{l \cdot 10^9} \cdot c} .$$

From this $N_1^2 = N^2 (C + c) \frac{N_1^2}{N^2} = C + c$

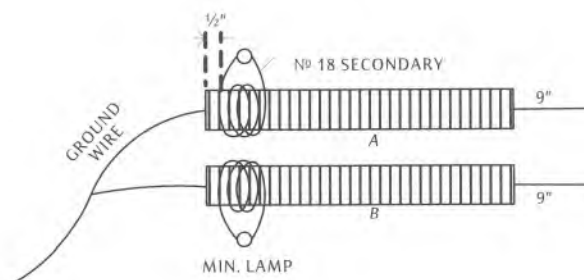
This is a relation which may be very useful.

Note. Two coils of different diameters may be tuned for same period and a relation of their ideal capacities obtained. A known capacity may then be added first to one and next to the other and an other relation obtained containing this capacity as taken. Valuable results by winding same wire successively on cores of different diameters and determining the ideal capacity in each core. Plotting the curve of those will be highly valuable. To follow up.

June 8, 1901

Experiments and observations with tuned coils continued

Coils A, B, C, and D previously described were again used. The "free" end of each was straightened and cut off to 9". Ground wire 14 feet long laid close to cable connection on base of condensers was employed for excitation. Resonance was detected by miniature lamps and for this purpose each coil had a secondary five turns No. 18 Okonite wire wound $\frac{1}{2}$ " from grounded end on top of the primary long winding. This was not the position in which the secondary received most of the energy but suited the observation. All secondaries were placed as nearly as possible alike and the excitation was also kept as uniform as practicable in all experiments. The method of using the apparatus did not permit to keep the energy exactly uniform or to determine it exactly in every instance but the estimates were thought sufficiently close for the present purposes.



1. Exp.

Coils A and B (№ 23 and № 24 wire respectively) both excited as indicated in diagram.

Resonance: 3 turns in Regul. 4 jars in each set of condensers

Observation. Lamp in coil A only lights.

2. Exp.

Coil A taken off, B only remaining. Resonance was obtained with $3\frac{5}{16}$ turns in Regul. 4 jars in each set of condensers.

Observation: Excitation of ground wire had to be much increased in order to light lamp of B.

3. Exp.

Coil A again connected. Same excitation as last. Lamp on coil B again does not light. Lamp on coil A very strong.

Observ. In agreement with theory formulated.

4. Exp.

Coils A and C (25 wire thinner insulation) now used as above.

Resonance: $4\frac{5}{8}$ turns in Regul 4 jars in each set.

Observation: This was resonating condition for coil C alone still when coil B was connected. Lamp on C did not light. All in agreement with theory.

5. Exp.

Coil A was disconnected and lamp on C lightened then.

Observation: Though lamp lightened it was much weaker than with coil B. It shows that coil C for same excitation receives less energy than coil B.

6. Exp.

Coils A and D (№ 26 wire) used as described before. Resonating condition corresponding coil D (alone) was secured with 4 turns of Regul. coil, 4 jars in each condenser set. The result was the same as in preceding experiments: When the coil D was excited alone the lamp lights, when coil A connected only lamp on latter lights.

7. Exp.

Observation special: When lamp on coil A screwed out of its socket to open the secondary circuit lamp on coil D lighted but weaker than when coil A was entirely off.

Important: Resonance with both coils connected was obtained with 3 turns in Regulator and 4 jars in each cond. set. This corresponds to vibration of coil A alone. It is evident that coil A in this case determines and governs preventing the weaker vibration of D to assert itself.

8. Exp.

Coils A and D used again to verify observation made.

Observation now: Both coils connected only lamp of coil A lights, but when lamp of coil D screwed out the lamp of coil A glows less.

9. Exp.

Observation: Coil C did not seem to behave as it ought to have, namely its lamp glowed much less than the others. Why? The coil was wound with wire of thinner insulation. Evidently the capacity of the coil is therefore much greater, this means that the vibration can not assert itself properly. To light a

lamp that is to consume a part of vibrational energy of primary the momentum in latter must be great, same as in a mechanical oscillatory system. Great capacity is a drawback. This surely must be correct. It is however in accordance with my previous observations. The resonating condition again established with $4\frac{9}{16}$ turns in Regul. and 4 jars in each set. The vibration was slightly different than before found. This was no doubt due to the fact that an other lamp was used in socket. If the lamp took more current the mutual induction effect is increased and vibration in primary quickened.

10. Exp.

Coils *B* and *C* used as before.

Resonance with $3\frac{7}{8}$ turns Regul. 4 jars in each condenser set.

Observation: Lamp of coil *B* lights, that of *C* not.

11. Exp.

Coils *C* and *D* used gave resonance with $3\frac{13}{16}$ turns and 4 jars in each cond. set.

Observation: Coil *D* lights the lamp not coil *C*. This should not be. So at least it was thought at first. The internal capacity being greater, however, in coil *C* the vibration can not properly take place. Capacity counteracts self-induction hence the momentum must be smaller in *C* than in *D*. This is the best explanation so far.

12. Exp.

The positions of coils *C* and *D* were reversed it being thought possible that the oscillatory apparatus used in the tests affected results.

Observation: lamp of coil *D* again lights and other conditions are found exactly the same as far as can be judged, hence no error in this or preceding experiments which would be traceable to position relative to exciting apparatus.

13. Exp.

Coils *B* and *D*. Both connected gave resonating conditions with: $3\frac{9}{16}$ turns in Regulator and 4 jars in each condenser set.

Observation: Both, lamps of *B* and *D* light. The lamp of coil *D* seems a little stronger. Why? Coil is wound with thicker wire and less turns. Coil *D* has thinner wire and more turns. What one gains by reduction of resistance the other gains in turns. The magnifying factor is in one $\frac{lp_1}{T}$, in the other $\frac{Lp_2}{R}$.

Here $p_1 = p_2$ and all depends on values of resistance and inductance. We should have if lamps light equally $\frac{1}{2} I^2 = \frac{1}{2} Li^2$. I current in coil *B*, i current in *D*. From this

$$\text{relation } I : i = \sqrt{\frac{L}{l}},$$

and with reference to above it will be probably true that also

$$\sqrt{\frac{L}{l}} = \sqrt{\frac{R}{r}}; R = \text{resistance of coil } D,$$

$$r = \text{resistance of coil } B.$$

14. Exp.

Coils *B* and *D* connected with free ends in multiple, otherwise conditions same. Resonance was with $3\frac{3}{16}$ turns in Regulator 4 jars in each cond. set.

Observation: The coils were slightly shifted together. This quickened the vibration. In previous experiment it was trifle slower.

15. Exp.

The free ends of coils *B* and *D* were again separated without any change in the position of coils. No change took place in rate of vibration. Resonating condition exactly as before.

Observation: Important to bear in mind that the coils give twice the energy or nearly so. This is in favor of multiple receiver as experimented with in Colorado.

16. Exp.

Coil *B* and *D* were now connected in series with the latter nearer to the ground wire and the small lamps were left in their sockets. Resonating condition was established with 6 jars in one set (that is equivalent to 12 jars in each of the two sets in series) the other set of condensers being short-circuited. $4\frac{1}{4}$ turns in Self. Regul. Lamp on coil *D* lighted but feebly.

Observation: The wire used to close the terminals of the condenser set was used though thick, was strongly heated by currents magnified through condensers in the way known.

17. Exp.

The coils *B* and *D* were again used as before but the lamp in coil *B* which was in preceding experiment screwed a little out of the socket was inserted. Resonance was again with 6 jars (resp. 12) and $4\frac{1}{4}$ turns. The screwing in of lamp on *B* weakened lamp of *D*.

Observation: Tried to get lower and upper tones. Experiments showed that above was fundamental vibration. This confirms former experience.

18. Exp.

In the preceding coil *D* was connected to the ground wire while coil *B* was on the free end. Inasmuch as latter coil was of larger section it was thought that it might affect results appreciably if coil *B* were connected to ground wire or placed in the portion of the circuit in which the current is stronger. Accordingly the position of the two coils was reversed. The resonating condition now took place with 6 jars (resp. 12) and 4 turns in Regulator.

Observation: Lamp on coil *B* now glowed stronger than lamp on coil *D* in previous trial. This confirms theory. By right section of conductor nearer to ground should be greater. In the construction of large oscillators this should not be overlooked. In Colorado test type the section was made twice as great near ground.

19. Exp.

Coils *B D* and *A* were connected in series in order named beginning from ground wire. The fundamental note was inconvenient to obtain and harmonies were tried. They were too weak to observe with lamps.

Observation: All goes to confirm former experience that it is best to always use quarter wave adjustment and large capacity on end.

20. Exp.

Coil *B* was now used alone and effect of capacity changes on terminal upon amount of energy collected was observed. Tinfoil pieces of various wires and small bodies were successively connected to free terminal. Invariably the addition of capacity diminished the energy furnished to the lamp. Three causes evidently cooperated here:

Observation: 1) The ohmic loss was comparatively great and consequently the capacity magnified the frictional component; 2) There was a loss in the air 3) The inductance was diminished and vibration could not properly assert itself. A part of the electric movement – that near the capacity terminal was of little effect upon the secondary and the lamp.

Observation: relative to preceding: Evidently when determining the resonant rise with a lamp or frictional resistance as in these tests an error is easily made. The capacity prevents a vigorous vibration to take place in the region of the circuit acting upon secondary including the lamp and it may happen that the effect upon the latter is smaller on this account even if the energy going into the circuit through the ground connection is the same or greater. The old experience is again confirmed: a large inductance is always an advantage when conversion through a secondary is resorted to

21. Exp.

To get an idea if air loss is appreciable a polished sphere 3" diam. was connected to free terminal of coil *B*. Resonance was obtained with 5 ¼ turns in Regulator 4 jars in each set of condensers.

Observation: The sphere diminished the spark length. Evidently then the two other causes were of greater moment and probably the capacity effect the most important element.

22. Exp.

A coil was now employed with a great magnifying factor. It was before referred to having 1100 turns, length about 5 feet. Winding: green Bellwire Nr.18. Resonance took place with 2¼ turns and 4 jars in each condenser set

Observation: A small secondary consisting of 4 turns similar to those on other coils was employed in same manner to light miniature lamp. The effect was too strong and secondary was reduced to one turn this still lighting lamp strongly. For same excitation of ground wire energy was eight times as great. Shows how important the magnifying ratio is. When sphere above mentioned was attached to free end vibration was not perceptibly affected and also energy collected was practically the same. Sphere weakens the spark nevertheless. With a sphere 5" diam. the vibration is 3¼ turns 4 jars in each set. With coil *D* connected also to ground wire, without capacity on free terminal the vibration is slightly quickened: 2½ turns 4 jars in each set.

Note. These experiments with one boy to assist took about one hour. Shows convenience of the arrangements now employed. Improvement still to be made in estimating energy.

June 8, 1901

Transmission of energy through Earth. Low frequency considered

Assume frequency of dynamo on plant under process of construction 60 cycles p. sec. and capacity *C* of terminal insulated 10 000 cm. With full steam pressure on one of boilers I can easily get 150 H.P. This will be only half of actual output. To use the power to the full extent we must charge the terminal to a pressure *P* given by the equation:

$$\frac{1}{2} P^2 \cdot C \times 2 \times 60 = 150 \times 746 \text{ from which } P^2 = \frac{111900}{60C} = \frac{111900}{60 \times \frac{10000}{9 \times 10^{11}}} = 16785 \times 10^7 \text{ and } P = 10^3$$

$$\sqrt{167850} = 10^3 \times 409.7 = 409700.$$

To take up whole energy we would have to have 409700 Volts initial e.m.f.

It is evident that for direct charge at that frequency this e.m.f. would be too large and hardly practicable. But with my spiral coils it might be so. At any rate let us take $e = 409700$ Volts as initial e.m.f. This e.m.f. would be magnified to e.m.f. $E = \frac{Lp}{R}e$. The magnifying factor I think can easily be 1000 so that we could get 400,000,000 Volts approx. With large curvature terminal I do not think this e.m.f. impossible.

Now estimates of June 2. and previous show that with 82×10^6 and 100 000 per sec. 8000 Volts were obtainable at polar cap. Considering relation $e_1 = e \sqrt{\frac{n}{n_1}}$ we would get with 82,000,000 Volts and 60 cycles per sec. on polar cap $e_1 = 8000 \sqrt{\frac{60}{100000}} = 80 \sqrt{6} = 196$ Volts. With 400×10^6 we may say, as rough approximation 1000 Volts. Under these conditions we would get with a capacity of say 100 000 cm which can be easily obtained with wires: $\frac{1}{2} \cdot 1000^2 \cdot \frac{100000}{9 \times 10^{11}} \cdot 2\pi \times 60 = 2$ Watts about. This is enough to demonstrate practicability of power transmission. As for telegraphy we only want capacity of 100 cm. We would get to work instruments $\frac{2}{1000}$ Watts. Current at transmitter 10000 cm, terminal capacity $I = eC\omega = 1700$ Amp roughly. This I think is realizable.

June 9, 1901

Vibrations determined, using new ground wire 14 feet long, excited as before.

Large spiral coil; miniature lamp for detecting max. effect. Lamp in secondary.

a) Resonance with 6 jars in each set $5\frac{7}{8}$ turns Coil normally excited

b) " " 6 " " $12\frac{1}{2}$ " " oppositely "

Note: The two tests show detrimental effect of capacity. The magnifying ratio is much smaller in latter test.

Large spiral coil with open secondary spark analysis:

a) 6 jars in each set $6\frac{3}{4}$ turns in Regul. spark strong

b) 6 " " 13 " (about) spark does not jump.

Note: Large capacity is greater drawback still when a device requiring high e.m.f. is used in telegraphy as sensitive receiver than when device frictional as bolometer etc.

Inductance coil used in connection with spiral coil:

Resonance with $3\frac{1}{2}$ turns 4 jars in each set of condensers.

Observ.: Spark on analyzing gap remarkably small: $\frac{1}{8}$ ". Illustrates again advantage of small diameter on high tension resonating coils. Arrangements as in Colorado are best to employ.

With 6 jars in each set $2\frac{1}{16} - 2\frac{1}{8}$ turns a harmonic obtained.

Observ.: The spark is stronger ($\frac{3}{16} - \frac{1}{4}$) but exciting current is also greater. It is not sure that note fundamental.

Same coil with lamp analysis; lamp placed on loop on lower end of coil consisting of one turn.

Resonance:

4 jars in each set $3\frac{3}{8}$ turns Lamp bright

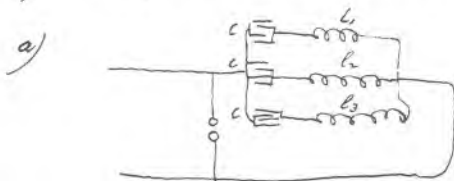
With 6 jars $1\frac{13}{16}$ turns Lamp much brighter

Observ. The latter tests again do not settle doubt as to whether test note fundamental. This is not first time that difficulty noted has presented itself. Accidentally the conditions are such. Shows necessity of keeping always account of the amount of energy used in exciting circuit.

June 13. 1901.

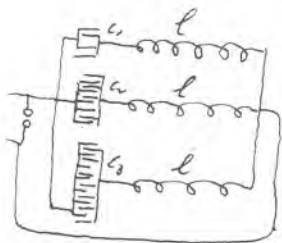


Some of the arrangements experimented with before to be reconsidered with view of getting at best transmission of complex vibrations.



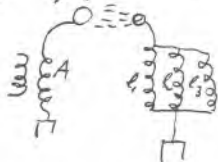
In this case equal capacities C, C, C and different inductances L_1, L_2, L_3 are employed which give a complex tone chiefly of three distinct vibrations.

- b) Similar arrangement with different capacities C_1, C_2, C_3 and same inductances is practicable but hardly is advantageous as the first. Arrangement under c) below named allows more latitude in adjustment. It is important in all three cases to get same energy. Not necessarily the same actual energy but as in telegraphy the same energy qualitatively.



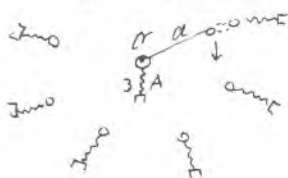
- c) Arrangement with different capacities and different inductances. In all these three cases best results by far are obtainable with resonating secondaries.

- d) following disposition is excellent to use with small apparatus. A resonating secondary discharging the accumulated energy into complex transmission. The three circuits can be together. I find it practicable to work seven in this manner.



Working principle of complex receivers the number is probably as large as will be required in telegraphy across sea.

- e) Better however is to separate circuits L_1, L_2, L_3 - i.e. and discharge successively and in rapid repetition as illustrated below. The circuit AC into the transmitter grounded on same or different points. It is easy when spark discharge is used to rotate the device at establishing the successive contacts at great speed. Also with mercury break great speed practicable. The energy in circuit AC should be in excess and that is easy to secure.



June 11, 1901

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Results with tuned coils. Data for reference.

One of the new six coils made of steel loop and fibre 4" wide was employed. The loop of this flat steel was joined with fibre so as to be solid yet not closed. To the terminals of loop was connected a condenser approximately $\frac{1}{2} \mu\text{F}$ and a miniature lamp for analyzing maximum. Resonance was obtained with:

14 $\frac{1}{4}$ turns in Regulator $\frac{1}{2} \mu\text{F}$ Capacity.

Diameter of loop with be given later. This can be used for calculating frequency.

Large coil with white string tested by inducing currents with cable in square frame. Three tests were made:

Reson. with a)	5 $\frac{3}{4}$ turns	2 jars in each set	} This will do for establishing relation and equivalency of turns and jars etc.
	3 "	3 " "	
	0 "	4 " "	

Of the six coils three were wound with wire № 26 triple covered cotton 98 turns. Using miniature lamp in steel loop to analyze vibration resonance was found with

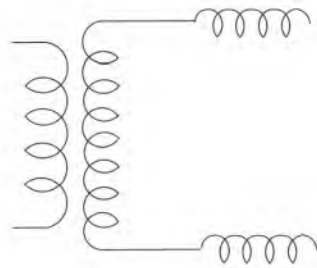
5 $\frac{1}{4}$ turns Regul. 4 jars in each cond. set.

In this test the large cable in square frame was included in the circuit.

Now the large cable was taken out and connection made in the normal way. Resonance took place with

8 $\frac{1}{4}$ turns Regul. 4 jars in each cond. set.

This coil was marked 1 and the others respectively 2 and 3. The two last named gave exactly same result: Resonance was with 8 $\frac{1}{4}$ turns and 4 jars as before. This shows that coils may be manufactured all right.



In the last test the three coils were connected in series. Resonance was obtained with 16 $\frac{1}{4}$ turns 4 jars. With the note of each no effect. With 16 $\frac{1}{4}$ turns 4 jars miniature lamp not much weaker than with single coil. To remember

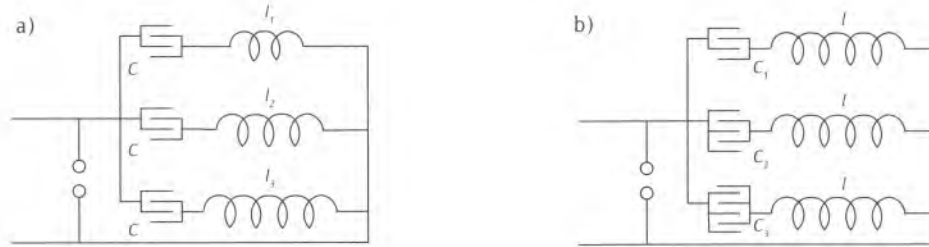
June 13, 1901

Some of the arrangements experimented with before to be reconsidered with view of getting at best transmitter of complex vibrations.

a) In this case equal capacities c c c and different inductances l_1 l_2 l_3 are employed which give a complex wave chiefly of three distinct vibrations.

b) Similar arrangement with different capacities c_1 c_2 c_3 and same inductances is practicable but hardly as advantageous as the first. Arrangement under c) below named allows more latitude in adjust-

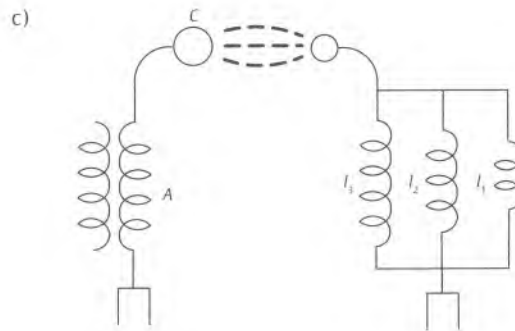
ment. It is important in all three cases to get same energy. Not necessarily the same actual energy but as in telegraphy the same energy qualitatively.



c) Arrangement with different capacities and different inductances.

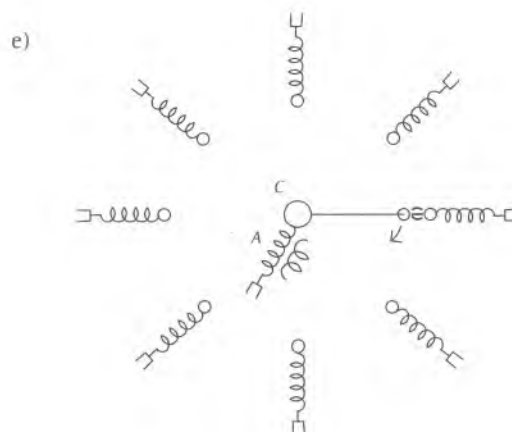
In all these three cases best results by far are obtainable with resonating secondaries.

d) Following disposition is excellent to use with small apparatus.



A resonating secondary discharging the accumulated energy into complex transmitter. The three circuits can be together. I find it practicable to work seven in this manner. Using principles of complex receivers the number is probably as large as will be required in telegraphy across sea.

e) Better however is to separate circuits $I_1 I_2 I_3$ etc. and discharge successively and in rapid repetition as illustrated below same in different points. It is easy when spark discharge is used to rotate the device *a* establishing the successive contacts at great speed. Also with mercury break great speed practicable. The energy in circuit AC should be in excess and that is easy to secure.



June 14, 1901

521

Small circle of thick aluminium wire and miniature lamp used in many experiments. Inductance of same

Diameter of circle $22.25'' = 56.5$ cm

Radius $A = 28.25$ cm

Diameter of aluminium wire $\frac{1}{4}'' = 0.635$ cm

radius $a = 0.317$ cm

$$8A = 28.25 \times 8 = 226$$

$$4A = \frac{226}{2} = 113$$

$$\frac{8A}{a} = 712 = 8 \times 89$$

$$\log_e \frac{8A}{a} = 2.08 + 4.49 = 6.57$$

$$L = \pi [113 (6.57 - 2) + 0.635(6.57 - 1.25)] =$$

$$\pi (516.4 + 3.4) = 3.1416 \times 520 = 1634 \text{ cm approx.}$$

This circle connected to condenser small $\frac{1}{2}$ μ F probably gave resonance with:

5 jars in each set 12 turns in Regulator.

For further reference.



Two coils as nearly alike as practicable were made for the purpose of ascertaining vibrations of large laboratory apparatus by means of $\frac{1}{2}$ μ F standard condenser.

The core of wood was 3.1 cm diam. It was wound with special wire № 14 ($\frac{64}{1000}$ diam.) covered with very thick insulation rubber and bredding. Diameter of wire over insulation $\frac{4}{10}'' = 1$ cm. This gives real diameter (inside) of core $3.1 + 1 = 4.1$ cm. From this:

$$\text{Area } 4.1^2 \times 0.7854 = 13.2 \text{ sq. cm.}$$

Turns coil a 42.75

" " b 42.50

Length of coil a 46 cm

" " b 46 "

Average inductance:

$$L = \frac{42.5^2 \times 12.57 \times 13.2}{46} =$$

$$L = 6520 \text{ cm.}$$

Both coils in series:

$$L_2 = 13040 \text{ cm.}$$

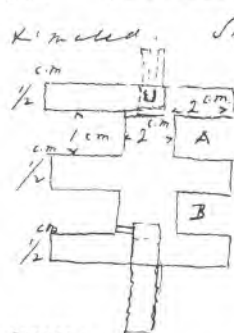
For future reference



June 24. 1901.

Approximate estimate of coils to be used in connection with vacuum tubes in shop. Two coils are to be placed in series with each tube to effect regulation as well as improve working. The impedance of the coils should be high as compared with resistance of tube so that variation in latter will not much affect the current through coils. At the same time the actual loss of energy in the inductance should be small. The coils should be properly tuned and it is proposed to use small condensers each of a few c.m. of surface.

Coils should be of a form to give highest inductance. The theoretically best dimensions can not be taken but approximated.



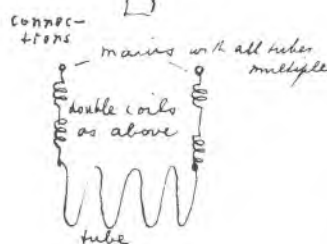
Sketch below shows frame or bobbin of hard rubber with brass plugs for connections. The sizes given are convenient because of commercial dimensions of rubber rods.

By Maxwell for each part A or B we get

$$L = 8 \pi n^2 \text{ approx. m.c.g.}$$

Total Self-induction in circuit with

$$\text{tube will be } L = 4 \times 8 \pi n^2 = 100 n^2 \text{ c.m. approx.}$$



Suppose we use wire No. 26, we shall get about 500 turns in each part A or B.

This will give $L = 100 \times 25 \times 10^6 = 25 \times 10^6$. Total will give $L = 10^8 \text{ c.m.}$ or $L = \frac{1}{10} \text{ Henry}$.

I think with this inductance capacity of sockets on tubes will probably suffice.

To be ascertained by experiment.

June 15, 1901

523

It has been assumed in previous experiments that a circuit grounded on one end and free on the other vibrate just half as fast as when free on both ends. To verify this one of the new coils with breaded paraffined wire was taken and suspended in the vertical square frame. It was first excited with both ends insulated and resonance was obtained with $8\frac{1}{4}$ turns in Regul. 1 jar in each set. Being now grounded on one end the resonating condition should have been

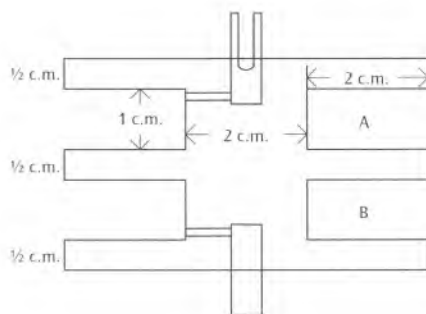
Coil { turns:
diam.: established with 4 jars and $8\frac{1}{4}$
length:

But it was found that it took place with 4 jars and $4\frac{1}{2}$ turns in Regulator. The vibration was quicker than expected. The explanation is easily found. When the circuit is open the internal capacity – the effective – is of greater moment. Various jars were placed in circuit in succession to avoid error due to different capacity of individual jars and resonance was obtained with $8\frac{1}{2}$, $7\frac{1}{4}$, $4\frac{1}{2}$, $8\frac{1}{2}$ etc. But when coil again grounded on one end resonance was with 4 jars and $3\frac{1}{4}$ turns in Regulator selfind. It follows from this that with open circuit grounded we get always a little smaller wavelength than twice that obtained with circuit not grounded. I think this demonstrates that it is always better to use circuits grounded on one side. They will give stronger effects.

June 24, 1901

Approximate estimate of coils to be used in connection with vacuum tubes in shop. Two coils are to be placed in series with each tube to effect regulation as well as improve working. The impedance of the coils should be high as compared with resistance of tube so that variation in latter will not much affect the current through coils. At the same time the actual loss of energy in the inductance should be small. The coils should be properly tuned and it is proposed to use small condensers each of a few cm sq. surface.

Coils should be of a form to give highest inductance. The theoretically best dimensions can not be taken but approximated. Sketch below shows frame or bobbin of hard rubber with brass plugs for connections. The sizes given are convenient because of commercial dimensions of rubber rods.





June 27, 1901.

Experiments with tuned coils.

Two coils in all respects alike were wound on wooden cylinders of exactly the same dimensions as those used for coils A B C D before described. The two coils were wound with H. green annealed bell wire. There were 547 turns in each coil. In testing the excitation by means of the ground wire 14' long was resorted to, the wire being tied by tape to the front cable leading from top terminal of condenser on left to spark gap. The part of ground wire exposed to strong induction from cable was about two feet.

Observations:

Resonance with one of the coils connected as described was obtained with:

$1\frac{15}{16}$ turns in Regl. 1 jar on each side

Analyzing spark just jumped $\frac{5}{8}$ "

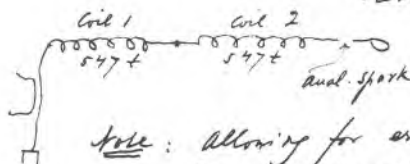
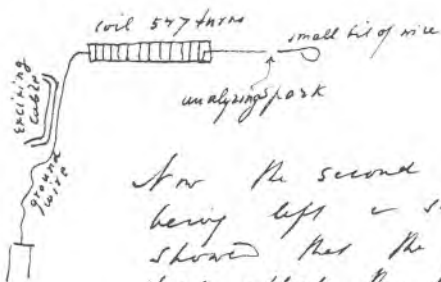
Now the second coil was put in line with the first, there being left a small space for a spark between. Test showed that the placing of the second coil did not perceptibly affect the vibration of the first. Resonance was exactly as above. The two coils were now connected in series. In first experiment

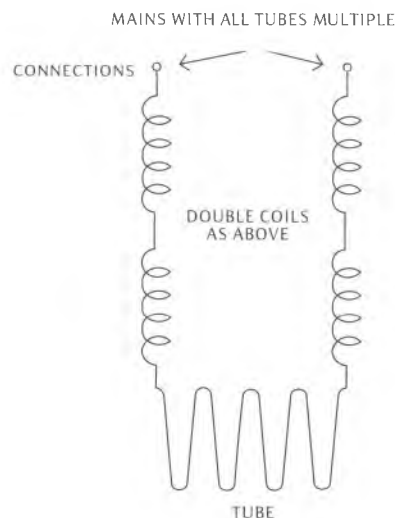
resonance was obtained with:

$7\frac{5}{8}$ turns and 1 jar in each set of condensers

The analyzing spark was just a little over $\frac{1}{8}$ "

Note: Allowing for error the e.m.f. with two coils in series was with same intensity of excitation just $\frac{1}{4}$ of e.m.f. obtained with one analyzing spark gap with one single coil. Theoretically this should be so, for we had just kept the frequency as the wavelength was twice, resistance and self-induction double. Evidently the magnifying factor $\frac{L}{R}$ was with two coils in series just one half, since ϕ was one





By Maxwell for each part A or B we get $l = 8\pi n^2$ approximately. Total self-induction in circuit with tube will be $L = 4 \times 8\pi n^2 = 100 n^2$ cm approx.

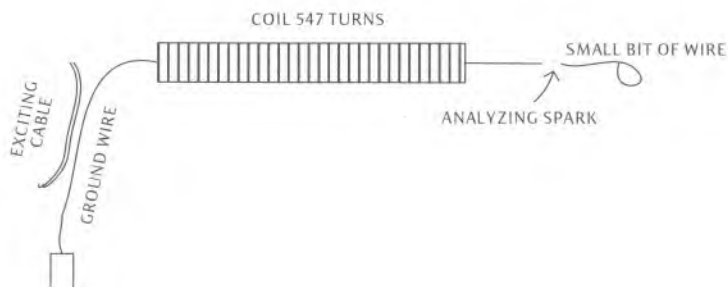
Suppose we use wire No 26. We shall get about 500 turns in each part A or B . This will give $l = 100 \times 25 \times 10^4 = 25 \times 10^6$. Total will give $L = 10^8$ cm or $L = \frac{1}{10}$ Henry.

I think with this inductance capacity of sockets on tubes will probably suffice. To be ascertained by experiment.

June 27, 1901

Experiments with tuned coils.

Two coils in all respects alike were wound on wooden cylinders of exactly the same dimensions as those used for coils $A B C D$ before described. The two coils were wound with Nr... green covered bell wire. There were 547 turns in each coil. In testing, the excitation by means of the ground wire 14' long was resorted to, the wire being tied by tape to the front cable leading from the terminal of condenser set on left to spark gap. The part of ground wire exposed to strong induction from cable was about two feet.



Observations:

Resonance with one of the coils connected as described was obtained with:

$1\frac{15}{16}$ turns in Regul. 1 jar on each side

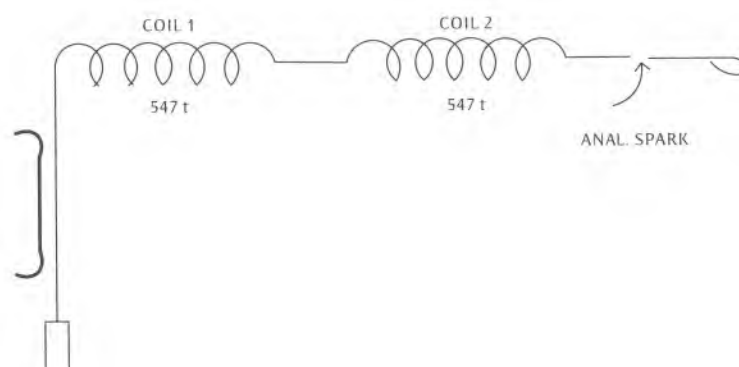
Analyzing spark just jumped $\frac{5}{8}$ "

Now the second coil was put in line with the first, there being left a small space for a spark between. Test showed that the placing of the second coil did not perceptibly affect the vibration of the first. Resonance was exactly as above.

The two coils were now connected in series. In first experiment resonance was obtained with:

$7\frac{5}{8}$ turns and 1 jar in each set of condensers.

The analyzing spark was just a little over $\frac{1}{8}$ "



Note. Allowing for error the e.m.f. with two coils in series was with same intensity of excitation just $\frac{1}{4}$ of e.m.f. obtained at the analyzing spark gap with one single coil. Theoretically this should be so, for we had just half the frequency as the wavelength was twice, resistance and self-induction double.

Evidently the magnifying power $\frac{pL}{R}$ was with two coils in series just one half, since p was one half of what it had been with one coil alone. This would give one half of e.m.f. obtained in first experiment. But it should be remembered that while the condensers were excited to same degree as in experiment with one coil, the exciting current through cable inducing in ground wire was smaller. We had with same capacity in primary four times the inductance in experiments with two coils connected in series. Now four times the inductance would have meant one fourth of the current through exciting cable, had the frequency been the same as in first experiment. But the frequency was only one half, the current through cable therefore one half and not one quarter of primary current obtained in first experiment.

To sum up: in second experiment we had $\frac{1}{2}$ of exciting current and $\frac{1}{2}$ of the frequency hence just $\frac{1}{4}$ of the e.m.f. on analyzing spark gap because $\frac{\text{inductance}}{\text{resistance}}$ remained the same in both cases. The above is important to bear in mind.

Experiments were now continued with two coils in series and capacity was gradually increased in primary. The results were as follows:

2 jars on each side	$4\frac{13}{16}$ turns	Spark analyzing $\frac{3}{8}$ "
3 " "	$2\frac{7}{8}$ "	" $\frac{1}{2}$ "
4 " "	$1\frac{13}{16}$ "	" $\frac{5}{8}$ "

Note. We see that the spark at analyzing gap increases as the exciting current in primary gets stronger until with just four times the capacity and inductance just the same as in experiment with one coil we get same e.m.f. on gap.

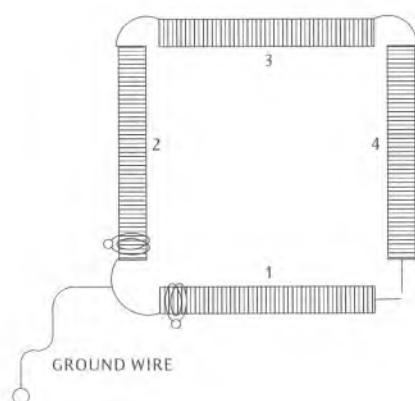
Experiment was now tried with the two coils connected in multiple arc. The resonating condition was obtained with $\frac{1}{2}$ jar in each condenser set and 4 turns in Regulator. The inductance in the double coil was evidently reduced to one half.

Note. There is perhaps an error in above reasoning. To be resumed.

July 6, 1901

Experiment with four coils exactly alike, 547 turns each. Dimensions to be given later in detail. The object of the experiments was to see in how far the effect in a measuring apparatus connected to the ground may be increased by mutual action of circuits.

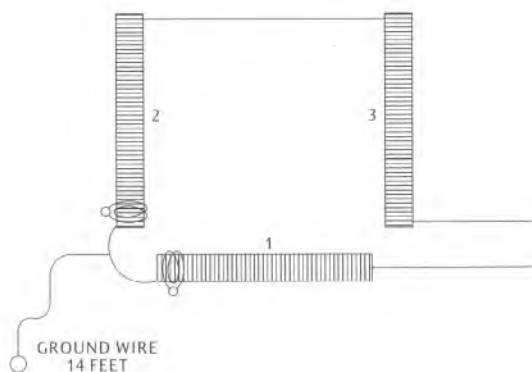
I. Exp.



The coils were connected as indicated, two systems being formed which were in multiple to the ground wire, the latter being energized by back cable on condensers as described on a previous occasion, System 1 had one quarter of wavelength, system 2, 3, 4 three quarter.

No matter how tried the one with one quarter wavelength lighted the lamp (miniature, taking little energy) better. This, however, may not be absolute proof that the system was better for relatively fewer turns were utilized in system 2, 3, 4. Perhaps by putting a secondary on middle portion of coil 3 the additional energy might have been obtained. Minute sparks at e could never be overcome. Quite probably they were due to harmonics which in the system 2, 3, 4, were necessarily different from those in system 1.

II. Exp.



Connected as here indicated; when system 2, 3 was added the lamp of 1 lighted the same, there being no change whatsoever. When end wires of 1 were brought together so as to have capacity increased again no change in intensity of lamp of coil 1.

When wires at 1 connected together again no effect. Here the system 2, 3 had one half and system 1 one quarter wave. Capacity influence was beautifully shown with these coils: when the hand was brought near coil 1 - the vibration of primary being first slowed down; lamp of coil 1 first brightened, then went out by further approach.

Note: Today when jars adjusted, primary inductance was the same. This to be further investigated.

July 7, 1901

Circuit for controlling model boat in laboratory by induction from the large cable was constituted as follows:

In the inside of the boat three turns of rubber covered wire were laid which were joined in series with a small condenser (one of the twenty four used in experiments in Colorado) and a coil of 20 turns rubber-wire same wire (No 16) wound on a new wooden spool 3" diameter. The apparatus for producing the oscillations in the cable was adjusted until resonance was obtained with

8¼ turns Regul. Inductance

2 jars in each set of condensers.

Approximate estimate of vibration period:

The total inductance in the primary exciting circuit including the cable was about 100000 cm or

$\frac{1}{10^4}$ H. The capacity was that of one jar about 0.019 μ F.

$$\text{Hence } T = \frac{2\pi}{10^3} \sqrt{0.019 \cdot \frac{1}{10^4}} = \frac{2\pi}{10^5} \cdot 0.138 = \frac{0.866}{10^5} = \frac{866}{10^8}.$$

From this $n = \frac{10^8}{866} = 115000$ per second.

In associating with the 20 turns on new spool a secondary, the period will quicken somewhat so that we may take about 120000 per sec. For this frequency a secondary should be wound **without capacity** on the terminals. Using as detector a simple spark gap capacity should be as small as practicable.

The wavelength λ will be roughly $\frac{186000}{120000} = \frac{186}{120}$ miles and the length of the secondary theoretically $\frac{\lambda}{2} = \frac{186}{240} = 0.7833$ miles = approx. 4000 feet. As each turn of secondary will be about 9 inches we want about 5000 turns rather less.

July 8, 1901

529

Particulars about small oscillator with mercury stream break used for running vacuum tubes in laboratory

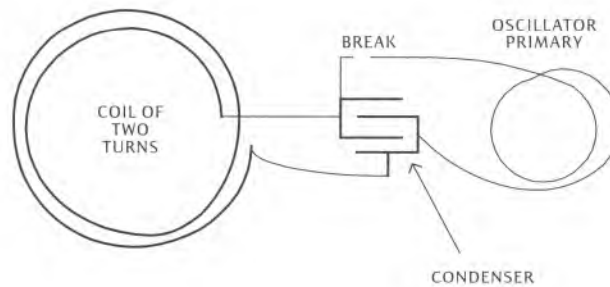
Secondary coil rewind:	}	Each part 40 + 345 = 385 turns.
each side of coil 40 turns in first 2 layers		Condenser about 3.5 μ F
+ 15 layers $\approx$ 23 turns		Total turns in secondary 775

Primary of copper sheet $\frac{1}{100}$ " thick, $6\frac{1}{4}$ " wide, mean diam. of coil of $7\frac{1}{4}$ " nearly.

Approximate estimate of vibration period:

Resonance method was employed as follows: Large cable in room has a loop. This loop was wrapped together with a coil of two turns of wire and the currents induced by the cable loop in the coil were used to ascertain vibration of the system of small oscillator. In the test the mercury control was replaced by a wire connection of small resistance.

The sketch illustrates arrangement.



The frequency of the currents in coil with two turns excited from cable loop was raised until resonance was obtained.

For detection a miniature lamp employed which was included in a secondary winding of few turns placed in inductive relation to primary of oscillator. Resonance with the primary exciting system was obtained with constants in the primary exciting system as follows:

Inductance:

a) all turns of regulating coil and connections	say	90000 cm
b) two turns of stout cable on square frame series	"	32000 "
c) large cable around room	"	50000 "
d) Inductance coil 18 turns Okonite № 10	approxim.	326000 "
	total	498 000 cm

Capacity: 5 jars approx. $5 \times 0.0195 = 0.0975 \mu\text{F}$.

$$\text{From this } T = \frac{2\pi}{10^3} \sqrt{0.0975 \cdot \frac{498}{10^6}} \text{ roughly } T = \frac{44}{10^6} \text{ } n = 23000 \text{ per sec.}$$

Estimated in an other way: Inductance of primary coil of small oscillator was determined and for 8 turns found 17600 cm. Presently, however, the primary had six turns. Considering connections the inductance of all will not be far from 12000 cm. With condenser 3.5 μ F this would give for period T value

$$= \frac{2\pi}{10^3} \sqrt{3.5 \cdot \frac{12}{10^6}} = \frac{2\pi}{10^6} \cdot 6.48 = \frac{40.7}{10^6} \text{ and } n = 24500 \text{ per sec.}$$

The former estimate is more reliable.

July 8. 1901.



Particulars about Small oscillator with mercury stream break
used for running vacuum tubes in laboratory.

Secondary coil revolved: Each side of coil 40 turns in first 2 layers }
+ 10 layers = 23 turns

Each part $40 \times 345 = 380$ turns

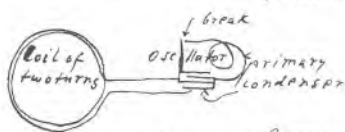
Condenser about 3.5 M.F.

Total turns in secondary 770

Primary of copper sheet $\frac{1}{100}$ " thick $6\frac{1}{4}$ " wide mean diam. of coil $7\frac{1}{4}$ " nearly.

Approximate estimate of vibration period:

Resonance method was employed as follows: Large cable in room has a loop. This loop was wrapped together with a coil of two turns of wire and the currents induced by the cable in the coil were used to ascertain vibration of the system of small oscillator. In the test the mercury contact was replaced by a wire connection of small resistance. The sketch illustrates arrangement.



The frequency of the currents in coil with two turns excited from cable loop was raised until resonance was obtained. For detection

a vibration loop employed which was included in a secondary winding of few turns placed in inductive relation to primary of oscillator. Resonance with the primary exciting system was obtained with condenser in the primary exciting system as below:

Inductance:

- a) all turns of regulating coil and connections say 90,000 C.M.
- b) two turns of steel cable in square frame series " 32,000 "
- c) large cable around room say " 50,000 "
- d) Inductance coil 18 turns Okorik H. 10 approx. 32,600 "

Total 494,600 C.M.

Capacit 5 jars approx $5 \times 0.0195 = 0.0975$ M.F.

From this $T = \frac{2\pi}{100} \cdot \sqrt{0.0975 \cdot \frac{498}{106}}$ roughly $T = \frac{44}{106}$ and $n = \underline{23,000}$ per Sec.

Estimated in another way: Inductance of primary coil of small oscillator was determined and for 8 turns found 17,600 C.M. Presumably however the primary had six turns. Considering connections the inductance of all will not be far from 12,000 C.M. with condenser 3.5 M.F. this would give for period

$T \text{ value} = \frac{2\pi}{100} \sqrt{3.5 \cdot \frac{12}{106}} = \frac{2\pi}{100} \cdot 6.48 = \frac{40.7}{106}$ and $n = \underline{24,500}$ per Sec.
The former estimate is more reliable.

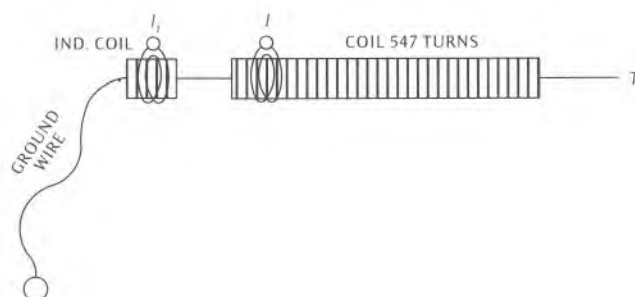
Experiments with tuned coils excited through the ground.



One of the four coils, 547 turns each, before described was used in many ways, capacity being attached to free terminal T . No matter what capacity was given to T it was found that when a fixed amount of energy was supplied through the ground wire to the coil the best result was obtained with no capacity on terminal T .

The lamp I before mentioned lighted always stronger when the capacity of the system was smaller. This was found already in previous experiments. This would agree perfectly with theory. When more capacity is added to the excited system it becomes slacker and hence a small frictional resistance can not be so easily overcome as when the system has a great amount of self-induction and little capacity that is when it is resembling a very stiff spring loaded with a big weight. The conclusion of importance is that one can not follow a better rule in the construction of receiving circuit than the one before given – that is to construct the circuits so that they will have the greatest amount of self-induction and the least capacity.

In order to perform experiments as the above under better conditions a small inductance coil was inserted in the ground wire. The coil had six turns of secondary. The primary was formed by a wire same as the ground wire wound in two layers and having about 14 turns.



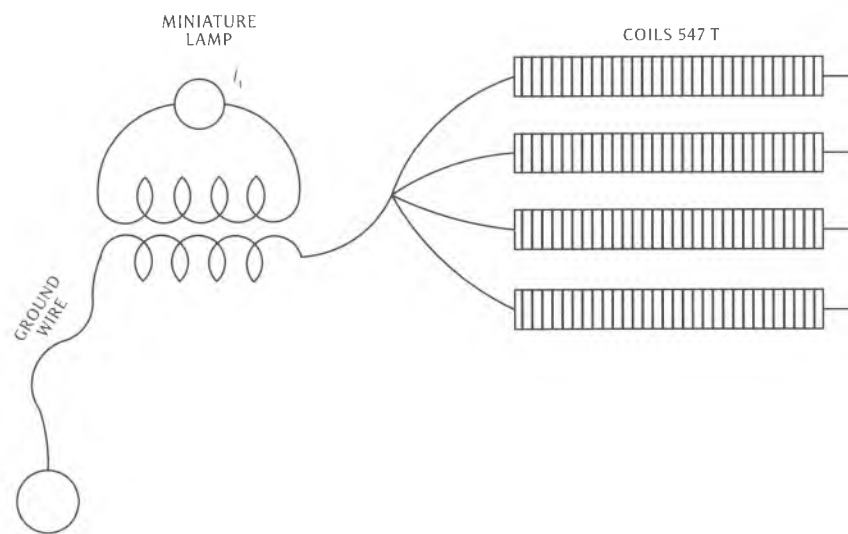
The chief idea in employing the small induction coil in the ground wire was to keep the same analyzer in all experiments; furthermore to dispense with the lamp I on the coils tested.

When the arrangement as indicated in sketch was tried, it was observed that when the lamp I on coil (547 turns) lighted, the lamp I_1 included in the secondary of the induction coil did not light. When lamp I was turned off, I_1 lighted, but weaker than I . The difference in the intensity of both the lamps did not mean anything in itself, for it was clear that it was merely a question of turns which lamp lighted stronger. The important observation was that I_1 did not light at all when I lighted strongly. Evidently when the latter lamp was inserted the current through the ground wire was weaker than when the lamp was off. The best explanation of the phenomenon seems to be the following: When lamp I is not inserted in the secondary of coil with 547 turns there is a strong movement in the latter owing to the absence of frictional resistance, hence a greater rise of current and lamp I_1 lights. But when lamp I is inserted the frictional load pulls the vibration down and the current is reduced so that lamp I_1 can not light. It should be remembered however that the frictional load is greater with both lamps in and therefore the resonating rise smaller when they are both used than when inserted singly. The phenomenon may how-

ever to a small extent be due to the well known action of two unequal inductances or unequally loaded transformers in series.

The small induction coil above described inserted in the ground wire was now used to ascertain how the energy taken up changes with the number of coils. The four coils each 547 turns were used in the experiments, the small secondaries with their lamps as / being done away with. It was found that by the addition of coils the current passing through the ground wire was increased. Numerous experiments showed:

- a) The energy taken up through the ground wire increases exactly in proportion to the number of coils. Four coils take up four times as much as a single coil.
- b) The vibrations quicken as more coils are added, that is when four coils are connected the system vibrates somewhat quicker than when a single coil is used.

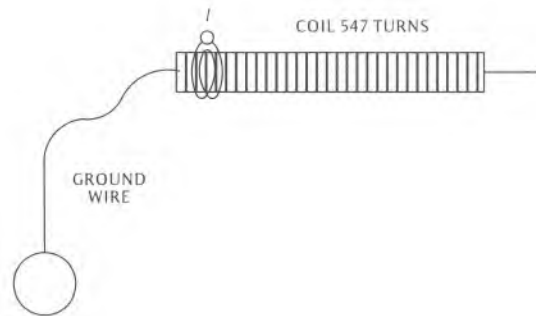


Evidently this is due to the fact that the inductance of the whole is smaller than the inductance of each single part or coil. A conclusion of importance: The **greater** the **number** of coils the **longer** can be each **individual** coil and this means virtually a greater magnifying ratio. A receiver constructed on lines of above experiment is **undoubtedly the best**.

July 9, 1901

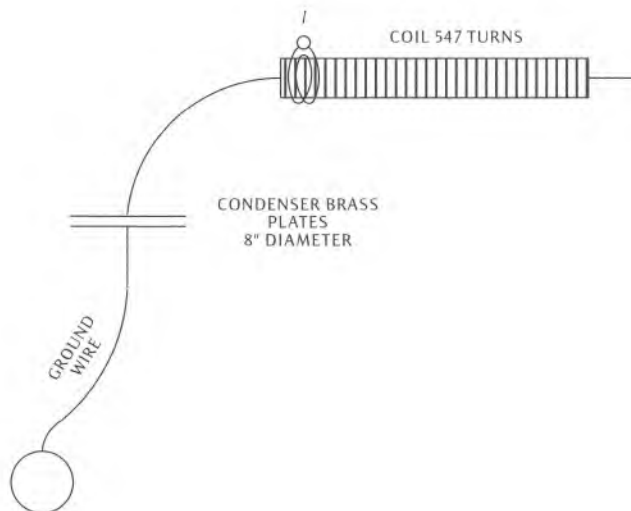
533

Experiments with tuned coils

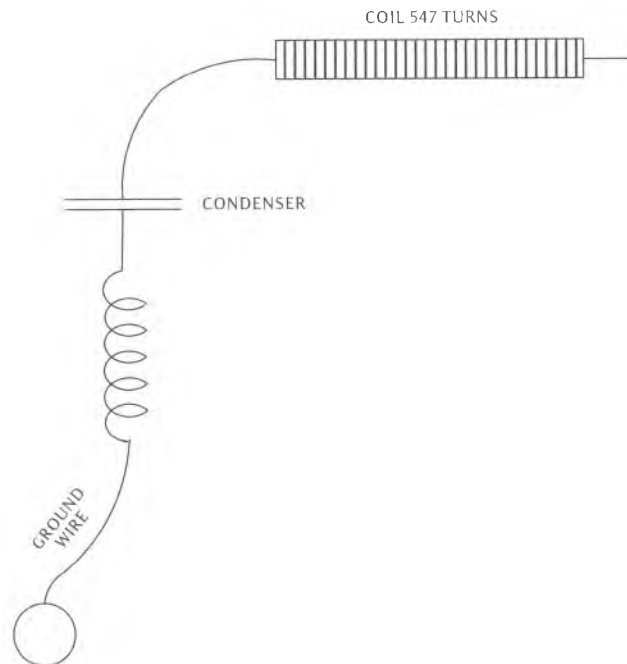


One of the four coils before experimented with, 547 turns each, miniature lamp *I* included, in secondary 3 turns as indicated was used and resonance obtained with $1\frac{1}{2}$ turns of ind. Regul. and one jar in each condenser set.

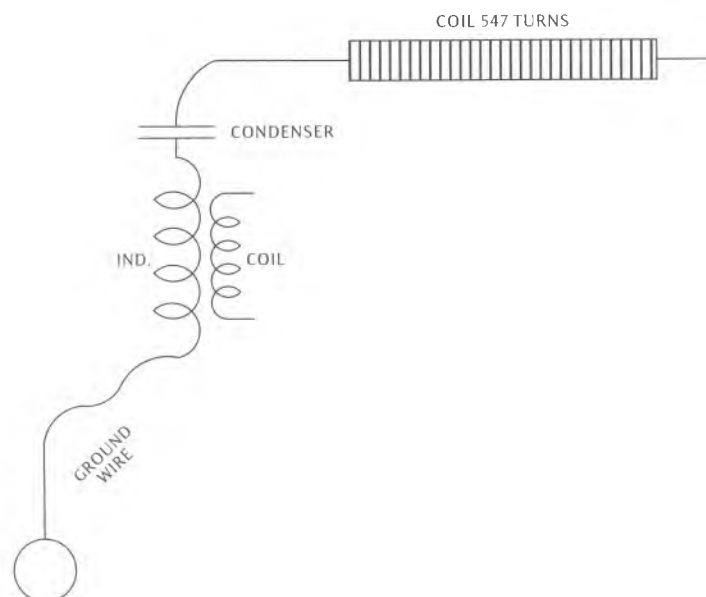
A condenser consisting of two parallel plates, 8" d. of brass was now inserted in series with the coil as shown in sketch and resonance obtained with plates $\frac{1}{8}$ " apart: $1\frac{1}{16}$ turns of regulator, one jar in each set of condensers.



Note: The lamp lighted brighter in this experiment. This may have been due in a small measure to the fact that less turns were used in regul. coil which made the exciting current slightly stronger. The chief cause was probably the condenser which enabled a better and more economical excitation through the ground wire. If this is not so, then I would attribute the greater intensity of the lamp to the capacity effect produced in the coil. Namely the presence of the condenser causes a different distribution of the capacity in the vibrating coil and it is evident that the current closer to the end must be relatively stronger, hence the induction effect upon the secondary on the end nearer to the capacity relatively greater. This will be further investigated. For the present it does not appear that because the lamp lights stronger the system as a whole takes up more energy. The effect may be simply due to the modified distribution of the current in the turns of coil with 547 turns.

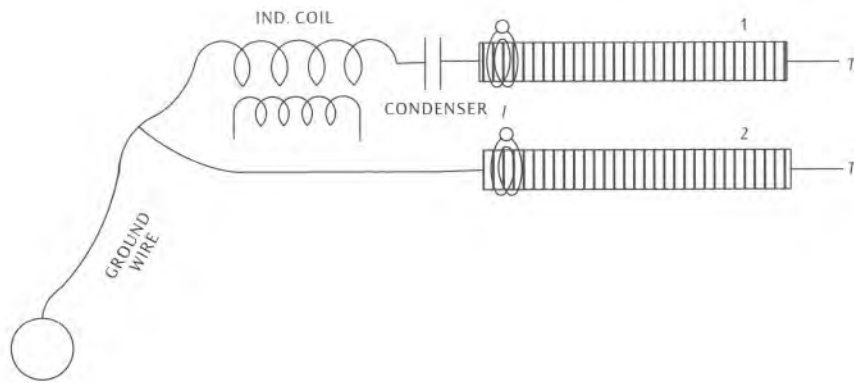


The observation with the condenser in series as above suggests arrangement as indicated in sketch with inductance in ground wire being such that the lower part from ground connection to the lower condenser plate is one quarter of wave length. The coil added should then be **one half** wavelength or an even number of half wavelength's. Condensers may be inserted between the successive parts. Such arrangements were however experimented with especially in Colorado. (See notes Col.)



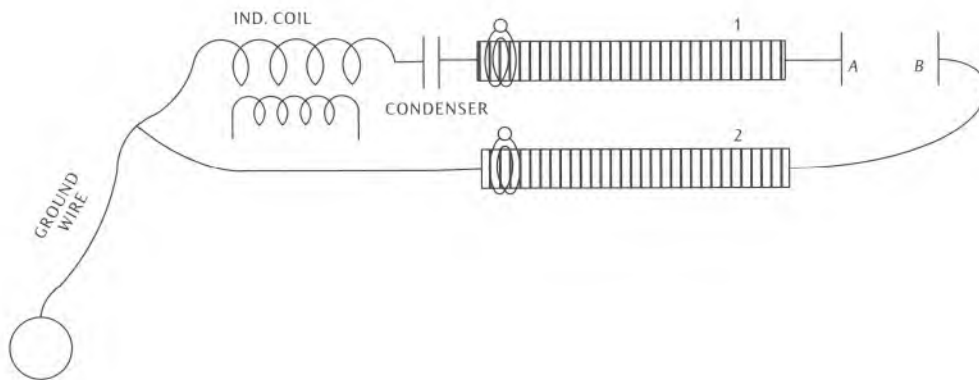
In this experiment the small induction coil before referred to was inserted in the ground wire. Resonance was obtained with: $1\frac{1}{8}$ turns Reg. coil and one jar in each condenser set.

The insertion of the induction coil slowed down the vibration a trifle, otherwise the conditions remained same. The two systems vibrate as **one** which is the rate of the larger system. If there are independent short oscillations in the small system their effect upon lamp is inappreciable.

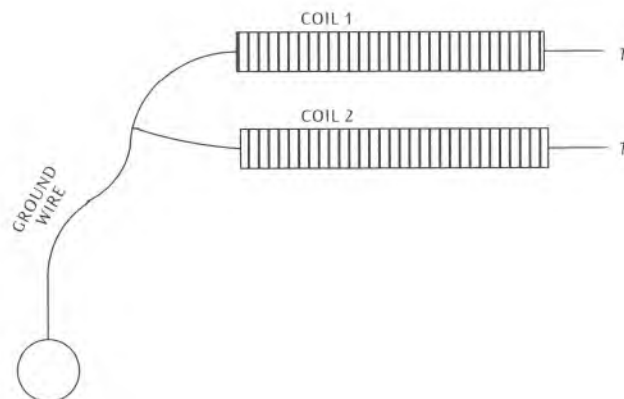


In this experiment the lamp on coil 2 lighted **alone**. Even with stronger excitation lamp of coil 1 remained dark.

Important to notice: When system 1 as illustrated was used singly and one of the brass plates 8" diam. was attached to terminal *T* it produced scarcely any difference on the lamp, but when the plate was attached to terminal *T* of system 2 the lamp on 2 did not light and could not be made to light with very strong excitation of ground wire.



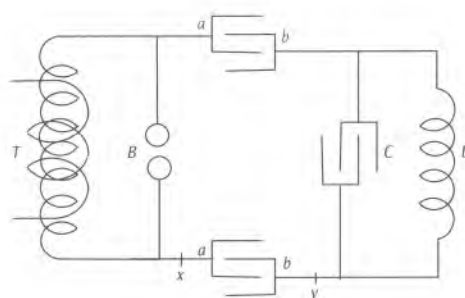
In this experiment when plates *A* and *B* were far apart the lamp of coil 2 did not light. When the plates were gradually brought near, the lamp of this coil began to light and finally when plates were quite close or in contact **both lamps** on coil 1 and 2 lighted exactly well the same as when the two coils were connected in multiple in a previous experiment.



A curious observation was made with two coils in multiple as shown. When one of the brass plates 8" diam. of condenser was connected to terminal *T* of coil 1 lamp of coil 2 lighted. When plate on coil 1 disconnected, lamp on 2 does not light. When coil 1 disconnected, lamp of coil 2 lights. These phenomena can be easily explained. The investigation will be followed up.

July 13, 1901

When using connection as indicated in diagram below curious observations are made which raise a doubt as to the amount of energy consumed on either side of the condenser when one side includes a spark gap and the other has none.



Obviously more energy is consumed on left side of condensers *ab ab* that is on side to which coatings *a a* are connected because the current of the secondary of transformer *T* passes through the arc *B*.

There may be, however, other causes, as the giving off from the arc of short waves. These statements assume that the circuit is otherwise symmetrical to the condensers *ab ab*.

As bearing on above following experiments were made:

1) A coil of 3 turns № 10 wire, 4" diam. was wound on top of which more turns of thinner wire serving as secondary were placed. This secondary included a miniature lamp requiring minute current. A fixed quantity of energy was supplied from transformer *T* to condensers *ab ab*. The primary circuit – that is the three turns – of the induction coil was first inserted in series with the spark gap and coatings *a a* on place marked *x* and then at *y* in the part of the circuit not including the spark gap but simply coatings *b b* and condenser *C*. The lamp lighted the same, took equal amount of energy as far as could be ascertained.

2) The e.m.f. on secondary of small coil was the same in both cases but this did not settle doubt for the frequency might have been different owing to harmonics chiefly on one side. The condenser *C* was much larger than *ab ab*. The frequency considered in its totality might have been smaller on right side and current proportionately stronger, hence e.m.f. on secondary of small induction coil the same as before. The coil was replaced by an iron wire and again the same result was obtained.

3) Inductance coil *L* was now connected but although it modified greatly the distribution of the current in the main and branch circuit the iron wire was affected equally at both places *x* and *y*.

Conclusion: Total energy consumed may be different in the both sides although perfectly symmetrical if one contains arc and the other not, irrespective of the arc itself. A delicate test is to be applied.

Capacity of Condensers

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Tank I			Tank II		
Jar №	Capacity expressed in microfarads centimeters		Jar №	Capacity expressed in microfarads centimeters	
1	0.0193	17,340	7	0.0209	18,810
2	0.0182	16,380	8	0.0190	17,100
3	0.0180	16,200	9	0.0185	16,650
4	0.0190	17,100	10	0.0200	18,000
5	0.0196	17,640	11	0.0245	22,050
6	0.0200	18,000	12	0.0191	17,190
Total from measurement of individual jars	0.1141	102,690	Total from measurement of individual jars	0.1220	109,800
Total from measurement of tank as a whole	0.1158	104,220	Total from measurement of tank as a whole	0.1228	110,520

Capacity of Tanks I and II in Series

Value derived from	Capacity expressed in	
	microfarads	centimeters
Measurement of individual jars	0.0581	52,290
Measurement of each tank separate	0.0596	53,640
Measurement of tanks in series	0.0582	52,380

Capacity of condensers with the two tanks connected in series

Tank I	Tank II	Capacity in μF	Capacity in cm
Jars 1	Jars 7	0.0100 μF	9000 cm
" 2	" 8	0.0093 μF	8370 cm
" 3	" 9	0.0091 μF	8190 cm
" 4	" 10	0.0097 μF	8730 cm
" 5	" 11	0.0110 μF	9900 cm
" 6	" 12	0.0098 μF	8820 cm
" 1,2	" 7,8	0.0193 μF	17370 cm
" 1,2,3	" 7,8,9	0.0284 μF	25560 cm
" 1,2,3,4	" 7,8,9,10	0.0381 μF	34290 cm
" 1,2,3,4,5	" 7,8,9,10,11	0.0491 μF	44190 cm
" 1,2,3,4,5,6	" 7,8,9,10,11,12	0.0589 μF	53010 cm

July 13, 1901



Capacity of condensers with the two tanks connected in Series

Tank	I.	Tank II.	Capacity in M.F.	Capacity in C.M.
Jars	1	Jars 7	0.0100	9000 "
"	2	" 8	0.0093	8370 "
"	3	" 9	0.0091	8190 "
"	4	" 10	0.0097	8730 "
"	5	" 11	0.0110	9900 "
"	6	" 12	0.0098	8820 "
"	1, 2	" 7, 8	0.0193	17370 "
"	1, 2, 3	" 7, 8, 9	0.0284	25560 "
"	1, 2, 3, 4	" 7, 8, 9, 10	0.0381	34290 "
"	1, 2, 3, 4, 5	" 7, 8, 9, 10, 11	0.0491	44190 "
"	1, 2, 3, 4, 5, 6	" 7, 8, 9, 10, 11, 12	0.0585	53010 "

Capacity Average

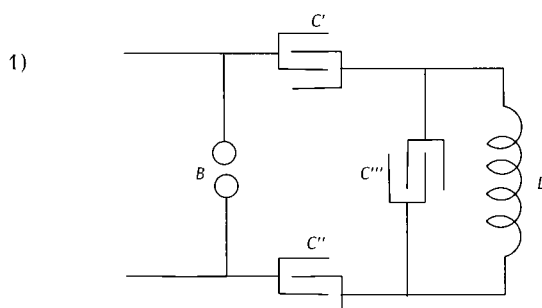
1 jar in each tank	0.009740 M.F.	8766 C.M.
2 " " "	0.01948 "	17532 "
3 " " "	0.02922 "	26298 "
4 " " "	0.03896 "	35064 "
5 " " "	0.04870 "	43830 "
6 " " "	0.05844 "	52596 "
Average Value of one jar in tank I.	0.0190 "	17100 "
" " " " II	0.0200 "	18000 "

Tank I	Tank II	Capacity in μF	Capacity in cm
Capacity average			
1 jar	in each tank	0.009740 μF	8766 cm
2 "		0.01948 μF	17532 cm
3 "		0.02922 μF	26298 cm
4 "		0.03896 μF	35064 cm
5 "		0.04870 μF	43830 cm
6 "		0.05844 μF	52596 cm
Average value of one jar in tank I		0.0190 μF	17100 cm
Average value of one jar in tank II		0.0200 μF	18000 cm

July 13, 1901

From old notes

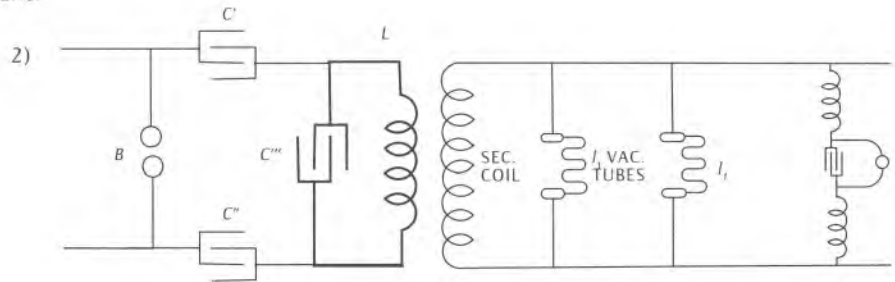
Following arrangements of apparatus offer specific advantages particularly in cases when only high frequencies are desirable. Diagram 1 illustrates ordinary arrangements of condensers C' C'' make and break B and conductor L . In the present modification the conductor is shunted by a condenser C''' and in this way two circuits are formed. By varying the capacities and inductances in the two circuits very striking effects are obtained especially by observing proper rules of tuning.



Enormous electromotive forces per unit length of conductor L are obtainable and also currents which may reach many hundreds of thousands of amperes. To produce such currents it is necessary to construct condenser C''' of copper or aluminium sheet as tinfoil melts. I construct conductor and condenser in one, so that there is no joint except at the ends to the coatings of the condensers C' C'' which are the outer coatings and of heavy metal. It is astonishing that with say twenty turns of conductor L – the turn about 1 foot diameter a bulb 1 foot diameter, exhausted as high as practicable with my mercury pump, is lighted up by induction and the gas inside brought instantly to a very high temperature. It is not absolutely necessary to tune the circuits in this arrangement, for the circuit can be forced through conductor L simply by reducing its impedance. I find that in this form of apparatus a relatively very intense higher note can be obtained. For the best performance of course the two circuits should be tuned to the same fundamental note. In this case L must be just half the wavelength. It may be however adjusted for the next octave and as above stated the results are surprisingly good. A peculiar advantage of the arrangement in diagram 1. is that the current through the make and break B may be very small as compared with that through conductor L . This is sometimes a great improvement but not necessarily

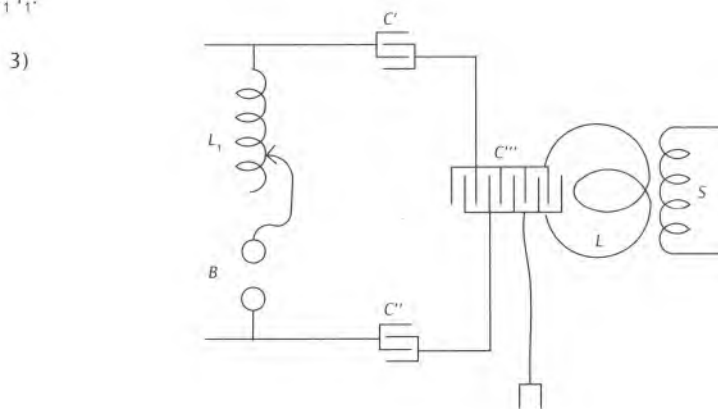
so in all forms of my apparatus. With mercury interrupters the resistance at B can be reduced as far as desired.

A very great practical advantage is however that the condenser C''' may be an ordinary mica condenser but constructed as before indicated of copper or aluminium sheet. I calculate the condenser and inductance L for the frequency of the oscillation through B . The circuit LC''' I connect to ground so that despite of great tension on the condensers $C' C''$ perfect safety results. A secondary coil may then be used for running lamps through the building or other purposes. The diagram 2 illustrates this special arrangement.



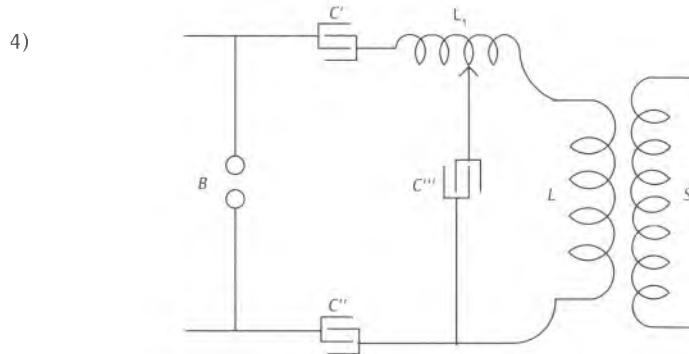
Here $C' C''$ are condensers of small capacity, C''' condenser for small pressure large capacity, L stout short conductor.

The secondary S may also be connected to ground if desired. The condenser C''' is of course protected by conductor L otherwise it could not withstand the strain. The coil L keeps the pressure at the terminals of C''' as low as desired. When the condenser C''' is also of small capacity then L has many turns and in this case I generally convert down so that the secondary S has a fewer, or perhaps the same number of turns, at any rate a number of turns dictated by the requirements of circuit which the secondary S supplies. In such a case the secondary is invariably connected to the ground. If it is desired to connect the coil L also to ground in case it has many turns the middle point should be connected otherwise the circuit would be asymmetrical or of the form of grounded circuits used in my system of transmission through natural media. The secondary should then be arranged relative to the primary L in the ways indicated in my previous records of this kind of apparatus. These arrangements last described give very good results with vacuum tubes because of high frequency and also on account of small damping of oscillations in circuit LC''' . The secondary S should also be tuned to LC''' so that preferably all these circuits are vibrating the same note. I also tune the individual circuits supplying the lamps or devices $I_1 I_2$.



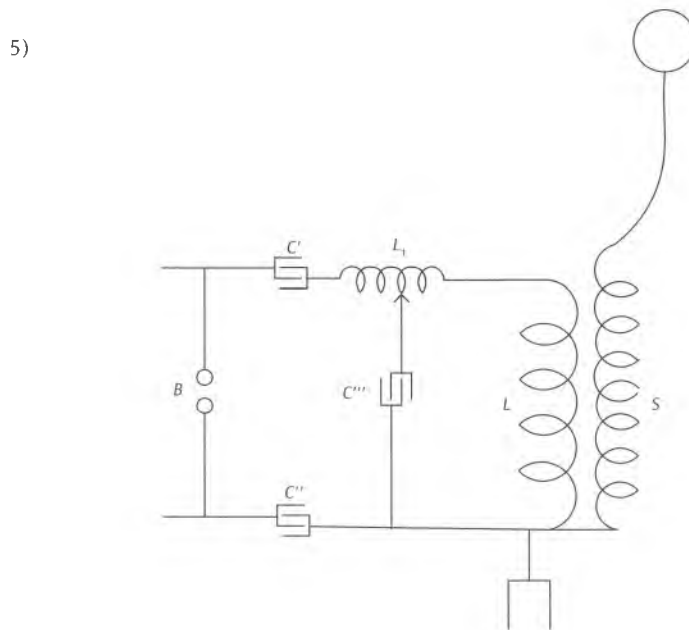
To prolong the oscillations through device B the inductance in circuit $C' B C''$ is increased. This can be done without departing from the high frequency because the tension of the source can be very high and condensers $C' C''$ very small, hence inductance considerable. The diagram 3. illustrates modified apparatus in one of its forms.

By making the inductance L_1 very large the oscillations may be greatly prolonged and particularly when the circuit $C'''L$ is tuned to the same note a great advantage is so secured.



In diagram 4. is shown a modification of diagram 3. which I find suitable in the instances especially when the capacity C''' is likewise small. It is very easy to tune the circuits merely by shifting the contact point c of one of the terminals of the condenser C''' and inductance L .

The last described modification is very good in connection with transmission through natural media in accordance with my system. I use this arrangement as shown in diagram 5.

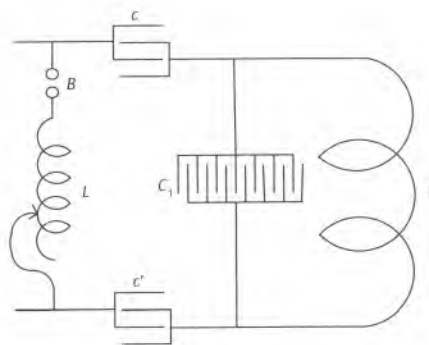


For the sake of simplicity the condenser C'' is not employed. The transmitter S with capacity C'' is in this form very effective. The circuit through B is traversed by a small current and the oscillation in it, owing to small damping and great momentum persists very long after each closure of device B . The circuit LC''' being sharply tuned to same note magnifies the movement greatly during the oscillation through B . When however the circuit through B is interrupted the oscillations through L continue long. All this contributes to the intensity of the movement obtained in the system SC'' .

Other modifications to follow.

July 15, 1901

Design of condenser to be used in shunt to a coil or loop of inappreciable resistance, for the purpose of obtaining currents of very high frequency, great intensity and persisting very long.

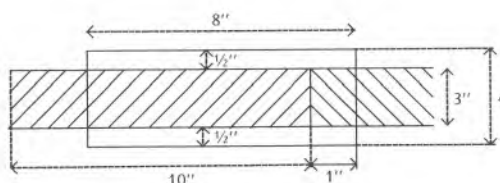


Theory. When the local circuit $C_1 l$ formed as indicated in diagram, vibrates in unison with main exciting circuit $cBLc'$ the impedance of the path $C_1 l$ is reduced to the ohmic resistance which is entirely negligible and hence the vibration of the exciting circuit is merely dependent on the inductance L and capacity of condensers $c c'$. The inductance L reduces the rate of vibration but has the advantage of prolonging the oscillation and producing a greater resonating rise in the local circuit. It is therefore better to use inductance in the exciting circuit. This however is easily practicable without great sacrifice of frequency as the source supplying the energy to condensers $c c'$ can be of very high tension and hence the condensers $c c'$ as small as desired. I shall assume that 10000 cm is the inductance of the exciting circuit which, with all condensers – six in each set – connected, will give a vibration not far from 200000 p. s.

The vibration period of exciting circuit under the conditions above assumed will be $T = 2\pi\sqrt{\frac{c}{2}l}$, $c = c'$, and this must be also the period of the local circuit. Hence $T = 2\pi\sqrt{c_1 l}$ from which $c_1 l = \frac{c}{2}l$. In the present apparatus $\frac{c}{2}l$ (both tanks in series) = $0.0586 \mu F$, L as before assumed (including all connections) = 10000 cm or $\frac{1}{10^5}$ H. Substituting we have $c_1 l = \frac{0.0586}{10^6} \cdot \frac{1}{10^5} = \frac{586}{10^{15}}$.

Here c_1 is in farads and l in Henry's. Taking both in centimeters we shall have $c_1 l = \frac{586 \times 9 \times 10^{11} \times 10^9}{10^{15}} = 5274 \times 10^5$.

Construction of condensers. With very heavy currents as obtainable in this way a tinfoil condenser is of no use. The coatings must be constructed to stand the enormous current and copper or aluminium sheet should be used or also an electrolytic condenser as the main condensers $c c'$ ought to be employed. In fact I think that the latter are best of all. In the present instance for convenience the condenser is to be made of mica and copper sheet as follows:



20 copper sheets $\frac{10}{1000}$ " thick sheet each 10" long 3" wide. Mica 8" x 4" lapping over copper $\frac{1}{2}$ " on each side and 1" on the narrow ends.

There will be 19 plates of mica and 10 copper strips in each of the armatures.

Effective area will be $19 \times 3 \times 6$ sq. inches = $A = 116$ cm sq. Each mica sheet $\frac{15}{1000}$ " thick, hence $d = 0.038$ cm. Taking for this mica sp. ind. capacity = 6 we have:

$$C_1 = \frac{19k \cdot A}{4\pi d} = k \cdot \frac{116 \times 19}{12.57 \times 0.038} = k \frac{2204}{0.478} = 6 \times 4611 = 27666 \text{ cm.} = 0.0307 \mu\text{F.}$$

With reference to above equation we have $c_1 l = 5274 \times 10^5 = 27666 l$ from which

$$l = \frac{5274}{27666} \cdot 10^5 \text{ centimeters} = 19063 \text{ or roughly } 19000 \text{ cm.}$$

Taking a coil of diameter of about 13" stout wire for lighting a large bulb 12" diameter etc. one turn will have not far from 4000 cm and two turns close together will probably have not far from above value. Conclusion: Two turns on a trifle larger diam. are to be used.

— . —

When a wire is stretched out straight it has a certain capacity given by formulas. So if it be cylindrical and of length l the capacity c_1 will be $c_1 = \frac{l}{2 \log_e \frac{l}{r}}$. Usually however it has not the value given by

this formula, for if it be placed vertical the capacity increases with the elevation and on the other hand if it be stretched horizontally it has a capacity with reference to the Earth's surface. Suppose it is placed above ground at a distance d from the same then it has a capacity $c_2 = \frac{l}{2 \log_e \frac{2d}{r}}$. These two are equal when $\frac{2d}{r} = \frac{l}{r}$ or $l = 2d$.

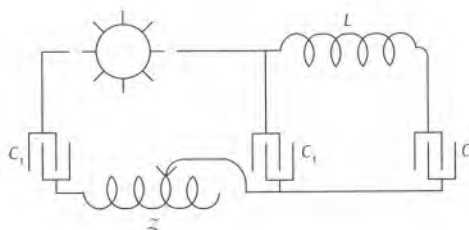
In my system of transmission by conduction with grounded circuit the effective capacity is $\frac{c_1}{c_1 + c_2}$.

This has been demonstrated in many experiments. Hence it is of great importance 1) to reduce the capacity with reference to other objects and 2) to elevate the wire as the capacity increases with height at a rate of about $\frac{1}{2}$ of one percent per foot.

If the same wire be coiled up it may have a smaller or greater capacity. This will also depend on the diameter of the coil. When wound on a coil the wire acquires an other capacity which grows in proportion to the square of the diameter as shown in Colorado experiments from which practical formulas have been derived. But while the wire is cramped in a smaller space the capacity designated c_1 diminishes so that the capacity of a coil is normally much smaller than that of the wire stretched out. But if the diameter be very large then the capacity of the coil may be much greater. This is important to consider in constructing rigid electrical systems.

July 20, 1901

Experiments with condenser in shunt to part of primary discharge circuit of large laboratory apparatus.



In this case L was inductance of the two turns of cable (in series) contained in square frame $8' \times 8'$, frequency referred to. L is the self-induction regulator.

- 1) $C_1 C_1$ three jars each $C_1 = 3 \times 0.0195 = 0.0585 \mu\text{F}$.
 C 2 jars $C = 2 \times 0.0195 = 0.039 \mu\text{F}$.

Capacity in branch C_2 from equation:

$$\frac{1}{C_1} + \frac{1}{C} = \frac{1}{C_2} = \frac{C + C_1}{CC_1} = \frac{\frac{2}{3}C_1 + C_1}{C_1^2} \text{ from this } C = \frac{2}{3}C_1, C_2 = \frac{3}{5}C_1.$$

Now resonance was obtained with $L = 6\frac{3}{4}$ turns. In this case the impedance of the condenser and inductance path was just equal to Ohmic resistance i.e. negligible. The capacity in primary exciting circuit was thus C_1 and total inductance $L = 6\frac{3}{4}$ turns and connections. We have then

$$C_2 L = C_1 L \text{ or } L \cdot \frac{3}{5} C_1 = C_1 L \text{ from which } L = \frac{5}{3} L.$$

Taking from tables value of $L = 6\frac{3}{4}$ turns = 20000 cm approximately $L = \frac{5}{3} \cdot 20000 = 33000$ cm about. It should be 32000 cm.

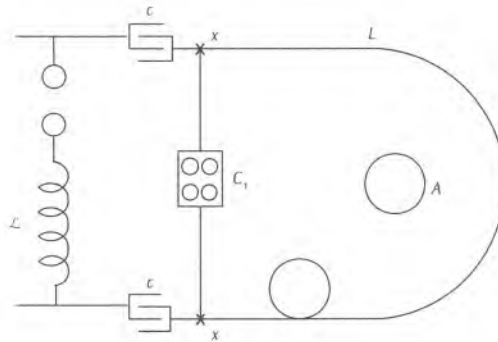
2) $C_1 C_1$ each	two jars,	C one jar	Resonance	$6\frac{3}{4}$ turns of $\mathcal{L}$ as before.
3) $C_1 C_1$ "	"	C three jars	"	$8\frac{1}{4}$ " $\mathcal{L}$ "
4) $C_1 C_1$ "	three "	C one jar	"	$4\frac{1}{4}$ " $\mathcal{L}$ "
5) C_1 (left)	2 jars,	C_1 (right) three jars; C one jar	"	$5\frac{3}{4}$ " $\mathcal{L}$ "
6) $C_1 C_1$	one jar	C one jar	"	$7\frac{3}{4}$ " $\mathcal{L}$ "
7) $C_1 C_1$	two jars	C two jars	"	7 " $\mathcal{L}$ "
8) $C_1 C_1$	three "	C three	"	7 " $\mathcal{L}$ "

— . —

1) $C_1 C_1 C$	one jar each	Resonance with	$11\frac{1}{2}$	"	$\mathcal{L}$	"
2) " " "	two jars "	"	$10\frac{1}{2}$	"	$\mathcal{L}$	"
3) " " "	three "	"	$9\frac{1}{2}$	"	$\mathcal{L}$	"
4) " " "	four "	"	$8\frac{1}{2}$	"	$\mathcal{L}$	"
5) " " "	five "	"	$7\frac{1}{2}$	"	$\mathcal{L}$	"
6) " " "	six "	"	$6\frac{1}{2}$	"	$\mathcal{L}$	"

Note: Evidently no change in relation when the ratio of capacities in both the circuits is kept the same. The diminishing number of turns with increasing number of jars is in all probability due to the smaller inductance when all jars connected. This is to be verified.

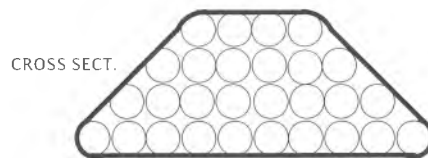
Data for reference



L cable around laboratory, C_1 condenser in shunt, L Regulating inductance coil, A coil in center of room. The constants of circuit $L c c L$ were adjusted until resonance was obtained in coil A . This took place when there were 13 turns of Reg. Ind. coil in circuit and 6 jars in each condenser set.

C_1 four old jars in multiple.

Particulars relative to coil for exciting large vacuum bulb etc. Okonite wire № 10 wound around a form. Cross section as in sketch 18 turns, mean diameter of coil about 14". This coil was connected to points $x x$ instead of cable L . Resonance was obtained with $16\frac{1}{4}$ turns of Reg. Coil L 6 jars in each set of condensers, C_1 as before.



In this case condensers $c c = 0.0582 \mu F$ $C_1 = 0.01$ about.

The inductance L with connections was about 56000 cm from tables. From this approximate inductance L of coil of Okonite wire would be $0.0582 L = 0.01 L$, $L = 326000$ cm.

Test of large spiral coil with ground wire excitation for purpose of ascertaining influence of ball 8" diam. at the free terminal

	Turns in Reg. Coil	Capacity primary
Resonance with ball	7	6 jars each side
" without ball	$6\frac{5}{16}$	6 " "

Large mercury break old casting last modification

diameter of bore between teeth $13\frac{17}{32}" = 13.53"$

Circumference 42.5"

3 contact streams 16 teeth supported by a common ring hollow for catching the mercury.

The space for one make and one break if both equal would be $\frac{42.5}{96} = 0.4427"$.

Conclusion: Teeth and outlet rods for streamers are to be on face $\frac{1}{4}"$ wide.

Stationary waves will be useful in connection with light houses, ocean liners etc. as they enable to ascertain the direction from which disturbances are coming. The simplest way of producing the waves will be by connecting the oscillating circuit at **two** points to Earth. For this no powerful apparatus is required. They may be also produced by two oscillating circuits each connected to ground and to an elevated terminal. Stationary waves in a limited region may then be obtained by interference. Very powerful apparatus is necessary if but a single circuit connected to Earth and to an insulated terminal is used. Both the direction and distance of a moving object, as a vessel, may be determined by a circuit carried on the same. It will be best to connect the circuit at two points to the ground or else two circuits each connected to the ground and to an insulated terminal as usual may be employed. The distance may be however approximately determined by using a single circuit tuned and having a resistance in the secondary. This resistance – which still better may be in an independent circuit will be heated less in proportion as the distance from the source of the disturbance increases. The device may be calculated so that the value of the resistance will at once give the distance.

Stationary waves may enable also the height to be indicated. It is quite possible that the waves are reflected and may give nodal and ventral points.

Instead of using stationary waves it will be possible to employ ordinary direct or alternating currents. The generator being connected to two points of the ground direction can be indicated. When using such currents condenser method will be the best. For example with direct currents passing through the ground in a given direction it is possible to charge a condenser during a definite time interval determined by a pendulum or clockwork and from the energy of the discharge the distance from source may be computed. Various arrangements on these lines will be worked out.

July 22, 1901

Approximate estimate of inductance of connections on large apparatus with the two sets of condensers in series as usual, arcs included.

One of the coils before described 547 turns on $3\frac{1}{2}$ " core connected to ground through the ground wire 14 feet long gives resonance with $1\frac{1}{2}$ turns Regul. and 1 jar in each set.

Circumference of coil 11", length of wire $547 \times 11 = 6017" = 501.4$ feet. To this ground wire to be added gives $\frac{\lambda}{4} = 516$ feet roughly. Rather more than less. Allowing 4 feet for girder we have about 520 feet = $\frac{\lambda}{4}$. The vibration should be

$$n = \frac{186000 \times 5280}{520 \times 4} = 472000 \text{ p. s.}$$

Calling the inductance of connections L , we have ($C = \frac{0.0195}{2} = 0.00975 \mu\text{F}$)

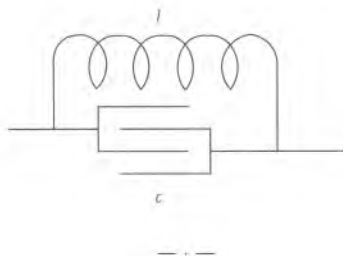
$$\frac{1}{472000} = \frac{2\pi}{10^3} \sqrt{L \frac{975}{10^5}} = \frac{10^3}{472000 \times 2\pi} = \frac{1}{100} \sqrt{L \cdot 97.5} \text{ and from this}$$

$$\left(\frac{100}{472 \times 2\pi} \right)^2 \cdot \frac{1}{97.5} = L = \frac{10^3}{4 \times 97.5 \times 222784} \text{ Henry;}$$

$$L = \frac{100}{39 \times 222784} = \text{approx. } \frac{1}{39 \times 2228} = 11500 \text{ cm.}$$

The Colorado connections had 7300 cm approx. The above amount (11500 cm) is evidently too large because coil has appreciable capacity. This is to be eliminated.

Note: Best result is obtained by tuning system like this, l , c , both known.

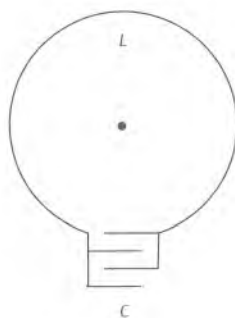


Experiment with condenser and loop to be used in determining vibration. Also for purpose of obtaining very strong current.

Loop 2 feet diam. circular. $r = 30$ cm about.

Wire $\frac{5}{16}$ " diam. $a = \frac{5}{16} \cdot \frac{1}{2} = 0.4$ cm.

Inductance of loop $L = 4\pi r \log \frac{8r}{a} = 1000$ cm roughly.



C condenser mica about $0.031 \mu\text{F}$ (calculated).

The period of system should be:

$$T = \frac{2\pi}{10^3} \sqrt{\frac{1000}{10^9} \cdot 0.031} = \frac{2.14}{10^6}; \text{ from this}$$

$$n = 470\,000 \text{ per sec}$$

The exciting system comprised loop **single** in square frame and few turns in Regul. coil, 2 jars in each set of condensers of large apparatus all in series. Resonance was obtained with: 3 turns Regul. coil 4 jars in each set.

Capacity of 4 jars in series all four is about $0.005 \mu\text{F}$. From this we may determine the inductance of loop. The inductance in primary was nearly $24000 \text{ cm} = L_p$. Now

$$L_p \cdot 0.005 = Lc = \frac{1}{10^6} 24 \times 0.005 = L \cdot 0.031.$$

Hence $L = \frac{24 \times 0.005}{0.031 \times 10^6} = 4000 \text{ cm}$ approxim. Evidently the system was tuned to undertone as inductance of loop is just four times the calculated.

July 30, 1901

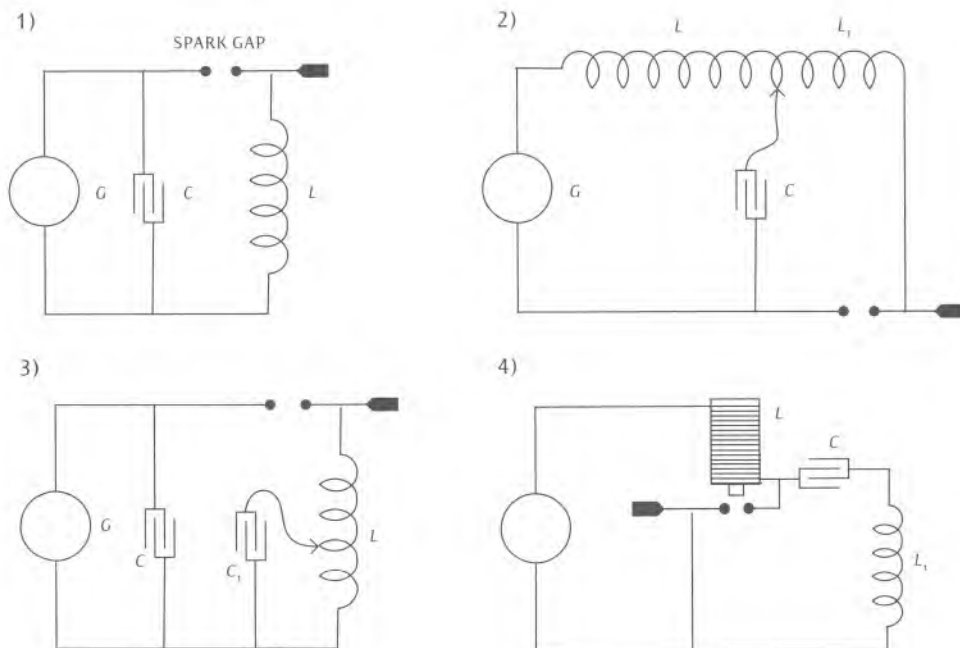
From old notes

Several arrangements have been so far experimented with for the purpose of eliminating entirely the effects of the fundamental disturbance of low frequency which disturb telephones and also limit resonating rise in many cases. It would be desirable to obtain a clear high note from disturbances of much lower frequency such as obtainable by a mechanical break or with a dynamo. It seems out of question to use high frequency dynamos giving vibrations beyond the limit of audition and with mercury breaks or arcs the fundamental discharges can be scarcely more than a few thousand per second.

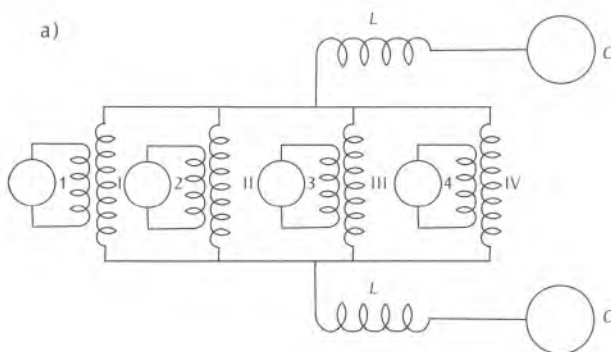
By using a source of continuous pressure, preferably very high, and charging a condenser by the same which discharges under conditions necessary for oscillations, the rates of charging and discharge can be so adjusted that more than 50000 (fifty thousand) individual discharges through a gap are obtained and in this way the effects upon the telephones can be eliminated in a large part if not entirely. A number of arrangements considerably improved over the old, have been experimented with apparently with good success. They are illustrated below:

In 1) the free vibration of system LC is so adjusted as to secure resonance with makes and breaks. The free vibration and fundamental are the same. The source is a high tension rotating transformer G having the high tension winding or it may be any other source of high tension.

In 2) the source G is an ordinary direct current dynamo. The tension is raised by the coil LL_1 , a part of which forms a local circuit with condenser C and gap. The periods of the two circuits are again the same, the adjustment is made by flexible conductor as indicated. In 3) modified arrangement is shown with a source of high tension and local circuit containing no break. In 4) a magnet L is used to blow out the arc and the adjustment is the same as before that is, the circuit including the magnet and condenser is so adjusted that the free oscillation of the system and the fundamental through the gap are the same. The local circuits in 2), 3) and 4) may be of the same or of a higher period, this is not important so long as the above condition is fulfilled. It is always possible to attain the result by proper adjustment of the inductance, capacity and gap or by modifying the e.m.f. until the rates of charging and discharging are such that there is just twice that number of charges which designates the frequency of the free oscillations of the elastic system.

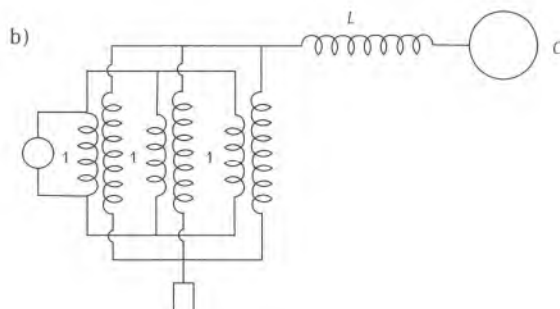


An other line of experiment which is being followed up promises better results. The principle involved may be best explained with reference to diagram a) illustrating one of the arrangements experimented with.



In this diagram 1 2 3 4 ...n are individual circuits, each containing a make and break device. These circuits excite parts I, II, III, IV which in turn excite the whole of system LC .

The inductance LL is sufficiently great to entirely govern the movement or else the circuits LC are independent and tuned to the frequency of the oscillations impressed upon parts I, II, III, IV...n.



When there are many break devices or respectively circuits the chief vibration – that of LC will dominate.

Diagram b) shows a further improvement. Each source (one shown) furnishes currents which differ in phase. To follow up.

From old notes

Following seems to be a good arrangement in rapid telegraphy etc. either through natural or artificial channels.

A complex of waves or vibrations is sent out from a transmitting station and at the receiving station there are elements each responding to one or more elements of the complex disturbance of the transmitter. The elements of the receiver control contacts which may be in series. Each contact is shunted by a device which is operated when contact is opened by the tuned sensitive circuit. Each of the devices may be used say to print a particular letter of the alphabet. In this way very rapid telegraphy or printing is possible. On each side there may be a typewriter and the message can be directly sent by the typewriter from the transmitting station and printed at the receiving station. It is not difficult to adapt this idea to the ordinary typewriter system.

Aug. 3, 1901

Possible effect of apparatus on Long Island plant

Assume terminal capacity only 4000 cm. If the wood structure does not limit pressure we may expect following:

$$I = E c \omega \text{ Energy} = E^2 c \omega C = \frac{4000}{9 \times 10^{11}} \omega = 6 \times 10^5.$$

If we take energy in secondary to be 300×750 Watts,

$$E^2 = \frac{300 \times 750 \times 9 \times 10^{11}}{4000 \times 6 \times 10^5} = 10^6 \times 84.38$$

$$E = 9.2 \times 10^3 = 9200 \text{ Volts.}$$

$$\text{Now } I = Ec\omega = 9200 \frac{4000}{9 \times 10^{11}} \times 6 \times 10^5 = 24.75 \text{ Amp.}$$

This current passes through the Earth. Now Energy is contained in each half wave: Hence we have $\frac{300 \times 750}{24.75} = E_1 = 9091$ Volt. This means to say that we shall get at two points one half wave length apart theoretically 9091 Volt!

The magnification has no other effect than simply to increase the current through Earth and also proportionately the e.m.f. between two points situated as above. If we have a current of 2475 Amp. the e.m.f. will be 100 times as great, that is – 909100 Volts! This would be great! If the e.m.f. is not dependent on size of conductor – that is a big If! At any rate, the actual energy on each unit of area can be only that which is obtained by making ratio of area to area of half wave zone and multiplying by energy of transmitter.

Aug. 19, 1901

(Rewritten from old notes)

India rubber contracts when heated, forming exception to general rule.

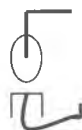
Can odors be transmitted electrically? Will propagation be quickened by cathodic or similar action? If a cup be connected to a pole of a high tension electric source will the odor of a substance placed in the cup penetrate quicker and stronger through space?

There seems to exist a fallacy in the experiments of Joule and Thomson and Gay Lussac with gas escaping through porous plug. In later case only higher velocity is given to the gas – but temperature remains the same. Methods of detection very sensitive suggest themselves. The telephone, bridge, thermo battery and telephone will show whether actual cooling takes place. The use of an oscillator producing currents in the passage may be resorted to. The mechanical oscillations of a small piston may be thus used to ascertain the amount of work performed.

Principle in refrigeration: Wollaston's Cryophorus seems of practical value. Vapor of water sucked away by machinery will freeze economically. This should be followed up.

Cold mixture of carbonic acid snow dissolved.

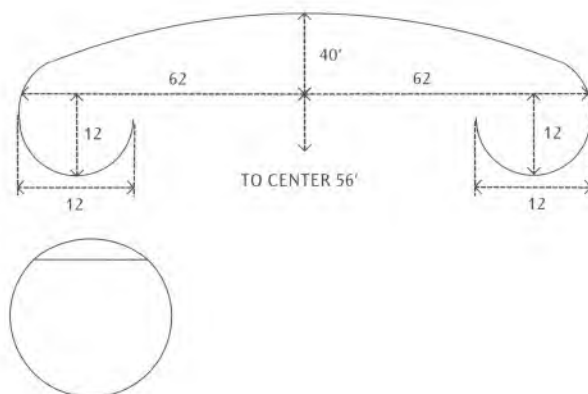
Circuit breaking device: drop in spheroidal state may be interesting



Use always Hydrogen where large capacity of cooling required. Not to forget.

Use of singing flame in connection with telephone for magnifying voice. Interesting.

Aug. 26, 1901



Cupola to be made of spherical surfaces, curvature 4 feet = radius

The above curvature will permit raising the e.m.f. to about 4×10^6 Volts.

Approximate estimate of capacity

Surface of calotte is $s = 2\pi \times 96 \times 40$ sq. feet. This will give roughly $\frac{2\pi \times 96 \times 40}{16} =$ about 1500 squares 4×4 feet curved.

/.... /* tore only outside will be effective. We may take about three rows of curved sheets.

* Illegible – Ed. note

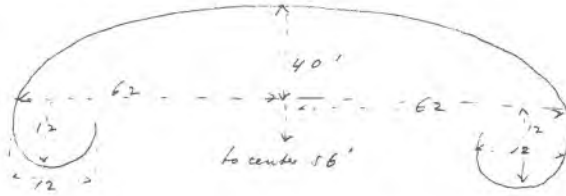
Circumference of large circle is $124 \times \pi$. We will get about $\frac{124 \times \pi \times 3}{4} =$ roughly 300 sheets. Both together will give about 1800 effective sheets. Now the capacity roughly estimated of one of the square sheets may be taken to be in the same ratio smaller than capacity of complete sphere as the surface of the sheet is smaller. The surface of complete sphere 4 feet radius would be $4\pi r^2 = 4\pi \times 16$ and surface of sheet roughly 16 square feet. Hence the ratio $\frac{16}{4\pi \times 16} = \frac{1}{4\pi}$ multiplied with the capacity of such sphere will give the capacity of one sheet. Calling it C we have $C = \frac{1}{4\pi} \cdot r$ in centimeter; r being 4 feet = $4 \times 30 = 120$ cm we have $C = 120 \times \frac{1}{4\pi}$ roughly 10 cm. The total sheet will however not be effective and I think it will be not far from truth to adopt $C = 6$ cm as effective value for each sheet. Calling C the capacity it should be $1800 \times 6 = 10800$ cm. But at a height of 250 feet we should have increase of about $\frac{1}{2}\%$ per foot as determined in Colorado, hence $C = 20000$ cm not less rather more. Accordingly taking $T = \frac{1}{10^5}$ we have $L = 112500$ cm. For $T_1 = \frac{1}{50000}$ $L_1 = 450,000$ cm.

Assume charge 240 times per sec – at 40000 Volts.

$$240 \times \frac{1}{2} \times 16 \times 10^8 \cdot \frac{1}{4 \times 10^6} = 48 \times 10^3.$$

$$48000 : 750 = 64 \text{ H.P.}$$

Aug. 26. 1901 94



Capsule to be made
of spherical surfaces
curvature 4 feet = radius

The above curvature will permit raising the d. r. f. to
about 4×10^5 volts.

Approximate estimate of Capacity

Surface of capsule is $s = 2\pi \times 96 \times 40$ sq. feet. This will give roughly
 $\frac{2\pi \times 96 \times 40}{16} =$ about 1500 squares 4×4 feet curved.

Second layer on outside will be effective. We may take about
three rows of curved sheets. Circumference of large circle
is $124 \times \pi$. We will get about $\frac{124 \times \pi \times 3}{4} =$ roughly 300 sheets.

Took together will give about 1800 effective sheets. Now

the capacity roughly estimated of one of the square sheets
may be taken to be a the same value smaller than

capacity of complete sphere as the surface
of the sheet is smaller. The surface of complete
sphere of 4 feet radius would be $4\pi r^2 = 4\pi \times 16$ and surface
of sheet roughly 16 square feet hence the ratio $\frac{16}{4\pi \times 16} = \frac{1}{4\pi}$ multiplied
with the capacity of such sphere will give the capacity of one
sheet. Calling it C we have $C = \frac{1}{4\pi} \times$ a certain value

if having 4 feet = $4 \times 20 = 120$ C. A. we have $C = 120 \times \frac{1}{4\pi}$ roughly = 10 C. A.

The total sheet will however not be effective and I think
it will be not far from truth to adopt $C = 6$ C. A. as
effective value for each sheet. Calling C the capacity

it should be $1800 \times 6 = 10800$ C. A. But at a height of
250 feet we should have increase of about $\frac{1}{2}$ to per foot as
determined in Colorado hence $C = 20000$ C. A. not less rather more

Accordingly taking $T = \frac{1}{10^5}$ we have $L = 112500$ C. M. for $T = \frac{1}{50000}$ $L = 459000$ C. M.

Note. Here occurs idea of using arcs in series and determining their number so that arcs will persist just during the required time intervals. Experiment will show how long arc on transformer persists when electrodes separated after the arc has jumped. Suppose the length with 40000 Volts to be l . Then if n be the number of arcs each will have length $\frac{l}{n}$. This enables to calculate n so that arc persists during required time interval. For if disk rotates with velocity v then length $\frac{l}{n}$ will require $\frac{l}{nv}$ parts of a second. C is known and v also, hence n can be determined from previous experiment. The great number of arcs is however objectionable on account high resistance as arc lengthens. Better always short arc: Closure not until the electrodes are close and opening sudden when electrodes are still close. This would seem commendable employment of air blast outside of disk. Good idea.

Aug. 28, 1901

Note relative to transmission of energy through Earth without wire

Stationary waves and other phenomena and facts derived show that by my transmitter, when radiation negligible, the entire energy of the same can be recovered at the Earth's surface.

Assume 300 H.P. be used on my plant that is a supply of energy at a rate of 300×750 Watts approximately then roughly the energy received per square foot of Earth surface – assuming further uniform distribution for the moment – will be $\frac{300 \times 750}{4\pi(4000 \times 5300)^2} = \text{about to } \frac{4}{10^7}$ Watts per each 10000 square feet of surface. This much energy could be received by using an insulated roof 100×100 feet on any point of the globe and passing the current from Earth to roof through a device properly constructed. Theoretically, it is interesting to note that $\frac{12 \times 4000 \times 4000 \times 5300 \times 5300}{10000} = 537 \times 10^9$ instruments could be operated, each consuming energy at the above rate.

The energy however will be supplied from my apparatus at a much higher rate than from dynamo for the condensers discharge in a much shorter time interval. Suppose the plan proposed is adopted and condensers charged 480 times per sec. Three waves being used differing in phase ($0^\circ, 45^\circ, 90^\circ \dots$) there will be 480 discharges and 480 charges, hence energy delivered will be at least doubled, losses in apparatus neglected. At any rate 25% could be safely added. The transformers however can be easily overloaded during the short intervals succeeding each other. It is easy to get energy delivery at a rate of $1000 \times 1000 = 10^6$ Watts from same apparatus, since it serves intermittently. For instance we may use large condensers. It is not unreasonable to expect from these facts alone a delivery rate of actual energy of $4 \times \frac{4}{10^7} = \frac{16}{10^7}$ Watts – in fact $\frac{2}{10^6}$ Watts. Considering however that waves are formed along the Earth surface and the energy is transmitted from one to another position, as demonstrated in Colorado, we shall get with 100 000 per second on equatorial belt $\frac{S}{s}$ times the energy rate = $\frac{12 \times 4000 \times 4000}{24000} \cdot \frac{2}{10^6} = \frac{16}{10^3}$ Watts. In average zone $\frac{32}{10^3}$ Watts and in the region of polar cap, spot 100 miles from pole, something like $\frac{6}{10}$ W and on cap 96 Watts, with circuit still more.

Sept. 8, 1901.

Transmissions of energy for purposes of wireless telegraphy



Assume roof as now proposed with plate of 1 meter curvature. The active area may be taken as equal to $S_1 + S_2$. Now $S_1 = 2\pi r_1 h$ and $S_2 = \pi r_2 u$ u being mean circumference of toroidal surface S_2 . As now planned $u = 112$ feet $r_2 = 6$ feet $r_1 = 96$ feet $h = 34$ feet from this

$$S_1 = 6.28 \times 96 \times 34 = 20500 \text{ feet square approx.}$$

$$S_2 = 3.14 \times 6 \times 112 = 2100 \text{ " "}$$



Surface active $S_1 + S_2 = 22600$ square feet about.

If we make half-spherical pieces about 1 meter curvature each would take the space of about 9 square feet, hence we would have $\frac{22600}{9} = 2500$ such half spheres. The capacity of one sphere of diameter as above would be at small height 100 c.m. of half the sphere it would be 50 c.m. but as the action of full one can be counted as more than 25 c.m. each. Suppose this value be nearly correct at small height we should have capacity of whole structure or roof $2500 \times 25 = 62500$ c.m. and at a height of 200 feet certainly not less than

$$\frac{100000 \text{ c.m.}}$$

On the basis of above estimate if I were to adopt 50000 feet squared I would have

$$\frac{1}{5 \times 10^5} = \frac{2\pi}{10^3} \sqrt{\frac{10^5}{9 \times 10^5}} L \text{ and } \left(\frac{3}{2\pi \times 59} \right)^2 = L = \frac{9}{10^5} \text{ being } 900000 \text{ c.m.}$$

1)

Sept. 3, 1901

555

General considerations relative to transmission of energy by conduction through Earth with my system

The problem in any given case is to displace a certain quantity of electricity per unit of time. This quantity should be the largest possible with the means at disposal. Here then is the first practical limit – the quantity given. Calling it Q we have $Q = Pc$. From the equation it follows that for a fixed value of Q , the greater c the smaller will be the potential P . This in itself imposes no limitation as to P , in fact it may be sometimes better to work with a small P and make c very large. But we must remember that the density imposes a limit. Now the density $D = \frac{Q}{S} = \frac{Pc}{S}$, s being the surface of the free terminal. Evidently then if D stands for the maximum practical density which it should be an object to attain within a reasonable limit, then P will be all the greater the greater $\frac{c}{S}$.* This means to say that to get high pressure c should be small. Logical conclusion is that sphere best to employ. It should be furthermore as high in the air as possible. The sphere has least metal, largest pressure or effect, the system is rigid. Following is useful to remember:

* i.e. the smaller $\frac{c}{S}$

$$D = \frac{Pc}{S} \text{ for insulated terminal and } d = \frac{pC}{S} \text{ for Earth.}$$

Now $S = 4\pi R^2 C = R$ hence:

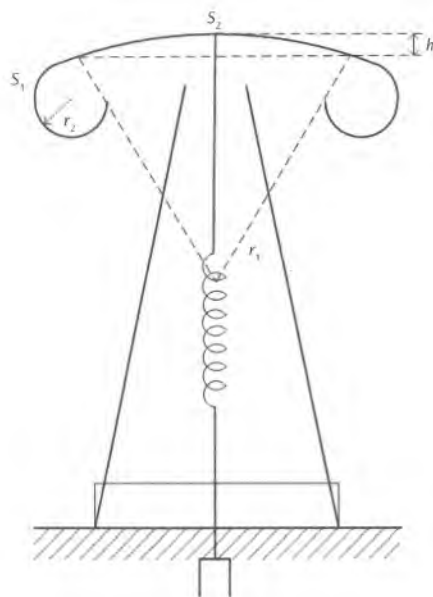
$$\frac{Sd}{C} = p = d \cdot 4\pi R \text{ now } pR = d \cdot 4\pi R^2 \text{ but } pR = Pc = Q.$$

Therefore $Q = dS$ and $Q = Ds$. From this follows

$$D : d = S : s$$

Sept. 8, 1901

Transmission of energy for purposes of "Welttelegraphie"





Assume roof as now proposed with plates of 1 meter curvature. The active area may be taken as equal to $s_1 + s_2$. Now $s_1 = 2\pi r_1 h$ and $s_2 = \pi r_2 u$, u being mean circumference of toroidal surface s_2 . As now planned

$u = 112$ feet, $r_2 = 6$ feet, $r_1 = 96$ feet, $h = 34$ feet. From this

$s_1 = 6.28 \times 96 \times 34 = 20500$ feet square approx.,

$s_2 = 3.14 \times 6 \times 112 = 2100$ " " " .

Surface active $s_1 + s_2 = 22600$ square feet about.

If we make half-spherical pieces about 1 meter curvature each would take the space of about 9 square feet, hence we would have $\frac{22600}{9} = 2500$ such half spheres. The capacity of one sphere of diameter as above would be at small height 100 cm. Of half the sphere it would be 50 cm but as a matter of fact we can not count on more than 25 cm each. Suppose this value be nearly correct at small height we should have capacity of total structure on roof $2500 \times 25 = 62500$ cm and at a height of 200 feet certainly not less than 100000 cm.

On the basis of above estimate if I were to adopt 50000 per second I would have

$$\frac{1}{5 \times 10^4} = \frac{2\pi}{10^3} \sqrt{\frac{10^5}{9 \times 10^5}} L \quad \text{and} \quad \left(\frac{3}{2\pi \times 50} \right)^2 = L = \frac{9}{10^5} \text{ Henry} = 90000 \text{ cm.}$$

Now with 50000 per sec. $\frac{\lambda}{2} = 1.86$ miles = 9820 feet approx.

Equatorial belt would be: $8000 \times 5280 \times \pi \times 9820$.

If we assume the roof to be in the form of a sphere of same capacity it would be of a radius = 1000 meters. The surface of this would be taking feet $3280 \times 3280 \times \pi \times 4$.

The ratio of the small to the large surface (equatorial belt) would be:

$$\frac{3280 \times 3280 \times \pi \times 4}{8000 \times 5280 \times \pi \times 9820} = \frac{328 \times 328}{20 \times 5280 \times 9820}.$$

This ratio would also be the ratio of the pressure on the roof to the impressed pressure on ground. Suppose we had on roof only 500 000 Volts we would have on equatorial zone:

$$\frac{328 \times 328 \times 500000}{528 \times 982 \times 2000} = \frac{328 \times 328 \times 500}{2 \times 528 \times 982} = 52 \text{ Volts nearly.}$$

This would be the impressed e.m.f. and could be easily raised to a 200 times higher value.

The current in transmitting terminal would be:

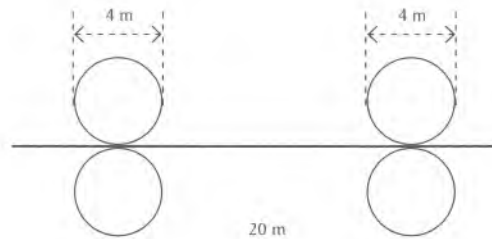
$$I = EC\omega = 500000 \times \frac{10^5}{9 \times 10^{11}} \cdot 50000 \times 6.28 = 17500 \text{ Amp.}$$

For the time of closure – certainly too great.

Sept. 18, 1901

Following results may be confidently expected with smaller tower 200 feet and terminal roof of cheap construction as last designed. The roof will comprise a single platform with spherical bodies of large curvature on rim. The construction of latter will be given in detail. The platform 20 meter diameter, 15 round surfaces on top and 15 on bottom as shown in sketch below. It is difficult to estimate in advance the capacity of the structure with precision but an approximate idea may be obtained.





The spherical bodies will be made of a capacity of 200 cm. This would give $30 \times 200 = 6000$ cm without taking elevation into consideration. But owing to proximity capacity will be much smaller. Estimates place the minimum value at not less than 1000 cm (elevation not considered). This means to say that of each spherical body only $\frac{1}{6}$ of the surface is fully utilized. Now surface of one spherical

body will be $\pi \times 400^2$. Calling σ density we would have on $\frac{1}{6}$ of surface $\frac{\pi \times 400^2}{6 \times 3 \times 10^8} \sigma$ Coul. of electricity.

We can safely make $\sigma = 10$ minimum. This would give on the whole structure $\frac{\pi \times 400^2 \times 10 \times 30}{6 \times 3 \times 10^8} =$ roughly

at least $\frac{8}{10^3}$ Coulombs. Now if we put capacity as 1000 cm we would have

$$\frac{8}{10^3} = \frac{1000}{9 \times 10^{11}} V \text{ and } V = \frac{9 \times 8 \times 10^{11}}{10^6} = 7,200,000 \text{ Volts.}$$

This estimate is surely small and we may take safely 10 000 000 Volts with 1000 cm capacity.

Considering simply Earth as ball and leaving out short waves we have since $cP = Cp$
 $V = P = 10^7$ Volts $c = 1000$ cm. $C =$ capacity of Earth $= 636 \times 9 \times 10^5$, $\frac{1000}{9 \times 10^{11}} P = \frac{636 \times 9 \times 10^5}{9 \times 10^{11}} p$. $p =$ roughly 16 Volts. This means variation $2p = 32$ Volts all over globe.

— —

Results to be expected on bases of preceding with waves of about 2 miles length.

The minimum effect will be on equatorial belt. Area of belt will be $\pi \times 8000 \times 5300$ square feet.

Effective area of roof terminal as assumed before $\frac{\pi}{6} \times 12^2 \times 30$ sq. feet. Since the voltages will be inversely as the areas we shall have:

$$\frac{\pi}{6} \times 12^2 \times 30 : 8000 \times 5300 \times \pi = x : 10^7$$

$$72 : 800 \times 5300 = x : 10^7$$

$$x = \frac{72 \times 10^7}{8 \times 53 \times 10^4} = \frac{72000}{424} = 170 \text{ Volts roughly,}$$

or total variation 340 Volt. From this at the average parallel circle or belt we may expect to get variation of 680 Volt! At a distance of pole such that diameter of belt would be say 100 miles we

would have density $\frac{8000}{100}$ times and therefore the voltage 80 times greater than at equatorial

belt. Hence we may get variation of $340 \times 80 = 27200$ Volts. Taking capacity of about 1000 cm we could collect apparent energy $\frac{1}{2} \cdot \frac{1000}{9 \times 10^{11}} \cdot 27^2 \times 10^6 = \frac{4}{10}$ Watt approx. And with say 100000 per sec

$\omega = 6 \times 10^5$ about we would get $6 \times 10^5 \times \frac{4}{10} = 640000$ Watts* apparent energy, but this is impossi-

* I.e. 240000 Watts.

ble as the circuit could not draw from Earth except within a limited radius from ground connection.

Real energy $\frac{\text{real on generator}}{\text{apparent on receiver}} \times 64 \times 10^4 = \frac{150 \times 750}{6666 \times 10^7} \times 640000 = \text{roughly } \frac{2}{100}$ Watts for 150 H.P. on generator.

Preceding results further considered

Data: Capacity of terminal 1000 cm.

Effective area = $\frac{\pi \times 12^2 \times 30}{6}$ square feet.

Volt $10^7 \omega = 6 \times 10^5$ (roughly), $\frac{\lambda}{2} = 1$ mile approx.

(This is only to get idea of effects at distance.)

Surface of equatorial belt $\pi \times 8000 \times 5300$ square feet

Taking at terminal roof of transmitter $\sigma = 10$ we have density on ground equatorial belt:

$$\sigma_1 = \frac{\pi \times 144 \times 30}{6 \times \pi \times 8000 \times 5300} \cdot 10 = \frac{72}{8000 \times 53}$$

With a similar roof terminal at receiving end we could get:

$$\frac{\pi \times 144 \times 30 \times 144 \times 6.5}{6} \times \frac{72}{8000 \times 53} \times \frac{1}{3 \times 10^9} \text{ Coulomb.}$$

With $\omega = 6 \times 10^5$ we have

$$\begin{aligned} &= \frac{\pi \times 3 \times 6.5 \times 144 \times 144 \times 72 \times 6 \times 10^5}{6 \times 8000 \times 53 \times 3 \times 10^9} = \\ &= \frac{52.22 \times 20736 \times 72}{8000 \times 10^4 \times 159} = \frac{7798 \times 10^4}{10^7 \times 1272} = \frac{7798}{1272 \times 10^3} = \frac{6}{10^3} \end{aligned}$$

This in amperes without resonating rise.

Roughly we shall have $I = \epsilon C \omega$

$$\frac{6}{10^3} = \epsilon \frac{1000}{9 \times 10^{11}} \cdot 6 \times 10^5 \quad \epsilon = 9 \text{ Volts.}$$

Energy would be: $\epsilon i = \frac{9 \times 6}{10^3} = \frac{54}{10^3}$ Watts.

Energy per cm square with 200 H.P. at generator would be roughly:

$$\begin{aligned} &\frac{54}{10^3 \times \pi \times 144 \times 30 \times 144 \times 6.5} \text{ Watts per 10000 square meter} \\ &\frac{10000 \times 10000 \times 54}{10^4 \times 3 \times \pi \times 144 \times 144 \times 6.5} = \frac{54 \times 10^4}{9.42 \times 6.5 \times 144 \times 144} = \frac{540}{21 \times 61} \\ &= \frac{540}{1280} = \frac{54}{128} = \text{Say } \frac{1}{2} \text{ Watt (This can not be true).} \end{aligned}$$

Comments and Explanations of New York Notes

Aleksandar Marinić



Capacity expressed in microfarads	Centimeters	Jar No.	Capacity expressed microfarads
0.0193	17,370	7	0.0209
0.0182	16,380	8	0.0190
0.0180	16,200	9	0.0185
0.0190	17,100	10	0.0200
0.0196	17,640	11	0.0245
0.0200	18,000	12	0.0191
0.1141	102,690	Total from measurement of individual jars.	0.1220
0.1158	104,220	Total from measurement of tank as a whole	0.1228

Capacity of Tanks I and II in Series

Capacity expressed microfarads	Centimeters
0.0581	
0.0506	

Remark: Among newly found notes which Tesla wrote after he was in Colorado Springs, there are three documents that are missing in the published book "Nikola Tesla: Colorado Springs Notes 1899-1900", Nolit, Belgrade, 1976. Here we give some short comments on these documents.

Colorado Springs

August 4, 1899

Between August 2 and 14, 1899, Tesla considered a number of receiver arrangements with sensitive devices and involving condenser method of magnifying effects including "self-exciting" process. Some of these arrangements are patented in^{84, 85}. Recently some more insight into this type of receiver can be found in a published paper⁸⁶. There is no note dated August 4, 1899 in the "Colorado Springs Notes 1899-1900". In the newly found note Tesla describes "*Sensitive receiver for detecting feeble disturbances*", and mentions that it is based on a principle briefly described "*on a previous occasion which formed the subject of experiments about two years ago*" (1897). Tesla's work on detecting feeble signals is often mentioned in his notes and patents but without detailed explanations we do not know how applicable they were.

Colorado Springs

Sept. 5, 1899

In the "Colorado Springs Notes 1899-1900" dated September 5, 1899 one can find circuit connections and explanation of "coil vibration" measuring technique. There Tesla explained the way he measured inductance of "freshly wound experimental coil" with wires № 18 and № 20. The coil that is mentioned in the new document is an old coil wound with wires № 18 and № 22, and it is not clear why Tesla excluded it from the Notes.

Colorado Springs

Sept. 7, 1899

There seems that the newly found note does not contain any new results – the table is written somewhat different but the data are the same.

After returning from Colorado Springs and before moving to a new laboratory in Long Island Tesla wrote again notes – not regularly as in Colorado Springs. So far, in the Archive of the Nikola Tesla Museum in Belgrade only six-days notes are found from 1900, and somewhat more in the first half of 1901. As the notes are mainly written on memorandums of the Waldorf – Astoria hotel in New York, he wrote them either in New York or in Long Island when he was visiting future site of his Wardenclyffe laboratory. In June 1902, Tesla moved his laboratory operations from his Houston Street laboratory to Wardenclyffe.

New York

June 2, 1900

Like in his "Colorado Springs Notes 1899-1900", at the beginning of his research there (see notes of June 2, 1899, June 3, 1899 and June 4, 1899), Tesla begins his new notes with a review of interesting topics. In connection with insulating of conductors affected by cooling Tesla obtained patent⁸⁷ and in connection with the diminution of resistance another patent⁸⁸. There is no evidence that he used cooling in order to reduce the coil resistance.

New York

July 23, 1900

Here Tesla considers excitation in his "system of transmission through the Earth". In his attempts to obtain good contact with the ground he tried a possibility to use a conductive ball placed in the ground and surrounded by a conducting enclosure. In this way he obtained neutral point away from the imperfect ground. It is interesting to know that similar requirement about the length of wire "from ground to top" appears in his patent "Art of transmitting electrical energy through natural media", applied May 16, 1900, renewed June 17, 1902 and issued as US patent № 787,412, dated April 18, 1905. In that patent he also stated "that the planet behaves like a perfectly smooth or polished conductor of inappreciable resistance with capacity and self induction uniformly distributed along the axis of symmetry of wave propagation and transmitting slow electrical oscillations without sensible distortion and attenuation".

The Waldorf Astoria

August 5, 1900

At this point it is not known why he considers heat transfer – obviously it is in connection with his list given on June 2, 1900 under headings: Heat supplied at rate computed; Cooling agents {gas, fluid liquid} and Special care when air is used. Some connections exist between considered questions and his patent "Method of insulating electrical conductors", applied June 15, 1900 and issued under US Pat. № 655,838, dated August 14, 1900.

New York

September 3, 1900 (dok.102)

These calculations are in connection with his interest for nature production of carbon dioxide and oxygen by the forest.

New York

November 24, 1900

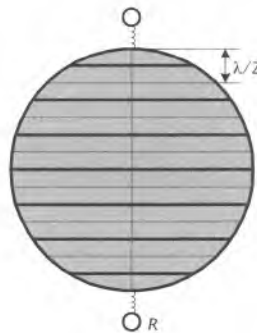
In order to get some indication as to the Earth capacitance and inductance Tesla considered Earth as a straight conductor of length 8000 miles and the mean diameter 4000 miles. This is a very crud model because the calculation of inductance is based on assumed straight conductor inductance and capacitance is calculated from the radius of the sphere in cm divided by 9×10^{11} to get it in farads (it is in fact obtained from the expression for the electrostatic capacitance of an isolated sphere in SI units: $C_{SI} = 4\pi\epsilon_0 R$, where R is radius of the sphere, and ϵ_0 is the free space permittivity). The period Tesla calculated from Thomson's formula $T = 2\pi\sqrt{LC}$, as if we have an LC resonant circuit!

There is also a numerical error in calculation of the Earth vibration – it is 10 times higher and consequently the wavelength is 10 times shorter.

New York,

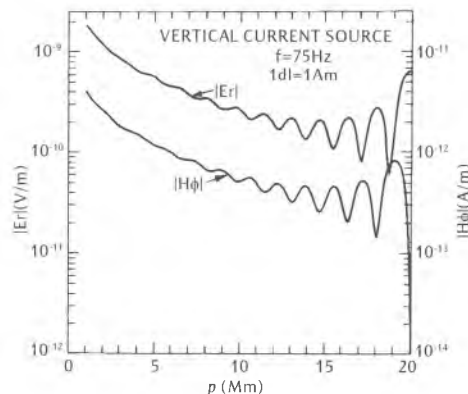
November 28, 1900 (dok.252)

Calculation performed is based on the electrostatic case, but with assumption that it can be applied as well for relatively low frequencies. Tesla assumes that if we have two spheres of surfaces S_1 and S_2 and charge them with $+q$ and $-q$, respectively, the ratio of sphere potentials is $\frac{p_1}{p_2} = \frac{S_2}{S_1}$. For isolated sphere its surface is proportional to the capacitance of the same so we can write $\left| \frac{p}{p} \right| = \frac{C}{c}$ (see picture)



Due to proximity effect this capacitance is changed and Tesla takes that in some way by saying that the isolated capacity is changing with the height! In his low frequency case he assumed that S_2 is the half-wavelength sector on the globe over which he assumes charge of the same polarity. The particular equator sector is cylindrical and its surface is given by $S_{2e} = \frac{\lambda}{2} \pi D$. The potential along this belt is, according to Tesla, $p_{2e} = \frac{2S_1}{\lambda \pi D} p_1$. As a next step he assumes that if resonance is used the voltage p_{2e} is multiplied by a factor Q . Energy per charge is assumed to be $W = \frac{1}{2} C_r (p_{2e} Q)^2$, where C_r is the capacitance of receiver. For one cycle of the source, received energy is $2W$ and the power received would be given by $P_r = 2Wf$.

Many objections as to the validity of Tesla's approach can be made, let we mention some: even the problem of two unequal size metallic spheres would require full correction for the proximity effect; expectations that the standing wave will be established are also very unlikely in the amount that would enable efficient electrical energy transmission; his model of transmission through the Earth axis is questionable etc.

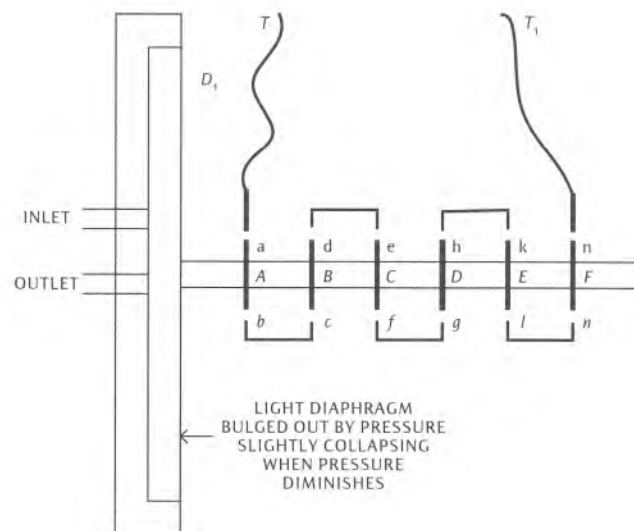


As an illustration, proving that Tesla had a premonition of unusual transmission phenomenon at very low frequencies, in the above graph we present the field distribution calculated over the Earth from a vertical line current (the source strength is $1dl = 1\text{Am}$) and the frequency 75 Hz.⁹³ This calculation is the principal field in the Earth-ionosphere waveguide radiated by a vertical electric current source. It is clear that a standing wave is detectable from about the equator region and it is most pronounced at the antipodal region.

New York

Nov. 28, 1900

In the "Colorado Springs Notes 1899-1900" on June 14, 1899 Tesla described similar arrangements "suitable for telephony at a distance without wires and for such purposes where it is necessary to effect control of a powerful apparatus by feeble impulses such as those produced by a human voice".



In this arrangement vibration of the diaphragm D_1 causes multiple arc disturbance of the current flow between T and T_1 which, in Tesla's opinion, is better than the similar control of a single arc. Controlling output power of a transmitter by air flow modulated by human voice acting on an arc Tesla tried to patent judging from the prepared diagrams found in the Archives of Nikola Tesla Museum in Belgrade and published in the "Colorado Springs Notes 1899-1900", Nolit, Belgrade, 1976.

Few months in 1901 Tesla continued to write notes preparing new equipment and further developing his theory of wireless energy transmission.

New York

January 24, 1901

Here we have insight into Tesla's approach to designing motor windings.

New York

January 29, 1901

This is continuation of notes from Nov. 24, 1900 regarding estimation of Earth's constants – capacitance and inductance. Now Tesla considers the Earth as a cylindrical conductor, assumes that the length of conductor is the same as the diameter of the Earth, and calculates radius of this conductor to have the same capacitance as the Earth sphere.

According to Jordan⁸⁹, if we equalize capacitance of a sphere of diameter D and capacitance of a cylindrical conductor of length D and radius r_1 , after simple calculation we obtain a nonlinear equation

$$x - 1 + a \sinh(x^{-1}) - \sqrt{1 + x^2} = 0,$$

where $x = \frac{r_1}{D}$. Solving the above equation numerically we get $x=0.382909$, and for $D=3957$ miles, we get $r_1 = 3030$ miles, not much different from 2910 miles obtained by Tesla.

On Nov. 24, 1900 Tesla calculated inductance by assuming mean Earth radius $D/2 = 4000$ miles! Then he obtained for inductance of Earth 1.63 H. With the new equivalent cylinder he obtained 2.4 H.

It should be borne in mind that Tesla had been developing his "wireless transmission of energy" on many questionable assumptions, relaying too much on intuition, and on some measurements on July 3, 1899 when he was convinced that he was observing stationary waves caused by a storm followed by a numerous electrical discharges.

New York

February 2, 1901

Modern theory of lossless transmission line, which Tesla considers in this case, is based on the solution of two equations

$$U_l = U_r \cos \beta l + j Z_c I_r \sin \beta l$$

$$I_l = I_r \cos \beta l + j \frac{U_r}{Z_c} \sin \beta l$$

where U_r and I_r are terminating voltage and current at the end of line, and U_l and I_l are the voltage and current at the distance l from the end of line.

The line phase constant is $\beta = \omega \sqrt{L_u C_u} = \omega \frac{\sqrt{\epsilon_r}}{3 \cdot 10^8}$, and the characteristic impedance $Z_c = \sqrt{\frac{L_u}{C_u}} = \frac{138}{\sqrt{\epsilon_r}} \log \frac{R}{r}$. In the latter two expressions L_u and C_u are inductance and capacitance per unit length of line, respectively. If the line is open $I_r = 0$, then the open line voltage is $U_r = U_l / \cos \beta l$ and the input impedance is $Z_l = j Z_c \tan \beta l$. In Tesla's notation, the condition for "transmitting energy under conditions exceptionally favorable" is achieved under the condition $p = \frac{1}{\sqrt{LC}} = \frac{1}{l \sqrt{L_u C_u}}$. At this particu-

lar frequency the line phase constant is $\beta_{\omega=p} = \frac{1}{l}$, and $U_l = U_i / \cos(\beta_{\omega=p} l)$. In SI system of unit, distance at which this condition is fulfilled is obtained from equation

$$l_p = \frac{3 \cdot 10^8}{p \cdot \sqrt{\epsilon_r}} = \frac{2 \cdot 10^8}{6 \cdot 10^4} = 333 \text{ m.}$$

Tesla did not consider transmission line equations although they were known long time (William Thomson 1855, Gustav Kirchoff, 1857, Oliver Heaviside, Michael Pupin, and others). He followed his own guesses, probably thinking that at a particular frequency when a series inductance and shunt capacitance (which is equivalent circuit of a section of the line) counteract each other we have a favorable condition for transmission.

New York

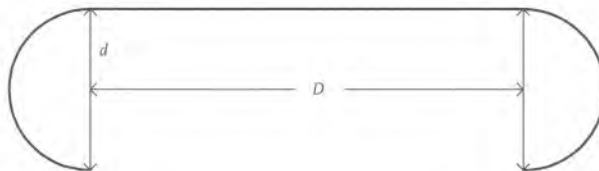
February 14, 1901

Considering operation of his coupled resonant circuits Tesla tried to investigate the effect of different resonant frequency of the two coupled circuits. The reason for this is probably his observance that there are intermittent sparks from the secondary terminal which reduce primary inductance from L_p to $L_p(1-k^2)$, if secondary is short circuited and $k = M^2/(L_p L_s)$ is the coupling coefficient. There are many variables in coupled circuit system: frequencies of the free vibration of primary and secondary coils, coupling between coils and losses. Besides circuit parameters the spark that discharges primary capacitance considerably affects the operation of the system. In the "Colorado Springs Notes 1899-1900" in Appendix I, some results of the coupled circuit theory are presented. If coupling is relatively strong, very fast transmission of energy from the primary circuit is possible: in the case of equal frequencies of the two circuits, this time is determined by a simple relation $\Delta\tau = \frac{1}{2(f_a - f_b)}$, where $f_a = \frac{f_0}{\sqrt{1-k}}$; $f_b = \frac{f_0}{\sqrt{1+k}}$. Obviously, the stronger coupling the energy transfer is faster, but in the period of $\Delta\tau$ the system generate two frequencies and if the spark is after $\Delta\tau$ extinguished, the secondary continue to oscillate at its own resonant frequency.

New York

March 1, 1901

Here Tesla specifies new capacitive terminal – flat metal roof without sharp edges. Neglecting some small numerical error he calculates inductance that would with the roof capacitance be in series resonance at two frequencies: 50 kHz and 125 Hz. In the first case inductance is no problem but in the second case he has to consider using iron core inductance.



Calculation of the received power at a point along the equatorial belt is the same as already explained on Nov.28, 1900 notes. As he assumes belt 1 mile wide, according to his theory the belt should be $\lambda/2$ or $186000/(2 \cdot 50000) = 1.86$ miles, his calculations are for $f=50$ kHz, and magnifying factor 10000. He did not calculate received signal under similar conditions for frequency of 125 Hz. The

latter received signal would be much smaller because of greater belt size (400 times), smaller magnification factor (0.0016 times) and lower frequency (400 times). We estimate that the signal would be $4 \cdot 10^{-14}$ times smaller!

New York

March 24, 1901

These are investigations into some of his "preferred arrangements" for tuning primary and secondary. In the first arrangement he uses a variable part of the secondary inductance as a primary circuit inductance. In arrangements a) and b) he fixes the coupling point and adjusts primary reactance by adding a variable inductance or variable capacitance, respectively. The last arrangement is the most complex – it has three resonant circuits and he expects better results to be attainable with it.

New York

April 1, 1901

These are consideration based on old notes. Here he applies his theory again as on Nov. 28, 1900 and March 1, 1901 but extends it to find power at the pole. Again he selects frequency 50 kHz, and a magnifying factor 10000, initial charge one million volts. For the first time he derives power that could be received at the pole – according to his model the received power is 53 W! He considers this result "Great". He did not explain how he got the density at the pole 4000/3 times greater.

The same day he discusses arrangements when the apparatus is used alternatively as transmitter and receiver. He uses the same high frequency transformer (Tesla coil) both in transmitting and receiving arrangements. The differences between the two arrangements are in the position of the break. When an ordinary arc break is used it can stay in the receiver disposition because it is open circuit for the small receiving signal.

New York

April 15, 1901

This is further development of consideration regarding elevated conducting terminal. Starting from parallel plate disk condenser, and neglecting the edge effect he calculate capacitance from classical formula $C = \epsilon_r \frac{S}{4\pi b}$ in CGS system, where the disk area is $S = \pi r^2$, b is the disks separation and ϵ_r is relative permittivity of the dielectric between plates. All calculations he made in order to clarify some design point in making elevated terminal.

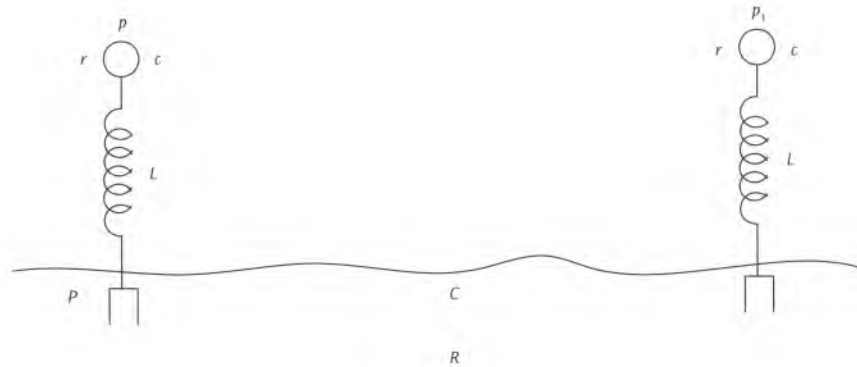
Under the same date, a note was found in another folder that deals with transmitter design. In it Tesla gives calculation of inductance coil to be placed in series with the output of the main transformer in order to prevent short-circuiting by the break.

New York

April 28, 1901

Here is continuation of consideration of terminal capacitance vs. actual size of terminal and available charge. With smaller capacitance and increased pressure he expect to have the same electrical movement in view of the relation $p'C' = p''C''$, but when considering the change of energy he founds

that their ratio is $W'/W'' = C''/C'$ which means that decrease in capacitance require proportional increase of energy supplied for the same electrical movement.



Next, he considers signaling through the Earth by his model of low frequency propagation based on initial relation of equal charge supplied to an elevated terminal and the earth region. In each period he assumes that the total variation of charge is $2q$ (neglecting time variation and taking rather "step" functional periodic signal). Here he gives some more details about his theory by stating that the electric densities on the sphere and on Earth surface are q/s and Q/S , s and S being the surfaces of the sphere and of Earth, respectively. The total variation of density during one whole cycle on surface of Earth he found to be $2q/S$, and states that this requires slow variation of charge of the order 4 c/s .

To realize a source of frequency 4 c/s he assumes to use a two-pole machine rotating $240/60=4\text{ rev/sec}$. From energy per cycle of this machine (not Watts but Joules) and assumed terminal capacitance he finds pressure (voltage on the sphere) 288000 Volts while it should be 10 times higher.

Consequently, all other calculations relaying on this value have to be changed.

For improving sensitivity of the receiver here Tesla mentions his patent on "integrate and damp receiver"⁹⁰. In spite of the numerical error Tesla concludes that he expects "That signals can be transmitted to any distance by my system is therefore perfectly sure."

Next Tesla increased frequency to 60 c/s . This frequency corresponds to that of the generator ordered for new laboratory. Belt of alternating high and low density in this case is 2665000 miles . Compared with the previous case, the operating frequency for the same other conditions will be greater as the ratio of the whole earth surface and the surface of the equatorial belt in the second case which is $2D/\lambda = 4.76 \times \pi$. Here Tesla assumes higher magnification factor of $2\pi \cdot 60$, and increased energy 15^2 times. Overall improvements he estimates to be considerable. Tesla was aware that his approach to transmission "without radiation" relies on the static charge redistribution and this can work only for very low frequency.

If higher frequency is used, Tesla's theory predicts considerably increase of the received signal. In his model improvements are due to increasing frequency leading to a smaller belt area which results in higher charge density, and higher performance factor due to resonance.

Just to see what would happen if much higher frequency of 100 kHz is used Tesla calculated improvements and discusses modulation rate if digital signals are used.

Following idea of signaling Tesla described a receiver with a wire heated by the incoming signal and by its elongation affects a microphone contact in an induction coil primary.

New York

May 1, 1901

Now Tesla assumes power of five million horse power and calculates the voltage to which the capacitance of an elevated terminal must be charged at the rate 40 per sec. From this voltage and the ratio of elevated terminal capacitance and capacitance of Earth he finds potential on Earth per half cycle from the equation $p_A C_A = p_E C_E$, where index A refers to elevated terminal and E to Earth (p potential and C capacitance). At such high power of 3750 MW, received power with magnification by resonance of 10 is 8000 W, so only approximately $2 \cdot 10^{-6}$ part of the transmitted power is received. However, Tesla seems to be impressed by this result and concludes that even transmission to other planet is possible!

New York

May 4, 1901

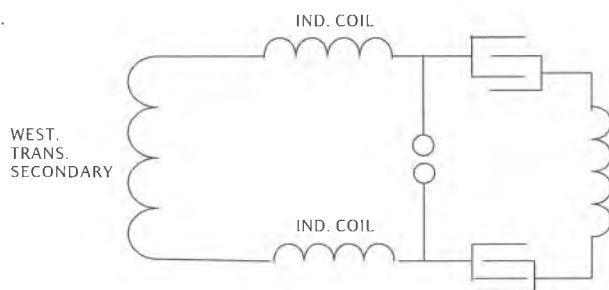
A short note about readjustment of laboratory apparatus mentions three coils: one central in the laboratory and another for "physiological effects" and third for lighting tubes in hand.

Note explains observation of unexpected coupling behavior of two loops: one placed in the laboratory and other movable with small incandescent lamp as indicator of received power.

New York

May 10, 1901

In this note we can see the whole design procedure of induction coils placed between the main Westinghouse transformer and Tesla's spark oscillator. These induction coils prevent short-circuiting of the main transformer when sparks initiate discharging of the condensers through the primary of high frequency transformer.



The coils are selected for known frequency of makes and breaks and condensers in the oscillator circuit. The condensers are charged periodically and selection of inductance L is such that we have a series resonance in the charging series resonant circuit of inductance $2L$ and capacitance $C/2$.

New York

May 19, 1901

Several pages of the notes under this date describe various things. The first page deals with the *grounding* of the transmitter secondary. The lower terminal of the secondary can be connected directly to the grounded plate or through a capacitance. In view of relatively low frequency with which he operated his apparatus, he had poor ground connection even with few square meters metal plate buried in the ground. The reason for different behavior of the three cases may be unequal loading of the secondary circuit.

Insulation of terminal is another problem to Tesla. Here he sketched two possible solutions: first in which metallic roof has to be isolated and feeding is from multiple secondary; with the second arrangement metallic supports of the roof terminal are acceptable and they form a kind of loop coupled with a number of primary loops as shown in picture.

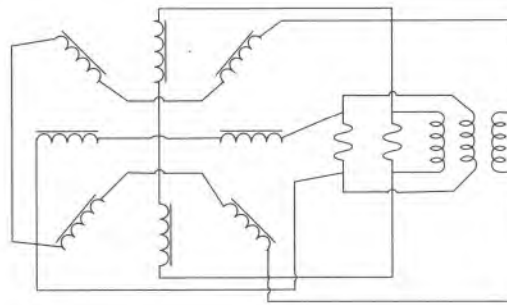
Determination of capacities is based on resonance method – it is continuation of measuring technique practiced from October 21, 1899 and for several other days. Here he determines the voltage distribution along the coil L and from the size of spark locates a neutral point m by minimum spark.



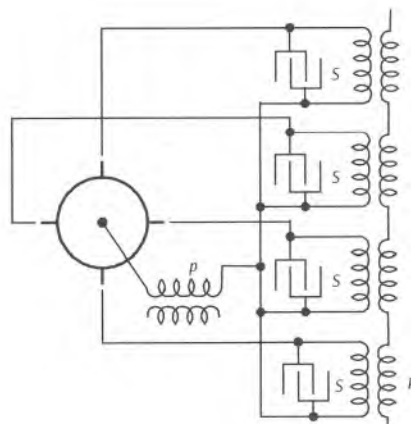
Under a subtitle "From old note" he considers two different questions:

Message transmission to a planet Mars by making rhythmical variation of the potential of Earth through a powerful oscillator. It seems that in this case he does not consider radiation but again electrostatic influence at a huge distance between the Earth and Mars!

Motor with great torque and no dead point is interesting in that it operates from a two-phase alternating current system but with suitable transformers it is converted into a four phase motor. To Tesla, this is better than a three phase motor and the similar technique he thinks it can be applied to three-phase motors.



New York
May 24, 1901

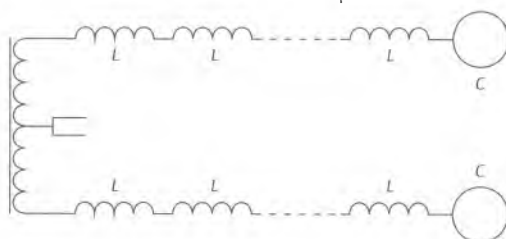


Here Tesla again reconsiders arrangements with several condensers charged in sequence into the system shown in Figure. With this arrangement he can charge four condensers from one mains transformer and reduce noise coming from the sparks. He claims that in this way the loss is reduced as through each spark gap only $\frac{1}{4}$ of the currents passes as compared to full current when only one spark gap is used.

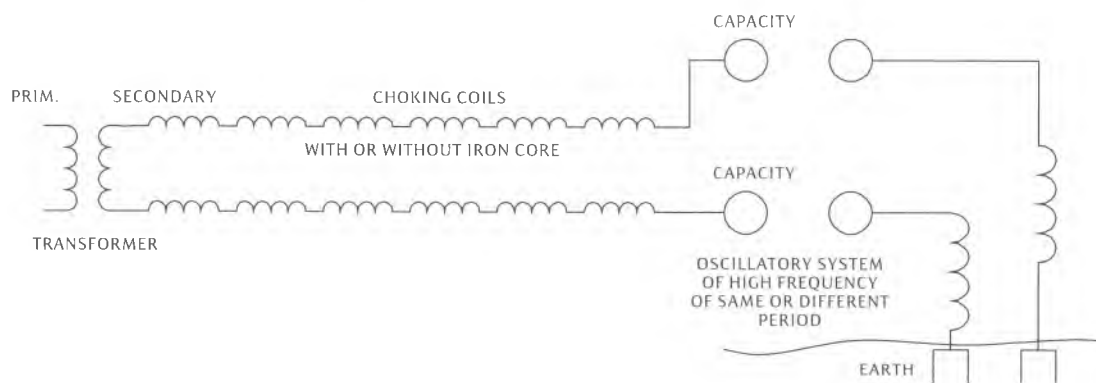
New York

May 26, 1901

On May 10, 1901 Tesla investigated the use of two simple circuits consisting of the series inductances (chock coils) and large capacities on each terminal end. The driving source of these circuits is high tension secondary of the mains transformer with center tap.



Tesla assumes that if the central point of the mains transformer is connected to ground, there will be two series resonant circuits which have to satisfy equation $\omega_r = 1/\sqrt{nLC}$ in order to get maximum voltage on capacity C . For work with 130 Hz source he estimates that 444 coils are needed and that is not feasible. He then assumes 10 times higher terminal capacitance and finer wire in making chock coils and for the same frequency he reduces number of coils to about 11, or 6 coils in each leg. Voltage on the capacitance he calculates from $e \frac{\omega_r L_r}{R_r}$ as if the internal resistance of the mains transformer is zero. His conclusion was that this can work and be used in telegraphy without wires. He provides a scheme



where initial high voltage is used to drive another two circuits which may be of the same or different period and produce current in the Earth as "in the two systems in accordance with my method".

New York

May 29, 1901

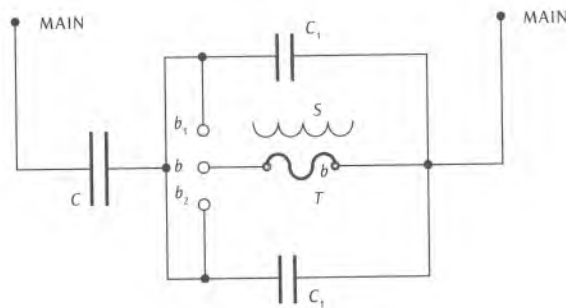
Notes from October 1900 are not among these notes. According to present note he considered modulation format needed in message transmission. So far Tesla experimented with a number of ways of controlling oscillators, of which the first two are interpreted in a modern way as a) Intensity modula-

tion, b) and c) Frequency or phase modulation. The case d) has one fixed and other variable frequency and is a combination of intensity and angle modulation. It seems that e) to h) belong to receiver design as well as m) and n). Generally, in order to have strong effect on the carrier by applying a small power of message signal, Tesla looked for special techniques to achieve this.

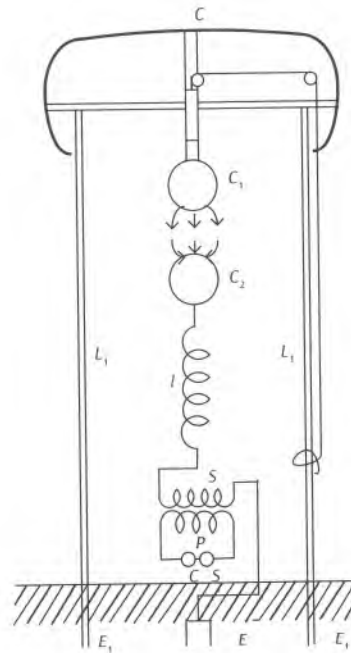
At the time when in the world only pulse modulation had been developing, Tesla already had experience with amplitude, angle and pulse modulation techniques.

Following "old note" Tesla presented "an excellent arrangement in signaling without wires suitable for both transmitter and receiver". In that arrangement he expected to use two circuits tightly coupled and when one circuit produce frequency slightly different from the other, the great intensity variation of transmitted signal is achieved. If one signal is $u_1(t) = U \cos(\omega t)$ and the other with slightly different frequency but the same amplitude $u_2(t) = U \cos((\omega + 2\delta\omega)t)$, the signal emitted would be $u_{1+2}(t) = 2 \cdot U \cdot \cos(\delta\omega \cdot t) \cos[(\omega + \delta\omega)t]$.

Hence the signal is amplitude modulated and even for small $\delta\omega/\omega$ the effect of frequency shift is significant.



Another "old notes of experiments" analyze oscillatory arrangements with a series condenser C that prevents short-circuit effect of the break. With no connections bb_1 or bb_2 both condensers C_1 are



charged through C . When bb_1 is shorted by arc or break, condenser C_1 discharges into primary T and generates high frequency current. Similarly when in the next moment bb_2 is shorted by arc or break

lower condenser C_2 discharges into the same primary T . Tesla experimented with similar arrangements by taking 24 condensers!

Still another "From old notes" deal with a terminal supported on conducting supports. Having in mind difficulties if an isolated terminal C is required, Tesla tries to avoid it by using another resonant circuit composed of $c_1CL_1L_1$. It is not stated whether the driving coil P is also a part of primary resonant circuit. Brief calculation of resonance for the considered roof supporting structure was made for 100 kHz signal. As this is much higher frequency than needed, Tesla concludes that there is not enough inductance to achieve low frequency resonance of $c_1CL_1L_1$ system.

New York

May 30, 1901

In summarizing some previous calculation Tesla again uses unit *watt* for energy instead of *joule*. When multiplied by number of charges per second then it is the power. If energy per charge would be 1000 joules, and when considering 5000 charges per second in 1 second we would require energy of 5000000 joules/second, i.e. the required power is 5 MW! Considering charging and discharging he reduces this to 2.5 MW (he call Watt rate).

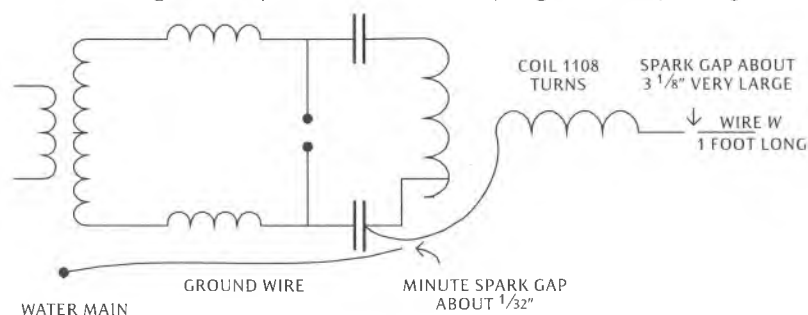
Further reduction of required power Tesla expect because of pulsed signaling which do not require continuous operation of the transmitter.

The same day Tesla changed the subject and discussed transmission through a wire print, pictures or images. Here he explains how a picture can be split into elements, each element projected on a miniature selenium cell and electrical signals from the cells be transmitted by his multi-frequency combination signals – all through a single wire without interference. At the receiving side the signals are separated and projected in the same order as on the transmitter side. This would be a kind of parallel transmission similar to the transmission of picture signals from the eye through a bundle of nerves to the brain. Tesla's system does not require a bundle of wires because he proposes multiple frequency signals that can be transmitted through a single wire without interference.

New York

June 1, 1901

The operating frequency of Tesla coil spark-gap oscillator is dependant on all circuit parameters. Any addition of wire or change in the position of coils, coupling or even sparking will change the frequency.



In this experiment Tesla tried to examine the effect of ground wire connected to water main on resonant circuit composed of two series capacitances and regulating coil (variable inductance). In this way it is difficult to exactly determine the effects but it confirms expectations that any addition of wire would change the operating frequency. By measuring the spark intensity Tesla determined the resonance and the difference is shown in different number of regulating coil.

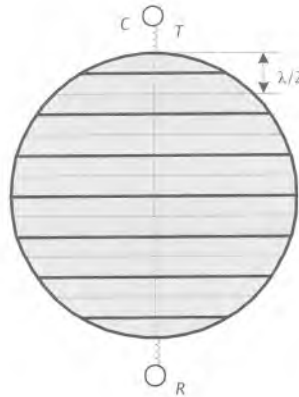
With the same arrangement but instead of coil with 1108 turns he connected large secondary spiral coil with one primary turn connected to a small lamp. The resonance measurements by lamp illumination Tesla prefer to determining resonance by the largest spark between the upper terminal of spiral coil and a piece of wire. With the same apparatus Tesla measured "extra coil" inductance.

Repeating measurements of spiral coil Tesla reduced inductance of the regulating coil until he obtained resonance with approximately $\frac{3}{4}\lambda$ length of wire in the spiral coil.

New York

June 2, 1901

The notes written on this date have 14 pages. Tesla's model of low frequency current distribution through the Earth from a transmitter of capacitance C is shown graphically with a standing wave: dashed lines are "zero" current, full thick lines are "peak" current lines. Standing waves and the conditions under which they can be formed are explained in his patent "Art of transmitting Electrical Energy through the natural mediums", applied May 16, 1900, renewed June 17, 1902 and issued on April 18, 1905⁴².



As already explained (see for example note of November 28, 1900) he assumes that standing waves can be established on the earth as graphically shown in the above Figure. Transmitter antenna is charging alternatively zone with positive and negative charge and this creates a progressive wave which after the reflection from the antipode returns and produces standing wave.

For the moment Tesla assumes no loss and uniform distribution of charge over the zones!

This time he selected high frequency (100 kHz) as the earlier investigations with frequencies 4 Hz (see note April 28, 1901) or 60 Hz did not give optimistic results. The reason why higher frequency would give better results can be seen from the following equation which we derived on the basis of his hypothesis (Tesla calls it "theory") for the power received at the equatorial zone:

$$P_{RE} = C_R f_T \left(\frac{2S_T}{\lambda_T \pi D} p_T Q_R \right)^2$$

where S_T is the area of elevated transmitting terminal, p_T is potential on S_T , C_R is the capacitance of receiving antenna, Q_T is the improvement factor of receiving system, D is diameter of the Earth, f_T is the operating frequency and λ_T is the wavelength. If we take $Q_R = 2\pi f_T \frac{L_R}{R_R}$, from the above equation we find that the received power is proportional to f_T^4 , providing all the parameters are the same and independent of frequency.

In his notes Tesla raised a question of charge and power transfer by his system. If all charge is available at some zone, he asked whether by increasing capacitance of antenna we can collect all the

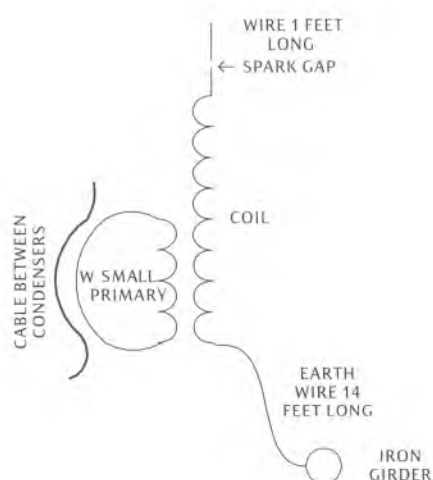
charge from the zone. Then if we collect all the charge will it enable full power transfer? To collect more charge Tesla assumed to use many wires at the polar cup arranged in concentric circles.

As some kind of conclusion at the end Tesla stated that his "estimates show that high frequency currents are imperative to employ".

New York

June 4, 1901

After a long discussion in connection with "Transmission of electrical energy by conduction through Earth" on June 2, 1901, Tesla returned to experiments and measurements of inductances. First he measured self-resonance of a spiral coil and then inductances of several new coils.



The measuring technique and equipments are as used on June 1, 1901. This time, instead of direct connection of the coil to a terminal of condenser (see June 1, 1901), loose coupling is made using a primary (of spiral coil) or auxiliary few turns small primary (for other coils) connected to wire w coupled to a cable connecting the two condensers in the oscillator circuit as shown in the figure.

New York

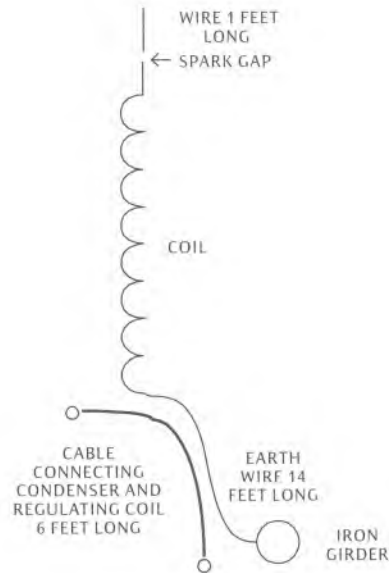
June 5, 1901

Measurements of the self-resonance of coils (or "freely vibrating circuit") are delicate in view of influence of coupling with the oscillator. As the coupling must be small, Tesla modified the previous circuit (see June 4, 1901) so that the induced signal comes from the oscillator through the ground cable 14 feet long which was passing near the 6 feet long cable connecting two condensers in the oscillator. In this way he obtained enough coupling which again, like many times before, he judges as acceptable by the size of the spark at resonance between the upper terminal of coil and a piece of wire 1 foot long.

In the presence of another coil – whether it was connected to the common ground wire or not – he detected influence and found, as could be expected, that this is a disturbing factor.

Throughout the "Colorado Springs Notes 1899-1900", in calculating inductance of coils wound on long cylinder, Tesla used formula valid for infinitely long cylindrical coil. On October 26, 1899 in "Comments and Remarks" we presented Russel's⁵⁷ formula with correcting terms for shorter coils. Tesla also did not take into account that his formula does not take into account frequency dependence of measured inductance caused by self-capacitance of coil. In fact, he was fully aware of the coil capaci-

tance and measured it from the knowledge of the free vibration of coil and calculated inductance, or measured inductance at low frequency.



New York

June 8, 1901

It is not quite clear why Tesla made so many measurements under various conditions with four coils described on June 4, 1901. He recorded 22 experiments investigating intensity of excitation by observing a small lamp connected to an auxiliary few turns primary wound around tested coils.

The same day he again returned to calculations of transmission of energy through Earth at frequency of 60 Hz. He was in the process of construction of an alternating current dynamo operating at 60 Hz. He compared results with those obtained on June 2, 1901 for a similar arrangement but operating at 100 kHz. First he calculates the voltage to which the capacitance C of transmitter has to be charged $2 \cdot f_G$ times per second so that all energy from the generator is to be used:

$$P = \sqrt{\frac{P_G}{C f_G}}$$

where P_G is the available power and f_G is the operating frequency of the generator. Subsequent calculation has not been supported by full explanation because we know that there are differences in parameters for the two considered frequencies.

New York

June 9, 1901

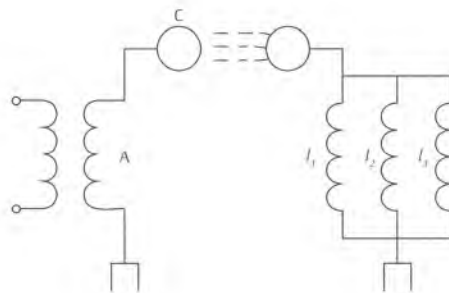
This is again continuation of measurements with the apparatus used on June 4 and 5, 1901.

New York
June 11, 1901

Here Tesla collects data about various earlier made coils and six new coils. He presents results of measurements in the number of turns of regulating coil and number of jars in the capacity bank.

New York
June 13, 1901

It is known that Tesla had two patents on System of Signaling and Method of Signaling³⁸, in which he used transmitter generating two frequencies aimed at reducing interference and improving individualization (protection) of transmitted messages. Here he refers to some experiments in which he



worked with seven coils excited through spark discharge into a complex transmitter. Such system would generate complex signal. Still better he considers separating resonant coils and feeding then successively one after the other.

New York
June 14, 1901

Preparing for future experiments Tesla continued to measure inductances of auxiliary loop coil and coils made for ascertaining vibration of large laboratory apparatus.

New York
June 15, 1901

Here Tesla experimented with a coil suspended in air and then grounded on one side. The first resonance of a coil free on both ends is almost twice that when the same coil is grounded on one side. By careful measurements Tesla found that grounded coil have resonance somewhat higher than expected and he explains that it was due to the internal coil capacity which has different role in the two coil arrangements. He recommends grounded coil as a better combination, less affected by external influences.

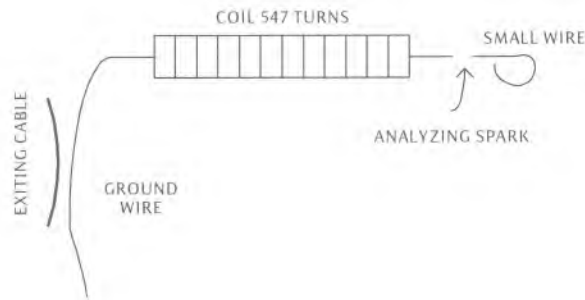
New York
June 24, 1901

This note is interesting as it shows how Tesla operated vacuum tubes – probably for illumination. He designed series coils – current limiter – which are necessary for this type of tubes when connected to the mains.

New York

June 27, 1901

Using the same arrangements as on June 5, 1901 Tesla made measurements of new coils. First he measured one coil and then a series connection of two identical coils. With two coils inductance was



doubled but because resonant frequency is halved the quality factor of two coils in series is halved! The analyzing spark, which is indication of excitation level, dropped in the second measurements and Tesla explained why this happens.

New York

July 6, 1901

Here Tesla investigated mutual action of several identical coils connected in various ways. In the first experiment he connected to the ground two coils with perpendicular axes to minimize coupling. One coil is alone and the other had two additional coils connected in series, but again with perpendicular axes to minimize coupling. This is the test of single coil resonance vs. three coils in resonance. The resonances were indicated by small lamps as indicated on the figures. The second experiment is with one coil alone and two coils in series in the second branch. This is the test of single coil resonance vs. two coils in resonance.

New York

July 7, 1901

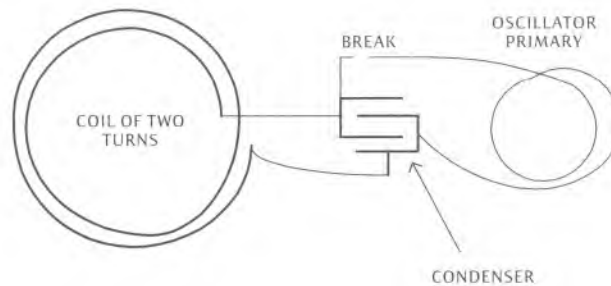
Here Tesla considers construction of a circuit for controlling model boat built more than three years ago. In the boat he put resonant circuit made of three turns coil and a condenser. The operating frequency seems to be about 120 kHz. He wanted to control the boat in the laboratory by induction from a large cable.

New York

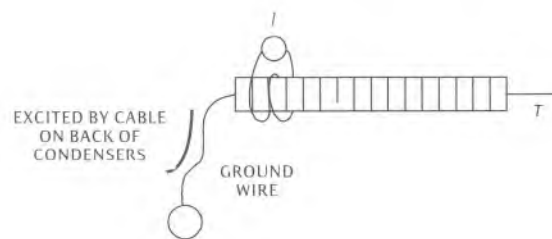
July 8, 1901

Frequency of small oscillator used for running vacuum tubes in laboratory operates around 24 kHz. To test its frequency, signal from an external oscillator is coupled through "coil of two turns", and "break" is bridged by a wire. Frequency of the external oscillator is varied until resonance of small oscillator is detected by a small lamp included in a secondary winding of few turns.

With the arrangements as on June 27, 1901 Tesla again measured free vibration of coil with 547 turns by observing maximum lighting of the lamp *l*. In numerous experiments with added capacitances on the terminal T, for constant excitation by the cable on the back of condensers, he found that the lamp *l* lighted always stronger with no capacitance attached.



Examining excitation through the ground wire Tesla inserted small air-core transformer with the lamp I_1 and observed variation of its lighting under various conditions. It is interesting that he measured illumination when connecting several identical coils in parallel as this is in connection with



his multi-feed transmitter (see Notes May 19, 1901). He found that current through the ground wire increase in proportion to the number of parallel connected identical coils. The arrangement with several coils in parallel is mentioned earlier in connection with "distributed" receivers for collecting more electrical charge (see Notes June2, 1901).

New York

July 9, 1901

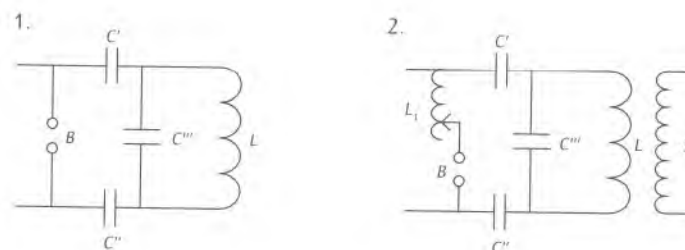
With the same basic arrangement Tesla continued measurements as on the previous day but in the ground wire he introduced a parallel plate condenser, then that condenser and a coil. It seems that Tesla made these experiments in order to learn more about various combinations of multiple coils connections.

New York

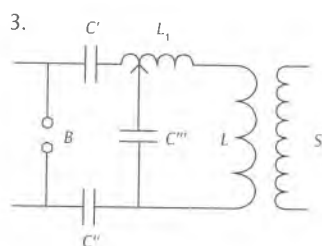
July 13, 1901

It is not clear why Tesla suspected that more energy is consumed on left side of condensers than on the right side *"when one side includes spark gap and the other has none"*. In the typical spark oscillator there is no capacitor C in the primary of "Tesla coil". The question wheatear the currents passing through points x and y are identical is difficult to resolve particularly in view of technique and method used to measure these currents. Without final conclusion Tesla put a note that "A delicate test is to be applied".

Continuing some earlier work ("From old notes") Tesla developed several circuits with adding a condenser C''' in his standard "Tesla coil" arrangement. With the circuit 1)



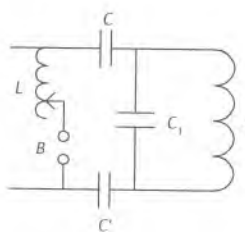
only condenser is added. In the circuit 2) a variable inductance is added in series with



the break, while in 3) similar inductance is added in series with $C'L_1L$. Since Tesla did not give any calculation here, his explanations of circuits operation are basically reduced to requirement that all resonant circuits be tuned to the same frequency. In the case 2) the three circuits seems to be: $C'L_1C''$, LC'' and secondary S . He does not say anything about coupling between L and S .

New York

July 15, 1901

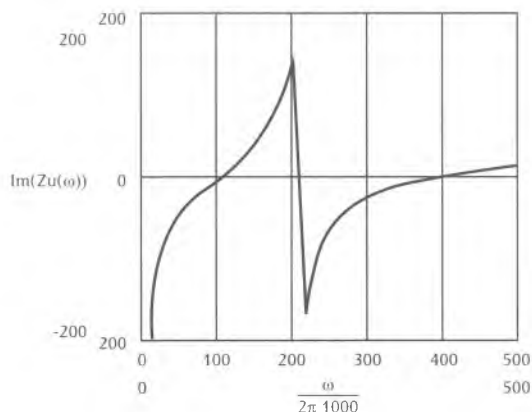


This is arrangement similar to 2) shown on July 13, 1901 but this time with different letters describing components and without secondary S . The two resonant circuits $C'BLC$ and C_1I he select with the same resonance so that we have $C_1I = L\frac{C}{2} = \frac{1}{\omega_r^2}$, since he assumes $C'=C$. With parameters that he selected and calculated in his notes, the resonant frequency was 207.9 kHz, not far from his estimation 200000 p.s. The impedance of the system with reference to spark-gap B is

$$Z_u(\omega) = R + j\left(\omega L - \frac{2}{\omega C}\right) + \frac{r + j\omega I}{1 - \omega^2 I C_1 + j r \omega C_1}$$

where we have taken that inductance L have resistance R and inductance I have resistance r .

Imaginary part of impedance $Z_u(\omega)$ has two zeroes and one pole close to calculated resonant frequency, and the frequency where Tesla expected that this system works. Full analysis would require solution of differential equations with initial conditions.



In various circuits Tesla often used relatively long connecting wires and in order to have “more accurate” results he included in calculations capacitances of wires when they are vertical or horizontal at known height above the ground. These considerations are in connection with designing of the future plant at Long Island.

New York

July 20, 1901

This circuit has the same elements as the circuit given on July 15, 1901, but here one condenser is placed in series with the inductance L . This inductance is made by two turn's cable wound on a square frame.

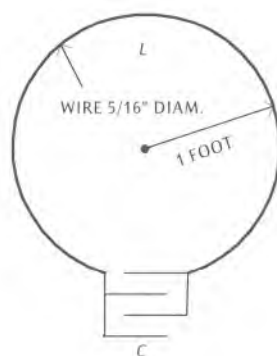
The same test circuit he used to measure coil intended for exciting large vacuum tubes and a large spiral coil.

The same day he returned to “old notes” and the stationary waves in connection with light houses, navigation, direction finding, distance etc. These stationary waves he proposes to obtain from two transmitters at various location and of definite frequency. It is interesting that he thinks that distance can be measured by determining the signal level! He thinks that even height can be estimated from standing waves.

Although in an elementary stage of idea development, this shows how Tesla's mind traced future navigation system to be used both at land, sea and in air.

New York

July 22, 1901



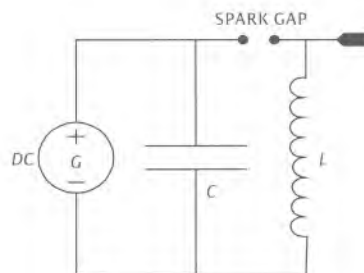
This is continuation of measurements of coils including reactance of the connecting wires with standard resonance method. The instrument for determining vibration of high frequency oscillators – called now the wave meter – Tesla made with condenser and a loop of 2 feet diameter.

This “wave meter” is similar to the one that was first used by Hertz in his famous experiments with electromagnetic waves, with the difference that C was at the same time a variable capacitance and a miniature spark gap for determining the moment of LC circuit resonance.

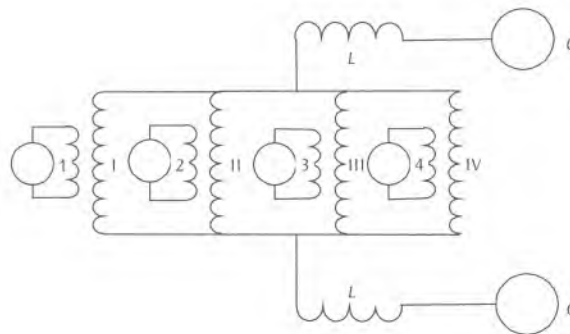
New York

July 30, 1901

Again starting “From old notes” Tesla continued investigations of high frequency oscillator in order to eliminate disturbing effects in wireless telephony caused by arcs or makes and breaks. In addition to enabling high frequency generation, arcs or makes and breaks induce unwanted audible modulation, much more with alternating current sources than with the direct current sources. He experimented with several arrangements considerable improved over the old ones. In addition to using high voltage direct currents source he required that the free vibration of LC system (see scheme 1) in July 30, 1901 Notes, or figure below) is in resonance with “makes and breaks”.



In another set of experiments Tesla combined several circuits with simple LC circuits as shown on the previous figure. It seems that all these experiments are directed towards producing highest power using parallel connection of smaller arrangements.



Another “From old notes” deals with some ideas in connection with wireless telegraphy. It is in connection with discussion of multi-driving system which can produce complex signals and which can be detected in multi-action receiver. Such signals, Tesla said, can be used for direct transmission of printed messages – the technique known today as “teleprinting”.

New York

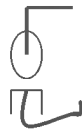
August 3, 1901

Here Tesla considers again his model of wireless energy transmission and possible effects on antenna structure. His calculation of available transmitter energy is correct but that energy must be taken away in some way, either by radiation or by dissipation in the ground or environment. As his antennas are small compared to the wavelength, radiation resistance is very small, hence radiation is negligible (that is what Tesla wanted!); ground resistance is another element where power can be dissipated. In Tesla's model he assumes that instead of radiation there will be a current wave carrying the energy away from the capacitive transmitter. Modern science does not recognize such waves without electromagnetic wave presence, recognize existence of standing waves around the antipode region if extremely low frequency radiation is used and accept the Earth resonance phenomena. However, all these do not look promising that even with the use of extremely high voltages and short "umbrella" antennas transmission of "large amount of energy" is possible⁹¹.

New York

August 19, 1901

This is one day when Tesla used some old notes and left his imagination work freely! Jumping from



theme to theme, some of them connected with break device with drops of water (see figure), other with the "use of singing flame in connection with telephone for magnifying voice". The latter is most likely in connection with the work of Duddell⁹² which was published in 1901.

New York

August 26, 1901

This is consideration in connection with elevated capacity which must stand high voltage and because of that it has to be made with high curvature radius surfaces. In order to estimate capacity of this roof he calculated surface as composed of calotte and curved tore. Guessing elevated roof capacitance of $C=20000$ cm (or 22222 pF), and assuming to operate at 100 kHz, or 50 kHz he calculated required series inductance with which the roof capacitance would be in resonance. With assumed charge of the condenser C to voltage V , n times per second he calculated energy per second, in fact power, from

$$P = \frac{1}{2} C V^2 \cdot n$$

With assumed $V=40000$ volts, $n=240$ per sec, and $C=250$ nF, (this is not the capacitance of the roof calculated above) $P=48$ kW or 64 H.P.

New York

August 28, 1901

In the note relative to wireless transmission of energy through Earth Tesla again repeated his conviction that all energy of transmitter, if the radiation is negligible, can be recovered at the Earth surface. He calculates energy per area, per second, from equation: $\frac{P_T}{S_E}$, assuming here that all the energy is uniformly distributed over the entire Earth surface. At this moment he does not speak about "zones" and distribution of charge if frequency is taken into account. Another curious calculation is the number of receiver of selected size that would "consume" all energy from equation $\frac{P_T}{S_E} S_R$, where S_R is the receiving area. By assuming that all the energy per second (P_T) can be delivered in much shorter time than second, he talks, in fact, about peak power in the shorter than the second interval.

New York

September 3, 1901

In general consideration relative to wireless transmission of energy, unusual to his previous approaches, Tesla presents his formulae in general terms. The final formula about the ratio of charge densities has been formulated and used earlier.

New York

September 8, 1901

For "World telegraphy" antenna system here Tesla gives a set of data needed for the construction of the structure. Top capacitance of the antenna (roof in Tesla's notation) he selected with rounded shapes (calotte and toroidal surface) as he expected to apply high voltages to it. After calculating capacitance he calculates inductance for selected operating frequency.

Other steps in calculations are repetition of the previous considerations and finally he takes into account the magnification factor and finishes up with the transmitter feeding current of enormous value.

New York

September 18, 1901

Tesla considered design of several towers discussed before, and this time he is presenting a smaller tower of cheap construction. After selecting construction he calculates its capacitance. Here he uses σ for the charge density (he calls it only "density"), multiply it by the surface and obtain charge – expressing here for the first time in Coulombs! Then from

$$\text{energy} = \text{capacitance} \cdot \text{voltage}$$

he calculated voltage to which this condenser would be charged. Again using equation of equal charge on the capacitance c and on the Earth (considered to be a ball of capacitance C) he calculates potential on the earth as $p = \frac{c}{C} P$, again not considering frequency! When frequency is taken into account he assumes wavelength to be λ , and calculates voltage across the equatorial belt of area $\pi D \lambda / 2$.

With overall results he is not satisfied and at the end he concludes that "This can not be true."

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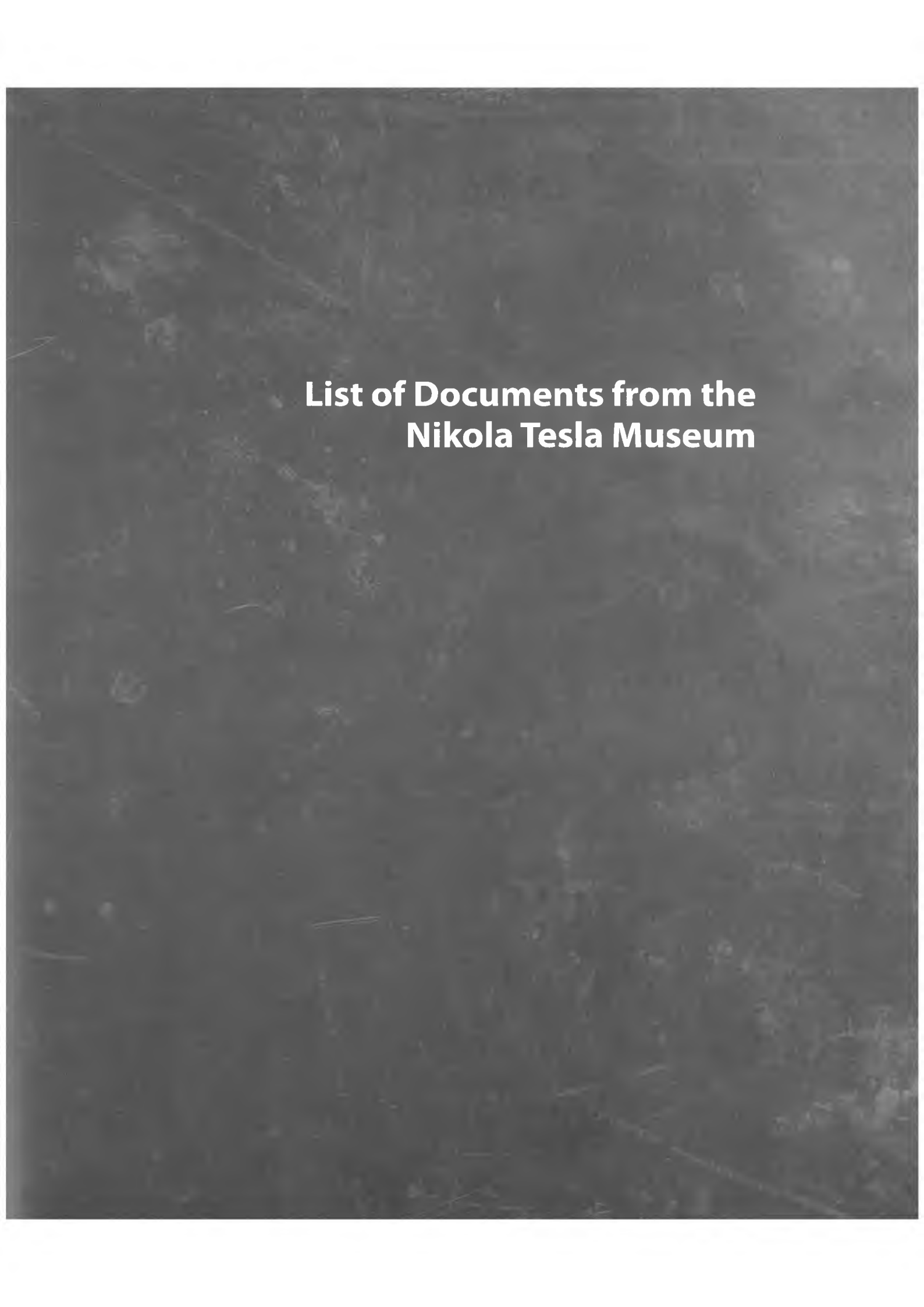


$$1.6 \text{ P}^2 = \frac{10^6}{10^4} = 20^2$$

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