The streams of Lenard and Roentgen and Novel Apparatus for their production

April 6, 1897

Lecture by Nikola Tesla, before the New York Academy of Sciences

Part 1

Improved apparatus for the production of powerful electric vibrations.

Novel frequency measurement methods

Part 1

Addition

Part 2

The hurtful actions of Lenard and Roentgen tubes

Part 3

The source of Roentgen Rays, the Practical construction and safe operation of Lenard tubes.

PART 1

IMPROVED APPARATUS FOR THE PRODUCTION OF POWERFUL ELECTRICAL VIBRATIONS; NOVEL HIGH FREQUENCY MEASUREMENT METHODS.

Ladies & Gentlemen:

You will still remember vividly, no doubt, the excitement which a year ago was caused by the announcement of the discoveries of Professor Roentgen. Suddenly, without any preparation, Roentgen surprised the world with two wonderful results. He showed us how to take a photographic impression of an object invisible to the eye and, what seemed more extraordinary, he enabled us, by the help of his luminous screen—now known as the fluoroscope—to see, with our own eyes, the outlines of the object. We are living in an age of exceptional intellectual activity, and important advances are often recorded, but these were almost of the order of the telescope and microscope and such discoveries come no more than once or twice in a century. Scarcely can any one of us hope to again witness in his lifetime an event of so widespread a scientific and popular interest. The desire to see things which seem forever hidden from sight is more or less strongly developed in every human being,through all degrees of this sentiment, from the idle curiosity of the unenlightened to the absorbing desire for knowledge of the highly refined, and this in itself was sufficient to engage universal attention; but, apart from this, these discoveries brought promise of relief to numberless sufferers and stirred all over the world the fibers of humanity. It is hardly necessary for me to tell you that the fever took hold of me also, but mine was a singular, grave case, and I had not recovered from its effects to this day. I hope you will pardon here a slight digression which I have a strong reason to make.

At the close of 1894, realizing the necessity of recovery from a straining task, on which I have been laboring for a number of years and which still commands my energies, it occurred to me to investigate the actinic action of phosphorescent bodies. The subject did not appear to have been studied, and I began the work at once, securing later, at the suggestion of some friends connected with the *Century Magazine,* the assistance of Messrs. Tonnelé & Company, artists' photographers, of this city, then doing work for this magazine. In these experiments, I employed an improved apparatus for the production of powerful electrical vibrations as well as one of my high frequency alternators of old design. A great variety of Crookes tubes, single-electrode globes, and vacuum bulbs without external electrodes were experimented upon. A surprising fact was soon brought to light; namely, that the actinic power of the Crookes bulbs varied greatly and that some, which emitted a comparatively strong luminosity, hardly showed an effect, while others, of much smaller light-giving power, produced strong impressions. I wish to state here, in order to be clear, that my efforts were directed toward investigating such actions of true phosphorescent light, as furnished from bulbs without appreciable emission of heat, and not so much those of incandescent vacuum tubes, although some photographs were likewise taken with these. As both the artists and myself were busy on other matters, the plates in their ordinary holders were frequently put in some corner of the laboratory until a suitable opportunity for carrying on the experiments was found. During these investigations many plates gave a result, while many others failed, and on some of these both Mr. Alley, who then assisted me, and myself noted unaccountable marks and defects. Mr. Alley particularly found it extraordinary, that, in spite of his care, many plates proved defective and unsuccessful. The taking of these photographic impressions by means of Crookes bulbs brought freshly to my mind the experiments of Lenard, some features of which, particularly the action on a sensitive plate, had fascinated me from the start, and I resolved to go over the ground covered by him with assistance and improved appliances. Just as my attention was arrested by this feature, my laboratory with almost everything it contained was destroyed; and the few months following passed in intense activity which made me temporarily forget my projects. I had hardly finished the work of reconstruction and resumed the course of my ideas when the news of Roentgen's achievement reached me. Instantly the truth flashed upon my mind. I hurried to repeat his incompletely reported experiments, and there I beheld the wonder myself. Then—too late—I realized that my guiding spirit had again prompted me and that I had failed to comprehend his mysterious signs.

The statement of these facts might have been misinterpreted at the time of Professor Roentgen's announcement, and I have kept silent, although I was unable to overcome entirely my feeling in the introductory lines of my first of a series of articles I wrote on this subject in the columns of the *Electrical Review*. Presently, however, I have no fear of a misunderstanding of my works, and I am recording my painful but stimulating experience solely to make some of those, who have lightly written about the history of this new art, more justly appreciate this new departure. I was quite well acquainted with the results of Lenard and naturally often thought of his beautiful and promising experiments, and yet the possibility of the plates being marked and spoiled by some action of the bulbs never presented itself to my mind. While some might see in this only an argument for my own shortsightedness, others, more kindly disposed towards me, will with myself, consider it rather a demonstration of Goethe's great words, which I will not repeat in the text, but which say that, what Nature does not want to reveal to one's mind, one cannot force it from her with screws and levers.

But while I have failed to see what others in my place might have perceived, it was always since my conviction, which is now firmer than ever, that I have not been forsaken by the kind spirit who then communed with me, but that, on the contrary, he has further guided me and guided me right in the comprehension of the nature of these marvelous manifestations. Perhaps, in bringing to your attention some new facts which I have since discovered in addition to those already announced, I may induce, at least some of you, to interpret these phenomena as I do. For fear, though, that I might miss my chief object this evening, I must ask your kind indulgence to dwell in a few works on the novel appliances which are exhibited here for your inspection. When I trace their origin, I find it clearly in my early recognition of the fact that an economical method of producing electrical vibrations of very high frequency was the key for the solution of a number of most important problems in science and industry. Insignificant as these machines may seem to you, they are nevertheless the result of labors extending through a number of years, and I can truthfully say that many times the difficulties which I have encountered in my endeavors to perfect them have appeared to me so great as to almost deprive me of the courage to continue the work. When the experimenter has to spend several years of patient effort only to recognize that a mere microscopical cavity or air bubble in the essential parts of this apparatus is fatal to the attainment of the result sought for by him; when he has to find that his machine does not perform well because a wire he uses is a quarter of an inch too long or too short; when he notes that now a part of his apparatus when in action will grow colder in an apparently inexplicable way, and next that the same part will get overheated, though to all appearance the conditions are unchanged; when he makes puzzling observations at every step and ordinary instruments and methods of measurement are not available, then his progress is necessarily slow and his energies are severely taxed. Finally, I am glad to say, I have triumphed over at least the chief obstacles, and nothing of any serious consequence stands now in the way of obtaining electrical oscillations of frequencies up to a few millions a second from ordinary supply circuits with simple and fairly economical appliances. What this means I need not discuss. It will be duly judged by those who have kept in touch with the development in this and allied fields. These machines you see are only a few of the types I have developed, and as they stand here they are chiefly intended to replace the ordinary induction coil in its numerous uses.

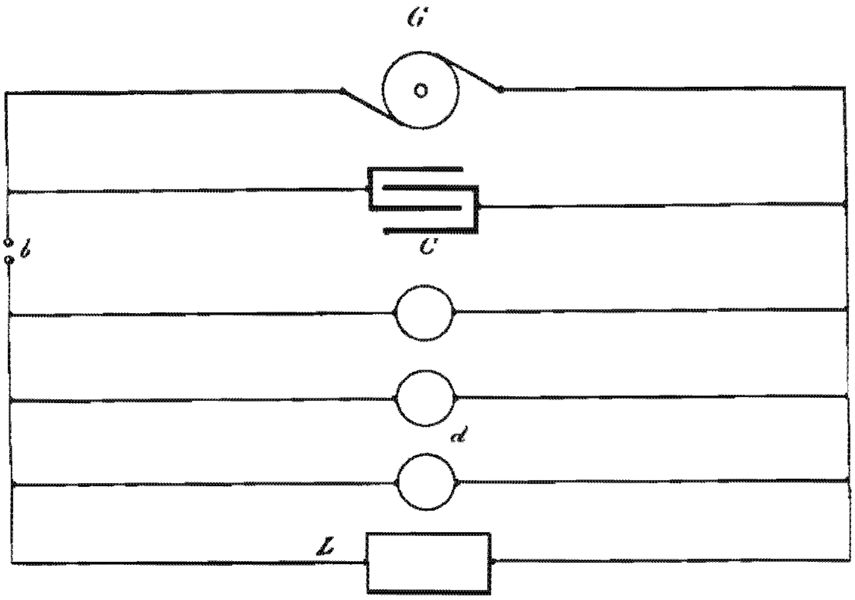


Fig. 1.—Method of transformation of electrical energy by oscillatory condenser discharges.

As to the broad principle, these transformers or electrical oscillators, as they might be most properly called, it is simple enough and has been advanced by me some five or six years ago. A condenser is charged from a suitable source and is then in any convenient way discharged through a circuit containing, as it does here, the primary of the transformer. The first diagram, Fig. 1, illustrates a generator *G*, a condenser *C*, and for charging and discharging the latter any kind of device *b* adapted to produce an intermittent break in the dielectric. The circuit *L* containing the high or low tension devices *d* through which the condenser discharges being properly adjusted, extremely rapid electrical vibrations which, so far we know are unattainable by any other means, result; and these set up, by inductive action in any neighboring circuits, similar vibrations which give rise to many curious phenomena. Having familiarized myself with these at the time when some laws governing them were not quite well understood, I have retained certain conceptions which I have then formed and which, though primitive, might stand even now in the light of our present advanced knowledge.

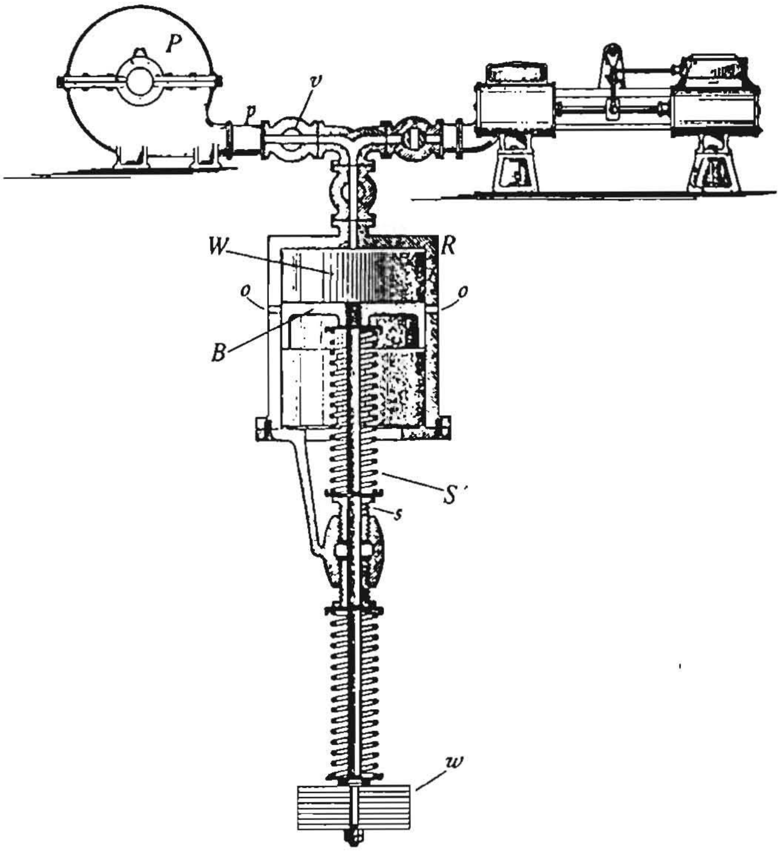


Fig. 2.—Mechanical analogy of electrical oscillator.

I have likened a condenser to a reservoir *R* into which by means of a pump *P* an incompressible fluid as water *W* is supplied through a feed pipe *p*, as illustrated in the second diagram, Fig 2, the fluid representing electricity, the pump the generator and the feed pipe the connecting wire. The reservoir has a movable bottom, held up by a spring *S*, and opens the ports *oo* when the fluid in the vessel has reached a certain height and the pressure has become sufficient to overcome the elastic force of the spring. To complete the model, adjustable weights *w*, a screw *s* for allowing the tension of the spring, and a valve *v* for regulating the flow of the fluid are provided. With the giving away of the bottom, the fluid in the reservoir acquires velocity and consequently momentum, which results in an increased pressure against the bottom causing the latter to open wider, and more of the fluid rushes out than the feed pipe can supply, whereupon the spring reasserts itself, closing again the ports, and the same process is repeated in more or less rapid succession. This opening and closing of the bottom may be likened to the making and breaking of the conducting path, the frictional resistance in this mechanical system to the ohmic resistance and, obviously, the inertia of the moving masses to the self-induction of the electric circuit. Now it is evident that, in order to keep in action the mechanism without the employment of auxiliary means, the average rate of supply through the pipe must be inferior to the average rate of discharge through the bottom; for, if it be otherwise, the ports will simply remain open and no vibration will take place. The more nearly the average rate of supply equals the average rate of discharge, the quicker will the bottom open and close; and it is furthermore clear from a consideration of simple mechanical principles that, if the fluid be supplied so fast through the feed pipe that the bottom vibrates as it would of its own accord, then the amplitude of the vibration will be the largest, the pressure against the bottom the strongest, and the greatest amount of fluid will be passed through the ports. All these considerations hold good for the electric circuit, and in experiments with high frequency machines, in which these effects were purposely magnified with the view of rendering their observation more easy, I have found that that condition is fulfilled when the capacity, self-induction, and frequency of vibration bear a certain relation, which observation I have since utilized in the adjustment of inductive circuits. You will note that this condition governing the rate of supply and discharge, most important in practice, especially when no positively acting mechanical means are employed for effecting the rupture of the dielectric, is a distinct one and should not be confounded with the condition determining the oscillatory character of the discharge investigated long ago by Lord Kelvin.

The next step in the evolution of the principle and its adaptation to practical uses was to associate with the system illustrated in Fig. 1 a self-induction coil *L*, as shown in diagram Fig. 3, which modified the action in many now well

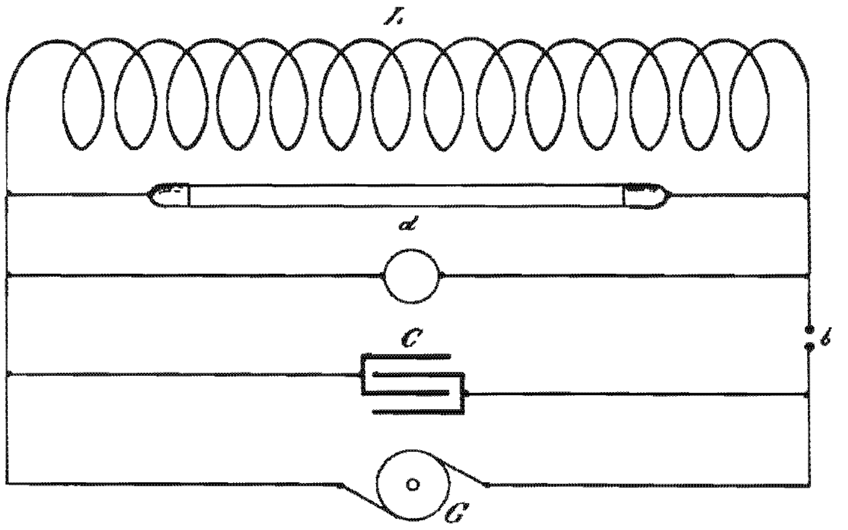


Fig. 3.—System illustrated in figure 1 with self-induction coil.

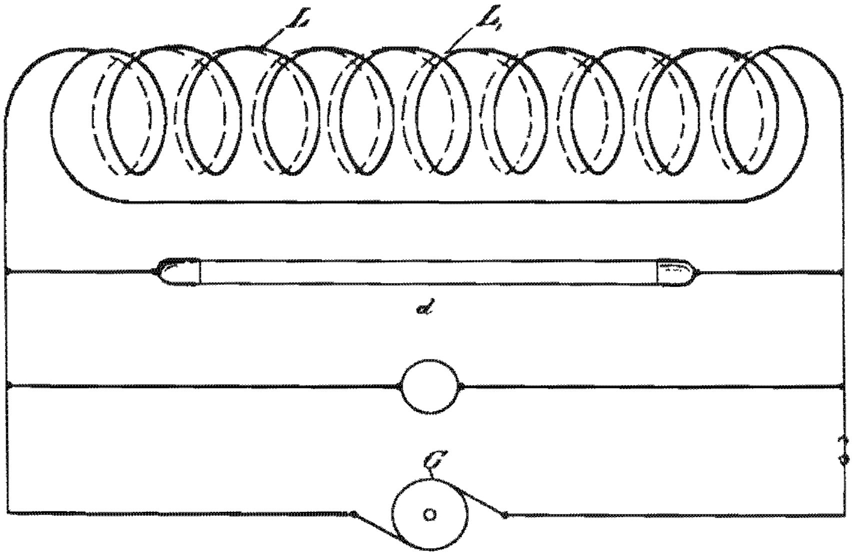


Fig. 4.—Coil wound to secure greatly increased capacity.

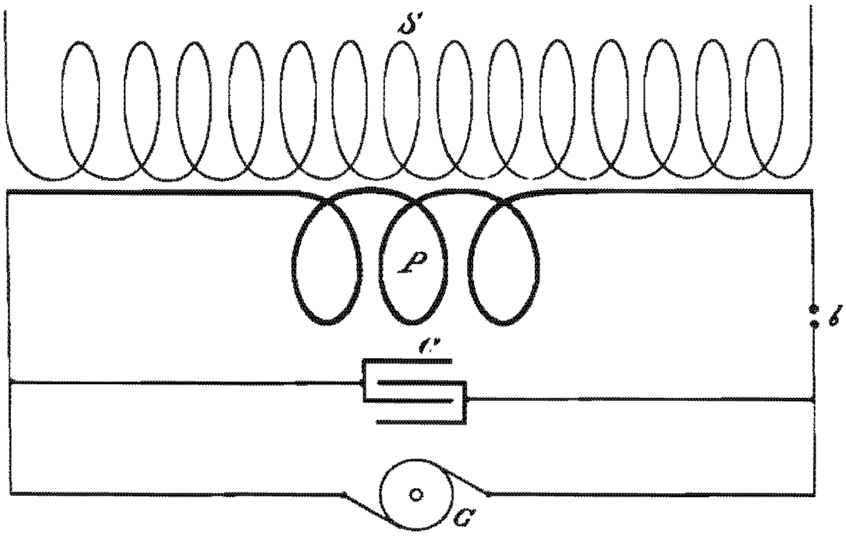


Fig. 5.—Associating a secondary coil with a primary circuit coil.

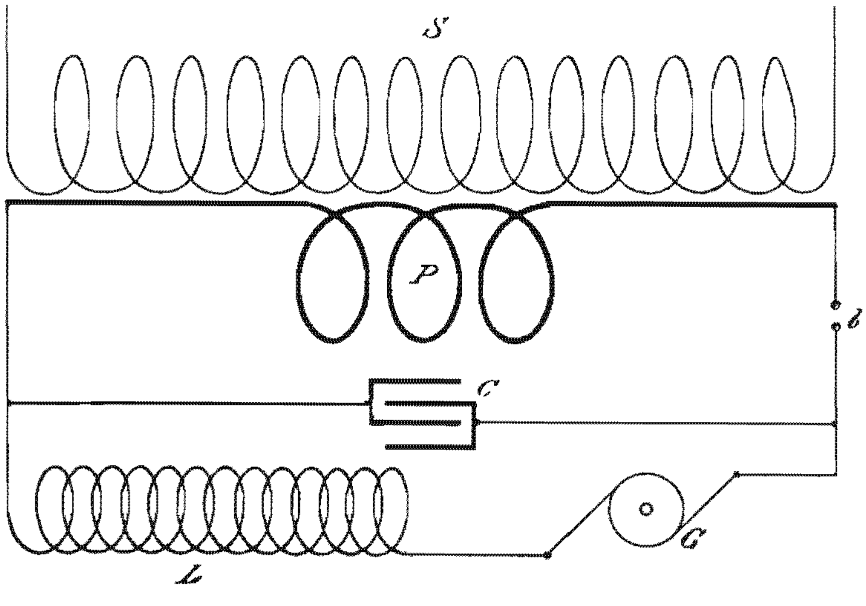


Fig. 6.—System adopted for existing municipal circuits.

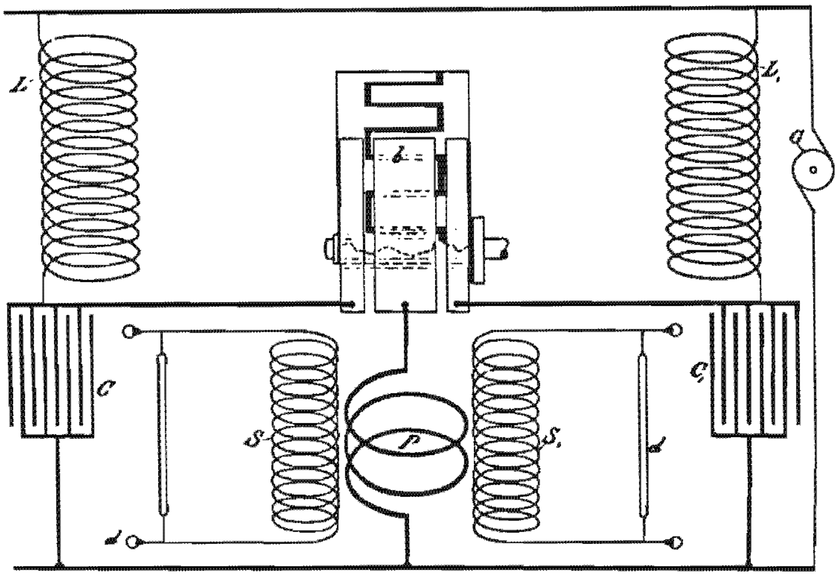


Fig. 7.—Circuit controller allowing condensers to discharge alternately and successively.

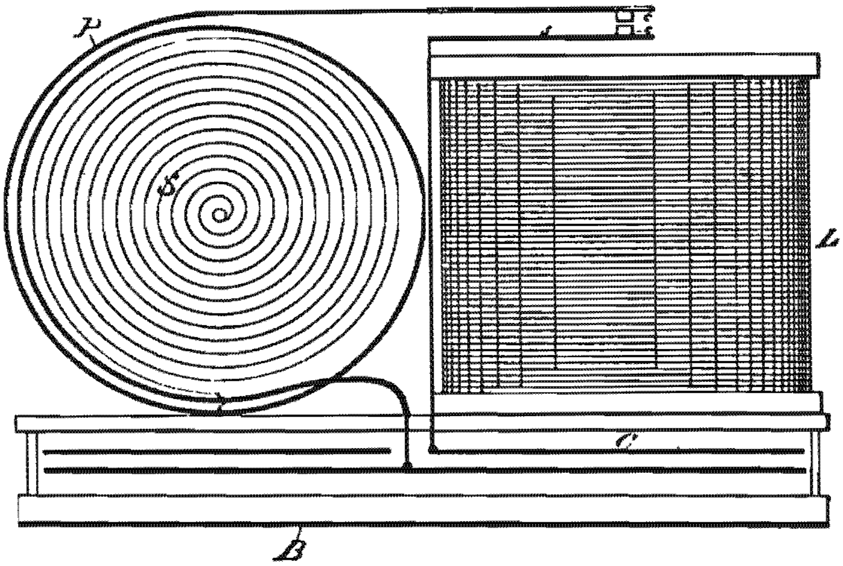


Fig. 8.—Arrangement of parts and circuits of a small oscillator.

understood ways. In a simplified form of this arrangement the condenser, as a distinctive part of the system, was done away with, the necessary capacity being given to the coil itself, and for this purpose the turns of the latter were wound as illustrated in Fig. 4 so as to allow the storage of the proper and generally the largest possible amount of energy. Then I associated a secondary coil *S* with the primary circuit *P*, as shown in Fig. 5, this enabling the obtaining of any tension required. After this, the arrangement in diagram Fig 6. was adopted as best suitable for the existing municipal circuits. Again, the self-explanatory diagram Fig 7. typically illustrates a further improved disposition as used in some of these machines with two or more circuits. A modification of this plan with one continuous contact common to the two circuits, and independent interrupters for each of these, allows easy adjustment of the phase of the currents through the primary, which is of practical advantage in some uses of the apparatus. Finally, in diagram Fig. 8 is shown the exact arrangement of the parts and circuits of one of these small oscillators with a break similar to that usually employed in connection with induction coils. Although the majority of the preceding arrangements have been described by me before, I thought it necessary to dwell on them here in order to present clearly and comprehensively the subject.

A specific result of value in the operation of Roentgen bulbs is obtainable by the use of two circuits linked as shown in Fig. 7, or otherwise, or entirely independent with two separate primaries. Namely, in the usual commercial bulbs the vacuum gets higher when the current is passed through the primary in a certain direction and is lowered when the direction of the current is reversed. This is a direct consequence of some conditions which, as a rule, are present in the operation of the usual apparatus; that is, the asymmetry of the opposite current impulses, the unequal size, configuration or temperature of the two electrodes, or like causes which tend to render unequal the dissipation of the energy from both the electrodes. It should be stated, though, that beyond a certain point, when the electrodes begin to act as entirely independent, the vacuum continues to increase no matter which way the current is passed through the primary. In the scheme illustrated in Fig. 7, or in its

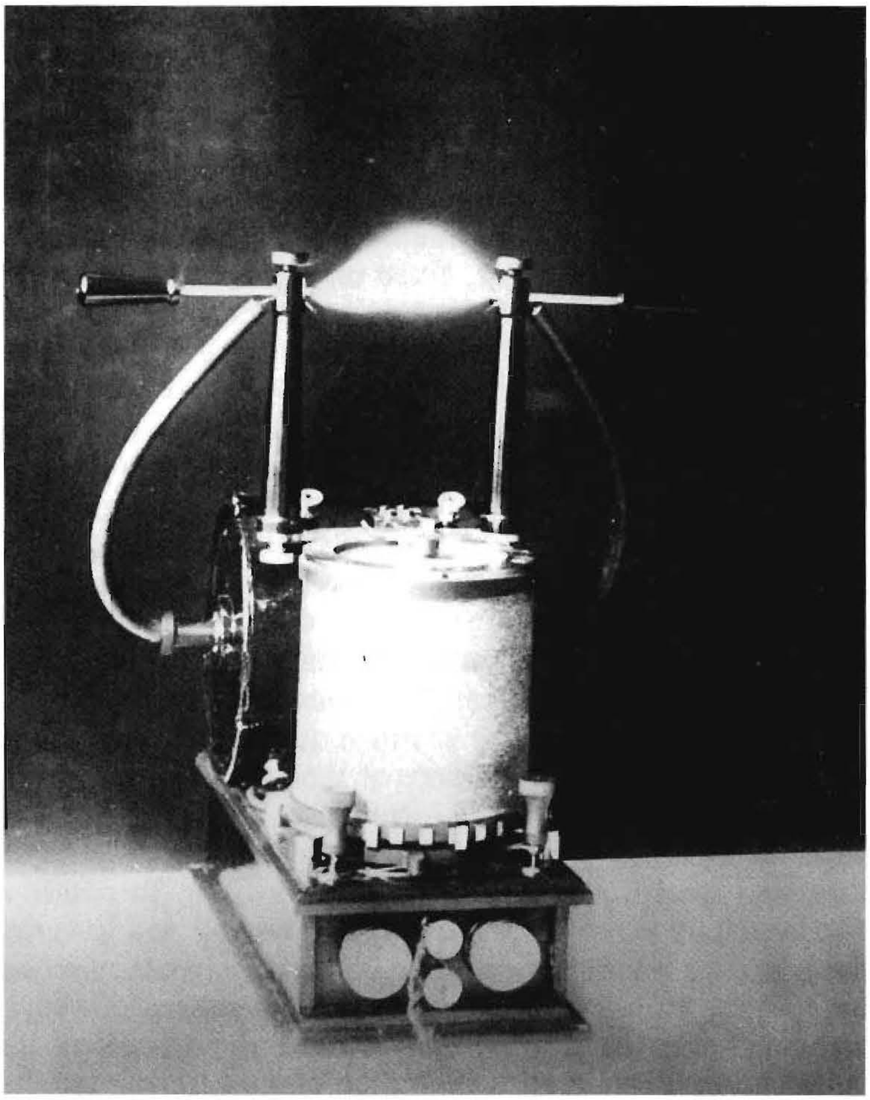


Fig. 9.—Photograph of small oscillator diagrammatically shown in figure 8.

modifications referred to, the trouble attendant upon the operation of ordinary apparatus is practically done away with as the current though the primary is automatically reversed, and in this manner a tube which is first brought to the proper degree of exhaustion by means of one circuit can be worked for a long time without appreciable increase of vacuum or diminution of effectiveness.

A photograph of one of these finished instruments, Fig. 9, especially adapted to be used in the operation of Roentgen bulbs, or in general as a laboratory appliance in place of the ordinary induction coil, gives an idea of the actual arrangement of the parts. The condenser *C*, Fig. 8, is contained in a box *B* upon which is mounted in front the motor for controlling the circuits, in this instance simply a coil *L* actuating a spring *s*, fixed on top of the same. This coil, designated as the charging coil, serves at the same time to raise the pressure of the source to any value desired for charging the condenser. This is an important practical advantage, as it enables reduction of the capacity of the latter so that it need not be more than a few percent of that otherwise needed for an equivalent conversion of energy. Besides, the smaller the capacity, the quicker is the vibration and the shorter need be the high tension secondary. The discharge circuit *P* surrounding the secondary coil *S* is formed of a few turns of copper ribbon and mounted on the top of the box behind the charging coil, all connections being as short as possible so as to reduce as much as it is practicable both the self-induction and resistance of the discharge circuit. On the front side of the box, Fig. 9, containing the condenser, there are mounted the binding posts for connection with the line, two small fuses, and a reversing switch. In addition, two adjusting screws are provided for raising and lowering the iron core within the charging coil as a convenient means for varying within considerable limits the current of supply and regulating thereby the discharge of the secondary circuit. The instrument with rubber columns carrying the discharge rods, which are visible on the top, dismounted, can be enclosed in a box of 12 x 9 x 6 inches inside measure.

The mode of operation may be explained as follows: At the start, the spring contacts *cc*, Fig. 8, being closed and the condenser practically short circuited, a strong current passes through the charging coil attracting the armature fastened to the spring and separating the contacts. Upon this, the energy stored in the coil, assuming the form of a high tension discharge, rushes into the condenser charging the same to a high potential. The current through the coil now subsiding, the attraction exerted upon the armature ceases, and the spring reasserts itself and closes again the contacts. With the closing of the latter the condenser is discharged through the primary or discharge circuit, the constants of which are so chosen that an extremely rapid vibration of the electromagnetic system including the condenser and primary coil results. The currents of very high frequency thus obtained induce corresponding currents of high tension in the secondary. Simultaneously, however, with the discharging of the condenser, the current from the source of supply again rushes through the charging coil and energy is stored for the next charge of the condenser, this process being repeated as often as the spring opens and closes the contacts.

Although the instrument contains all the essentials of an ordinary induction coil, it will be seen that its action is entirely different, and the advantages of this new principle over the old are so great as to hardly require any lengthy comment. Merely to convey a true and more complete information I may mention a few of the most important ones. Take, for instance, the economy. The instrument referred to takes on a 110-volt direct-current circuit, according to load and adjustment, from 5 to 30 watts. It gives a powerful stream of sparks 6 inches in length, but if it be desired this distance can be easily doubled without increasing the energy consumed; in fact, I have found it practicable to produce by the use of this principle sparks of 1 foot in length involving no greater expenditure of energy than 10 watts. But in an instrument designed for a variety of uses, a departure must be made from a design insuring the greatest spark length. Of the total energy consumed by the apparatus, fully 80 percent can be obtained in the secondary circuit. Owing to the small total energy consumed and the efficiency of conversion, all parts of the instrument remain cool by long continued working with the exception of the contacts which, of course, are slightly heated. The latter are subject to much less deterioration than is commonly the case, as the condenser is small and, moreover, the current from the same does not, like in an ordinary coil, pass simply through the contacts and a few short connections, but has to traverse the primary coil, this reducing the current and diminishing very much the heating effects.

Consider next the advantages of the absence of fine wire in the secondary coil. Owing to the rapidity of vibration of the primary currents, comparatively few turns of thick wire give the required pressure in the secondary circuit. To illustrate this feature by a practical experiment I take a simple paper cylinder, wound with only one layer of ordinary magnet wire, forming the secondary coil. In spite of there being only a few turns, long sparks—several inches in length—are obtained when the coil is inserted within or brought near to the discharge circuit of the instrument. A secondary of this form is simplest and best suitable for the production of long sparks, but it is somewhat inconvenient to handle.

The most advantageous features of these instruments lie, however, in the quality of the effects produced, which are the result of the rapidity or suddenness of the discharges obtained. To appreciate this feature we only need consider that a spark of, for instance, 6 inches in length, obtained with an instrument giving half a million vibrations a second, involves maximum pressures which, if produced with ordinary methods, would give sparks of many hundred feet, since the electrical force necessary to vibrate a certain quantity of electricity increases very rapidly; that is, with the square of the frequency of vibration. Therefore, pressures such as these here obtainable cannot be secured in any way by static machines or ordinary induction coils.

Still another feature of a more practical bearing I may illustrate by lighting a vacuum tube from an instrument furnishing currents of a frequency of much over half a million a second. Although the tube has a volume of only about 2½ [cubic] inches, it emits more light than a tube 6 or 7 feet long and 1½ inches in diameter, such as I have shown on other occasions, and that is a tube having 60 times the bulk and taking a proportionately larger amount of energy. So small a tube as this shown could not at all be brought to this luminosity by the use of the ordinary currents without soon getting overheated, and no better test of the increased efficiency of the light production can be had than by producing as high a luminosity in a small tube without undue heating.

Another convenient and advantageous feature of such an instrument will be found in its capability of being operated from alternating as well as from direct-current municipal circuits. With the special object in view of enabling their being used to the best advantage on alternating circuits also, I have determined the physical constants in a few types to suit circuits of the frequencies usually adopted here; that is, 60 or 125 cycles per second.

In the development and practical application of the principle underlying this kind of apparatus, one of the greatest difficulties encountered was the insulation of the secondary coils and condensers, particularly of the latter. The stored energy of a condenser is of an explosive nature, and when released suddenly in a way as it is in these instruments, it partakes much of the character of explosions of such a body as dynamite and enormous maximum pressures result, which strain the dielectric layers in the condensers and coils to their utmost. No matter how good and thick an insulation is provided, it cannot withstand such strains if there be even a slight absorption loss caused in any strained portion of the apparatus. An ordinary condenser, insulated as usual by thick layers of mica, which easily stands a few thousand volts of steady or slowly varying pressure, breaks down invariably; and no wonder it does; for, with vibrations of several hundred thousand a second, such a condenser with air bubbles or cavities of any kind, unavoidable when the usual method of construction is followed, will convert into heat the larger portion of the energy supplied to it. To investigate the flow of an alternating current through a coil with an iron core which is not laminated is hardly less crude than to carry on a research of rapid electrical vibrations with a condenser in which there are cavities or air bubbles, or in which, in general, air has access to the highly charged conductors. No estimate of the vibration period of an electromagnetic system can in such a case be made with any accuracy, whereas, when a proper plan of construction is followed and the dissipation of energy obviated, the experimental result closely agrees with the calculated period. By properly building up

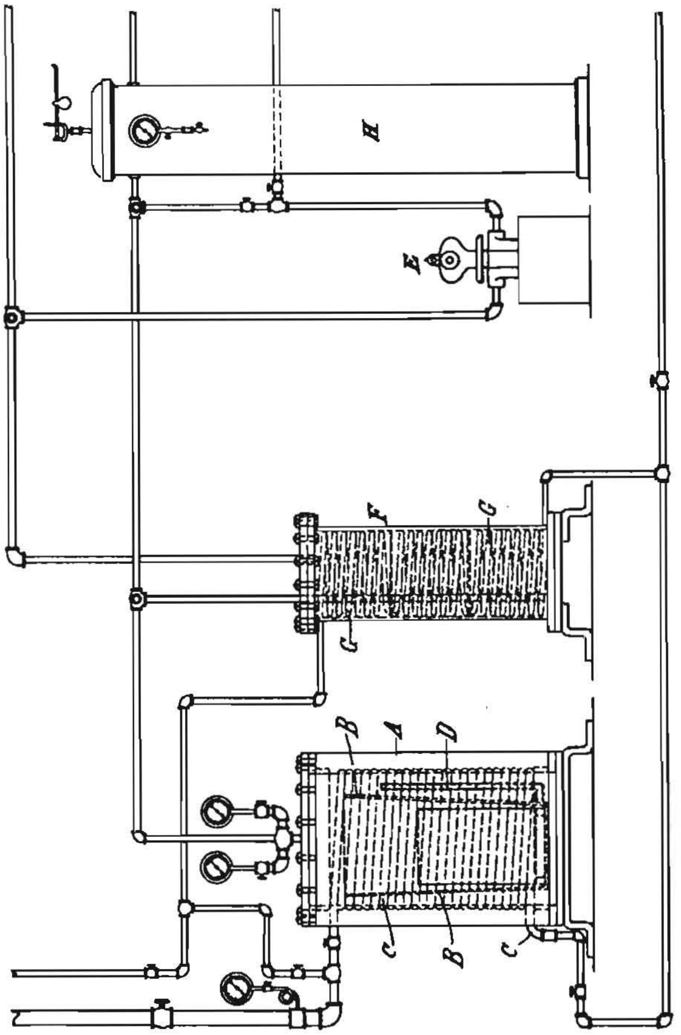


Fig. 10.—Apparatus for the manufacture of condensers and coils.

the condensers and coils, I have produced electromagnetic systems in which a slow vibration, once started, continues a minute or more, this indicating the absence of any serious friction loss. It is important to consider the preceding facts when dealing with standards and instruments of measure. A standard condenser prepared in the ordinary way of mica sheets and tinfoil, while indicating the correct value of capacity when used with a steady or slowly varying potential, will have its measured capacity greatly increased when the variation of potential becomes extremely rapid. In like manner, an electrostatic voltmeter with its vanes immersed in air, though a precious instrument with ordinary currents, is practically useless in the measurement of condenser discharges of frequencies of a few hundred thousand a second, its indication being far too low.

In view of the importance of the subject, a few words on the process of insulating, which has been adopted by me after several years of experimentation, may be of value. One form of apparatus as used by me is illustrated in diagram Fig. 10. *A* is a tank capable of withstanding great pressure, which is connected to a pump *E* and its reservoir *H* through a condensing reservoir *F*, kept cool by means of the coiled pipe *G*. The tank *A* is likewise provided with a coiled pipe *C*, through which either steam or cold water may be passed at will. The condenser is build up of insulating and conducting sheets in any convenient way, several layers of very thin paper being put together so as to avoid defects which may arise from small holes or punctures. For the same reason, it is advisable to mix up the sheets when received from the factory, as a great number of them may be injured at the same place. The condenser, having been tested by the application of moderate electrical pressure as that of a supply circuit of 220 volts, is placed in a tapering vessel *B*. A pipe *D*, reaching to the bottom of this vessel, may be provided, through which the insulation, when liquefied by the heat, may flow in, but this is of less importance. The vessel *B* containing the condenser being next placed in the tank *A*, and the top of the latter bolted down, steam is then passed through the coiled pipe *C* and the insulating mass is kept at the [proper] temperature which is a little above the melting point of the compound by regulating the steam supply. The pump is now connected with the tank by opening the proper valves, and a vacuum of about 29 inches or slightly more is established. When the melted compound has thoroughly permeated the interstices of the condenser, steam is then shut off and cold water passed through the coil *C*. The process of slow cooling being pushed far enough, the connections of the pump are reversed and air is forced into the tank *A* with the result of compressing strongly the fluid insulation and forcing it into all interstices. The pressure is preferably maintained until the mass is solidified. The application of the pressure is not only of great advantage because the insulation is forced into the interstices and prevented from shrinking away when cooling, but, in addition, any small gas bubble, which might remain in the condenser and would otherwise at ordinary atmospheric or smaller pressure be fatal to the instrument, is strongly compressed and the danger considerably lessened. The mass in the tank *A* being solidified, steam is again turned on the pipe *C* for a few minutes in order to soften the insulation on the periphery and allow the vessel *B* to be lifted out of the tank, whereupon the condenser is taken out of the vessel and the superfluous insulation cut off. In the same manner, primary and secondary coils are treated. As insulating material, I have found best to use a mixture of beeswax and paraffin of low melting point, about half of each being taken. This gives a tough mass which [but slightly] shrinks away from the metal upon cooling. Condensers and coils manufactured in this manner will withstand incredible pressures. Very often in adjusting the primary discharge circuit, it may happen that sparks of $^3/_8$ or $^1/_2$ inch dart across the condenser terminals, and yet it will

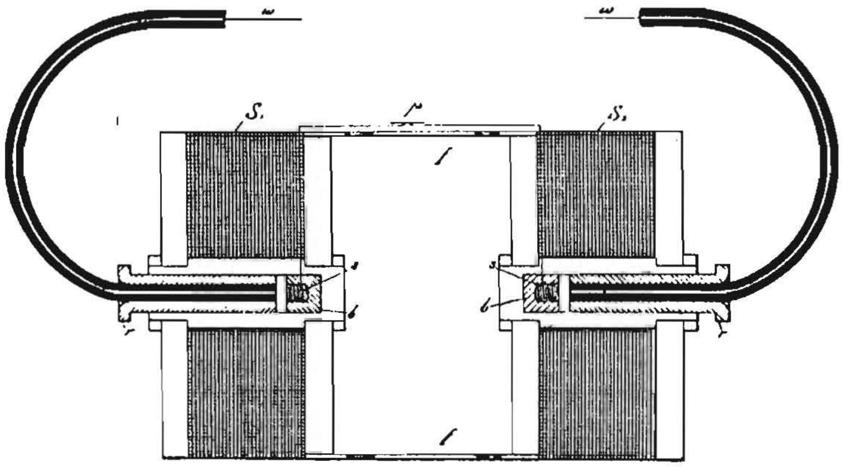


Fig. 11.—High potential coil system having terminals at centers.

not break down, although the dielectric is no more than a few thousandth of an inch in thickness. I have been unable to detect any increase of temperature whatever in the condenser after long working.

To enable the secondary coils to withstand the effect of the enormous pressures producible with these instruments, I have recognized it as necessary to build them on the general plan illustrated in Fig. 11. The diagram shows two flat spirally wound coils, S_1 S_2, which are connected with their outer ends to a contact plate *p* in the proper direction so as to form in reality one single secondary coil, the terminals of which are respectively at the centers of the two wooden spools upon which the two parts of the coil are wound. These spools are held together by a cylinder of thin fiber sheet *ff*, which is sufficiently strong to insure solidity and perforated in order to allow the melted wax to fill the hollow spaces when the coil is put through the insulating process before described. In the centers of the spools are fastened threaded brass bushings *bb* to which the free ends of the secondary coils S_1 S_2 are connected and into which can be screwed brass pieces *ss*. The latter are fastened to the end of the hollow plugs of hard rubber *rr*, through which pass flexible wires *ww*, very heavily insulated with gutta-percha, which serve to connect the secondary high potential ends to the discharge rods supported on the top of the instrument (Fig. 9). It is advisable not to insulate the wires *ww* with soft rubber, for this kind of insulation is soon destroyed by the ozone generated at their surface in consequence of the streamers which will form even if the rubber be very thick. The thickness of the insulation between the superimposed layers of secondaries is practically determined from an approximate estimate of the difference of potential between adjacent layers. Originally I have used heavily insulated wires with from two to four braids, but presently I am using ordinary magnet wire which, in manufacturing the coil, is wound together with a string of a thickness equal to that of the wire. This is a convenient mode of insulating, not requiring specially prepared wire and secures excellent results. The middle of the secondary circuit, or common joint of the two coils, is connected to ground, or so the mains, and this generally through the primary discharge circuit. The small contact plate, or spring *p*, serves to establish the connection upon the secondary spools being inserted in the primary coil. The length of each of the secondary coils is so determined that it is somewhat less or equal to a quarter of the wavelength of the electromagnetic disturbance produced in the secondary circuit based, of course, on the practical estimate of the speed of propagation of the disturbance through this circuit. It is obviously understood that the length of the secondary circuit is made to approximate more or less a quarter of the wavelength, according to how much allowance is made for the capacity of the circuit under normal working conditions. In the ordinary uses of the instrument, as [a] laboratory appliance chiefly for the production of qualitative effects of high tension discharges, little allowance is generally made for the capacity of the terminals; but if the apparatus is designed, for instance for generating a large quantity of streamers between plates of great surface, or for charging condensers from the secondary, or [other] such uses, then the length of the secondary wire is made much smaller, and advantageously an even fraction of a quarter of that wavelength, which is obtained without any allowance for capacity other than that possessed by the coil. Finally, if secondary currents of comparatively low tension are desired, the coil is constructed preferably of one single spool and of only few layers, all in close proximity to the primary so as to increase the mutual induction coefficient and reduce the resonant rise of potential as much as possible. The closure of the magnetic circuit by oxygen at ordinary or high pressure, while of little effect with low frequency currents, is of a remarkable influence with currents of these unusually high frequencies, especially when the conditions are favorable for the occurrence of resonant phenomena, and I am anticipating practical uses of oxygen in this connection.

A secondary coil constructed in the manner illustrated in Fig. 11 has many important advantages, the chief ones being the safety in handling and the facility it affords for obtaining potentials far beyond those producible if the ordinary methods of construction are followed. In order to convey an idea of the pressures obtainable even with so small an instrument as the one described, a photograph of the same in action with two loops of cotton-covered wire attached to the discharge rods, is added (Fig. 12). The outer wire loop was in the experiment only 22 inches in diameter to enable it being properly shown in the print, but it could have been much larger since two such parallel wires 15 feet long may be stretched from the secondary terminals of the instrument and practically the whole space between them, 4 inches wide, is seen in the dark covered with fine luminous streamers. This is a surface of 5 square feet, and yet the energy taken from the supply circuit during the performance is less than 35 watts. To produce with an ordinary transformer such a quantity of these streamers, which may be needed for the manufacture of ozone or similar purposes, would require a considerably greater amount of energy and a more costly apparatus.

These extreme differences of potential obtainable by the use of the principle here involved are the result of the enormous suddenness or rate of change of the primary current impulses. In the ordinary method of varying the strength of the primary current, either by alternating the same or breaking the conducting path, we are limited to the comparatively insignificant rate of change producible by means of a high frequency alternator or rapid break, but by the use of the condenser discharges there is practically no limit to the suddenness of the impulses, and any potentials and spark lengths desired can be readily obtained. So, for instance, I have been able to produce, by applying the principle in a peculiar manner, immense electrical pressures, the theoretical maximum value of which can be measured only in many millions of volts, causing showers of continuous streams of thick, thundering sparks to dart out into space to a distance of 8 or 9 feet from an insulated wire, which behave sometimes like veritable lightening bolts and have afforded to the few who have witnessed them during the last two or three years in my laboratory a spectacle not easily forgotten. Nor is it at all difficult to increase, in a large hall or open space,

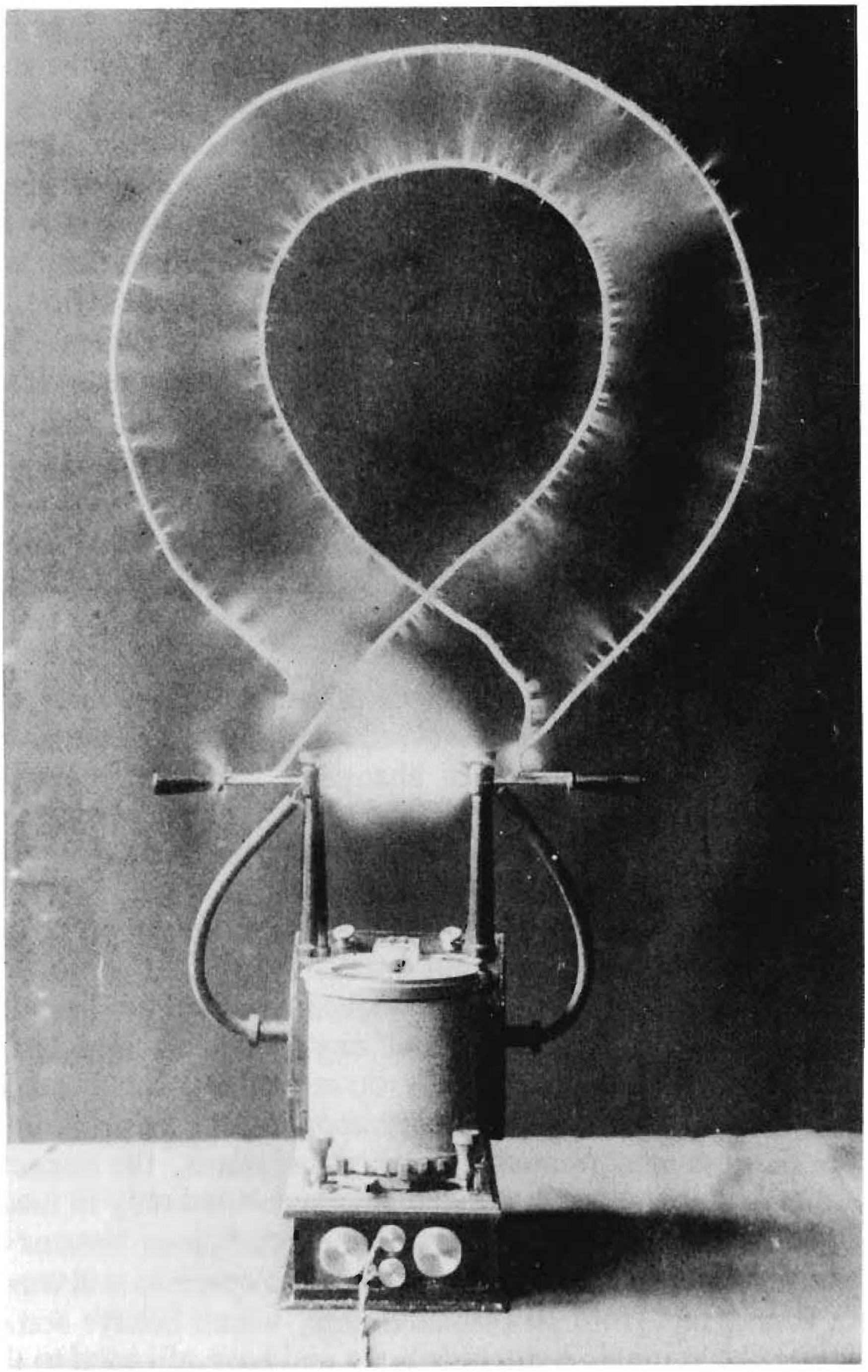


Fig. 12.—Photograph of coil system illustrated in figure 11 in action. Luminous streams cover an area of 5 square feet.

many times the potential and sparking distance by the employment of such means and methods.

Although in these oscillators the great suddenness of change in the strength of the currents depends chiefly on the electrical constants of the circuits, some advantages of minor but practical importance may be secured by a proper construction of the devices used as convenient, though not indispensable, accessories of the system for the purpose of arbitrarily making and breaking the circuits. Accordingly, I have devoted considerable time to their study and perfection, and in connection with the typical arrangements of the circuits illustrated in Figs. 1, 3, 4, and 5, I have dwelt in my earlier writings on this subject on a variety of such circuit interrupters in vacuum, air, and other fluids at low or great pressures.

It has been known long ago, since the investigations of Poggendorff, that, when the vibrator or break of an induction coil was enclosed in an exhausted vessel, the interruption of the currents was effected with greater suddenness, the vacuous space acting in a certain measure like a condenser, connected, as usual, around the break. My experiments with several kinds of such circuit breakers have led me to recognize that the vacuous space is not exactly the equivalent of a condenser, but rather of an absorbent, the increased suddenness being simply due to the rapid carrying away of the volatilized material forming the arc and, therefore, dependent on the velocity with which the disintegrated matter is carried away and also on the amount of the latter. Thus, with very hard platinum-iridium contacts and small currents, there is little difference; but, with soft platinum points and heavy currents, the influence of the vacuum is well noticeable, while, with mercury or in general easily volatilizable conductors, the difference is very great. The size of the exhausted vessel is also of some consequence, the break gaining in suddenness when the vessel is larger. Looking at Poggendorff's observations in this light, it appeared clear to me that only a small velocity of the particles composing the arc can be obtained since the effective pressure, at least with low frequency impulses depending on mechanical means, and with currents of limited strength which can be passed through the contacts without quickly destroying them, is necessarily only a minute fraction of the atmosphere being besides, very materially reduced by the oppositely acting attraction of the parallel-current elements of the arc. Pursuing further this train of reasoning, it seemed likewise evident that, if an insulating fluid be forced mechanically between the contact points with such velocity that the particles composing the arc were carried away quicker than it was possible with a small pressure producible in the gaseous matter in vacuum, the suddenness of disruption would be increased. This conclusion was borne out by my experiments in which I found that a fluid insulator, such as oil or alcohol, forced through the gap with even moderate velocity, increased very greatly the maximum rate of change of the primary current, and the length of secondary wire necessary for a certain spark length was in some instances reduced to 25 percent of that usually required. The length of the secondary was still further reduced by the use of insulating fluids under great pressure. As regards the suddenness of the current impulse following the closing of the contacts, the introduction of an insulating space or film of greater dielectric strength than that of the air at ordinary pressure, though producing a distinct effect, is of small consequence when the interrupter in its operation actually breaks the arc, since the electromotive force of a battery or municipal supply circuit is generally insufficient to break down an insulating film of even so small a thickness as 0.001 inch.

The continued effort to perfect the various automatic contrivances for controlling the supply current has clearly brought out their mechanical limitations, and the idea of utilizing the discharges of the condenser as a means for producing, independently of such mechanical devices, the sudden variations of the current which are needed for many purposes in the arts, appears evermore a happy and timely solution. In this novel process, a function of only minor importance is assigned to the mechanical means; namely, that of merely starting periodically the vibration of the electromagnetic system, and they have no other requirements to fulfill beyond those of reliability in operation and durability, features which are left to the skill of the mechanic and which, in a fair measure, it was not difficult to attain in a number of types.

Considering, then, that the rate of change of the discharge or primary current in these instruments is made to depend chiefly on the physical constants of the circuit through which the condenser discharges, it is evidently of utmost importance to construct properly the latter circuit, and in the investigations which were carried on with this object in view, several noteworthy observations have been made.

First of all, one draws the obvious conclusion that, inasmuch as the primary coil in a transformer of this kind consists usually of very few turns of copper ribbon of inappreciable resistances, the insulation between the turns should not require much care. But practical experience soon convinces him of his error, for, very often it happens that, owing to an exceptional resonant rise, the difference of potential between adjacent turns becomes so great as to rupture even a very good ordinary insulation. For this reason, it was found necessary to treat the primary coils likewise in the manner described, thus securing the additional advantage of stiffness, which results from the expansion of the metal sheets and thickening of the insulating layers during the heating in vacuum and subsequent contraction of the metal in cooling to the normal temperature after the insulation has solidified.

Next the experimenter is surprised when realizing the importance of the proper adjustment of the length of the primary coil and its connections. He is naturally prepared to find that, since the discharge circuit is of small length, the introduction in this circuit of a very small inductance or frictional resistance would produce an appreciable difference in the result obtained as, for instance, in the spark length of the secondary coil. But he certainly does not expect to observe that sometimes as little as 1/4 inch of conductor more or less would be of a telling effect. To illustrate: It is quite easy to produce with this kind of apparatus a spark of several feet in length, and by merely taking off or adding to the primary

1 inch of thick copper wire so reduce the spark length to one half. Observations of this kind impress the experimenter with the importance of the close adjustment of the circuits and accurate determination of their constants. His attention is forcibly attracted to the advantages of reducing as much as it is practicable the self-induction and resistance of the discharge circuit, the former with the object of securing the quickest possible vibration, the latter chiefly for reasons of economy. He also recognizes the necessity of bringing down to the minimum the length and resistance of all connecting wires. A well-constructed discharge circuit in a small instrument, such as the one described, should have no more than five percent of inactive conductor; its resistance should be negligible, and the self-induction should be not more than a few hundred centimeters.[*] I have found it almost imperative to use thin copper ribbon in the construction of the primary coils, and with these an observation, which is the most curious of all, has been made. It occurs, namely, that, under certain conditions, the primary coil gets perceptibly cooler by continued working. For a long time this result appeared doubtful, but finally it was positively ascertained and ascribed to an exaggerated Thomson effect, owing to which heat is carried from the primary copper ribbon to the tinfoil of the condenser.

It might not appear quite clear at first why the primary discharge circuit is so sensitive to variations of length, for a circuit of any length might be connected to the condenser and, provided that the relation between resistance, capacity and self-induction is such as to satisfy the condition laid down by Lord Kelvin, oscillatory discharge will take place. But it must be remembered that the velocity of propagation of the disturbance in the circuit depends on these quantities, and that the best result is attained when the velocity is such that a stationary wave is formed with a single node which is located generally, but not always, at a point of the discharge circuit or conductor equidistant from the opposite condenser coatings. Under such conditions, the maximum effective pressure at the terminals of the condenser is obtained. But

---

[*] In contemporary units, a few tenths microhenrys.

this state of things is only possible when the speed of the propagation through the discharge circuit is such that this circuit is traversed by the disturbance exactly in the time interval needed to complete half of one vibration. Now, since the speed is extreme and the length of the circuit very small, entirely insignificant variations of the length may often produce astonishing changes in the performance of the apparatus. These statements, of course, should not be construed as generally applicable, for they refer only to such cases in which the vibration in the discharge circuit, started by one operation of the circuit controller, does not die out before the succeeding operation of the controller. This may be made clear by a mechanical analogue. Suppose a weighted spring is clamped in a vise and a sudden blow is struck which sets the spring vibrating. Let the vibrations die out and let another blow be delivered. The spring will vibrate again as before, and it matters little what weight is attached to the spring, what the elasticity of the latter or, in general, what its period of vibration, and at what intervals the blows are delivered, the process of conversion of the energy of the blows into the energy of the vibrations will be effected with equal economy, except for secondary causes, immaterial for the present consideration. Exactly so is it with the electromagnetic system, and in the early stages of development and practical adaptation of the principle underlying the instruments described, I have employed condensers, either ordinary or electrolytic, of very large capacity and have caused them to discharge at comparatively long intervals through a primary circuit of negligible self-induction and resistance, thus producing current impulses which would sometimes reach, at least theoretically, maximum values of as much as 100,000 amperes. A high maximum rate of change in the primary current was thus producible, but, nevertheless, the average rate of change was still small. Considering again the mechanical analogue before mentioned, a valuable lesson is at once derived. Looking upon the weighted spring as an appliance for converting energy, both economy and output demand that the vibration of the spring should persist as long as possible and that the blows should be struck as often as it is practicable. To satisfy this twofold requirement, the blows must of necessity be delivered while the spring is still vibrating, and now it becomes most important to properly time the blows. Similarly again, in the electromagnetic system, the circuit controller must operate at definite intervals of time in order to secure the most vigorous vibration with the least supply of energy. In the construction of practical instruments, the number of the fundamental current impulses is arbitrarily adopted; the condenser, being prepared by a special process, cannot be adjusted without great inconvenience, and the size and to a certain extent also the turns of the primary coil are likewise determined beforehand from practical considerations. Furthermore, it is desirable, for reasons of economy, not to resort to an otherwise convenient method of adjustment, which would be to insert a variable self-induction in series with the primary coil. These conditions render more difficult the exact adjustment of the various quantities, and I have sometimes found it of advantage to adopt one or other plan such as will readily suggest themselves. For example, I have used an additional coil wound upon the primary and connected in parallel to the same, or I have completed the adjustments by determining properly the self-induction and capacity of the secondary coil.

In order to facilitate the observation and also to enable the exact determination of the oscillations of electromagnetic systems as well as of the vibrations or revolutions of mechanical devices, such as the circuit controllers used in connection, it was recognized as indispensable, in the course of these investigations, to construct a proper apparatus for such purposes. I determined from the outset to avail myself of what is known as visual synchronism. In this scheme, usually a disk or cylinder with marks or divisions, which is rotated with uniform velocity, is illuminated by a periodically varying or intermittent source of light, the divisions appearing stationary in space when the revolutions of the disk are synchronous with the variations in intensity or intermittence of the light-giving source. The chief virtue of such a method evidently resides in the uniformity of the velocity of rotation or eventually in the constancy of the period of the vibration produced. Having been early confronted with the problem of rotating a body with rigorously uniform velocity, which is required in many instances, or with the similar problem of producing a vibration of constant period, I have devoted some energy to the study of this subject, and in the course of time several solutions, more or less practical and satisfactory, have presented themselves.

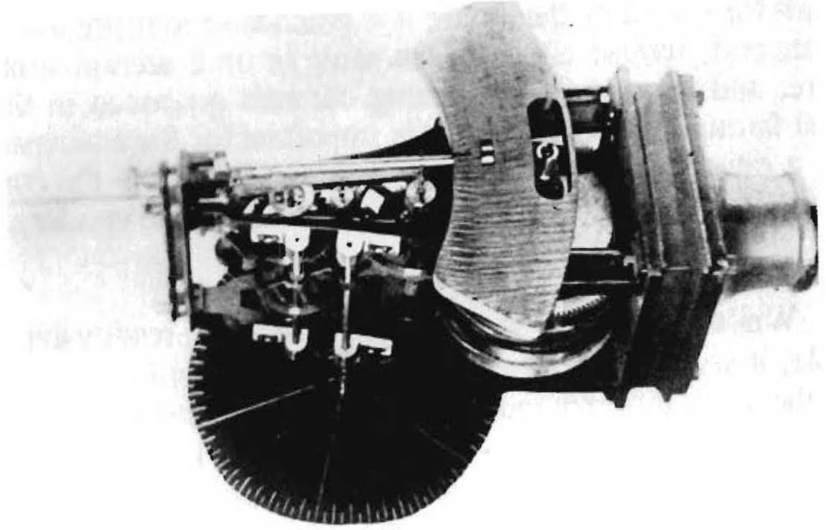
One of these, for instance, was to produce by means of compressed air or steam, the vibration of a freely movable plunger to which was rigidly connected a coil or core of an electric generator. By the reciprocating motion of the plunger, alternating currents were generated which were passed through a condenser or else through the primary of a transformer, in which case the secondary coil of the latter was joined to the terminals of the condenser. Care being taken that the air or steam pressure was applied only during a short interval of time when the plunger was passing through the center of vibration, and the oscillations of the electromagnetic system, composed of the condenser and generating coil, being properly determined so that fundamental resonance took place, it was found that, under such conditions, the electromagnetic system entirely governed the vibrations of the plunger; the variations of the applied fluid pressure, while capable of producing changes in the amplitude, were within very wide limits without any appreciable effect on the period of vibration of the mechanical system, the currents generated being therefore of rigorously constant period. The currents thus obtained were then utilized in a number of ways to produce uniform rotation.

Another way to reach the same result and in a more practical manner was to generate currents of differing phase by a steam engine of special design, in which the reciprocating motion of the work performing plungers and attached magnetic cores or coils was controlled by a freely oscillating slide valve, the period of which was maintained constant by mechanical means or by the use of an electromagnetic system, similarly as before. A synchronous alternating motor operated by the two or three phase currents thus generated rotated with so uniform a velocity as to drive the wheel work of a clock with fair accuracy.

Still other solutions of the problems referred to I may mention which, though less satisfactory, have proved sometimes convenient and sufficient for many purposes. For example, a direct-current motor with laminated fields, or without any iron, was connected in series with a condenser through a commutator or interrupter fastened on the shaft of a light [weight] armature. This device was so constructed that it alternately closed and opened the terminals of the condenser as usual in the instruments before described. The condenser terminals being closed, a strong current impulse passed through the motor, and upon the terminals being opened the discharge current of high tension rushed into the condenser. But the energy and duration of both of these succeeding current impulses, and consequently of all which passed through the motor, were made chiefly dependent on the self-induction of the motor coils and on the capacity of the condenser and were, therefore, with certain limits of variation of the applied electromotive force, little dependent on the latter, and consequently a motor with a negligible friction loss, operated in this manner, turned with nearly uniform velocity. The latter was the more nearly constant the greater the controlling influence of the electromagnetic system which, of course, was the most complete when the number of current impulses, the capacity, and self-induction were so adjusted that fundamental resonance was maintained. As before stated, in most of these novel instruments described, such adjustments are observed and, whether provided with rotating interrupters or circuit-controlling springs, they partake more or less of the virtue of the preceding principle. For this reason, the contact springs in these instruments do not fall into harmonics, as they often do in ordinary induction coils operated from supply circuits where the physical constants are generally such that similar adjustments are impracticable.

It should be remarked that, since a long time, it was known that a direct-current motor, driven with currents interrupted at regular intervals, shows a marked tendency to maintaining a constant speed; but by the introduction of a condenser in the circuit and the careful adjustment of the quantities, this tendency is very much increased, and for many purposes a sufficiently uniform velocity may be obtained in this manner. Instead of using interrupted currents for operating the motor, it is practicable to rotate a separate coil, wound either on the same or on a second armature, and to pass the alternating currents generated in this coil through the condenser. It is important for the attainment of a satisfactory result in such cases to determine the constants so that the amount of energy stored in the condenser should be as large as possible.

While a number of such arrangements were readily available, it was found, nevertheless, that they were inadequate to the many different requirements of the laboratory, and accordingly an instrument was devised which is illustrated in Fig. 13 ab. It has proved itself to be so necessary and valuable an implement in experimental investigations that its description here may afford useful information. The cut is intended to show a substantial and carefully constructed clock mechanism with the usual escapement *e*, gearwheels *ggg*, and a 1-second pendulum *P*. A small shaft *s*, carrying a disk *D* of large diameter, was geared to the clockwork through a pinion *p* of a proper number of teeth, such as to give to the shaft a velocity best suitable for observations. Now, in order to rotate the disk with a uniform velocity, some difficulties, well known to clockmakers, had to be overcome. The chief of these is due to the fact that the rotation of the shaft *s*, being controlled by the escapement *e*, which, at regular intervals, retards the train of wheels *ggg*, is not effected with uniform but periodically varying velocity, which may have all values from zero to a maximum, dependent on the driving weight *W*. Owing to this circumstance, when such a disk *D* of large diameter is rigidly geared to any kind of clockwork, it exerts, by reason of the great momentum which it necessarily acquires, a strong reaction upon the pendulum, altering the period of the same more or less, according to the momentum it possesses. This difficulty is known to exist, even in cases in which the step by step movement is practically done away with, as, for instance, in clockworks with centrifugal governors, or circular pendulums, in which slow oscillations are produced by the reaction of the moving mass upon the regulating mechanism.



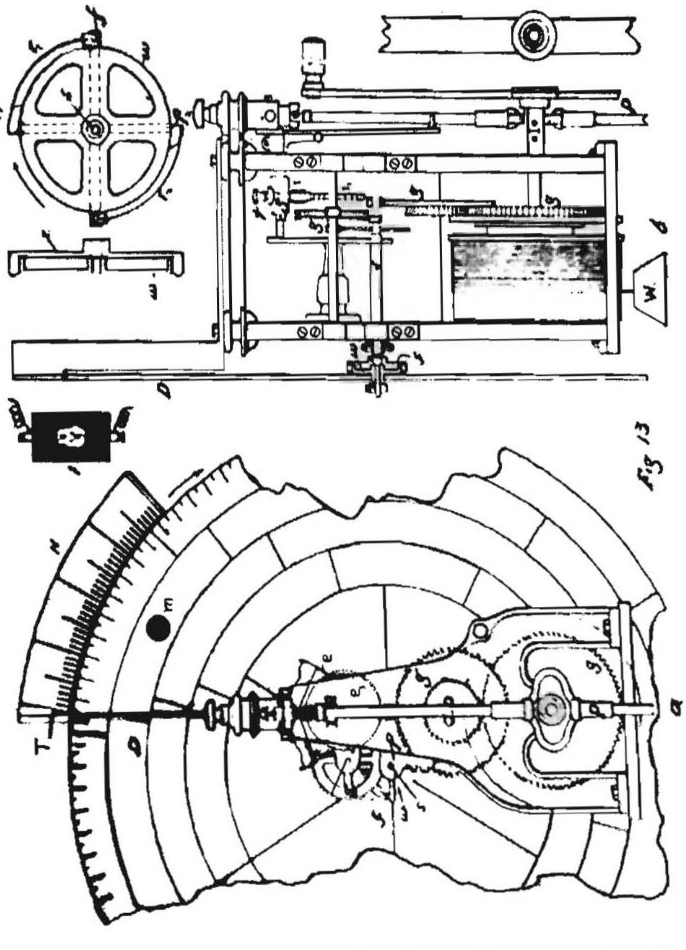


Fig. 13.—Special instrument to exactly determine wavelength and phase.

Some clockmakers have proposed an elastic connection between the body driven and the escapement, but this does not [do] away radically with the difficulty. On the other hand when, in an attempt to overcome this disadvantage of the step-by-step movement, a quick-acting escapement is used, whereby the periods of rest are reduced, and consequently the influence of the momentum of the rotated body upon the period of the pendulum, the result aimed at is but imperfectly attained and, besides, such an apparatus is less suitable for observation. Namely, it will be recognized as desirable for a number of reasons that the disk *D* should be rotated normally either once or twice a second, according to whether a 1- or ½-second pendulum is used. This being the case, the experimenter can render himself easily an account of the constancy of the speed by observing a mark *m* on the disk and noting that it occupies a fixed position in space, relative to that of the pendulum, in a convenient phase of vibration. Furthermore, the computation of the vibrations is rendered simpler and more convenient under such conditions.

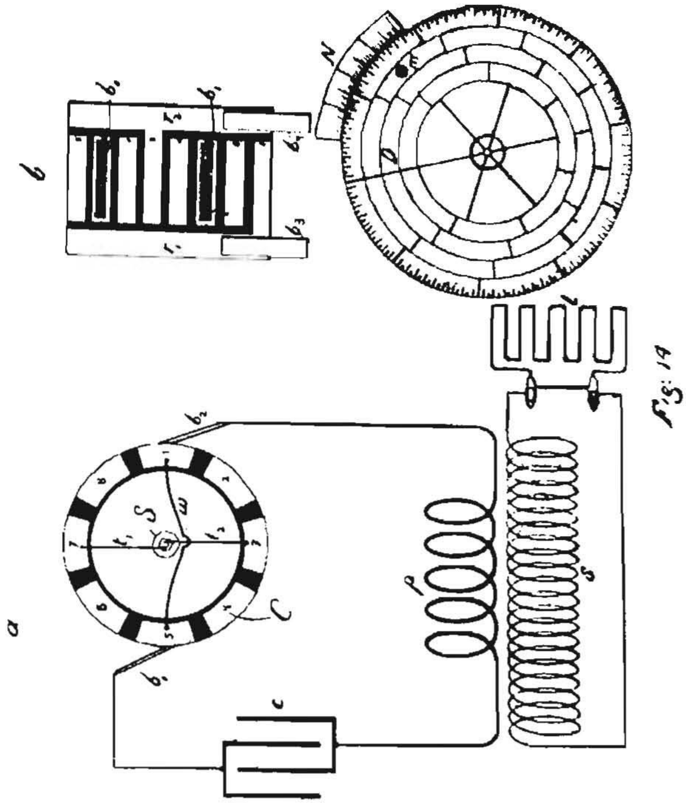
The problem, clearly put, was then to rotate a body as the disk *D*, or other body, with any desired but uniform velocity in a way such that the period of vibration of the pendulum was not much affected, even though the body rotated possessed considerable momentum. An entirely satisfactory solution of this problem was arrived at in the following manner. On the end of the shaft *s*, Fig. 13 b, was fastened a light metal piece *f* in the shape of a cross, carrying on two of its opposite sides pivoted pawls p_1 p_2, and on the other two light steel springs r_1 r_2, which pressed the pawls gently against the periphery of a washer *w*, which was provided with many very fine teeth or serrations cut sideways, similarly to those of escapement wheels. The washer *w* was arranged to turn very freely on the shaft *s*, and to it was fastened the disk *D*. The pawls p_1 p_2 were made with sharp edges to fit in the serrations of the washer *w*, and by these means the disk could rotate freely on the shaft *s* in the direction indicated by the arrows, but its rotation in the opposite direction was prevented by the pawls.

The operation of the apparatus will now be at once understood. On the start, the escapement wheel e was released by unscrewing the thumb screw t and shifting the sleeve S on its rocking support. The pendulum was next started and, when the escapement wheel had attained the normal velocity, the sleeve S was slipped back quickly and fastened—control of the escapement wheel being thus given to the pendulum. The wheel work and also the shaft s now moved with periodically varying velocity, but the disk D continued to move uniformly, the pawls p_1 p_2 slipping on the periphery of the washer w during the periods when the revolution of the shaft s was retarded by the pendulum. When, however, after some time, owing to the very small but unavoidable friction loss in the air and bearings, the speed of the disk would slowly diminish and fall below the maximum velocity which the shaft s was capable of imparting to it, then the pawls would give it a slight impulse, and in this manner the disk was kept constantly at the maximum velocity. By each swing of the pendulum, the disk would thus receive one impulse, and its velocity depended on the amount of energy imparted to it by each of the succeeding impulses. This amount of energy depended, of course, on the velocity of the shaft s during the period when the escapement wheel was free, and since this velocity was determined by the driving weight, the speed of the rotation of the disk could be varied within certain limits by adjusting the weight. It will be observed that, generally, the disk would rotate considerably faster than the shaft s, but it was easy to adjust the driving weight so that the disk rotated just once by one swing of the pendulum. In producing the rotation by these means, the influence of the momentum of the disk upon the period of the pendulum is found negligible. This result, of course, could not be attained by connecting the disk rigidly with the shaft s, even if a quick acting escapement would be used, as before suggested. The uniformity of rotation secured in this way leaves, for all practical purposes at least, nothing to be desired. The apparatus might have been improved by supporting the disk on an independent bearing and, perhaps, also by rotating it horizontally in a jeweled support. But the friction loss was very small, since, by arresting the shaft *s* suddenly, the disk would generally rotate something like 100 times or more before stopping, and such improvements were thought unnecessary. The vertical position was, however, chosen because it was much more convenient for purposes of observation. In order to reduce the weight of the disk *D* as much as possible, a light frame, consisting of a circular rim with narrow spokes, was cut out of thin aluminum sheet, and black paper glued on the frame—all marks and divisions of the former being, of course, white. I found it convenient to draw concentric circles with a number of marks such that all vibrations within the range of the apparatus could be read off. In addition, a segmental piece of hard rubber *N*, supported on a bar *T* and properly marked, was used to read fractions or, respectively, take corrections for any irregularity in the rotation during a prolonged period of time. Near the disk was placed a vacuum tube or, in its place, an adjustable spark gap *l*, which was connected to the secondary of a small transformer, the primary of which was positively controlled by the mechanical or electromagnetic system the vibrations of which were to be determined. In preparing a spring of the desired period of vibration for one of the instruments described, for instance, the spring was provisorily mounted on the instrument and the latter put in operation. The disk, intermittently illuminated by the discharges of the secondary coil, was released from the pendulum and rotated until synchronism was attained, the revolutions being computed by observing the white mark *m*. The constants of the spring were then modified after a simple calculation from the first result, and in the second trial, as a rule, the vibration was so close as to enable the use of the escapement, the adjustment then being completed, generally by altering the weight of the hammer on the spring until the marks on the disk, by the normal speed of rotation, appeared stationary in space.

The apparatus described in Fig. 13 will be found very convenient and time saving in a great many lines of experimentation. By means of the same, it is practicable to rotate a body of considerable weight with uniform and adjustable velocity, and it lends itself to the operation of circuit controllers, curve tracers, and all kinds of such devices. It will be found most useful in tracing current or electromotive-force curves and a variety of diagrams, and will afford material help in determining a number of physical quantities. But its most valuable use in the investigation of electrical vibrations is, perhaps, for the purpose of determining exactly the angular velocities of dynamos, particularly of alternators. Among the various quantities which, in alternate-current experimentation and practice, one has to determine very frequently, there are some, which even in a laboratory or shop in the midst of the disturbances of a city or factory can be ascertained with sufficient precision, while there are others which can be only approximated, particularly if, as is very often the case, practical methods of measure must be resorted to. So, for example, the close measurement of resistances offers no difficulty, nor does that of currents and electromotive forces, although the degree of exactitude is necessarily smaller; but in determining capacities, one is liable to make a considerable error, still a greater one in measuring inductances, and probably the greatest in estimating frequencies. In many places, such crude devices as speed counters or tachometers are still resorted to, and the experimenter is disappointed to realize that the accuracy of his long and painstaking tests is impaired because of his inability to determine exactly the frequency. To make matters worse, very often too, the latter is the largest and most important quantity. In view of these facts, a description of the method adopted by me for the determination of angular velocities may be of some value.

The devices commonly used are illustrated diagrammatically in Fig. 14, *a* and *b*. On the shaft *S*, Fig. 14 a, of the generator is fastened a commutator or circuit controller *C*, provided with any suitable number of segments, eight being

Fig. 14.—Method of impulse illumination of instrument disk.



shown in this instance. Four of these, *1, 3, 5,* and *7* serve to establish the connections of the circuits, while the intermediate ones, *2, 4, 6,* and *8* are entirely insulated, idle segments. Assuming the generator to be an alternate-current machine, the terminals t_1 t_2 of the armature winding, or of any desired coil or part of the same, are led through the hollow shaft, as may be the case, and connected to the diametrically opposite segments *3* and *7*, while the segments situated at right angles, that is *1* and *5*, are connected together through a wire w of inappreciable resistance. Two brushes b_1 b_2, supported in an ordinary holder allowing their being shifted in any position, are arranged to bear upon the periphery of the controller *C*. These brushes are connected to a circuit comprising a condenser c of proper capacity and a primary coil p, which has but a few turns of very small self-induction and resistance and is joined in series with the condenser.

The operation of the devices is as in the instruments before referred to. When, with the rotation of the shaft S, the brushes b_1 b_2 are brought in contact with the segments *1* and *3*, the condenser is charged to a potential which can be adjusted at will by shifting the brush holder. The condenser retains a certain charge until the brushes b_1 b_2 come to bear upon the connected segments *1* and *5*, whereupon an oscillatory discharge through the primary p takes place with the result of inducing strong current impulses in the secondary s, which momentarily light up the vacuum tube or spark gap l placed in proximity of the disk D, which is rotated with uniform velocity, as before described. With the rotation of the circuit controller, the brushes are again brought in contact with the segments *1* and *3*, and the operations are repeated, at each complete revolution of the armature shaft a definite number of impulses being passed through the vacuum tube or spark gap. In the device illustrated, there will be only two impulses for each revolution of the armature, but any greater number may be arranged for by augmenting the number of the segments and connecting them in the same manner. It should be stated that the current impulses, which pass into the condenser whenever the brushes b_1 b_2 are on those segments which are connected to the armature coil, ordinarily produce no appreciable effect in the secondary s. This might be the case if the number of segments would be very large and would then be at once noted. The proper adjustment of the circuit through which the condenser discharges is, of course, preferable but not absolutely necessary.

When it is inconvenient to use the armature current, as illustrated in Fig. 14 a, then the controller C is provided with two sliding rings r_1 r_2, Fig. 14 b, upon which are made to bear two additional brushes b_3 b_4. The latter are then connected to a direct-current source as the ordinary supply circuit, preferably through a self-induction coil, which serves to charge the condenser to a higher potential. The rings r_1 r_2 merely convey to the segments *1* and *3* the current for charging the condenser, otherwise nothing need be changed on the devices.

The marks or divisions on the periphery of the disk *D* are suitably made so that by the normal speed of the generator they appear stationary in space. This being the case, the speed may be at once and easily computed from the number of segments on the controller and that of divisions on the disk and from the speed of the latter. The frequency of the dynamo currents is then given by taking into consideration the number of poles.

In availing himself of this method, the experimenter can get the accurate value for the angular velocity, no matter how much the speed of the dynamo may vary, if he only takes the precaution to make his readings for electromotive force, current, etc., at the instant the marks on the disk are stationary. Should the reading consume more time, it is easy to take the correction for any variation by simply observing, with reference to a fixed line on the rubber piece *N*, the number of divisions which are to be added to, or deducted from, the speed of the disk.

ADDITION TO PART 1

"Arrangements for receiving"

Nikola Tesla On His Work With Alternating Currents

"The construction [of the instrument shown in Section I, Fig. 13 cut] was intended to produce an absolutely constant rotation so that certain intervals of time could be definitely fixed, and in relation to these intervals of time I could analyze the waves... The bottom of the diagram [Fig. 14] shows vacuum tubes designed for very minute currents. They were excited by the secondary of the transformer and illuminated the dial. If I used, for instance, two vibrations of different wavelength, then there was a beat, and I would notice, as this disc rotated, the marked lines travel one way or the other. When perfect synchronism was obtained, these lines appeared stationary.

"I am now showing [Fig. 15, top] a [drawing of a] device for telephonic and telegraphic signals I have used in my laboratory on Houston Street... That [left] is a transmitter ..., and [below] is an inductance which is bridged by a device such as that by speaking into it, or actuating it by hand or otherwise, variations in the intensity of the waves are produced.

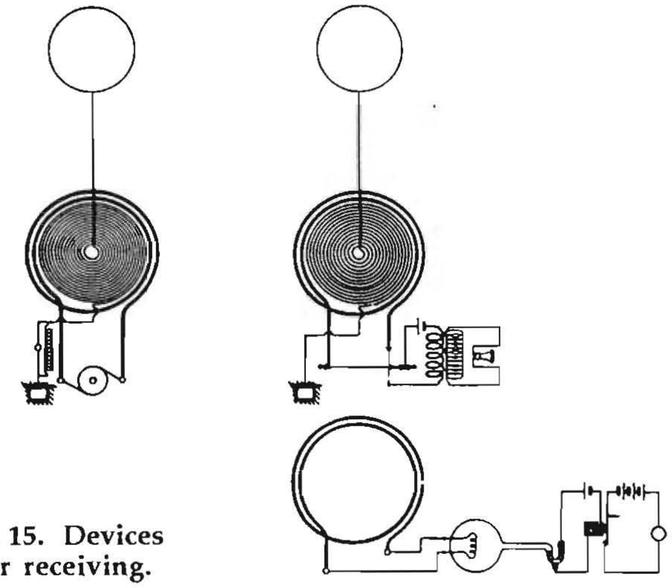


Fig. 15. Devices for receiving.

"On the receiver side [right] I have my antenna and self-inductance coil connected to the ground, and in the secondary I have a wire which is under a tension. Another wire, likewise under tension, controls two microphonic contacts or carbons. The tension of this wire is adjustable, and as I will show in another drawing, I can regulate the pressure of the contacts so that a certain current from a battery, here, will flow through this primary coil.

"When the transmitted oscillations are controlled and produce corresponding variations in the intensity of the received effects, then the current generated in [the secondary of the receiver] heats that wire more or less and the alternate heating and cooling of the latter results in periodic expansions and contractions vary[ing] the microphonic pressure of the contacts in obedience to the changes produced in the transmitter. In the secondary [of the transformer], I have a telephone [receiver] specially wound to reproduce the speech..."

"My transmitter was on Houston Street and I would take the receiver with me. For instance, I would take a few toy balloons, go on the roof, and then put my box there with the instruments and listen to the signals.

"This [Fig. 15, bottom] is another [drawing of a] device which I also used with success, but not telephonic. It operated on the principle of the Reis air thermometer ... [I]n the bulb is a resistance wire which is heated and cooled, owing to the fluctuations of the received currents. The attendant expansions and contractions of the air operate a little mercury column, pushing it back and forth. Curiously enough, for receiving telegraphic signals, this crude instrument was certainly good, but of course it was not suited for telephonic reception.

"That [shown in Fig. 16] ... illustrates a way of producing audible notes by reaction of the received impulses upon a magnetic field. [At upper left] is a transmitter, diagrammatically represented, with an arrangement for varying the intensity of the waves emitted, and on the receiver side I have, as you see, a grounded antenna. [The] secondary [has a conductor under tension in] a very powerful magnetic field, and [the reaction of] this conductor, traversed by the received currents in the field, causes the conductor to emit audible notes.

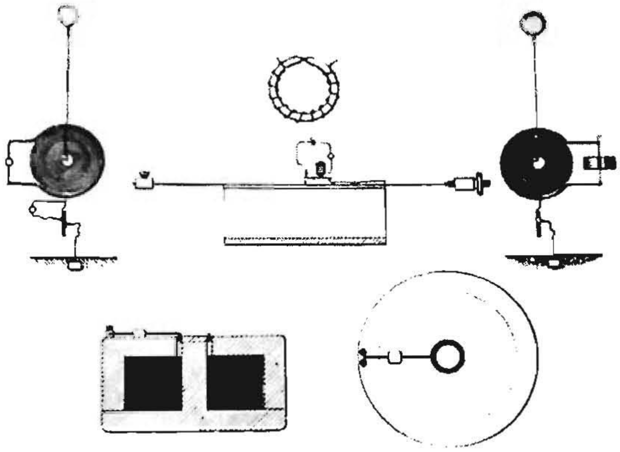


Fig. 16. Other Ways of receiving.

"I [have] several magnets of various forms, like this [Fig. 16, center], and employed a cord in the field, which, when the current traversed it, vibrated and established a contact. Or, I [use] a small coil ... through which the current was passed, and which by its vibrations produced the signal, an audible note, or anything else ... [I]n my writings ... I had already shown the reaction of the high frequency and low frequency currents on magnetic fields, and had specified the frequencies within which one has to keep in order to receive efficiently audible notes."

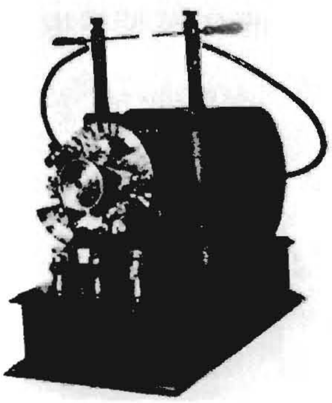


Fig. 17

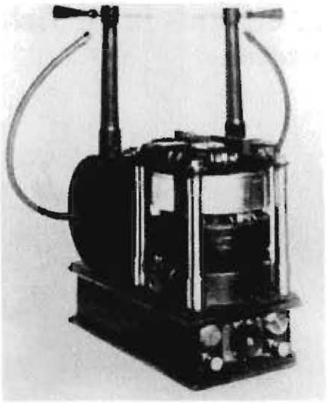


Fig. 18

These units were described by Tesla the following way years later as presented for the lecture.

U.S. Patent No. 568,179 of Sept. 22, 1896, "Method and Apparatus for Producing Currents of High Frequency," application filed July 6, 1896.

U.S. Patent No. 609,245 of Aug. 16, 1898, "Electrical-Circuit Controller," application filed Dec. 2, 1897

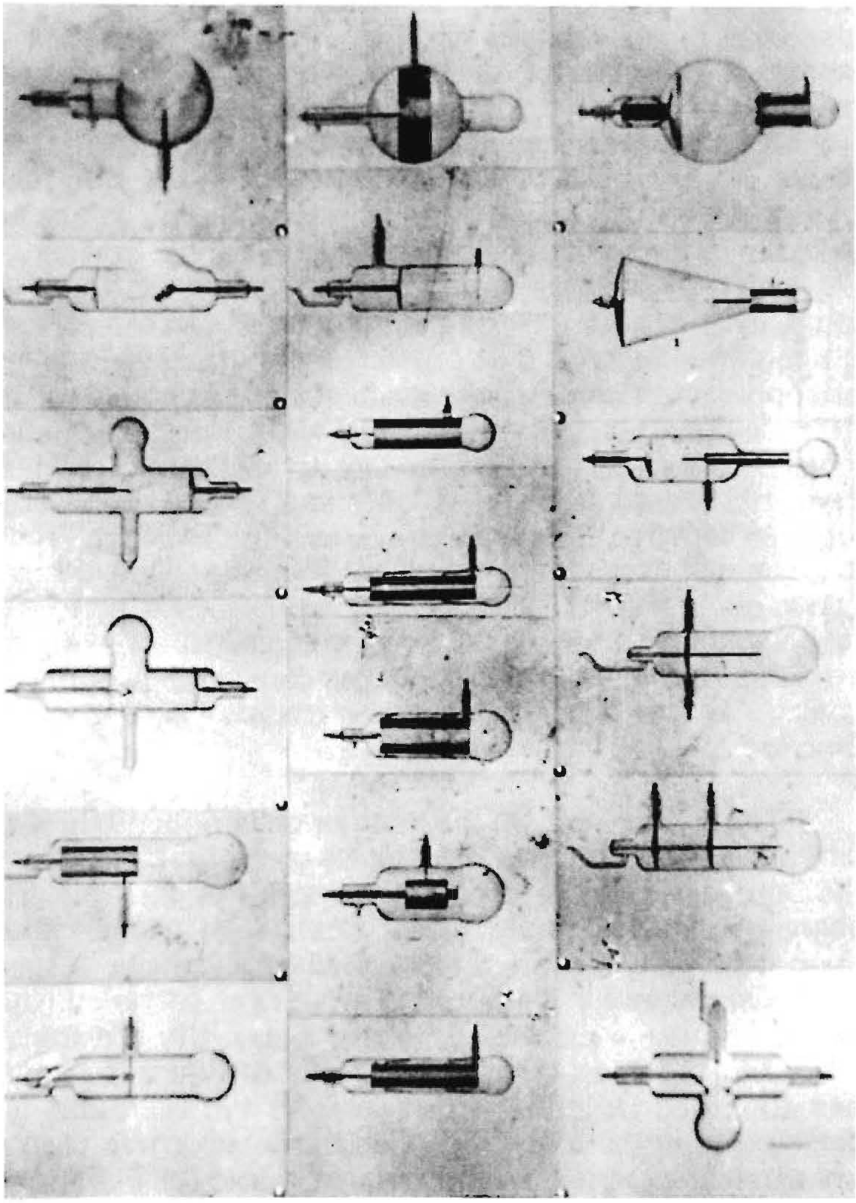
"[The unit in Fig. 17] represents a large oscillator ... intended for wireless experiments, production of Roentgen rays, and scientific research in general. It comprises a box containing two condensers of the same capacity on which are supported the charging coil and transformer. The automatic circuit controller, hand switch and connecting posts are mounted on the front plate of the inductance spool as is also one of the contact springs. The condenser box is equipped with three terminals, the two external ones serving merely for connection while the middle one carries a contact bar with a screw for regulating the interval during which the circuit is closed. The vibrating spring itself, the sole function of which is to cause periodic interruptions, can be adjusted in its strength as well as distance from the iron core in the center of the charging coil by four screws visible on the top plate so that any desired conditions of mechanical control might be secured. The primary coil of the transformer is of copper sheet and taps are made at suitable points for the purpose of varying, at will, the number of turns. The inductance coil is wound in two sections to adapt the instrument both to 110 and 220 volt circuits and several secondaries were provided to suit the various wavelengths of the primary. The output was approximately 500 watts with damped waves about 50,000 cycles per second. For short periods of time undamped oscillations were produced in screwing the vibrating spring tight against the iron core and separating the contacts by the adjusting screw *which also performed the function of a key.*

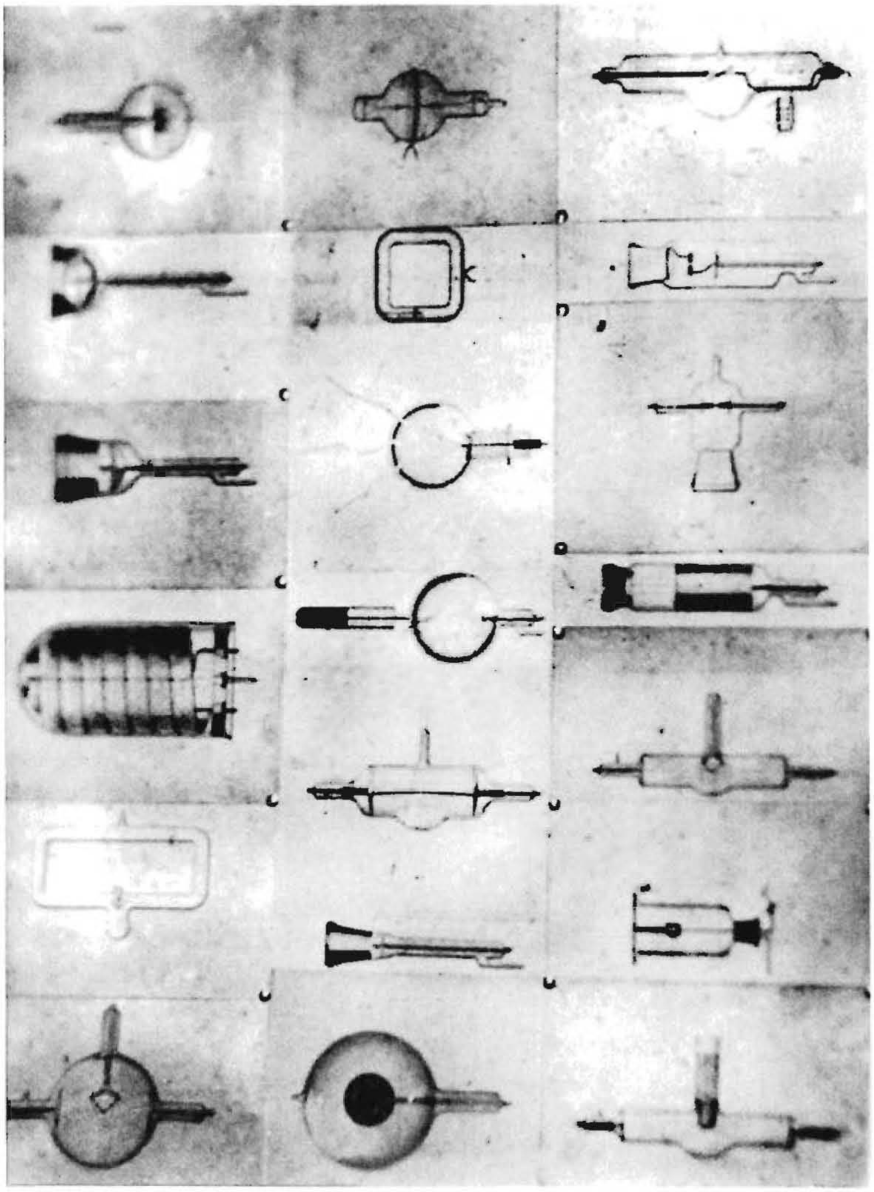
"[The unit in Fig. 18] illustrates a transformer with a rotary break. There are two condensers of the same capacity in the box which can be connected in series or multiple. The charging inductances are in the form of two long spools upon which are supported the secondary terminals. A small direct-current motor, the speed of which can be varied within wide limits, is employed to drive a specially constructed make and break. In other features, the oscillator is like the one illustrated [at left] and its operation will be readily understood from the foregoing. This transformer was used in my wireless experiments and frequently also for lighting the laboratory by my vacuum tubes."[51]

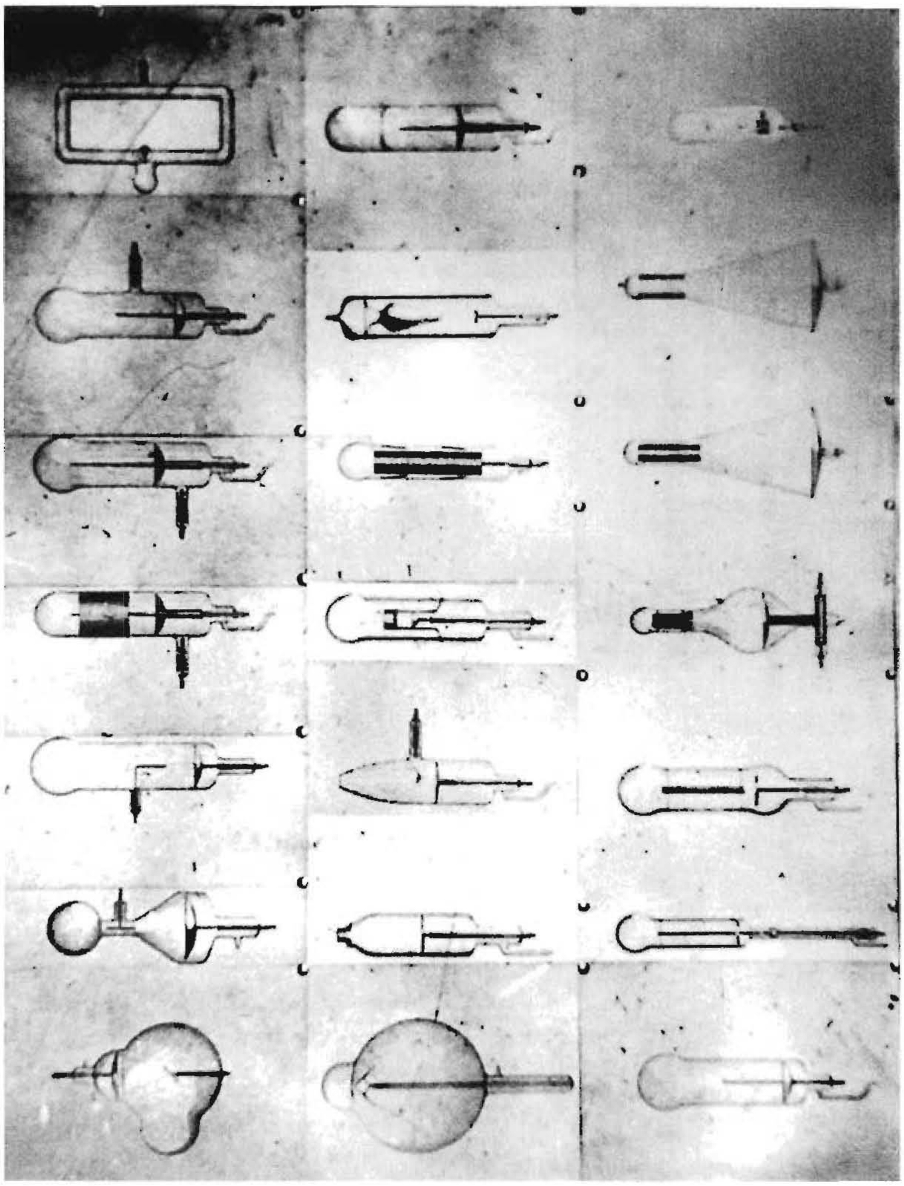
---

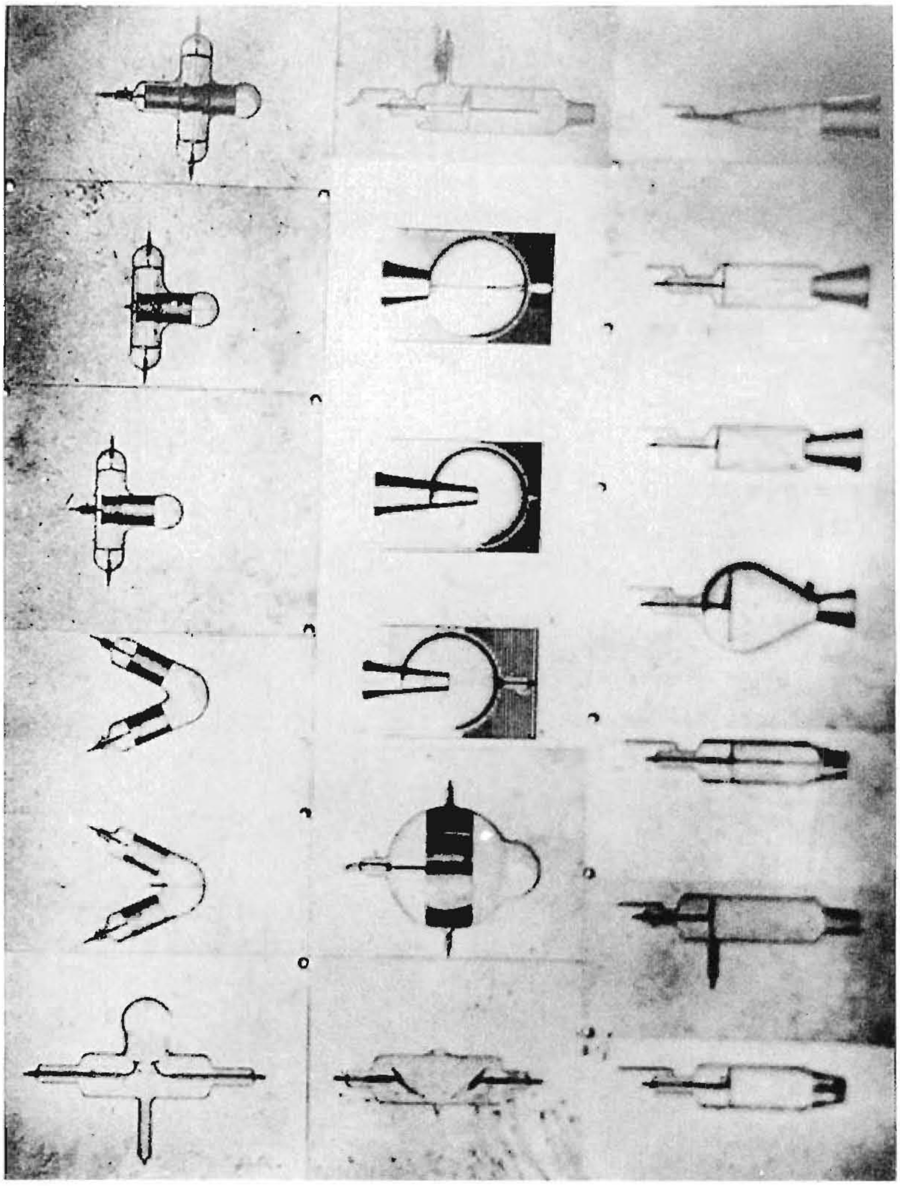
[51] Tesla, "Electrical Oscillators," *Electrical Experimenter*, July 1919, pp. 228-229, 259-260, 276, 276.

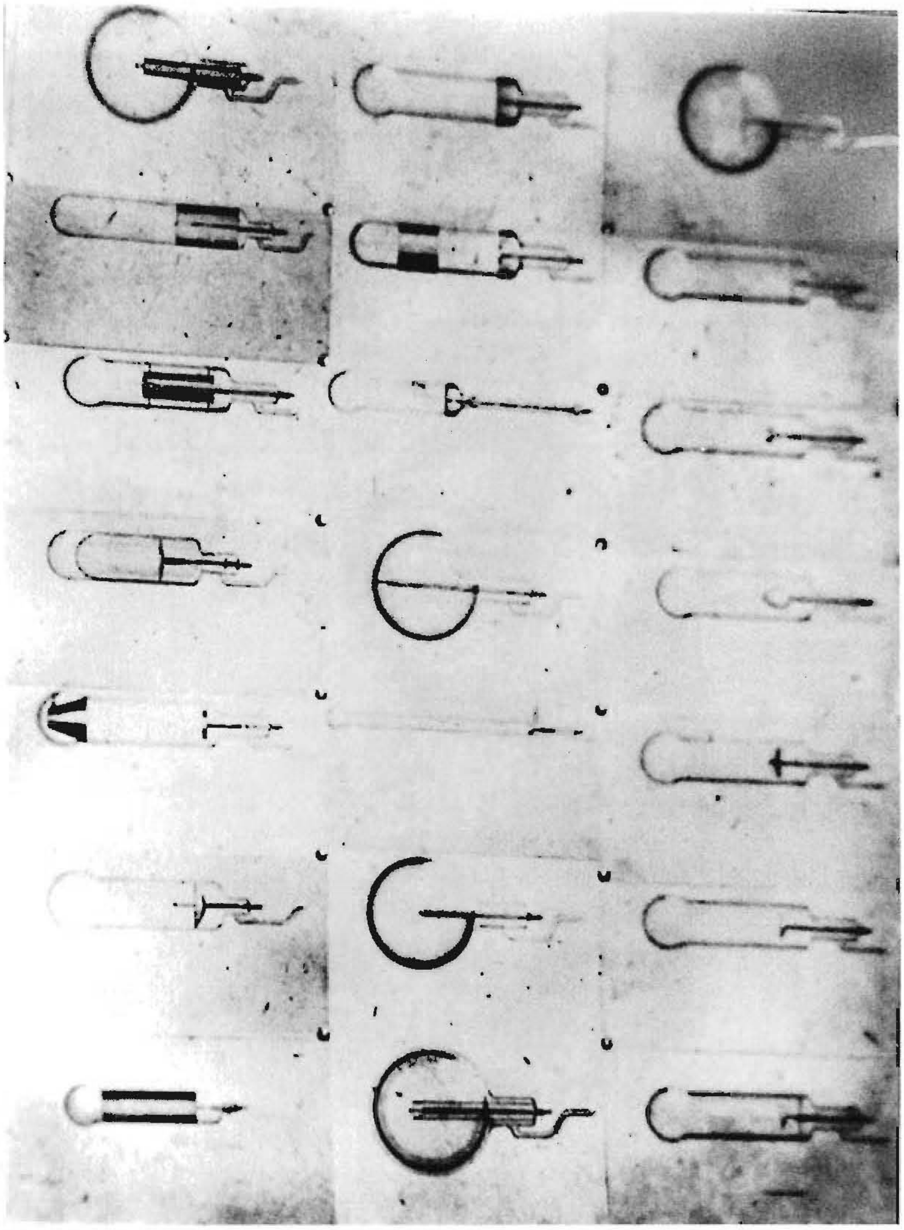
I now show on the wall of this Academy drawings of a great variety of bulbs I used. Every one that you see was built, not in one, but in several forms ... Among these bulbs I have a great number of receiving devices ...."

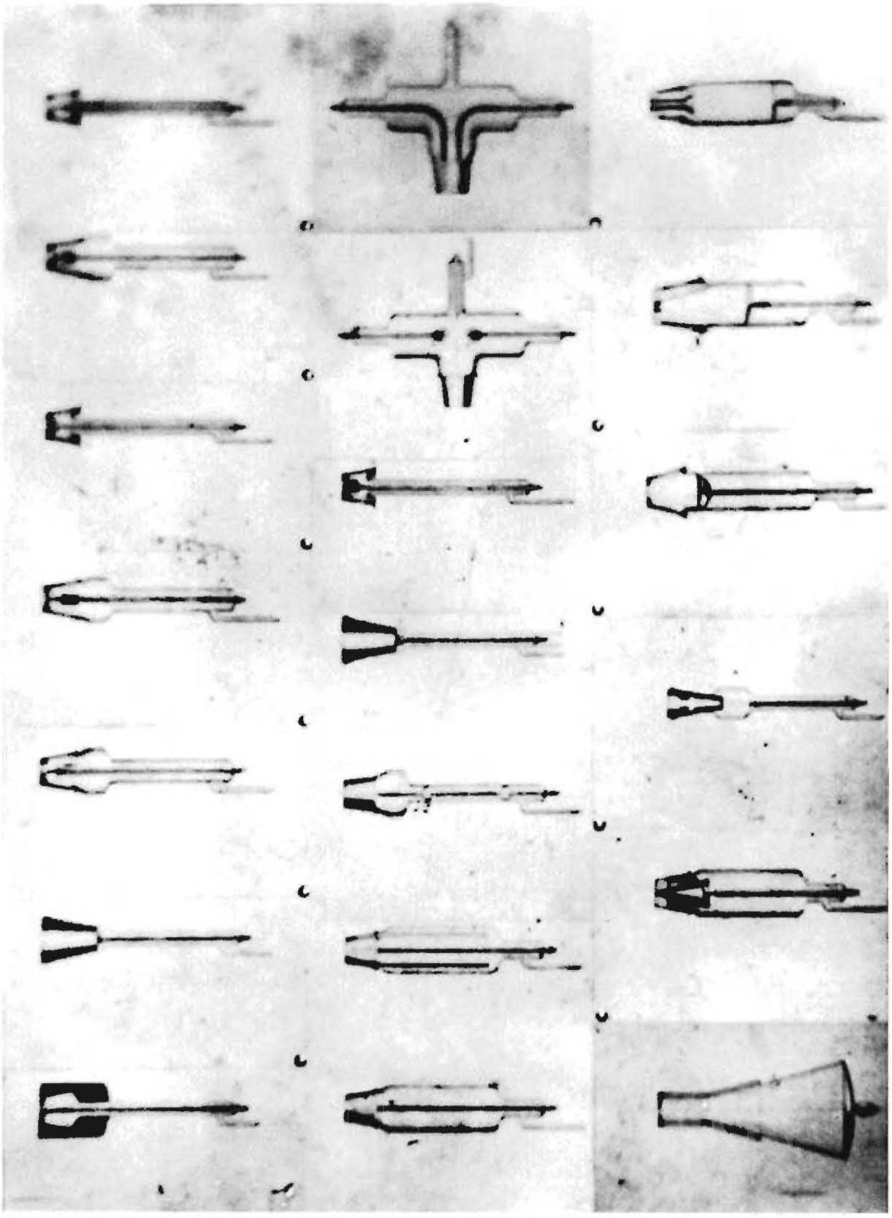












Part 2

The Hurtful Actions of Lenard and Roentgen Tubes

To the Editor of Electrical Review:

The rapidly extending use of the Lenard and Roentgen tubes or Crookes bulbs as implements of the physician, or as instruments of research in laboratories, makes it desirable, particularly in view of the possibility of certain hurtful actions on the human tissues, to investigate the nature of these influences, to ascertain the conditions under which they are liable to occur and --what is most important for the practitioner—to render all injury impossible by the observance of certain rules and the employment of unfailing remedies.

As I have stated in a previous communication to your esteemed journal (see *Electrical Review* of December 2, 1896), no experimenter need be deterred from using freely the Roentgen rays for fear of a poisonous or deleterious action, and it is entirely wrong to give room to expressions of a kind such as may tend to impede the progress and create a prejudice against an already highly beneficial and still more promising discovery; but it cannot be denied that it is equally uncommendable to ignore dangers now when we know that, under certain circumstances, they actually exist. I consider it the more necessary to be aware of these dangers, as I foresee the coming into general use of novel apparatus, capable of developing rays of incomparable great power. In scientific laboratories the instruments are usually in the hands of persons skilled in their manipulation and capable of approximately estimating the magnitude of the effects, and the omission of necessary precautions is, in the present state of our knowledge, not so much to be apprehended; but the physicians, who are keenly appreciating the immense benefits derived from the proper application of the new principle, and the numerous amateurs who are fascinated by the beauty of the novel manifestations, who are all passionately bent upon experimentation in the newly opened up fields, but many of whom are naturally not armed with the special knowledge of the electrician—all of these are much in need of reliable information from experts, and for these chiefly the following lines are written. However, in view of the still incomplete knowledge of these rays, I wish the statements which follow to be considered as devoid of authoritativeness, other than that which is based on the conscientiousness of my study and the faith in the precision of my senses and observations.

Ever since Professor Roentgen's discovery was made known I have carried on investigations in the direction indicated by him, and with perfected apparatus, producing rays of much greater intensity than it was possible to obtain with the usual appliances. Commonly, my bulbs were capable of showing the shadow of a hand on a phosphorescent screen at distances of 40 or 50 feet, or even more, and to the action of these bulbs myself and several of my assistants were exposed for hours at a time, and although the exposures took place every day, not the faintest hurtful action was noted —as long as certain precautions were taken. On the contrary, be it a coincidence, or an effect of the rays, or the result of some secondary cause present in the operation of the bulbs—as, for example, the generation of ozone—my own health, and that of two persons who were daily under the influence of the rays, more or less, has materially improved, and, whatever be the reason, it is a fact that a troublesome cough with which I was constantly afflicted has entirely disappeared, a similar improvement being observed on another person.

In getting the photographic impressions or studying the rays with a phosphorescent screen, I employed a plate of thin aluminum sheet or a gauze of aluminum wires, which was interposed between the bulb and the person, and connected to the ground directly or through a condenser. I adopted this precaution because it was known to me, a long time before, that a certain irritation of the skin is caused by very strong streamers, which, mostly at small distance, are formed on the body of a person through the electrostatic influence of a terminal of alternating high potential. I found that the occurrence of these streamers and their hurtful consequence was completely prevented by the employment of a conducting object, as a sheet of wire gauze placed and connected as described. It was observed, however, that the injurious effects mentioned did not seem to diminish gradually with the distance from the terminal, but ceased abruptly, and I could give no other explanation for the irritation of the skin which would be as plausible as that which I have expressed; namely, that the effect was due to ozone, which was abundantly produced. The latter peculiarity mentioned was also in agreement with this view, since the generation of ozone ceases abruptly at a definite distance from the terminal, making it evident that a certain intensity of action is absolutely required, as in a process of electrolytic decomposition.

In carrying further my investigations, I gradually modified the apparatus in several ways, and immediately I had opportunities to observe hurtful influences following the exposures. Inquiring now what changes I had introduced, I found that I had made three departures from the plan originally followed: First, the aluminum screen was not used; second, a bulb was employed which, instead of aluminum, contained platinum, either as electrode or impact plate; and third, the distances at which the exposures took place were smaller than usual.

It did not require a long time to ascertain that the interposed aluminum sheet was a very effective remedy against injury, for a hand could be exposed for a long time behind it without the skin being reddened, which otherwise invariably and very quickly occurred. This fact impressed me with the conviction that, whatever the nature of the hurtful influences, it was in a large measure dependent either on an electrostatic action, or electrification, or secondary effects resulting therefrom, such as are attendant to the formation of streamers. This view afforded an explanation why an observer could watch a bulb for any length of time, as long as he was holding the hand in front of the body, as in examining with a fluorescent screen, with perfect immunity to all parts of his body, with the exception of the hand. It likewise explained why burns were produced in some instances on the opposite side of the body, adjacent to the photographic plate, whereas portions on the directly exposed part of the body, which were much nearer to the bulb, and consequently subjected to by far stronger rays, remained unaffected. It also made it easy to understand why the patient experienced a prickling sensation on the exposed part of the body whenever an injurious action took place. Finally, this view agreed with the numerous observations that the hurtful actions occurred when air was present, clothing, however thick, affording no protection, while they practically ceased when a layer of a fluid, quite easily penetrated by the rays, but excluding all contact of the air with the skin, was used as a preventive.

Following, now, the second line of investigation, I compared bulbs containing aluminum only with those in which platinum was used besides, ordinarily as impact body, and soon there were enough evidences on hand to dispel all doubt as to the latter metal being by far the more injurious. In support of this statement, one of the experiences may be cited which, at the same time, may illustrate the necessity of taking proper precautions when operating bulbs of very high power. In order to carry out comparative tests, two tubes were constructed of an improved Lenard pattern, in size and most other respects alike. Both contained a concave cathode or reflector of nearly two inches in diameter, and both were provided with an aluminum cap or window. In one of the tubes the cathodic focus was made to coincide with the center of the cap, in the other the cathodic stream was concentrated upon a platinum wire supported on a glass stem axially with the tube a little in front of the window, and in each case the metal of the latter was thinned down in the central portion to such an extent as to be barely able to withstand the inward air pressure. In studying the action of the tubes, I exposed one hand to that containing aluminum only, and the other to the tube with the platinum wire. On turning on the former tube, I was surprised to observe that the aluminum window emitted a clear note, corresponding to the rhythmical impact of the cathodic stream. Placing the hand quite near the window, I felt distinctly that something warm was striking it. The sensation was unmistakable, and quite apart from the warmth felt, differed very much from that prickling feeling produced by streamers or minute sparks. Next I examined the tube with the platinum wire. No sound was emitted by the aluminum window, all the energy of the impact being seemingly spent on the platinum wire, which became incandescent, or else the matter composing the cathodic stream was so far disintegrated that the thin metal sheet offered no material obstruction to its passage. If big lumps are hurled against a wire netting with large meshes, there is considerable pressure exerted against the netting; if, on the contrary—for illustration—the lumps are very small as compared with the meshes, the pressure might not be manifest. But, although the window did not vibrate, I felt, nevertheless, again, and distinctly, that something was impinging against the hand, and the sensation of warmth was stronger than in the previous case. In the action on the screen there was apparently no difference between the two tubes, both rendering it very bright, and the definition of the shadows was the same, as far as it was possible to judge. I had looked through the screen at the second tube a few times only when something detracted my attention, and it was not until about 20 minutes later, when I observed that the hand exposed to it was much reddened and swollen. Thinking that it was due to some accidental injury, I turned again to the examination of the platinum tube, thrusting the same hand close to the window, and now I felt instantly a sensation of pain, which became more pronounced when the hand was placed repeatedly near the aluminum window. A peculiar feature was that the pain appeared to be seated, not at the surface, but deep in the tissues of the hand, or rather in the bones. Although the aggregate exposure was certainly not more than half a minute, I had to suffer severe pain for a few days afterward, and some time later I observed that all the hair was destroyed and that the nails on the injured hand had grown anew.

The bulb containing no platinum was now experimented with, more care being taken, but soon its comparative harmlessness was manifest, for, while it reddened the skin, the injury was not nearly as severe as with the other tube. The valuable experiences thus gained were: The evidence of something hot striking the exposed member; the pain *instantly* felt; the injury produced *immediately* after the exposure, and the increased violence due, in all probability, to the presence of the platinum.

Some time afterward I observed other remarkable actions at very small distances from powerful Lenard tubes. For instance, the hand being held near the window only for a few seconds, the skin seems to become tight, or else the muscles are stiffened, for some resistance is experienced in closing the fist, but upon opening and closing it repeatedly the sensation disappears, apparently no ill effect remaining. I have, furthermore, observed a decided influence on the nasal discharge organs similar to the effects of a cold just contracted. But the most interesting observation in this respect is the following: When such a powerful bulb is watched for some time, the head of the observer being brought very close, he soon after that experiences a sensation so peculiar that no one will fail to notice it when once his attention is called to it, it being almost as positive as touch. If one imagines himself looking at something like a cartridge, for instance, in close and dangerous proximity, and just about to explode, he will get a good idea of the sensation produced, only, in the case of the cartridge, one cannot render himself an account where the feeling exactly resides, for it seems to extend all over the body, this indicating that it comes from a general awareness of danger resulting from previous and manifold experiences, and not from the anticipation of an unpleasant impression directly upon one of the organs, as the eye or the ear; but, in the case of the Lenard bulb, one can at once, and with precision, locate the sensation: it is in the head. Now, this observation might not be of any value except, perhaps, in view of the peculiarity and acuteness of the feeling, were it not that exactly the same sensation is produced when working for some time with a noisy spark gap, or, in general, when exposing the ear to sharp noises or explosions. Since it seems impossible to imagine how the latter could cause such a sensation in any other way except by directly impressing the organs of hearing, I conclude that a Roentgen or Lenard tube, working in perfect silence as it may, nevertheless produces violent explosions or reports and concussions, which, though they are inaudible, take some material effect upon the bony structure of the head. Their inaudibility may be sufficiently explained by the well founded assumption that not the air, but some finer medium, is concerned in their propagation.

But it was in following up the third line of inquiry into the nature of these hurtful actions, namely, in studying the influence of distance, that the most important fact was unearthed. To illustrate it popularly, I will say that the Roentgen tube acts exactly like a source of intense heat. If one places the hand near to a red hot stove, he may be instantly injured. If he keeps the hand at a certain small distance, he may be able to withstand the rays for a few minutes or more, and may still be injured by prolonged exposure; but if he recedes only a little farther, where the heat is slightly less, he may withstand the heat in comfort and any length of time without receiving any injury, the radiations at that distance being too weak to seriously interfere with the life process of the skin. This is absolutely the way such a bulb acts. Beyond a certain distance, no hurtful effect whatever is produced on the skin, no matter *how long* the exposure. The character of the burns is also such as might be expected from a source of high heat. I have maintained, in all deference to the opinions of others, that those who have likened the effects on the skin and tissues to sunburns have misinterpreted them. There is no similarity in this respect, except insofar as the reddening and peeling of the skin is concerned, which may result from innumerable causes. The burns, when slight, rather resemble those people often receive when working close to a strong fire. But when the injury is severe, it is in all appearances like that received from contact with fire or from a red-hot iron. There may be no period of incubation at all, as is evident from the foregoing remarks, the rays taking effect immediately, not to say instantly. In a severe case the skin gets deeply colored and blackened in places, and ugly, ill-foreboding blisters form; thick layers come off, exposing the raw flesh, which, for a time, discharges freely. Burning pain, feverishness, and such symptoms are of course but natural accompaniments. One single injury of this kind, in the abdominal region, to a dear and zealous assistant—the only accident that ever happened to any one but myself in all my laboratory experience—I had the misfortune to witness. It occurred before all these and other experiences were gained, following directly an exposure of five minutes at the fairly safe distance of 11 inches to a very highly-charged platinum tube, the protecting aluminum screen having been unfortunately omitted, and it was such as to fill me with the gravest apprehensions. Fortunately, frequent warm baths, free application of Vaseline, cleaning, and general bodily care soon repaired the ravages of the destructive agent, and I breathed again freely. Had I known more than I did of these injurious actions, such unfortunate exposure would not have been made; had I known less than I did, it might have been made at a smaller distance, and a serious, perhaps irremediable, injury might have resulted.

I am using the first opportunity to comply with the bitter duty of recording the accident. I hope that others will do likewise, so that the most complete knowledge of these dangerous actions may soon be acquired. My apprehensions led me to consider, with keener interest than I would have felt otherwise, what the probabilities were in such a case of the internal tissues being seriously injured. I came to the very comforting conclusion that, no matter what the rays are ultimately recognized to be, practically all their destructive energy must spend itself on the surface of the body, the internal tissues being, in all probability, safe, unless the bulb would placed in very close proximity to the skin, or else, that rays of far greater intensity than now producible were generated. There are many reasons why this should be so, some of which will appear clear from my foregoing statements referring to the nature of the hurtful agencies, but I may be able to cite new facts in support of this view. A significant feature of the case reported may be mentioned. It was observed that on three places, which were covered by thick bone buttons, the skin was entirely unaffected, while it was entirely destroyed under each of the small holes in the buttons. Now, it was impossible for the rays, as investigation showed, to reach these points of the skin in straight lines drawn from the bulb, and this would seem to indicate that not all the injury was due to the rays or radiations under consideration, which unmistakably propagate in straight lines, but that, at least in part, concomitant causes were responsible. A further experimental demonstration of this fact may be obtained in the following manner: The experimenter may excite a bulb to a suitable and rather small degree, so as to illuminate the fluorescent screen to a certain intensity at a distance of, say 7 inches. He may expose his hand at that distance, and the skin will be reddened after a certain duration of exposure. He may now force the bulb up to a much higher power, until, at a distance of 14 inches, the screen is illuminated even stronger than it was before at half that distance. The rays are now evidently stronger at the greater distance, and yet he may expose the hand a very long time, and it is safe to assert that he will not be injured. Of course, it is possible to bring forth arguments which might deprive the above demonstration of force. So, it might be stated, that the actions on the screen or photographic plate do not give us an idea as to the density and other quantitative features of the rays, these actions being entirely of a qualitative character. Suppose the rays are formed by streams of material particles, as I believe, it is thinkable that it might be of no particular consequence, insofar as the visible impression on the screen or film is concerned, whether a trillion of particles per square millimeter strike the sensitive layer or only a million, for example; but with the actions on the skin it is different; these must surely and very materially depend on the quantity of the streams.

As soon as the before-mentioned fact was recognized, namely, that beyond a certain distance even the most powerful tubes are incapable of producing injurious action, no matter how long the exposure may last, it became important to ascertain the safe distance. Going over all my previous experiences, I found that, very frequently, I have had tubes which at a distance of 12 feet, for illustration, gave a strong impression of the chest of a person with an exposure of a few minutes, and many times persons have been subjected to the rays from these tubes at a distance of from 18 to 24 inches, the time of exposure varying from 10 to 45 minutes, and never the faintest trace of an injurious action was observed. With such tubes I have even made long exposures at distances of 14 inches, always, of course, through a thin sheet or wire gauze of aluminum connected to the ground, and, in each case, observing the precaution that the metal would not give any spark when the person was touching it with the hand, as it might sometimes be when the electrical vibration is of extremely high frequency, in which case a ground connection, through a condenser of proper capacity, should be resorted to. In all these instances bulbs containing only aluminum were used, and I therefore still lack sufficient data to form an exact idea of what distance would have been safe with a platinum tube. From the case previously cited, we see that a grave injury resulted at a distance of 11 inches, but I believe that, had the protecting screen been used, the injury, if any, would have been very slight. Taking all my experiences together, I am convinced that no serious injury can result if the distance is greater than 16 inches and the impression is taken in the manner I have described.

Having been successful in a number of lines of inquiry pertaining to this new department of science, I am able at present to form a broader view of the actions of the bulbs, which, I hope, will soon assume a quite definite shape. For the present, the following brief statement may be sufficient. According to the evidences I am obtaining, the bulb, when in action, is emitting a stream of small material particles. There are some experiments which seem to indicate that these particles start from the outer wall of the bulb; there are others which seem to prove that there is an actual penetration of the wall, and in the case of a thin aluminum window, I have now not the least doubt that some of the finely disintegrated cathodic matter is actually forced through. These streams may simply be projected to a great distance, the velocity gradually diminishing without the formation of any waves, or they may give rise to concussions and longitudinal waves. This, for the present consideration, is entirely immaterial, but, assuming the existence of such streams of particles, and disregarding such actions as might be due to the properties, chemical or physical, of the projected matter, we have to consider the following specific actions:

First.. There is the thermal effect. The temperature of the electrode or impact body does not in any way give us an idea of the degree of heat of the particles, but, if we consider the probable velocities only, they correspond to temperatures which may be as high as 100,000 degrees centigrade. It may be sufficient that the particles are simply at a high temperature to produce an injurious action, and in fact, many evidences point in this direction. But against this is the experimental fact that we cannot demonstrate such a transference of heat, and no satisfactory explanation is found yet, although, in carrying my investigations in this direction, I have arrived at some results.

Second, there is the purely electrical effect. We have absolute experimental evidence that that particles or rays, to express myself generally, convey an immense amount of electricity, and I have even found a way of how to estimate and measure that amount. Now it is likewise possible that the mere fact of these particles being highly electrified is sufficient to cause the destruction of the tissue. Certainly, on contact with the skin, the electrical charges will be given off, and may give rise to strong and destructive local currents in minute paths of the tissue. Experimental results are in accord with this view, and, in pushing my inquiry in this direction, I have been still more successful than in the first. Yet, while as I have suggested before, this view explains best the action on a sensitive layer, experiment shows that, when the supposed particles traverse a grounded plate, they are not deprived entirely of their electrification, which is not satisfactorily explained.

The *third* effect to be considered is the electro-chemical. The charged particles give rise to an abundant generation of ozone and other gases, and these we know, by experiment, destroy even such a thing as rubber, and are, therefore, the most likely agent in the destruction of the skin, and the evidences are strongest in this direction, since a small layer of a fluid, preventing the contact of gaseous matter with the skin, seems to stop all action.

The *last* effect to be considered is the purely mechanical. It is thinkable that material particles, moving with great speed, may, merely by a mechanical impact and unavoidable heating at such speeds, be sufficient to deteriorate the tissues, and in such a case deeper layers might also be injured, whereas it is very probable that no such thing would occur if any of the former explanations would be found to hold.

Summing up my experimental experiences and the conclusions derived from them, it would seem advisable, first, to abandon the use of bulbs containing platinum; second, to substitute for them a properly constructed Lenard tube, containing pure aluminum only, a tube of this kind having, besides, the advantage that it can be constructed with great mechanical precision, and therefore is capable of producing much sharper impressions; third, to use a protecting screen of aluminum sheet, as suggested, or, instead of this, a wet cloth or layer of a fluid; fourth, to make the exposures at distances of, at least, 14 inches, and preferably expose longer at a larger distance.

New York, May 1, 1897.

Part 3

The Source of Roentgen Rays, the Practical Construction and Safe Operation of Lenard Tubes

THE SOURCE OF ROENTGEN RAYS AND THE PRACTICAL CONSTRUCTION AND SAFE OPERATION OF LENARD TUBES.

To the Editor of Electrical Review:

I have for some time felt that a few indications in regard to the practical construction of Lenard tubes of improved designs, a great number of which I have recently exhibited before the New York Academy of Sciences [April 6, 1897], would be useful and timely, particularly as by their proper construction and use much of the danger attending the experimentation with the rays may be avoided. The simple precautions which I have suggested in my previous communications to your esteemed journal are seemingly disregarded, and cases of injury to patients are being almost daily reported, and in view of this only, were it for no other reason, the following lines, referring to this subject, would have been written before had not again pressing and unavoidable duties prevented me from doing so. A short and, I may say, most unwelcome interruption of the work which has been claiming my attention makes this now possible. However, as these opportunities are scarce, I will utilize the present to dwell in a few words on some other matters in connection with this subject, and particularly on a result of importance which I have reached some time ago by the aid of such a Lenard tube, and which, if I am correctly informed, I can only in part consider as my own, since it seems that practically it has been expressed in other words by Professor Roentgen in a recent communication to the Academy of Sciences of Berlin. The result alluded to has reference to the much disputed question of the source of the Roentgen rays. As will be remembered, in the first announcement of his discovery, Roentgen was of the opinion that the rays which affected the sensitive layer emanated from the fluorescent spot on the glass wall of the bulb; other scientific men next made the cathode responsible; still others the anode, while some thought that the rays were emitted solely from fluorescent powders or surfaces, and speculations, mostly unfounded, increased to such an extent that, despairingly, one would exclaim with the poet:

> "O glücklich, wer noch hoffen kann,
> Aus diesem Meer des Irrtums aufzutauchen!"

My own experiments led me to recognize that, regardless of the location, the chief source of these rays was the place of the *first* impact of the projected stream of particles within the bulb. This was merely a broad statement, of which that of Professor Roentgen was a special case, as in his first experiments the fluorescent spot on the glass wall was, incidentally, the place of the first impact of the cathodic stream. Investigations carried on up to the present day have only confirmed the correctness of the above opinion, and the place of the first collision of the stream of particles—be it an anode or independent impact body, the glass wall or an aluminum window—is still found to be the principal source of the rays. But as will be seen presently, it is not the only source.

Since recording the above fact my efforts were directed to finding answers to the following questions: First, is it necessary that the impact body should be within the tube? Second, is it required that the obstacle in the path of the cathodic stream should be a solid or liquid? And, third, to what extent is the velocity of the stream necessary for the generation of and influence upon the character of the rays emitted?

In order to ascertain whether a body located outside of the tube and in the path or in the direction of the stream of particles was capable of producing the same peculiar phenomena as an object located inside, it appeared necessary to first show that there is an actual penetration of the particles through the wall, or otherwise that the actions of the supposed streams, of whatever nature they might be, were sufficiently pronounced in the outer region close to the wall of the bulb as to produce some of the effects which are peculiar

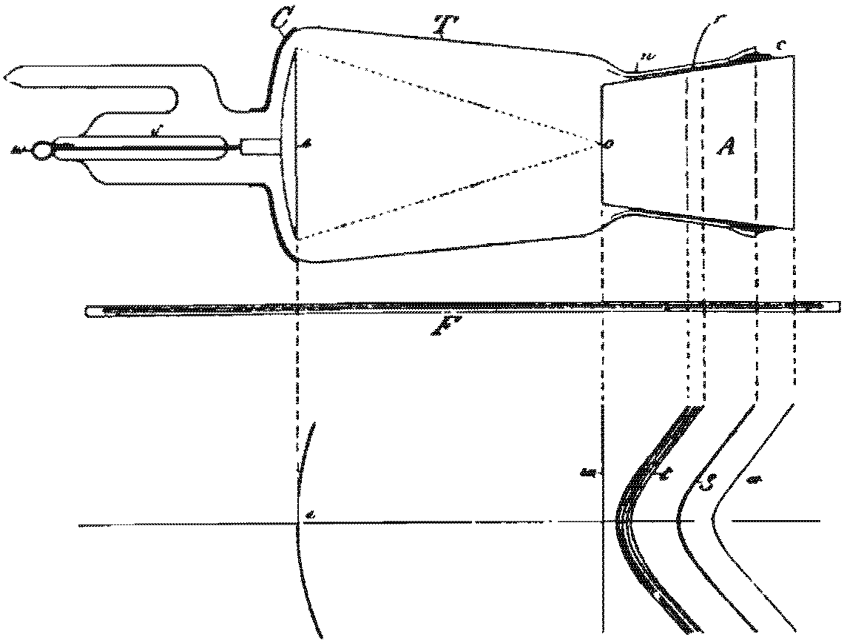


Fig. 1. Illustrating an experiment revealing the real source of the Roentgen rays.

to a cathodic stream. It was not difficult to obtain with a properly prepared Lenard tube, having an exceedingly thin window, many and at first surprising evidences of this character. Some of these have already been pointed out, and it is thought sufficient to cite here one more which I have since observed. In the hollow aluminum cap *A* of a tube as shown in diagram Fig. 1, which will be described in detail, I placed a half-dollar silver piece, supporting it at a small distance from and parallel to the window or bottom of the cap by strips of mica in such a manner that it was not touching the metal of the tube, an air space being left all around it. Upon exciting the bulb for about 30 to 45 seconds by the secondary discharge of a powerful coil of a novel type now well known, it was found that the silver piece was rendered so hot as to actually scorch the hand; yet the aluminum window, which offered a very insignificant obstacle to the cathodic stream, was only moderately warmed. Thus it was shown that the silver alloy, owing to its density and thickness, took up most of the energy of the impact, being acted upon by the particles almost identically as if it had been inside of the bulb, and what is more, indications were obtained, by observing the shadow, that it behaved like a second source of the rays, inasmuch as the outlines of the shadows, instead of being sharp and clear as when the half-dollar peace was removed, were dimmed. It was immaterial for the chief object of the inquiry to decide by more exact methods whether the cathodic particles actually penetrated the window, or whether a new and separate stream was projected from the outer side of the window. In my mind there exists not the least doubt that the former was the case, as in this respect I have been able to obtain numerous additional proofs, upon which I may dwell in the near future.

I next endeavored to ascertain whether it was necessary that the obstacle outside was, as in this case, a solid body, or a liquid, or broadly, a body of measurable dimensions, and it was in investigating in this direction that I came upon the important result to which I referred in the introductory statements of this communication. I namely observed rather accidentally, although I was following up a systematic inquiry, what is illustrated in diagram Fig. 1. The diagram shows a Lenard tube of improved design, consisting of a tube *T* of thick glass tapering towards the open end, or neck *n*, into which is fitted an aluminum cap *A*, and a spherical cathode *e*, supported on a glass stem *s*, and platinum wire *w* sealed in the opposite end of the tube as usual. The aluminum cap *A*, as will be observed, is not in actual contact with the ground glass wall, being held at a small distance from the latter by a narrow and continuous ring of tinfoil *r*. The outer space between the glass and the cap *A* is filled with cement *c*, in a manner which I shall later describe. *F* is a Roentgen screen such as is ordinarily used in making the observations.

Now, in looking upon the screen in the direction from *F* to *T*, the dark lines indicated on the lower part of the diagram were seen on the illuminated background. The curved line *e* and the straight line *W* were, of course, at once recognized as the outlines of the cathode *e* and the bottom of the cap *A* respectively, although, in consequence of a confusing optical illusion, they appeared much closer together than they actually were. For instance, if the distance between *e* and *o* was 5 inches, these lines would appear on the screen about 2 inches apart, as nearly as I could judge by the eye. This illusion may be easily explained and is quite unimportant, except that it might be of some moment to physicians to keep this fact in mind when making examinations with the screen as, owing to the above effect, which is sometimes exaggerated to a degree hard to believe, a completely erroneous idea of the distance of the various parts of the object under examination might be gained, to the detriment of the surgical operation. But while the lines *e* and *W* were easily accounted for, the curved lines *t*, *g*, *a* were at first puzzling. Soon, however, it was ascertained that the faint line *a* was the shadow of the edge of the aluminum cap, the much darker line *g* that of the rim of the glass tube *T*, and *t* the shadow of the tinfoil ring *r*. These shadows on the screen *F* clearly showed that the agency which affected the fluorescent material was proceeding from the space outside of the bulb towards the aluminum cap, and chiefly from the region through which the primary disturbances or streams emitted from the tube through the window were passing, which observation could not be explained in a more plausible manner than by assuming that the air and dust particles outside, in the path of the projected streams, afforded an obstacle to their passage and gave rise to impacts and collisions spreading through the air in all directions, thus producing continuously new sources of the rays. It is this fact which, in his recent communication before mentioned, Roentgen has brought out. So, at least, I have interpreted his reported statement that the rays emanate from the irradiated air. It now remains to be shown whether the air, from which carefully all foreign particles are removed, is capable of behaving as an impact body and source of the rays, in order to decide whether the generation of the latter is dependent on the presence in the air of impact particles of measurable dimensions. I have reasons to think so.

With the knowledge of this fact we are now able to form a more general idea of the process of generation of the radiations which have been discovered by Lenard and Roentgen. It may be comprised in the statement that the streams of minute material particles projected from an electrode with great velocity in encountering obstacles wherever they may be, within the bulb, in the air or other medium or in the sensitive layers themselves, give rise to rays or radiations possessing many of the properties of those known as light. If this physical process of generation of these rays is undoubtedly demonstrated as true, it will have most important consequences, as it will induce physicists to again critically examine many phenomena which are presently attributed to transverse ether waves, which may lead to a radical modification of existing views and theories in regard to these phenomena, if not as to their essence so, at least, as to the mode of their production.

My effort to arrive at an answer to the third of the above questions led me to the establishment, by actual photographs, of the close relationship which exists between the Lenard and Roentgen rays. The photographs bearing on this point were exhibited at a meeting of the New York Academy of Sciences—before referred to—April 6, 1897, but unfortunately, owing to the shortness of my address, and concentration of thought on other matters, I omitted what was most important; namely, to describe the manner in which these photographs were obtained, an oversight which I was able to only partially repair the day following. I did, however, on that occasion illustrate and describe experiments in which was shown the deflectibility of the Roentgen rays by a magnet, which establishes a still closer relationship, if not identity, of the rays named after these two discoverers. But the description of these experiments in detail, as well as of other investigations and results in harmony with and restricted to the subject I brought before that scientific body, will appear in a longer communication which I am slowly preparing.[*]

[*] The "longer communication" referred to is undoubtedly the lecture, "High Frequency Oscillation for Electro-Therapeutics and Other Purposes," presented before The American Electro-Therapeutics Association, Sept. 14, 1898.

To bring out clearly the significance of the photographs in question, I would recall that, in some of my previous contributions to scientific societies, I have endeavored to dispel a popular opinion before existing that the phenomena known as those of Crookes were dependent on and indicative of high vacua. With this object in view, I showed that phosphorescence and most of the phenomena in Crookes bulbs were producible at greater pressures of the gases in the bulbs by the use of much higher or more sudden electromotive impulses. Having this well demonstrated fact before me, I prepared a tube in the manner described by Lenard in his first classical communication on this subject. The tube was exhausted to a moderate degree, either by chance or of necessity, and it was found that, when operated by an ordinary high-tension coil of a low rate of change in the current, no rays of any of the two kinds could be detected, even when the tube was so highly strained as to become very hot in a few moments. Now, I expected that, if the suddenness of the impulses through the bulb were sufficiently increased, rays would be emitted. To test this I employed a coil of a type which I have repeatedly described, in which the primary is operated by the discharges of a condenser. With such an instrument any desired suddenness of the impulses may be secured, there being practically no limit in this respect, as the energy accumulated in the condenser is the most violently explosive agent we know, and any potential or electrical pressure is obtainable. Indeed, I found that in increasing the suddenness of the electromotive impulses through the tube—without, however, increasing, but rather diminishing the total energy conveyed to it—phosphorescence was observed and rays began to appear, first the feebler Lenard rays and later, by pushing the suddenness far enough, Roentgen rays of great intensity, which enable me to obtain photographs showing the finest texture of the bones. Still, the same tube, when again operated with the ordinary coil of a low rate of change in the primary current, emitted practically no rays, even when, as before stated, much more energy, as judged from the heating, was passed through it. This experience, together with the fact that I have succeeded in producing by the use of immense electrical pressures, obtainable with certain apparatus designed for this express purpose, some impressions in free air, have led me to the conclusion that in lightning discharges Lenard and Roentgen rays must be generated at ordinary atmospheric pressure.

At this juncture I realize, by a perusal of the preceding lines, that my scientific interest has dominated the practical, and that the following remarks must be devoted to the primary object of this communication—that is, to giving some data for the construction to those engaged in the manufacture of the tubes and, perhaps, a few useful hints to practicing physicians who are dependent on such information. The foregoing was, nevertheless, not lost for this object, inasmuch as it has shown how much the result obtained depends on the proper construction of the instruments, for with ordinary implements, most of the above observations could not have been made.

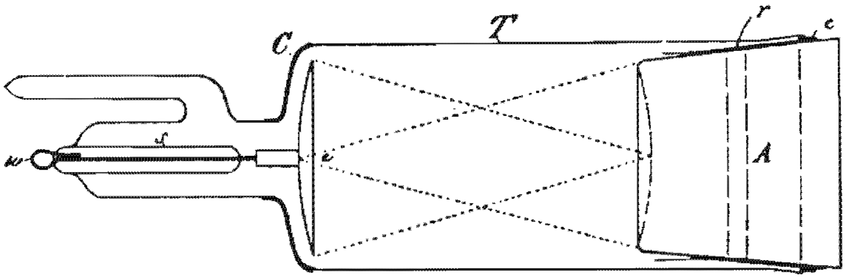


Fig. 2.—Improved Lenard tube.

I have already described the form of tube illustrated in Fig. 1, and in Fig. 2 another still further improved design is shown. In this case the aluminum cap A, instead of having a straight bottom as before, is shaped spherically, the center of the sphere coinciding with that of the electrode *e*, which itself, as in Fig. 1, has its focus in the center of the window of cap *A*, as indicated by the dotted lines. The aluminum cap *A* has a tinfoil ring *r*, as that in Fig. 1, or else the metal of the cap is spun out on that place so as to afford a bearing of small surface between the metal and the glass. This is an important practical detail as, by making the bearing surface small, the pressure per unit of area is increased and a more perfect joint made. The ring *r* should be first spun out and then ground to fit the neck of the bulb. If a tinfoil ring is

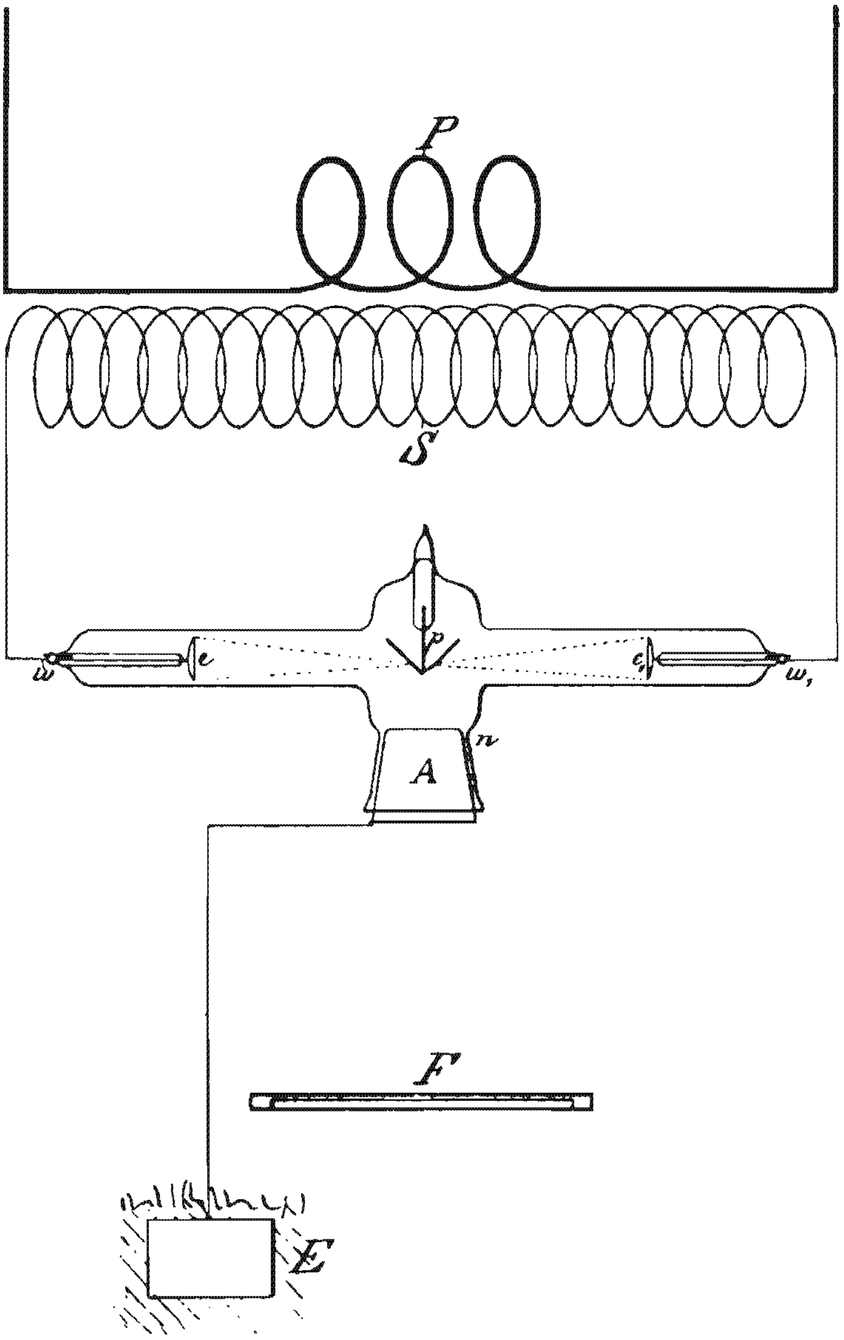


Fig. 3.—Illustrating arrangement with improved double-focus tube for reducing injurious actions.

used instead, it may be cut out of one of the ordinary tinfoil caps obtainable in the market, care being taken that the ring is very smooth.

In Fig. 3 I have shown a modified design of tube which, as the two types before described, was comprised in the collection I exhibited. This, as will be observed, is a double-focus tube, with impact plates of iridium alloy and an aluminum cap *A* opposite the same. The tube is not shown because of any originality in design, but simply to illustrate a practical feature. It will be noted that the aluminum caps in the tubes described are fitted inside of the necks and not outside, as is frequently done. Long experience as demonstrated that it is practically impossible to maintain a high vacuum in a tube with an outside cap. The only way I have been able to do this in a fair measure is by cooling the cap by a jet of air, for instance, and observing the following precautions: The air jet is first turned on slightly and upon this the tube is excited. The current through the latter, and also the air pressure, are then gradually increased and brought to the normal working condition. Upon completing the experiment the air pressure and current through the tube are both gradually reduced and both so manipulated that no great differences in temperature result between the glass and aluminum cap. If these precautions are not observed the vacuum will be immediately impaired in consequence of the uneven expansion of the glass and metal.

With tubes as these presently described, it is quite unnecessary to observe this precaution if proper care is taken in their preparation. In inserting the cap the latter is cooled down as low as it is deemed advisable without endangering the glass, and it is then gently pushed in the neck of the tube, taking care that it sets straight.

The two most important operations in the manufacture of such a tube are, however, the thinning down of the aluminum window and the sealing in of the cap. The metal of the latter may be one thirty-second or even one-sixteenth of an inch thick, and in such case the central portion may be thinned down by a countersink tool about one-fourth of an inch in diameter as far as it is possible without tearing the sheet. The further thinning down may then be done by hand with a scraping tool; and, finally, the metal should be gently beaten down so as to surely close the pores which might permit a slow leak. Instead of proceeding in this way I have employed a cap with a hole in the center, which I have closed with a sheet of pure aluminum a few thousandths of an inch thick, riveted to the cap by means of a washer of thick metal, but the results were not quite as satisfactory.

In sealing the cap I have adopted the following procedure: The tube is fastened on the pump in the proper position and exhausted until a permanent condition is reached. The degree of exhaustion is a measure of perfection of the joint. The leak is usually considerable, but this is not so serious a defect as might be thought. Heat is now gradually applied to the tube by means of a gas stove until a temperature up to about the boiling point of sealing wax is reached. The space between the cap and the glass is then filled with sealing wax of good quality; and, when the latter begins to boil, the temperature is reduced to allow its settling in the cavity. The heat is then again increased, and this process of heating and cooling is repeated several times until the entire cavity, upon reduction of the temperature, is found to be filled uniformly with the wax, all bubbles having disappeared. A little more wax is then put on the top and the exhaustion carried on for an hour or so, according to the capacity of the pump, by application of moderate heat much below the melting point of the wax.

A tube prepared in this manner will maintain the vacuum very well, and will last indefinitely. If not used for a few months, it may gradually lose the high vacuum, but it can be quickly worked up. However, if after long use it becomes necessary to clean the tube, this is easily done by gently warming it and taking off the cap. The cleaning may be done first with acid, then with highly diluted alkali, next with distilled water, and finally with pure rectified alcohol.

These tubes, when properly prepared, give impressions much sharper and reveal much more detail than those of ordinary make. It is important for the clearness of the impressions that the electrode should be properly shaped, and that the focus should be exactly in the center of the cap or slightly inside. In fitting in the cap, the distance from the electrode should be measured as exactly as possible. It should also be remarked that the thinner the window, the sharper are the impressions, but it is not advisable to make it too thin, as it is apt to melt at a point on turning on the current.

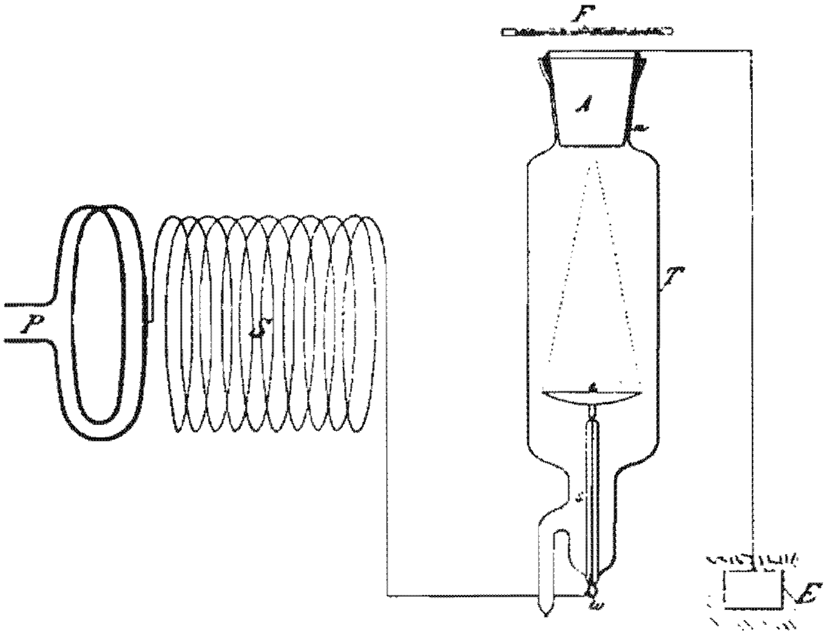


Fig. 4.—Illustrating arrangement with a Lenard tube for safe working at close range.

The above advantages are not the only ones which these tubes offer. They are also better adapted for purposes of examination by surgeons, particularly if used in the peculiar manner illustrated in diagrams Fig. 3 and Fig. 4, which are self-explanatory. It will be seen that in each of these the cap is connected to the ground. This decidedly diminishes the injurious action and enables also to take impressions with very short exposures of a few seconds only at close range, inasmuch as, during the operation of the bulb, one can easily touch the cap without any inconvenience, owing to the ground connection. The arrangement shown in Fig. 4 is particularly advantageous with a form of single terminal, which coil I have described on other occasions and which is diagrammatically illustrated, P being the primary and S the secondary. In this instance the high-potential terminal is connected to the electrode, while the cap is grounded. The tube may be placed in the position indicated in the drawing, under the operating table and quite close, or even in contact with the body of the patient, if the impression requires only a few seconds as, for instance, in examining parts of the members. I have taken many impressions with such tubes and have observed no injurious action, but I would advise not to expose for longer than 2 or 3 minutes at very short distances. In this respect the experimenter should bear in mind what I have stated in previous communications. At all events it is certain that, in proceeding in the manner described, additional safety is obtained and the process of taking impressions much quickened. To cool the cap, a jet of air may be used, as before stated, or else a small quantity of water may be poured in the cap each time when an impression is taken. The water only slightly impairs the action of the tube, while it maintains the window at a safe temperature. I may add that the tubes are improved by providing back of the electrode a metallic coating C, shown in Fig. 3 and Fig 4.[*]

New York, August 9, 1897.

***correction fig 1 and fig 2**