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A LABORATORY METHOD OF PRODUCING HIGH POTENTIALS

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Abstract

Details are given of the experimental arrangement by which, using Tesla coils in oil, very high potentials have been produced and measured. Excited at the rate of 120 sparks per second Tesla coils have been operated at 3,000,000 volts in ordinary transformer oil at atmospheric pressure. In oil under a pressure of 500 pounds per square inch, voltages as high as 5,200,000 have been produced with intermittent excitation. These voltages (peak values) are measured by a simple capacity-potentiometer, in which an insulated electrode "picks up" a known fraction of the total voltage, this fractional voltage being measured by means of a sphere gap. Measurements are given of the voltage-distribution along Tesla coils. Calculations and measurements of the efficiency and power-output of such coils show that at 120 sparks per second, a coil operating at 5,000,000 volts provides sufficient power, if used to accelerate helium nuclei in a suitable vacuum-tube, to yield the equivalent of about 2,600 grams of radium.

THE importance of obtaining sources of high-speed electrons and atomic nuclei for physical investigations is so obvious that an explanation of the aim of the present work is hardly needed. It may be permitted however to say a few words about the part played by experiments with penetrating radiations in the past and to mention briefly some of the current problems for the solution of which the development of new and more powerful sources than have been available appears to be essential.

The Rutherford-Bohr atomic model was suggested by experiments on the scattering of α-particles. Their penetrating nature made it possible to obtain a simple interpretation of the results. The understanding of the nature of the solid state has received its main stimulus from experiments following Laue's discovery. Here the penetrating x-ray quanta offer direct and clear information; similarly with the Compton effect and with Rutherford's nuclear disintegration experiments. These very important experimental facts forming the foundation of modern theoretical conceptions have come out of experiments employing high-energy quanta, electrons, and α-particles. The historical reason for the importance of high-energy experiments is, of course, that classical physics corresponds to energy-jumps of zero-value so that the larger the energy concerned the more radical the departure from classical physics and the more interesting the phenomenon. Quantum mechanics has explained in recent years all of the fundamental facts in ordinary atomic structure. According to current theoretical opinion it is highly improbable that one shall find a serious contradiction to the present theoretical scheme by studies of line and band spectra. Apparently the main unsolved questions at present are Dirac's $\pm m$ difficulty and the combined relativistic treatment of matter and electrodynamics. The first of these as shown by Klein becomes particularly pronounced for potential walls of high absolute value. It may be hoped that light may be thrown on the question by studies on nuclei by means of particles with high kinetic energy.

The precise form of the equation for one electron is intimately concerned with the $\pm m$ difficulty. It will be noted that by studying the intensity of scattering of recoil-electrons by hard γ-rays, Skobeltzin[1] has recently obtained evidence for preferring Dirac's equation for a free electron to the older Schroedinger form. His intensities agree with the calculations of Klein-Nishina, which use Dirac's equation, rather than with the older calculations of Dirac employing the Schroedinger equation without spin. It is not altogether clear at present to what extent Skobeltzin's experiments prove the validity of Dirac's equation or deal only with the presence of the electronic spin. It is clear however that when repeated with still more penetrating radiation they will give very important evidence. The practical approach to the combined treatment of matter and the electromagnetic field is also in all probability to be obtained by studying systems containing two particles in a state of rapid relative motion. Experiments on atomic nuclei giving their energy-levels, conditions for disintegration, etc., may be expected to offer new and valuable evidence for these still unsolved theoretical points and may besides suggest quite different questions and difficulties which do not come up in dealing with phenomena outside atomic nuclei.

We have thought it worth while therefore to construct high-potential equipment of convenient laboratory dimensions to make it possible to perform experiments on high-velocity particles. The electrical problem of producing high potentials was solved without much difficulty over two years ago.[2] The construction of high-potential vacuum (x-ray) tubes has proved more difficult but is at present sufficiently advanced to make a progress-report of interest and to show that the Tesla coils used for producing high potentials are suited for supplying the potentials to vacuum-tubes. The details of the electrical arrangement not having been published before we have divided the matter into two parts the present paper being concerned with the electrical arrangements and the one following with the construction and experiences with high-potential vacuum-tubes.

The apparatus used for producing high potentials is old and well-known under the name of Elihu Thomson or Tesla coils. Since their invention Tesla coils have been known to give possibilities of producing with limited means potentials of the order of one million volts.[3] They have commonly been used in air, the insulating qualities of which constituted a limitation on their performance. It is difficult to construct Tesla coils of sufficiently large dimensions to prevent corona and sparking in air. The energy con-

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[1] D. Skobeltzin, Nature **123**, 411 (1929).

[2] G. Breit and M. A. Tuve, Nature **121**, 535 (1928).

[3] M. Wolfke, Phys. Zeits. **24**, 249 (1923).

sumed in the corona and sparking is so large that the Tesla coil ceases to operate as a resonance-transformer on account of the high damping and loses most of its advantages. If the dimensions of the coil are sufficiently large to prevent corona its electrostatic capacity becomes inconveniently large and necessitates unnecessarily cumbersome primary circuits. The main point in the operation of Tesla coils is therefore to prevent corona and sparking by using the high-potential parts of the coil in a medium of high dielectric strength. For a number of years two of us had in mind the possibility of using Tesla coils in a vacuum or in some other insulating medium. The method described here employs transformer oil which we have found sufficient for roughly five million volts when used under pressure and three million volts at atmospheric pressure. These figures are somewhat arbitrary, simply being the voltages obtained in the laboratory and not representing final limits in the voltages obtainable with oil. No doubt still higher voltages can be obtained by using oil for insulation. The practical advantages of oil over vacuum for preliminary trials are obvious when the question of repairs, changes in design, and baking out of metal parts is considered. The ultimate possibility of using Tesla coils in a vacuum is of course not excluded.

Experimental Arrangements

The principles underlying the operation of a Tesla coil are well known and need not be explained here in detail. The important thing is that two resonant oscillatory electrical circuits, the primary and the secondary, are coupled magnetically to each other. The primary circuit has a large capacity and a small inductance while the secondary (the Tesla coil) has a large inductance and a small capacity. The condenser of the primary circuit is charged to a high potential (of the order of 30 or 60 kv) and is allowed to discharge suddenly through a spark-gap and the primary inductance. An oscillatory discharge takes place. The secondary circuit being in resonance with the primary the energy is transferred with fair efficiency to the secondary before the damping appreciably reduces the amplitudes of oscillation. In the set-ups used the peak-voltage of the secondary circuit corresponds roughly to the transfer of one-fourth of the energy of the primary condenser to the secondary. The resonant frequencies of the coils used have been of the order of 100,000 cycles per second.

Figure 1 shows the arrangement for a Tesla coil in oil under pressure, with which over 5,000,000 volts were obtained. The condenser is fed on rectified current supplied by an x-ray machine. The primary gap is of the stationary type.* The use of rectified current is advisable if power consumption and large charging currents of the primary condenser are to be avoided. The arrangement can also be used without a rectifier, the primary condenser being then fed by a transformer and discharged through a syn-

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* It can be made cheaply out of ten-inch hollow zinc-balls used for decoration purposes and usually furnished in the form of two hemispheres. For long and continued use heavier electrodes are preferable.

chronous gap. For our highest voltages we have been forced to use the rectifier because our power-lines have the unusually small capacity of 50 KVA.

The synchronous gap has been used up to 3,000,000 volts secondary output. The transformer was fed on 60-cycle alternating current and the condenser was discharged 120 times per second. No pressure had to be applied to the oil for this voltage. Even at low voltages, however, we find it convenient to use the rectifier when possible because by so doing a weak spot in the insulation of the secondary can be detected before electrical breakdown causes too much damage. In our experiments with oil at atmospheric pressure, corona at the ends of the Tesla coil limited the voltage obtainable to about 3,000,000. With the high-pressure arrangement corona has not given any serious difficulty. Insulation between turns limited the voltage in this case to about 5,000,000 volts.

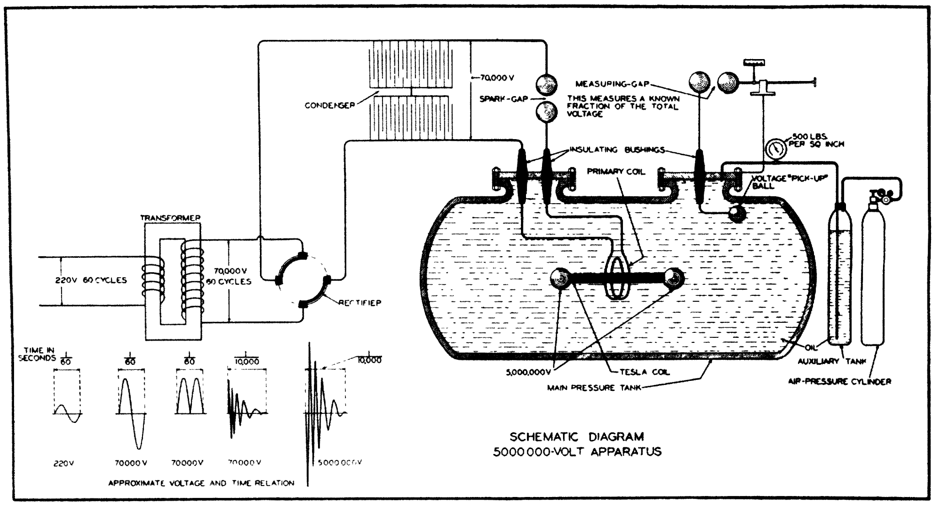

Fig. 1. Schematic diagram Tesla coil in oil under pressure.

Power-supply for the primary condenser.—For the production of 3,000,000 volts we used a small transformer giving about 30,000 volts and operating on 60 cycles with approximately a 3-kilowatt rating, kindly loaned to us by the Washington Navy Yard. For the intermittent production of the higher voltages we used a 10-KVA Kelley-Koett x-ray machine operating on a 220-volt 60-cycle supply. This or any other reliable x-ray machine contains the transformer mechanical rectifier and controls needed for charging the condenser. A potential of 120,000 volts could be supplied by the machine. In our experience we have rarely used it above 70,000 volts.

Condenser.—The work was begun by using a set of glass-in-oil Telefunken condensers loaned by the Washington Navy Yard; these had previously been used in a high power Navy spark-transmitter. Sixteen of these sufficed for the production of 3,000,000 volts. The capacity of each was 0.038 microfarad and each unit stood 15,000 volts (peak). For higher voltages however we constructed a special condenser similar to that used by Anderson for exploding wires. Lead foil 0.003 inch thick was applied to each side of 200 glass plates. The plates are 40 inches square of somewhat irregular thickness approximating one-eighth inch, being ordinary B-grade double-strength window-glass. They are assembled in wooden racks in air and constitute a generally useful as well as comparatively inexpensive piece of laboratory equipment. Figure 2 shows a condenser including part of the lower and most of the upper rack. The plates are spaced one-half inch apart. For reasons which are somewhat obscure it is essential that the plates be spaced to prevent breakage when the condenser is discharged. We found it very convenient to fasten the lead foil to the plates simply by an oil-film. Any lubricating oil of a not too heavy consistency is satisfactory, but linseed oil seems to be the most convenient material for this purpose both on account of being easily squeezed into a thin film under the lead foil and because it dries around

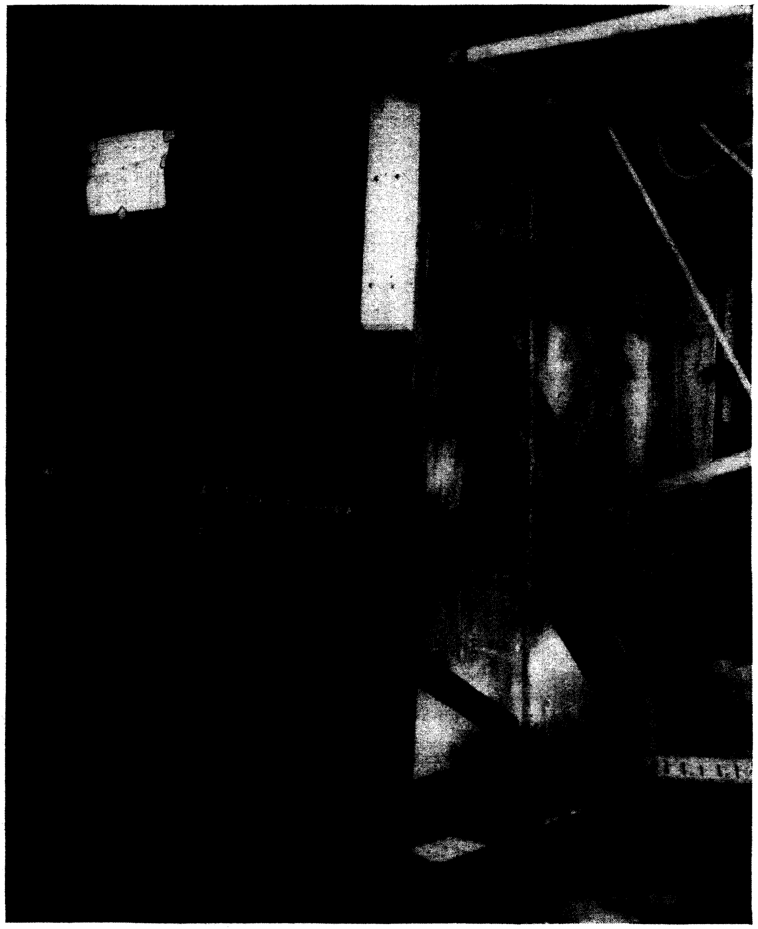

Fig. 2. View of section of the glass-plate condenser ($C=1.6\mu f$, 30,000 volts).

the edges. A margin of about 4 inches is left on the glass around the foil, allowing the plates to go up to a sufficiently high potential and yet providing a safety-gap around the edge of the glass plate. In two years we have not had a single puncture of the plates although the condenser has been repeatedly at the flash-over point. In case of breakage however the plates can be taken out of the racks with relative ease. Pieces of rubber tubing inserted between plates close to the edges help to secure a uniform distance between them. The side of the racks shown in the figure is provided with two pieces of angle brass (only one is visible) which serve as supports for the connectors to the plates and as bus-bars. The opposite side (not shown in the figure) has each bus-bar split into two insulated sections thus allowing the use of the plates either all in parallel, in two sections in series, or in four sections in series. The capacity of all plates in parallel is about 1.6 microfarads. The maximum voltage which can be used with the plates in parallel varies between 30,000 and 40,000 volts depending on the type of external circuit. As a rule a high inductance in the external circuit allows one to use a higher voltage on the condenser. If the voltage exceeds this limit a local flash-over occurs around the edge of a plate when the primary gap discharges. The exact nature of the flash-over is hard to explain but it is undoubtedly due to transients. When it occurs the primary circuit becomes inefficient but in our experience no particular damage to the condenser takes place. With the four sections in series we have used this condenser without flash-over at 120,000 volts.

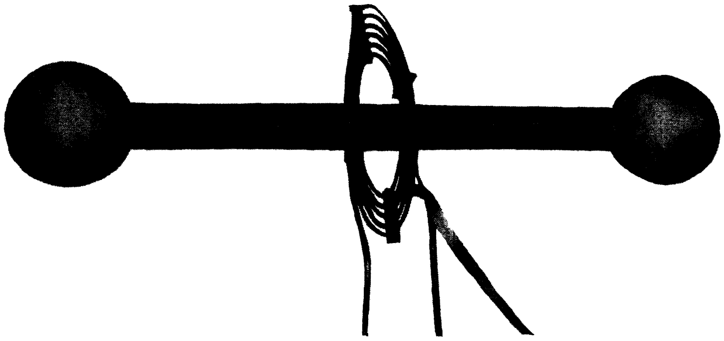

Fig. 3. Tesla coil and primary, showing the spun-zinc balls which serve as corona-shields at the ends of the Tesla coil.

Primary of Tesla transformer.—This as shown in Figure 3 is made of several turns of spirally-wound copper tubing. Some of the most efficient circuits employ only two turns.

Tesla coil.—This is shown also in Figure 3. It is convenient to wind a high-voltage Tesla coil on a piece of Pyrex glass tubing as supplied by the Corning Glass Works with an approximate diameter of 8 cm and length of about one meter. The wire is generally wound without spacing and always in a single layer. The ends are protected by approximately spherical caps, those shown in the figure being 25 cm in diameter. When the Tesla coil is immersed in oil it is important to eliminate the air which is likely to be trapped between the wires and the glass. If silk-covered wire is used soaking in oil is often sufficient to draw it in by capillary action. Vacuum impregnation is often advisable. For this purpose the coil is put in a tin tray and inserted into a horizontal piece of 6-inch pipe. The pipe is closed, exhausted, and oil is let in slowly with the vacuum-pump running. When the tray is full the pump is disconnected, the tray is taken out, and the coil is ready for use. Our best coils were made of No. 38 or No. 40 B.S. gauge copper wire, 5,000 to 7,000 turns. Either double silk, silk enamel, or the especially heavily enameled No. 40 wire (made by the General Electric Company) are satisfactory. It often happens that there are flaws in the insulation of the wire. These cause sparks between turns as soon as the coil is used and the coil is often burned out at such points. Having thus found out the weak points a few turns are unwound, the wire is scraped carefully at the ends, and is spliced; such a repaired coil is usually better than a fresh one. Insulation between turns usually gives no trouble up to 3,000,000 volts peak.

A screw is fixed permanently in the ball so that the ball can be screwed as a whole into a tapped hole in a brass end-piece fixed on the axis of the Tesla at its end. Incidentally, Houston's water putty made by the Gold Medal Polish Company (Racine, Wisconsin) provides a very convenient means for fastening attachments to Pyrex tubing. In most of our experiments the Tesla coil has been supported in the oil by a loop of silk fish-line at each end, which stands the full voltage to ground without trouble.

Oil and high-pressure tank.—Light transformer oil (not switch oil) purified by passing through a centrifuge has been used. Most of the oil employed by us has the trade name Transil 10 C. At its best clean oil is broken by about 46,000 volts across a 1-mm gap; in thicker layers its apparent dielectric strength is always less than this. The effective dielectric strength also depends to a large extent on the state of the electrodes between which the discharge takes place. No exact quantitative values can be assigned to it in our experience except by allowing a considerable safety-factor. It has proved possible to improve the performance of the oil by continued and judicious use. A preliminary discharge is often likely to take place while using a Tesla coil before the dielectric strength of pure oil is reached. We find it advantageous to "break in" the oil by allowing such discharges to occur. The procedure in this "breaking in" process is to bring up the Tesla voltage gradually. For very low voltages the caps on the ends of the coil show no discharge. As the voltage is brought up occasionally a corona "tree" shoots out from one of the caps into the oil. If the voltage is held at such a value that the "tree" occurs only seldom, the "trees" disappear after continued use. The voltage may then be brought up higher, "trees" occurring again occasionally and again disappearing after continued running. This process cannot be continued indefinitely but it is quite essential in improving the performance and obtaining as high a potential as possible. If the "trees" refuse to disappear it is often advisable to lower the potential to a point where they occur less frequently and to make them disappear there. The "breaking in" of the oil and cap surface can be done either with a Tesla using 60-cycle excitation with a synchronous primary gap, or else by the intermittent primary sparks produced when using the x-ray machine. We have no special evidence of the superiority of either method. The synchronous gap is likely to shorten the time required but it is also likely to carbonize the oil if too heavy discharges occur. Its main danger lies in burning out the fine wire of the Tesla at points where the insulation on the wire is defective. We have obtained 3,000,000 volts with a Tesla used on 60-cycle synchronous gap excitation, the ends of the Tesla being protected by 5-inch spun copper caps. The mode of oscillation of the coil was such that the middle of it was at ground while the ends were at each instant at equal and opposite potentials. Each 5-inch cap was therefore at 1,500,000 volts corresponding to a gradient of 240,000 volts per cm. We did not find it practical to use much higher gradients in oil at atmospheric pressure, the performance of the apparatus becoming unreliable due to the corona from the caps. Also the apparent gradient to which the oil may be brought up depends on the caps used. An increase in the diameter of the caps makes it possible to bring them up to a somewhat higher potential. However the gain in potential is always less than would be calculated from the diameter. The exact reason for this we do not know but the obvious difficulty of having a perfectly shaped light metal sphere of large diameter, and of keeping it clean and polished, has probably much to do with it. The nature of the "breaking in" process we also do not know much about. It may be connected with removing dirt or microscopic particles of moisture from the electrodes or even with a local purification of the oil due to driving moisture or small air bubbles away from regions in which the electric field is large. Our main concern with regard to the production of high voltages has been the purely practical one of using oil at as high a value of the electric field as possible in order to test the voltage and power-output limitations of the method.

To improve the performance of the oil beyond that which was obtainable by ordinary purification and "breaking in" at atmospheric pressure we resorted to the pressure-method.[4] The pressure container is shown to scale in proportion to the Tesla coil in Figure 1. It is a hammer-welded iron tank originally made by the M. W. Kellogg Company of Jersey City for use as a steam separator. It is designed for a working pressure of 450 pounds per square inch in accordance with the standard boiler safety-code. [The importance of precautions in the use of high pressures in large containers cannot be over-emphasized.]

The tank was furnished with solid manhole plates which were later machined with proper openings for the insulating bushings and peep-holes (not shown in the figure). A peep-hole was put in each manhole plate. Each hole, three inches in diameter is covered with two-inch plate-glass. The inside of the tank was illuminated with two automobile headlights, current being supplied through an ordinary spark-plug screwed into a third manhole of the crab type in one head of the tank. This third manhole has been

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[4] F. Koch, Elektr. Zeits. **36**, 85 and 99 (1915).

omitted in the figure. The pressure was applied to the oil by means of a carbon dioxide cylinder shown in the figure as "air-pressure cylinder." On account of the increase of volume of the tank under internal pressure and on account of the compressibility of the oil it is necessary to supply extra oil (several gallons) when pressure is applied. This is done by connecting the carbon dioxide pressure-cyclinder to the auxiliary oil tank shown in the figure.

The "breaking in" of the oil is essential also in this high-pressure arrangement. It is difficult to give exact figures for the improvement in the dielectric strength due to pressure. Roughly a factor of two is correct in our experience. The limitation which we encountered in the use of Tesla coils in oil under pressure was due to insulation between turns and not to "trees" (corona) off the caps. With longer Tesla coils it would be doubtless possible to exceed our voltages. The maximum which we obtained was 5,200,000 volts. The coil was wound with ordinary No. 40 enameled and silk-covered wire. The caps were 20 cm in diameter and the length of winding was approximately 90 cm. The mode of oscillation was again the half wave-length, that is, middle at ground and ends at opposite potentials. The application of pressure improves the insulation between turns as well as the insulation around the caps, there apparently always being a film of oil between turns. The improvement for the caps, however, proved to be so large that they offered no serious difficulty. The oil is purified at intervals by means of a Hydroil centrifugal purifier.

Measurement of high potentials.—We have used two methods of estimating the potentials. The first was used purely qualitatively although it can be developed into a quantitative one. It consisted in observing the deflection of a cathode-ray beam in a low voltage cathode-ray oscillograph. The latter was of the Johnson type made by the Western Electric Company giving cathode rays of 300-volt velocity observed visually on a fluorescent screen. The cathode-ray tube was put vertically in a wooden box the outside surface of which served as a support for a set of vertical grounded wires. These allowed only horizontal fields to affect the cathode rays. The sensitivity of the tube to electric fields inside the shield was determined experimentally by putting it in known fields produced by an electron-tube oscillator. One centimeter deflection on the screen could after the calibration be interpreted as a known electric field. When the cathode-ray box was put in the neighborhood of the Tesla coil the deflection on the screen was observed and the oscillating electric field due to the coil thus determined.[5] From a knowledge of the potential distribution on the coil and the distances involved the numerical value of the potential can be computed. The difficulty of this method lies in the extreme weakness of the trace on the fluorescent screen

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[5] For this experiment the Tesla coil was supported in an open wooden tank containing the oil, although for experiments at atmospheric pressure we now use a 1500-gallon steel gasoline storage tank with about one-fourth of the cylindrical surface cut away. No particular loss of efficiency is occasioned by operating these high-frequency coils inside of a metal tank. This is clear, of course, from the results with the thick-walled high-pressure tank.

due to the extremely short duration of the high potential on the Tesla coil. The visibility of the trace being so low no quantitative measurements could be made. The estimates thus formed were checked however by measurements by the second method. Photographic registration of the cathode ray, as in the Dufour cathode-ray oscillograph, would make the first method quantitative and we mention it mainly for this reason.

The second method can be described as a capacity-potentiometer or "pick-up" measurement. The principle is shown in Figure 1. The manhole on the right of the high-pressure tank is provided with an insulating bushing which supports a voltage "pick-up" ball. Since the potential on the Tesla coil alternates with a high frequency (approximately 100,000 per second) the potential assumed by the pick-up ball is determined by the capacities between the Tesla coil and the ball as well as between the ball and the ground. In order to know the potential of the coil it is sufficient therefore to measure the potential on the "pick-up" system and to determine the ratio of the potential on the coil to the potential on the "pick-up." The measurement of the potential on the "pick-up" system is made by means of a sphere-gap and the ratio of the two potentials is determined at low voltages where the potential of the Tesla coil can be measured directly. The direct measurements of the Tesla-coil voltages in the low range have been made in two ways. The most direct method is to connect a sphere-gap across the coil. In doing this care is taken to have the high-potential lead to the sphere-gap removed as far as possible from the "pick-up" ball so as not to change the relative distribution of capacities. Since this can never be done perfectly, although in general it leads to underestimating the true voltage, we have also determined the potential ratio, or calibration-factor, by a somewhat different method free from this objection.

The second way of determining the calibration-factor makes use of the fact that the potential at the middle of the Tesla coil is the same as that of the ground, and that a small capacity around a small section of the coil at its middle does not change appreciably the voltage-distribution along the coil. Thus the coil is provided with taps exactly at the middle as well as at one and two centimeters to each side of the middle. The coil is excited by sustained oscillations from an electron-tube oscillator. A bifilar electrometer is connected across the middle tap and one of the others, and another bifilar electrometer is connected across the measuring gap. The ratio of the two measured potentials gives therefore the ratio of the potential across one centimeter of the Tesla coil at its middle to the "pick-up" potential. In order to determine the calibration-factor it is now only necessary to find the ratio of the potential across the whole Tesla coil to the potential across a centimeter of it at its middle. This was determined by finding the potential distribution along the coil by special experiments.

It may be shown by calculation that the change in the resonant frequency of a Tesla coil when a capacity is connected across a section of it is proportional to this capacity and the square of the voltage across the section in question. This calculation presupposes that the change of frequency dealt with is small. Model Tesla coils were built with taps and the "detuning" effects were observed when a small fixed condenser was connected across the various sections. The square roots of the detuning effects $(\Delta C)^{1/2}$, when ΔC is the capacity-change required to retune an oscillator coupled to the Tesla coil, gave the potentials across the separate sections and hence by addition the potential distribution along the coil. The magnitude of the fixed capacity used was varied so as to make sure that it was small enough and not sufficient to cause partial resonance of a part of the coil which would vitiate the measurements. The condenser employed to produce the capacity-changes was made of two circular plates about 5 cm in diameter separated by a thin sheet of mica and thus had a fairly small capacity to ground. This capacity was sufficient to require a correction because it was found that if the condenser was connected to one of the taps it had a measurable detuning effect on the Tesla coil. This detuning effect was therefore ascertained for all the

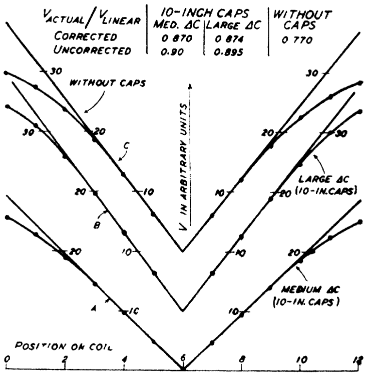

Fig. 4. Voltage-distribution curves for Tesla coils (points are plotted for corrected data only; the uncorrected points are almost indistinguishable from these on the scale of the figure).

taps and corrected for by subtracting it from the detuning effect of connecting the condenser across two adjacent taps. The remaining number gave the detuning due to a capacity across the two taps without having a capacity to ground. This correction reduced the resulting form-factor only two or three percent, however, (see Figure 4). When different condensers were used the voltage-distribution curves corrected for the capacity to ground of the "probing condenser" checked closely for different capacities of the condenser used. Such measurements were made on Tesla coils wound with different sizes of wire and with different caps on the ends. The voltage-distribution curves proved to be independent of the size of wire used for winding the Tesla coil. Experiment shows however that it depends appreciably on the capacity load at the ends and that it is different for different sizes of caps used. The results can be expressed most conveniently in terms of the ratio of the average slope of the voltage-length curve to the maximum slope at the middle of the coil. For coils of the dimensions used by us this ratio or "form-factor" is 0.77 for coils without caps (Figure 4C), 0.82 for 5-inch cast bronze caps, 0.87 for 10-inch caps. The voltage-distribution thus becomes more linear as the capacity-load at the ends is increased, as would be expected. Knowing the "form-factor" of the coil we obtain the potential across the coil from the potential across one centimeter of it at the middle by multiplying the latter potential by the length of the coil in centimeters and by the "form-factor."

We have ascertained the effects of the capacity of the electrometers used in the measurements by connecting a third electrometer either at the measuring sphere-gap or at the tap across the middle of the Tesla coil. These effects are small and corrected for. The calibrating-factors obtained by the first or second method of measuring the Tesla-coil voltage agree very closely. In both cases we also have made sure that the "pick-up" voltage is due to the potential on the Tesla coil itself rather than to induction from the primary and calibrating circuits by partially or completely detuning the primary circuits from the Tesla coil. This reduces the "pick-up" voltage to zero.

Every calibrating-factor depends on the setting of the measuring gap because the capacity of the "pick-up" system to ground is affected by the distance between the two measuring spheres. A curve for the calibrating-factor against the "pick-up" gap setting is plotted and used in the calculation of the voltage. The corrections due to this cause are of the order of 5 to 10 percent in our set-ups. The measurement of the "pick-up" voltage in actual operation consists in determining the separation between the spheres at which sparks definitely pass between them. The potential across the gap is then obtained from the data of Peek.[6] The potentials of the secondary gap are generally of the order of from 30,000 to 100,000 volts thus allowing one to make fairly accurate gap-settings. Since voltage-measurements by a sphere-gap may be subject to corrections due to local conditions such as air ionization, surface condition of gap, etc., as a precaution we have checked one of our gaps on 60 cycles against an electrostatic voltmeter and found the results to be in agreement with Peek's data. For our measuring gaps we always employ 25-cm (10-inch) diameter spheres, which are known from the work of Peek to be reliable indicators in the range of voltages used. A sphere-gap does not give as consistent readings immediately after polishing as it does after a number of sparks have passed. Freshly polished spheres will spark occasionally at a greater separation than will "used" spheres for a given voltage. We have always taken measurements with gaps in the "used" condition, leading to lower rather than higher voltage-estimates.

It may be observed that if the oil should become partially conducting under the influence of high electric fields the "pick-up" method would be seriously vitiated and would tend to give exaggerated values to the Tesla voltage. We have taken care therefore to make sure that this is not the case.

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[6] F. W. Peek, Jr. Dielectric phenomena in high-voltage engineering (McGraw-Hill, 1920) Chapter IV; Trans. A. I. E. E. **34,** 1857 (1915); J. Franklin Inst. **197,** 1 (1924) and **199,** 141 (1925); Smithsonian Inst. Report for 1925, 169 (1926). Also L. W. Chubb and C. Fortescue, Proc. A. I. E. E. **32,** 627 (1913).

Our main evidence lies in the fact that the measured Tesla voltages, with a given primary setting, are independent of the position of the "pick-up" (each position of course being separately calibrated at low voltage) as long as there are no "trees" from the caps in the oil. Since at low voltages used in the electrometer-calibrations there is absolutely no possibility of a non-uniform oil-conductivity we conclude that the oil-conductivity is uniform also when high potentials are used unless a visible breakdown occurs as shown by "trees" or bolts in the oil. In the second place we find that the measured Tesla-coil voltage is proportional to the potential to which the primary condenser is charged which is determined by the setting of the primary gap. This again would not be the case if the conductivity of oil and invisible discharges played any part in the measurements. If insufficient care is exercised in preventing corona in air or the discharges along the surface of the oil from the high-potential connections of the measuring gap, too low values of the Tesla voltage may result. The only deviations from linearity which we have observed have been due to these causes.

Data on the efficiency of Tesla coils.—We have made rough measurements of the potentials developed by Tesla coils with various sizes of caps in terms of the potential of the primary gap. The measurements given in the table were all made with a primary voltage of 6500 and with half wave-length excitation of the Tesla coil. V_T represents the total voltage between caps, measured by the capacity-potentiometer method. Each cap is therefore charged to a voltage $V_T/2$ above ground. The primary circuits and the coils may be rated either from the point of view of having a certain maximum usable primary potential or else on the basis of having a certain maximum number of plates for the primary condenser. For this reason we tabulate both the ratio V_T/V_P giving the voltage gain-factor of the Tesla over the primary and applying therefore to the case when the primary potential is the limitation, and also $C_P V_P^2/V_T^2$ expressed in micro-microfarads. The latter figure gives the effective capacity of the Tesla coil which for this purpose is defined to be such a capacity C_T which would attain a voltage V_T if all of the energy $C_P V_P^2/2$ of the primary condenser were transferred to the capacity C_T. The point is that a given number of plates available for the primary condenser whether used all in parallel or in several groups in series gives roughly the same maximum value of $C_P V_P^2$ and therefore if the limitation lies in the primary condenser a small value of $C_P V_P^2/V_T^2$ is an advantage.

It is seen from the table that if the primary voltage is fixed a small primary inductance and a large primary condenser constitute the best circuit. If however the number of glass plates available for the condenser is limited it is perhaps at times better to use a reasonably large number of primary turns and therefore less primary capacity but a higher voltage by subdividing the condenser into sections used in series. A too large number of sections in series is of course not practical, leading to overvoltages and increase of circuit-inductance. A too small primary inductance however is also frequently harmful, leading to explosion-like flash-overs of the condenser. The use of the table is therefore only to select rough values for the circuit-constants. The best arrangement is found afterwards by trial. The table applies to the particular circuits which were made up of the Telefunken condensers and therefore takes account of the particular lead-inductances used with them.

The table shows the relatively high energy efficiency of the Tesla coil, which is capable of storing in its very small capacity about one-fourth of the energy of the primary circuit. This is made clear by comparison of the last column of the table with the calculated capacities of the caps (remembering that each cap is charged only to $V_T/2$ above ground). Now a capacity of 1.5 microfarads at 30,000 volts contains 675 joules so that 170 joules can be put into the capacity of the Tesla coil. Even if it should be dissipated in one ten-thousandth second (about 10 cycles at a frequency of 10^5) this gives an instantaneous power of 1.7×10^3 kilowatts. By direct tests we find that a Tesla coil is able to feed about 20 megohms without having its voltage decreased to less than about half. Since insulation, rather than electrical efficiency, is the limiting factor at high voltages, the voltage under load may

TABLE I. *Data on efficiency of Tesla coils.*

Caps	Primary turns	Primary capacity in microfarads	Transformation ratio V_T/V_P	$C_P V^2_P V^2_T$ in micromicrofarads
	No. 36 double silk-covered wire			
5-inch	2	0.19	101	19
	3	.13	85	18
6-inch	2	.26	104	24
	3	.16	106	14
8-inch	2	.33	106	29
	3	.22	99	22
	4	.15	83	22
10-inch	2	.41	121	28
	3	.30	112	23
	4	.20	94	23
	No. 40 General Electric enameled wire			
5-inch	3	0.45	162	17
	4	.33	147	15
	5	.23	115	17
	6	.19	87	25
6-inch	4	.48	123	32
	5	.37	113	29
	6	.27	97	29
8-inch	4	.60	131	35
	5	.45	118	32
	6	.33	107	29
10-inch	5	.54	137	29
	6	.45	119	32

be brought up to that obtained without load by supplying extra power in the primary circuit. At 5,000,000 volts the power-consumption through 20 megohms is 1.2×10^3 kilowatts. The instantaneous power available in a Tesla coil is therefore of the order of one thousand kilowatts and at the high potentials produced the coil is capable of delivering fairly efficiently an instantaneous current of 5×10^6 volts/2×10^7 ohms$=0.25$ ampere. If now the coil is used on 60-cycle current, that is, with 120 primary sparks a second, and if only 10^{-6} second during each discharge (roughly one tenth of a cycle) is counted as effective in feeding a high-potential x-ray tube, the average current is $120\times10^{-6}\times0.25$ ampere$=3\times10^{-5}$ ampere. If only one spark a second is used an average current of 2.5×10^{-7} ampere can be drawn. The synchronous-gap excitation thus gives 1.9×10^{14} five-million-volt electrons per second and the one spark-a-second excitation gives 1.5×10^{12} electrons. For comparison with radioactive sources we recall that the number of α-particles emitted by a gram of radium per second is about 3.5×10^{10}. Thus at 5,000,000 volts one spark a second has sufficient power to drive 0.75×10^{12} α-particles equivalent to 21 grams of radium, and 120 sparks a second would be equivalent to 2600 grams. Such α-particles would have an energy of 10,000,000 electron volts, at least 2,000,000 volts higher than the highest energy α-particles obtainable from radioactive sources. We may conclude therefore that the amount of energy which may be drawn from Tesla coils is sufficient to obtain sufficient numbers of high-velocity particles for disintegration-experiments.

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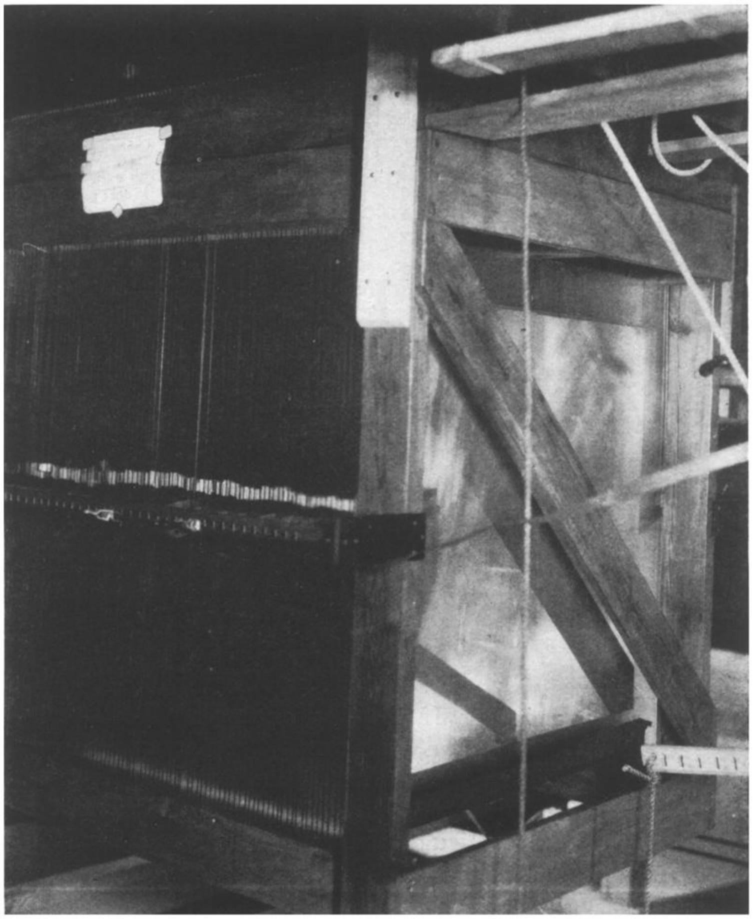

Fig. 2. View of section of the glass-plate condenser ($C = 1.6\mu\text{f}$, 30,000 volts).

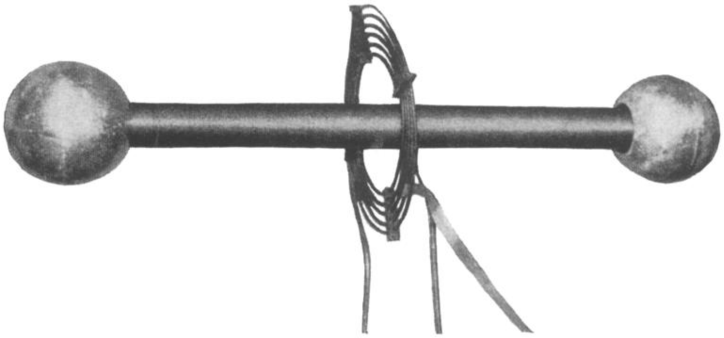

Fig. 3. Tesla coil and primary, showing the spun-zinc balls which serve as corona-shields at the ends of the Tesla coil.