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The Electrostatic Production of High Voltage for Nuclear Investigations

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Abstract

The developments in nuclear physics emphasize the need of a new technique adapted to deliver enormous energies in concentrated form in order to penetrate or disrupt atomic nuclei. This may be achieved by a generator of current at very high voltage. Economy, freedom from the inherent defects of an impulsive, alternating or rippling source and the logic of simplicity point to an electrostatic generator as a suitable tool for this technique. Any such generator needs a conducting terminal, its insulating support and a means for conveying electricity to the terminal. These needs are naturally met by a hollow metal sphere supported on an insulator and charged by a belt conveying electricity from earth potential and depositing it within the interior of the sphere. Four models of such a generator are described, three being successive developments of generators operating in air, and designed respectively for 80,000, 1,500,000 and 10,000,000 volts, and the fourth being an essentially similar generator operating in a highly evacuated tank. Methods are described for depositing electric charge on the belts either by external or by self-excitation. The upper limit to the attainable voltage is set by the breakdown strength of the insulating medium surrounding the sphere, and by its size. The upper limit to the current is set by the rate at which belt area enters the sphere, carrying a surface density of charge whose upper limit is that which causes a breakdown field in the

[1]National Research Fellow at Princeton from September 1929 to September 1931.

surrounding medium, e.g., 30,000 volts per cm if the medium is air at atmospheric pressure. The voltage and the current each vary as the breakdown strength of the surrounding medium and the power output as its square. Also the voltage, current and power vary respectively as the 1st, 2nd and 3rd powers of the linear dimensions.

1 Introduction

Any basic development in science calls for a new technique fundamentally adapted to the new purpose. Such a basic development has been in progress for the last thirty-six years and it has now reached such a stage as to be recognized as a major field of physics,–nuclear physics. To justify this statement it is only necessary to point out that in the atomic nuclei reside all the positive electricity, much of the negative electricity and by far the greater part of the mass and energy in the universe. As yet we know relatively little about this world of electricity, mass and energy, and our attempts to produce an impression on it have been still less successful. Nevertheless, recent years have demonstrated the possibility of successful attack upon the nucleus by one weapon, the high-speed particle. The new technique which is therefore demanded is a powerful, controllable source of high-speed particles. In this paper is described a high-voltage generator which, with accessory discharge tubes and sources of ions, appears adapted to this technique.

Since progress in this new field of nuclear physics will require a great investment in apparatus, time and effort, it is important to consider carefully the possible techniques and whether this investment may be justified by the importance of the results to be expected. This leads to a consideration of the effects on the progress of physical theory of basic experimental developments initiated at the close of the last century.

About 1895 the discovery of x-rays and other experimental developments made possible an effective entry into the outer structure of the atom and the investigation of this aspect of atomic structure has been the main business of physics since that time. The distinguishing feature of those experimental innovations which led to the present knowledge of the outer atom is that they made possible physical observations on a scale of dimensions thousands of times smaller, with resultant energy concentrations thousands of times larger than were previously possible. Thus it became possible to deal individually with the basic physical entities, thereby removing the limitations of the statistical approach formerly necessary. Such observations showed clearly the insufficiency of classical laws and paved the way for quantum theory and for relativity.

Just as x-rays and other radiation phenomena of extranuclear electrons unfolded for us the extranuclear structure of atoms, so the discovery of radioactivity in 1896 opened the way to the first knowledge of the inner structure of the atomic nucleus. Furthermore, the high-speed particles from radioactive substances have themselves been the agencies through which was obtained the first evidence of the possibility of atomic transformation. Simultaneously with these experimental developments, the theory of relativity, through Einstein's principle of interconvertibility of mass and energy, has given a partial basis for guidance in interpretation and investigation of nuclear changes. These developments in nuclear physics have suggested with increasing emphasis the tremendous possibilities which should accrue from further development in the technique of nuclear investigation, through the use of swift particles of controllable nature and speed produced and applied through the agency of high voltage. In fact, the recent brilliant experiments of Cockcroft and Walton[2] have given concrete evidence that these expectations were justifiable. It may be hoped that experimental entry into the nucleus will extend the technique of physical exploration in a manner analogous to the extension which opened up the outer structure of the atom. It will again be possible to study a system thousands of times smaller, with energy concentrations correspondingly greater, further facilitating the study of individual rather than statistical processes. This may result in a system of nuclear mechanics accompanied by the same sort of broadening of basic scientific and philosophical ideas as accompanied the creation of quantum mechanics.

Within the almost unknown nuclear world of electricity and energy may also lie the explanation of certain extranuclear phenomena, which, modern quantum theory notwithstanding, still remain obscure. Just as the discovery of nuclear charge led immediately to the interpretation and simplification of that complicated group of chemical phenomena partially classified by the periodic table, so similarly it is possible that further discoveries regarding the atomic nucleus may lead to a similar interpretation and simplification of some extranuclear problems still outstanding.

2 Production of High Voltage

In approaching the problem of a high-voltage technique fundamentally adapted to meet the new demands in the most perfect and ultimate manner,

[2] Cockcroft and Walton, Nature **129,** 649 (April, 1932); Proc. Roy. Soc. **A137,** 229 (1932).

it is well to review the development of the high-voltage art to its present state[3]. Before the time of Faraday electrostatic generators were employed. However, industrial developments of the past hundred years have found their most suitable embodiment in applications of Faraday's principles of electromagnetism. Thus modern high-voltage technique has evolved almost completely under this influence. Step-up transformers have been used, with the addition of rectifiers and condensers when an approximately steady direct current was desired. These electromagnetic devices are admirably suited for the production of large currents within the general range of voltages corresponding to extranuclear phenomena. There are, however, inherent difficulties in the extension of such devices into the range of extremely high voltages which are demanded by nuclear physics. Such difficulties include the tremendous expense and size of such generators, necessitated by insulation requirements. There is also the limitation that the efficiency of high-voltage a.c. devices decreases rapidly as higher voltages are sought, because of the parasitic charging currents which are required to bring the apparatus to high potential at every cycle, even though no power is being drawn by it. The importance of this feature is not generally realized, but may be illustrated by the statement that the most favorable arrangement of the two terminals alone, neglecting the circuits, would require about 10,000 kva to impress 10,000,000 volts at 60 cycles, exclusive of useful output or corona leakage.

There are, in addition, numerous other important advantages of steady direct current over any current of a surging, alternating or rippling character. These include:

(1) Possibility of obtaining strictly homogeneous beams of electrified particles.

(2) Possibility of accurate focussing which becomes relatively more important as the voltage and therefore the length of discharge tubes is increased.

(3) Elimination of stray radiation which arises in a variety of ways from a discharge tube and generating apparatus operating at unsteady voltages, and which renders difficult the careful shielding necessary to permit the use of the delicate instruments and sensitive amplifiers required in so many applications of these voltages.

(4) Ability to use the ion source to full capacity since the useful voltage

[3] Lack of space prevents discussion of methods now used for generating high-energy radiations, but reference may be made to such well-known work as that of Coolidge, Tuve, Lauritsen, Cockcroft and Walton, Brasch and Lange, and Lawrence, and their collaborators.

is applied all of the time. (The order of advantage in this respect runs from the impulse generator and Tesla coil, which utilize the source only during roughly a millionth of the time, through the induction coil, the a.c. transformer, the transformer with rectifier, to finally, the electrostatic d.c. generator.)

(5) Ability to measure the high potentials accurately as, for instance, by the use of null or compensation methods.

(6) Elimination of breakdown in vacuum tubes due to reversal of the voltage,–a phenomenon inherently associated with the walls of vacuum tubes even under the best available conditions of evacuation.

(7) Ability to utilize the advantages of geometrical dissymmetry between positive and negative electrodes in vacuum in such a way that the field is minimum at the surface of the negative electrode, where difficulties from field currents are most serious,–an advantage which finds its maximum embodiment when the cathode is a hollow sphere surrounding a central spherical anode.

(8) In a variety of other ways through the elimination of time variations in the electrical conditions of the apparatus.

In view of these considerations it seemed desirable to develop an electrostatic high-voltage generator, since electrostatic methods yield directly a steady unidirectional voltage such as is desired. Maximum simplicity was sought in the design. The simplest terminal assembly appeared to be a sphere mounted on an insulating column. Since the sphere must be charged and since the process should be continuous the charge carrier should approach the sphere, enter it, and, after depositing its charge inside should return parallel to its path of approach. This immediately suggested the action of a belt, a device long used for the transmission of mechanical power.

The logic of the situation therefore pointed directly to a generator consisting of a hollow spherical conducting terminal supported on an insulating column, a moving belt to carry electric charge to the sphere, a device for depositing the charge onto the belt in a region of low potential remote from the sphere, and a device for removing this charge from the belt inside the sphere and transferring it to the sphere. A refinement of these essentials was the addition of an induction device whereby charge of the opposite sign was carried by the belt on its return journey, thus doubling the current output. A second refinement consisted of a self-exciting charging device whereby the entire generator could be made to operate independently of any external source of electricity. Not only does this device attain the desired result in what appears to be the simplest possible manner, but it is also interesting to note that the energy transformations in its operations are exceedingly simple, consisting only in the transformation of the energy required to drive the belt into work done in separating and transferring electric charge from earth potential to sphere potential.

Historical note

The basic idea of a belt type of generator probably dates from Kelvin's famous water dropper[4], and in fact, Kelvin suggested such a generator, in which charges would be carried to the electrode on a belt conveyer consisting of alternately insulated metal segments. Righi[5] made such a generator with the segmented belt carried through the sphere. Later Burboa[6] designed a generator with a belt functioning somewhat as an elongated disk of a Wimshurst machine, with a complicated set of inductors and brushes. Mention also should be made of a generator designed by Swann[7], in which charge was conveyed by a succession of falling metal spheres, thus coming closer to Kelvin's original water dropper but with the added suggestion that this apparatus could be made to operate in vacua theoretically up to such voltages as would prevent the falling of the spheres by electrostatic forces. Still more recently Vollrath[8] constructed a similar generator in which the current is carried by an air blast of electrified dust in an insulating tube.

3 Principles of Operation

The simplest embodiment of these principles is illustrated schematically in Fig. 1, which is appropriate to a generator, where P and N are the positive and negative spherical terminals and the belts of silk, or any other flexible insulating material, are shown transporting positive and negative electricity, respectively, from the charging outfit connected with ground to the two spheres. The charge is "sprayed" onto each belt as it passes between a metallic surface and one or more sharp points so adjusted as to maintain a brush discharge from the points toward the surface. When connected as shown, one point sprays positive and the other sprays negative electricity onto its adjacent belt. Within each sphere the charge is drawn off the belt by adjacent sharp points and transferred to the spheres. Since the interior of the sphere is similar to the interior of a Faraday "ice pail" the charge

[4] John Gray, *Electrical Influence Machines,* Whittaker, London, 1890.
[5] John Gray, *Electrical Influence Machines,* Whittaker, London, 1890.
[6] Burboa, U. S. Patent Nos. 776, 997 (1904).
[7] Swann, J. Frank. Inst. **205,** 820 (1928).
[8] Vollrath, Phys. Rev. 42, 298 (1932).

passes readily between the charged belt and the sphere, irrespective of the potential of the sphere.

The voltage which is attainable in this device is limited only by the corona breakdown at the surface of the spheres, which depends in a known manner upon their size and varies somewhat with the degree of smoothness of their surfaces. The current output is equal to the rate at which charge is carried into the spheres and is therefore equal to the product of the surface

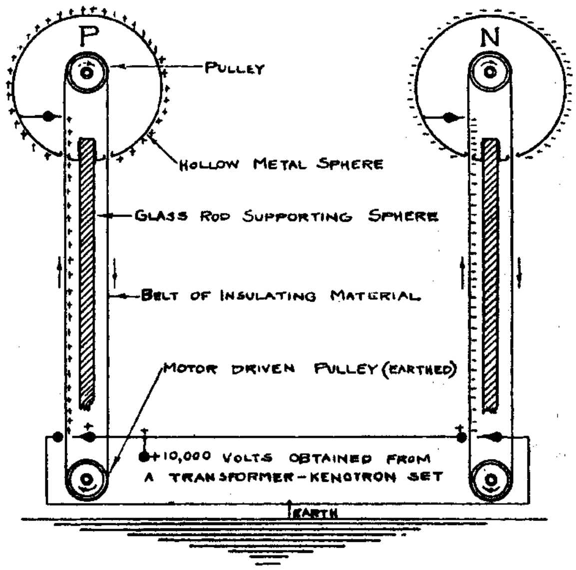

Figure 1:

density of charge on the belts multiplied by the areal velocity with which the belts enter the spheres. The upper limit for the surface density of charge on the belts is that which gives rise to an electric field equal to the "breakdown" strength of the surrounding air.

It is evident that other insulating media than air at atmospheric pressure might be used to advantage in the operation of such a generator[9]. We believe that its most useful embodiments will prove to be with operation in a high vacuum tank. In any case, the voltage is limited by the electrical breakdown of the surrounding medium whatever it may be, and the current output is determined by the width and velocity of the belt together with the charge density which can be placed on it.

[9] Barton, Mueller and Van Atta, *A Compact High-Potential Electrostatic Generator,* Phys. Rev. **42,** 901 A (1932).

In view of these considerations it is evident that the maximum voltage and also the current of such a generator each vary directly as the breakdown strength of the surrounding medium, so that the power output varies as the square of this breakdown strength. Since generally it will be desirable to provide as large a current output as possible, the belts will be designed to operate at the greatest practicable speed, and multiple belts will be placed as closely together as convenient. It is therefore evident that in any given insulating medium the voltage will vary as the first power, the current as the second power, and the power output as the third power of the linear dimensions. The variation of current with the square of linear dimensions is evident when it is considered that any increase in dimensions permits a corresponding increase in belt width and also a corresponding increase in the number of belts which can be introduced to operate in parallel.

In adapting the design of Fig. 1 to operate in some other medium, such as in a vacuum or in a liquid, it is only necessary to replace the brush discharge method of introducing charge to and from the belt, by some other charging and discharging device appropriate to the medium. Under such conditions

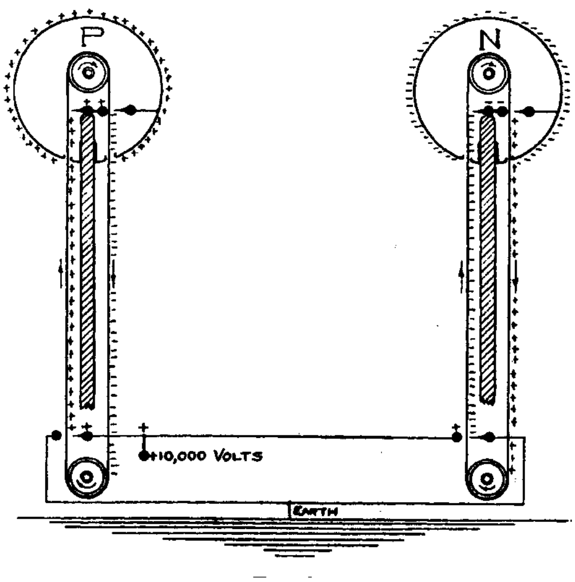

Figure 2:

it may also be advantageous to construct the belt of alternate conducting and insulating segments. It is obvious that the current output of this device can be doubled if the belt on its passage out of the sphere can carry away a charge equal and opposite to that brought in by the incoming belt. This can be realized very simply through the separation of induced charges by the arrangement which is shown schematically in Fig. 2. This exemplifies the first refinement referred to in the preceding section. The second refinement there mentioned is illustrated in Fig. 3, in which the transformerkenetron set which charges the belts is omitted and the connections are made in

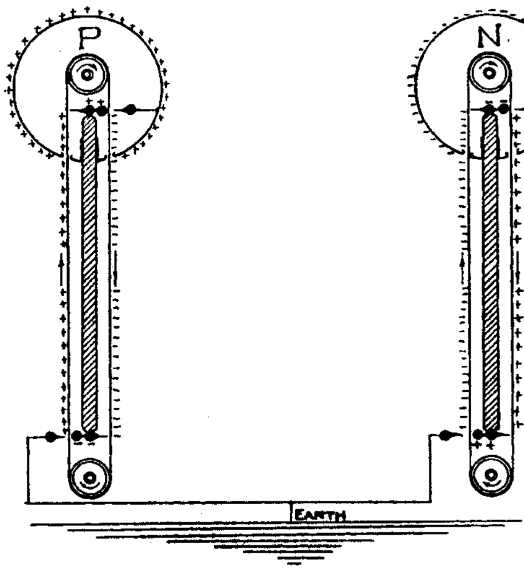

Figure 3:

such a way that a small charge on the moving belt, such as is present due to friction of the belts and pulleys, results in the cumulative separation of positive and negative electricity by induction, thus priming the machine, which immediately begins to operate self-exciting and at full power, in this way dispensing with the necessity of any external electrical connection.

4 Preliminary Models of the Generator

(1) In 1929 a small model was constructed and used to demonstrate the soundness of the principles involved. This model was hastily improvised but performed as expected. The highest voltage obtained was about 80,000 volts, being limited by the electrical breakdown of the surrounding air.

(2) Following this there was constructed a larger generator contained in a dismountable tank which could be highly evacuated by a suitably designed

combination of high-speed mercury condensation pump and liquid air trap. This type of generator is still in the stage of development but has operated in vacuum at 50,000 volts. Progress has been slow due to the necessity of developing certain necessary points of vacuum technique, and also due to the fact that this work had to be temporarily discontinued for the past eighteen months. However, no unexpected difficulties have been encountered and it is hoped that this generator will be in successful operation in a few months. Thus far experience has confirmed our confidence that vacuum insulation is the ultimate insulation for electrostatic devices and will open up tremendous possibilities in this field.

(3) When it became evident that considerable work would still be required to perfect the vacuum generator, construction was begun in June, 1931 of a generator operating in air, powerful enough to be of scientific use and to give a demonstration of the possibilities of generators of this type. This generator was designed for and developed about 1,500,000 volts and delivered a current of about 25 microamperes. It was constructed with 24-inch spherical electrodes mounted on 7-foot upright Pyrex rods and charged by 2.2-inch silk ribbon belts moving with a linear speed of 3500-foot per minute, and it operated either by self-excitation or by the spraying on of charge from a small 10,000-volt transformer kenetron set. It is interesting to note that although it was constructed at a total cost for materials of only about $100 it developed approximately twice the voltage of any previous direct-current source of which we have knowledge. This generator was described[10] at the Schenectady meeting of the American Physical Society in September, 1931.

Current output

If a charge is uniformly distributed on the surface of a linear strip in a region otherwise free from electrical forces, there is set up a field perpendicular to the strip and proportional to the surface density of charge as given by Coulomb's law. The maximum charge which can be held by the strip is that which gives rise to a field equal to the breakdown strength of the surrounding insulating medium. In the case of air this limiting field is about 30,000 volts per centimeter, from which we calculate that the maximum charge on a belt in air amounts to 2.65×10^{-9} coulombs per sq. cm on each side of the belt. This figure when multiplied by the number of sq. cm of belt surface which enter the sphere per second, gives the maximum possible

[10]Abstract, Phys. Rev. **38,** 1919 (1931).

current output in amperes. Of course, this current output will be doubled if the belt leaves the sphere also fully charged, but with electricity of opposite sign. In the generator described above as preliminary model 3, the actual current output amounted to about one-fourth of this theoretical maximum. The reasons for this discrepancy were known at the time, but were neglected in the construction of this demonstration model. By more careful design, the output may be brought closer to the theoretical limit, as more recent tests have shown.

There are several factors which account for this inability to attain ideally maximum current output. (1) Only one side of the belt is "sprayed" with charge. This may be overcome by using, for example, a double layer belt split by an earthed metal separator between two sets of converging spraying points and traversing the rest of its path simply as a 2-ply belt charged on both outside surfaces. (2) There are inevitable irregularities in the surface, and the breakdown of insulation in those regions which are electrically overstressed, results in a diminution of the charge carried in those localities. (3) There is an additional component to the electric field arising from the difference in potential between the sphere and the earth, so that the electric intensity at any point is the vector sum of this field and that arising from the charge of the belt. A nonlinear potential distribution along the belt may result in overstressing of the insulating medium in the region just outside the sphere, resulting in failure of the belt to retain its maximum charge while traversing that region. This difficulty is obviated by the use of a supplementary device for insuring uniform potential distribution, as described below. (4) Of course the charging device must be adequate to supply the charge. With a wide belt, a multiplicity of spraying points may be necessary to insure complete and adequate coverage. (5) If the belt is charged by a brush discharge, as in this model, the surrounding air is of course partially ionized, and this condition tends also to reduce the charge which can be placed on the belt by reducing the breakdown strength of the air in the charging locality to some value less than 30,000 volts per cm. This limitation could be removed by use of a non-ionizing device for charging the belts. The brush discharge method of charging, however, has the great advantage of simplicity.

It is impossible to increase the charge carrying capacity of the belt by any change in distribution of charge within the belt, such as by the substitution of volume charges in a moving element for surface charges. This is due to the fact that the limit to the net charge is set by the field just outside the surface of the moving element and is thus independent of the distribution of charges within it.

A consideration of the nature of the limiting electric field around the belts shows that the ascending and descending belts may be placed as close together as desired without reducing their current carrying capacity, the limitation being set only by mechanical considerations such as friction. For this reason it is possible to introduce multiple belts, alternately ascending and descending and packed very closely together and so to increase the current output to quite large values.

Efficiency

The work involved in operating this generator is consumed in overcoming the friction of the pulleys and the resistance to the motion of the belt in the surrounding medium, and in the transference of electric charge from earth potential to the potential of the spherical terminals. As is well known, a belt is one of the most efficient means of transferring power, and the two inherent types of electrical losses may be reduced to very small amounts. The first of these arises from electrical leakage, which may be controlled and reduced by methods described in the next section. The second is loss in the process of charging and discharging the belts, which may be reduced to that corresponding to the voltage required to maintain corona discharge from the spraying and discharging points, a voltage which is insignificant in comparison with the voltage generated. There are of course no magnetic losses. Thus this type of generator should be capable of operation with high efficiency.

Disturbing factors

The only disturbing factor which has been found to affect the satisfactory operation of the generator is electrical leakage which is closely identified with two factors, humidity and geometrical design of insulating support. The difficulty is not so much from direct electrical loss by leakage over the surface of the support, as from distortion of the electric field about the spheres by the charges which leak down the supporting insulator and in this way promote insulation breakdown of the air surrounding the insulator near where it enters the sphere. This disturbing factor is completely eliminated by proper design of the insulating support, consisting in the substitution of a hollow insulating cylinder for the insulating rod of model 3. The interior of this cylinder can be maintained at low relative humidity by warming the air within it, so that its interior and exterior surfaces, as well as the belts which run within it, are maintained in the most favorable conditions for elimination of leakage. In addition to improving insulation, the cylindrical support introduces increased mechanical strength, quietness of operation and safety, and certain other advantages.

A number of important advantages are secured by introducing on the surface of the supporting cylinder an artificial leak from the sphere to the ground, so constructed as to give the most favorable distribution of field between the sphere and the earth. This artificial leak may be constructed, for example, by rotating the cylinder in a lathe and drawing on its surface a continuous, closely spaced, helical, India ink line, extending from one end to the other. By means of this artificial leak the vertical field between the earth and the sphere may be made uniform, thus minimizing leakage to earth through the support or the surrounding air, and permitting the maximum charge to be carried by the belt throughout its entire path.

5 The Large Generator Under Construction at Round Hill

The favorable experience with the preliminary models described above appeared to justify the construction of a generator capable of yielding the maximum performance which can reasonably be expected in a generator operating in air, subject to limitations in voltage set by the size of the building in which it is placed. The generator was therefore designed to take full advantage of the largest laboratory space available, which was the airship dock on the estate of Colonel E. H. R. Green, kindly put at our disposal for this purpose. This dock is a building of structural steel covered by corrugated sheet metal and has dimensions approximately $140 \times 75 \times 75$ ft. In the back end of this building a row of low rooms has been erected to serve as shop and office head- quarters, while running lengthwise down the middle of the floor space there has been installed a railroad track of 14-ft. gauge, extending through the huge doors at the front of the building out into the open air for a distance of 160 ft. On this track each of the two generating units is mounted on a truck of structural steel, so that their distance may be varied and they may be run out-of-doors for experiments in the open air. In this connection it is interesting to note that Round Hill is extremely exposed to fogs from the ocean, so that the experience with this generator will afford a severe test of the utility of an electrostatic device under adverse conditions.

A schematic view of the large generator is given by Fig. 4. Its detailed description will be postponed to include its performance tests, but the following information may be of interest.

The spheres are of aluminum alloy 15 ft. in diameter with walls 1/4-inch thick. They were pressed and shipped in "orange peel" sections which were then welded together, and the outer surface ground and polished. Each sphere has four circular holes; a six foot hole on the bottom admits the multiple belts; a trap door on the lower side permits entrance via a ladder from the ground; a trap door on top permits access to the top of the sphere; a trap door on the equator will admit the end of a large discharge tube, spanning the gap between the spheres, to project within the sphere for attachment of subsidiary apparatus and connections and for operation. Preliminary tests on such a discharge tube have been made[11]. The inside of each sphere is itself a laboratory room, provided with a floor and containing accessory apparatus.

The insulating supports are cylinders of Textolite about 24 ft. high, 6 ft. in diameter and of 5/8-inch wall thickness. Each cylinder consists of three 8-foot sections, joined by internal Textolite bands fastened with Textolite dowel pins. Thus the external surface is smooth for easy application of the artificial surface leak and there is an absence of intermediate metal parts, as their presence would distort the field.

The trucks are made of structural steel and are so designed as to permit easy access to or change of the assembly of motors, pulleys and belts.

These three elements, sphere, insulating support and truck, are fundamental elements of any high-voltage assembly, and permit complete freedom for future experimentation and further development of the devices for generation. At the time of writing the spheres are built and polished, the trucks are completed and the main structure is now being assembled. The spheres were supplied by the Chicago Bridge and Iron Works and the Textolite cylinders (Shellac Compound, N. 974) by the General Electric Company, both of which organizations have been very cooperative in their efforts to make the generator successful.

On the basis both of theory and of past experience, we expect this generator to develop about 10,000,000 volts. The power output will depend on the number, size and speed of the belts. Present plans are for an output of about 20 kw. This could be greatly increased by the installation of additional belts, but for the initial adjustments only a portion of this power will be required.

Without the cooperation of many people this project could not have been carried through to its present state. It is impossible to make all the

[11] Van Atta, Van de Graaff and Barton, Phys. Rev. **43,** 158 (1933).

acknowledgments which are due, but we cannot let the opportunity pass for expressing the following acknowledgments.

We wish to express our great indebtedness to the Research Corporation

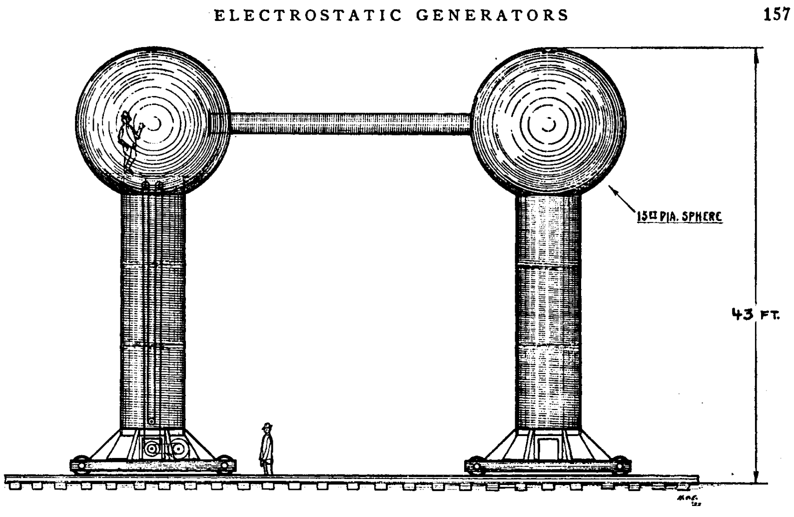

Figure 4:

of New York for a grant defraying a considerable portion of the expenses involved in the construction of this large generator, and for the great interest and help which its officers have given in the development of the engineering plans and the carrying through of the entire project up to the point of assembly.

This new high-voltage installation will be a significant addition to the facilities for scientific and engineering research in the Experiment Station of the Massachusetts Institute of Technology which is operated, with the generous cooperation and support of Colonel E. H. R. Green, on his estate at Round Hill. We wish particularly to thank him for his permission to transform the airship dock, equipped with electric power and other services, into a high-voltage laboratory. We are also greatly indebted to the New York, New Haven and Hartford Railroad for their donation of the railroad track.

Many of our colleagues have been very kind in their assistance. We wish particularly to mention Professor E. L. Bowles who is in supervisory charge of M. I. T. operations at Round Hill.

We wish finally to acknowledge the kind cooperation of Princeton University in whose Palmer Physical Laboratory the preliminary models of this generator were built, and which sponsored the project up to the time when the new facilities at Round Hill became available.