be neglected in rough calculations of the manner of variation of $\eta_{\Theta+\kappa}$ with $\kappa$ for small $\kappa$, since as will be shown presently the variation of $\eta_a$ with $\kappa$ is on a rather larger scale than $c\kappa^2$. We have

$$\eta_a=\tfrac{1}{2}(\eta_{1\Theta}+\eta_{2\Theta})$$
$$+\kappa^2-\tfrac{1}{2}[(\eta_{2\Theta}-\eta_{1\Theta})^2+16|\boldsymbol{\kappa}\cdot\mathbf{F}_{12}|^2]^{\frac{1}{2}}, \quad \text{(C)}$$

while $\eta_b$ has the same form with a plus sign before the radical. Successive differentiations of (C) with respect to $K$, and with respect to $r_s$ holding $Kr_s$ constant, establish the existence of the maxima and minima shown in Fig. 9, provided the difference $(\eta_{2\Theta}-\eta_{1\Theta})$ is sufficiently small.

The quantities

$$\beta_\Theta=\tfrac{1}{2}\frac{\partial^2\eta_{\Theta+\kappa}}{\partial\kappa^2}\bigg]_{K=0}\approx\tfrac{1}{2}\frac{\partial^2\eta_a}{\partial\kappa^2}\bigg]_{\kappa=0}$$

are easily obtained from (B) or (C). The required matrix elements $\mathbf{F}_{12}$ were calculated for several points $\mathbf{\Theta}$, using for the wave functions the best approximation which could be obtained from two constituent $\chi$-functions (for most of the ($s$) states it turned out that the wave function could not be well approximated by a single constituent $\chi$-function, but could be by two). These matrix elements were found to be within about 25 percent of the values they would have for almost free electrons.

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JULY 15, 1940 PHYSICAL REVIEW VOLUME 58

# Design and Preliminary Performance Tests of the Westinghouse Electrostatic Generator

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(Received May 3, 1940)

Design and performance characteristics of the Westinghouse electrostatic generator are discussed. Steady voltages of 1.3 Mv at atmospheric pressure and up to a maximum to date of 3.7 Mv at about 75 lb./sq. in. have been used to accelerate hydrogen ions. The maximum steady voltage is limited mainly by sparking along the belts. The voltage remains constant to within 0.5 percent for observing times of several minutes, and at times to within 0.2 percent for a half-minute or so.

## INTRODUCTION

During the past three years, a large electrostatic generator of the belt type, using compressed air insulation, has been constructed at the Westinghouse Research Laboratories in East Pittsburgh. It has been in satisfactory operation for nearly a year as a source of high energy protons for research in nuclear physics. This paper gives an account of the design features and a preliminary account of its performance. Details of the researches in nuclear physics carried out to date will be published soon in other papers.

The first successful utilization of air under high pressure as insulating medium for an endless-belt electrostatic generator was made by Barton, Mueller, and L. C. Van Atta[1] but they did not apply the potential to an accelerating tube. Herb, Parkinson, and Kerst,[2] using a somewhat similar generator successfully applied 400 kv to a vacuum tube to accelerate hydrogen ions. A larger generator was then constructed by them[3] and the performance of these generators indicated that further development to larger dimensions was a practical method of obtaining a beam of high energy ions having energy

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* Westinghouse Research Fellow.

[1] H. A. Barton, D. W. Mueller, L. C. Van Atta, Phys. Rev. **42**, 901 (1932).

[2] R. G. Herb, D. B. Parkinson, D. W. Kerst, Rev. Sci. Inst. **6**, 261 (1935).

[3] R. G. Herb, D. B. Parkinson, D. W. Kerst, Phys. Rev. **51**, 75 (1937); D. B. Parkinson, R. G. Herb, E. J. Bernet, J. L. McKibben, Phys. Rev. **53**, 642 (1938).

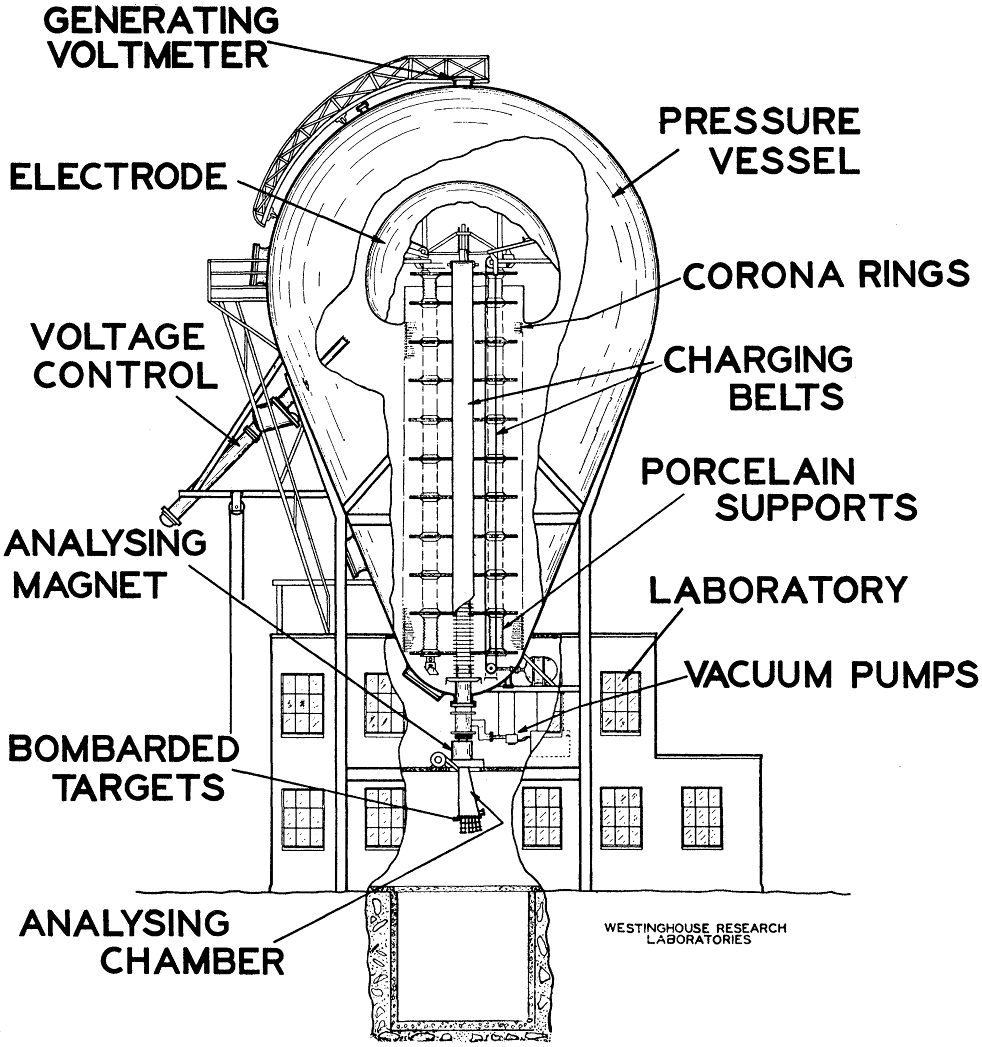

FIG. 1. Elevation view of generator.

homogeneous to a fraction of a percent which is the performance of electrostatic generators at atmospheric pressure.[4]

## PRESSURE VESSEL

Large spherical and cylindrical gas containers have been fabricated for a number of years, and the use of a large spherical container for a disk electrostatic machine was suggested by M. A. Tuve, L. R. Hafstad, and O. Dahl.[5] The pear-shaped pressure vessel inside which the generator is built is shown in Fig. 1. This vessel[6] is made up of two sections of spherical surfaces of 30 and 10 feet in diameter joined by a conical section to give a total vertical height of 47 feet. It is mounted on a tower structure so that the lower nozzle of the vessel is 14 feet from the ground in the center of the second floor of the associated laboratory building, as shown in Fig. 1.[7] This shape was chosen for the saving in

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[4] M. A. Tuve, L. R. Hafstad, O. Dahl, Phys. Rev. **48**, 315 (1935); L. C. Van Atta, D. L. Northrup, C. M. Van Atta, R. J. Van de Graaff, Phys. Rev. **49**, 761 (1936).

[5] M. A. Tuve, L. R. Hafstad, O. Dahl, Naturwiss. **24**, 625 (1936).

[6] Constructed in 1937 by Chicago Bridge and Iron Works, C. H. Jennings, The Welding Engineer **24**, Dec. (1939).

[7] W. H. Wells, J. App. Phys. **9**, 677 (1938); W. H. Wells, Phys. Rev. **5**, 599A (1939); W. H. Wells, R. O. Haxby, W. E. Shoupp, W. E. Stephens, Phys. Rev. **57**, 347A (1940).

weight of steel over that necessary to make a spherical or cylindrical vessel with the same minimum clearances from high voltage cap to the pressure vessel, both through the air gap and along the support insulators and belts. Since the best voltage distribution for highest total voltage along the belts and support towers is approximately linear, the clearances radially from tank wall to tower were made to vary linearly with height.

Maximum voltage difference for a given field strength at the inner electrode is obtained with concentric electrodes at a ratio of diameters of 2 for spheres and of $e(=2.718)$ for infinitely long cylinders. For the same diameter of inner electrode, the field strength at the surface of the inner electrode for concentric spheres is twice the value for the field strength with concentric cylinders when the condition for maximum voltage difference is fulfilled. Hence, in our design, the insulator length was increased by a factor of about three over that used in the larger generator at the University of Wisconsin, and the diameter of the inner electrode was increased by roughly a factor of 6.

The vessel was tested pneumatically so as to give an adequate safety factor over its maximum working pressure of 120 lb./in.$^2$. The lower shell is made of $\frac{5}{8}$-inch plate, twice the necessary thickness, so as to reduce stresses due to loading by the support tower and to permit drilling through the shell later for electrical leads or other purposes. There are three 30-inch diameter manholes provided as shown in Fig. 1. Each of these is provided with a 3-inch diameter sight-glass mounted to give a linear angle of view of about 90°. The lower manhole gives access to the inside of the support tower. A 12-inch nozzle at the top of the vessel is used to mount a generating voltmeter in a symmetric position with respect to the high voltage electrode. The vacuum tube comes out of the vessel through a 14-inch nozzle at the bottom of the vessel. The top dome of the vessel is of $\frac{7}{8}$-inch steel plate, and the upper conical plates are $1\frac{3}{4}$ inch thick with the lower conical plates of decreasing thickness. These plates were welded in position with the inner surfaces held flush and the welds then ground flush with the plate surfaces.

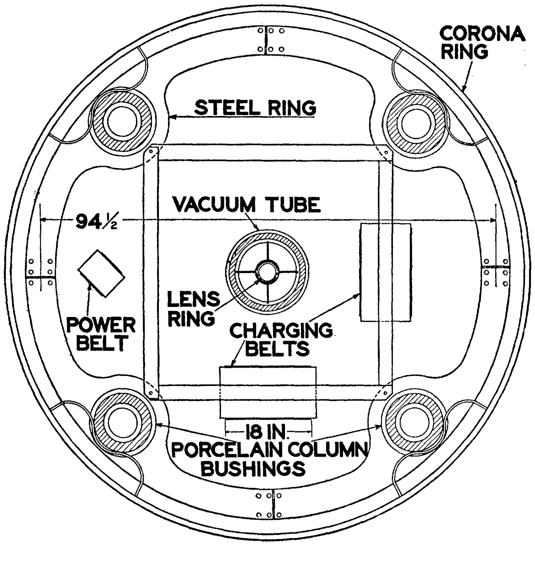

FIG. 2. Plan view of support tower showing location of belts, vacuum tube, corona rings, and removable channel irons.

## HIGH VOLTAGE ELECTRODE

The high voltage electrode is supported on a porcelain and steel insulating tower, as shown in Fig. 1. The upper part of the electrode has a radius of 7.5 feet. The lower half of the electrode curves in more rapidly than the upper spherical surface, as shown in Figs. 1 and 4, as the radial distance from the pressure vessel increases along the conical portion. This permits some gain in the support tower and charging belt length.

The electrode is of $\frac{3}{16}$-inch steel plate dished at the factory and welded in the field. The welds and all weld beads remaining were ground off. The electrode has irregularities of the surface due to difficulties which showed up in dishing this thin plate, and is out-of-round in some places by as much as $\frac{1}{8}$ of an inch in 3 or 4 inches. However, there has been no consistent sparking at atmospheric pressure from any one place on the electrode.

## SUPPORT TOWER

The support tower is constructed as shown in the two views Figs. 2 and 3. It is made with sufficient flexibility in the flat steel rings to limit the mechanical stresses in the porcelains to a low

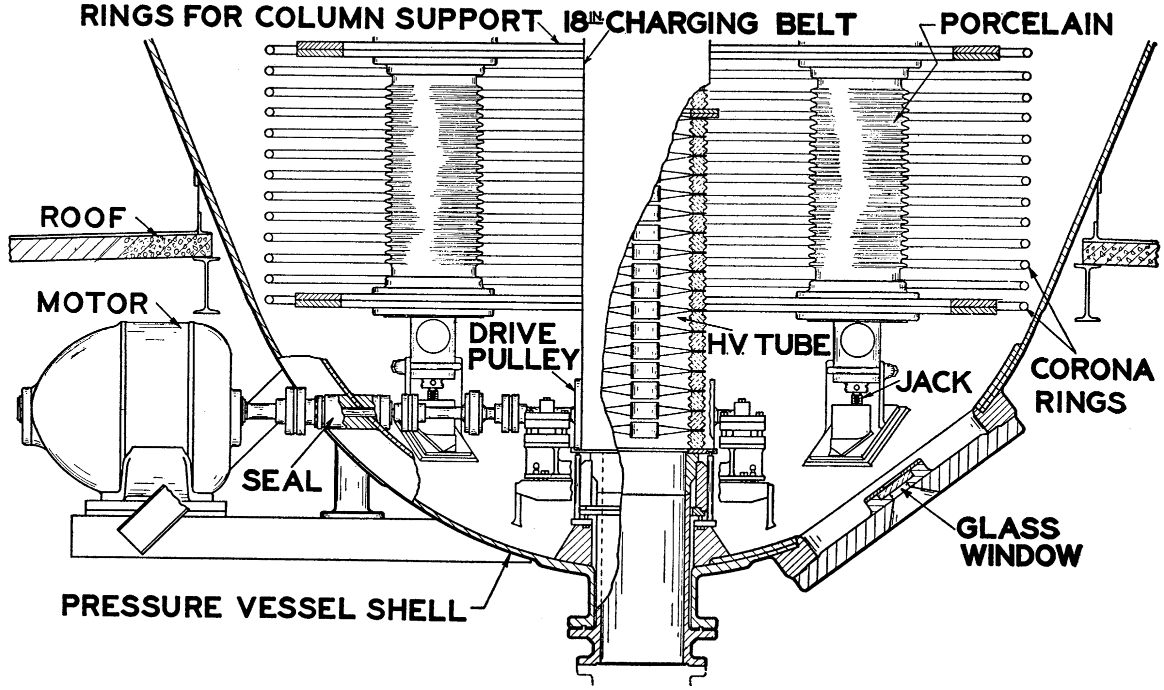

FIG. 3. Vertical section of base of pressure vessel and support tower.

value.[8] The tower is made up of a series of ten separate sections, nine of which are 3 feet in height while the upper one is 2 feet in height. Each section consists of two flat steel rings bolted to and held apart by four porcelain bushings. The flat steel rings are made up of four quadrant pieces for economy of fabrication and ease of assembly. The sections are stacked with the bushings in line vertically, to transmit the vertical load directly in compression. The successive sections are bolted together only at points halfway between the bushings with $\frac{1}{16}$-inch shims inserted between sections both below the bushings and at the points of bolting between sections.

Application of a lateral force to the upper end of the tower will cause the steel rings to deflect in bending and twist, thus limiting the tensile stresses in the bushings to low values. This design also avoids large stresses in the bushings due to temperature gradients between the sections, and due to errors in machining of the ring or assembly of the tower. The natural period of the tower is 0.77 second. From the measured damping, it was computed that a 150-lb. man swaying through an amplitude of 1 ft. in resonance with the tower could build up an amplitude of the tower about equal to that produced by a 450-lb. force statically applied, and the bending stress in the porcelain bushings at this value of lateral force is less than 50 lb. per sq. in., which is quite safe. The tower is

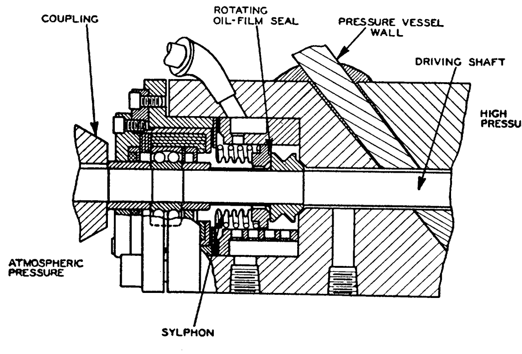

FIG. 4. Rotary oil film seal on driving shafts for the fabric belts.

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We wish to express our appreciation of the help given by the Mechanics Department of the Westinghouse Research Laboratories in the many mechanical problems which arose in the design and construction; in particular, to Dr. A. M. Wahl for calculations on the support tower design; and to Mr. B. F. Langer for many helpful discussions of mechanical problems.

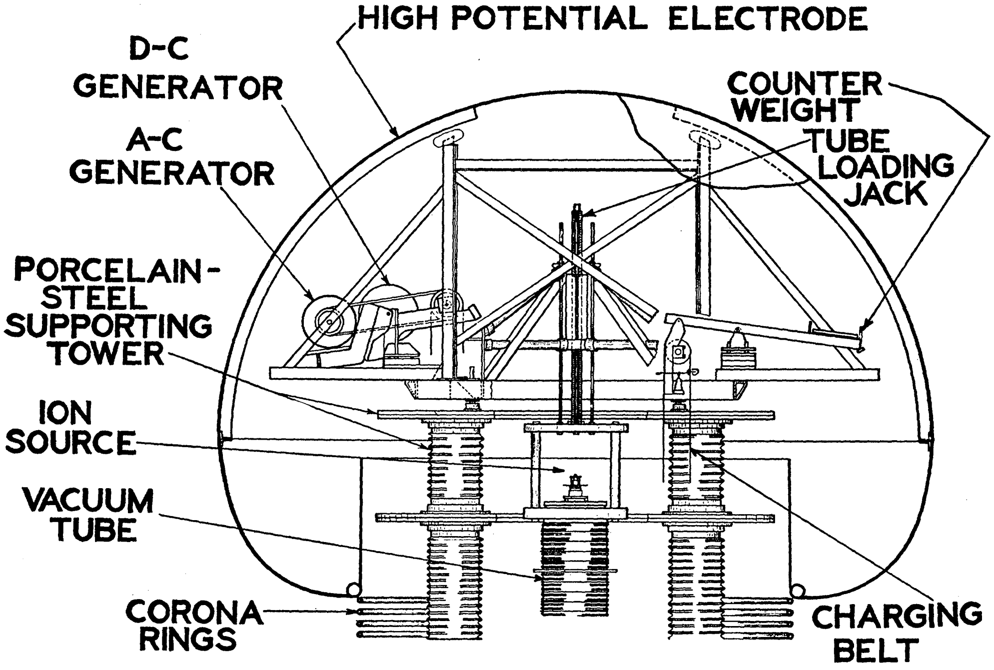

FIG. 5. Vertical section of high voltage electrode.

capable of standing erect in case of complete destruction of a bushing.

As shown in Fig. 3, the lower end of the tower rests on four jack screws to permit lateral adjustment of the tower after erection. Movement of over an inch vertically for one jack is permissible because of the flexibility of the towers. Likewise, four independent vertical jacks support the electrode on the tower to give a further vertical adjustment. The lower jacks are mounted on 12″ by 12″ pads welded to the pressure vessel wall to distribute the loading on the shell.

The porcelain bushings were fabricated at the Derry Works of the Westinghouse Electric and Manufacturing Company. The bushings have corrugations one inch deep both inside and outside with a central hole varying from 6 to 7 inches, and an outside diameter of 12 inches at the base where they were cemented to the end caps. The flat steel rings were machined smooth and the end caps of the bushings were likewise machined.

### BELTS, PULLEYS, AND MOTORS

Two charging belts, each 18 inches in width, run at right angles to each other in the positions shown in Fig. 2. The lower driving pulleys are $10\frac{1}{2}$ inches in diameter and 20 inches in length, with crowning of 0.01 inch per inch over the outer 3 inches. All of the pulleys are made of steel tubing welded to end plugs attached to the shafts and the assembly then dynamically balanced. The charging belts are driven by Westinghouse Type SK 15 hp, d.c. motors with speed variable between 400 r.p.m. and 2000 r.p.m. with the rotors dynamically balanced. The motors are mounted outside the vessel, as shown in Fig. 3, with the driving shaft passing through the pressure vessel wall. The pressure seals used are of the type used for refrigerator units[9] (see Fig. 4). Test showed only a small air leakage which was negligible considering the size of the pressure vessel. Three flexible Thomas couplings are used in each shaft, as shown in Fig. 3. The upper pulleys for the charging belts are $6\frac{3}{8}$ inches in diameter with the same crowning as the lower pulleys. The pulleys are mounted on the counter weight system, as shown in Fig. 5 so as to give a constant force of 200 lb. for each run of a belt, permitting of stretch of each run of a belt of more than 12 inches. The center-to-

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[9] Obtainable from Clifford Manufacturing Company, Boston, Mass.

center pulley distance is about $31\frac{1}{2}$ feet for new belts. The exact stretching for the different belt materials under this load has not been measured, but in general we are able to use the same belts for several months after they are once in alignment, without further adjustment. However, since the insertion of the aluminum tubes (as described later) close to the surfaces of the belts, it has been necessary to limit the lateral movement of the upper pulley so as to keep the belts from rubbing against the tubes. A belt six inches wide of the same material as the charging belts transmits power to the electrode. One 2-kw, 220-volt, a.c. generator and one 2-kw, 220-volt, d.c. generator are driven by the upper pulley of the six-inch belt. through intermediate V-belts. These generators supply power for the belt charging systems, ion source, and lights in the high voltage electrode.

Both the lower and upper pulleys for the charging belts are mounted on Micarta blocks to insulate them from ground and the electrode, respectively. We have used them as inductor plates, but burned out the shaft insulator when the lower pulley was $-20$ kv to ground and the points horizontally opposite the center of the pulley at $+20$ kv. The spray points were then moved to a position several inches above the pulley. Variacs are used to control the spray voltage on a set of office pins spaced $\frac{1}{2}$ inch apart and about $\frac{1}{4}$ inch from the belts, at both ground and high voltage end of the belts. Under pressure, with the different belt materials used, it has been necessary to adjust the charge on the two runs of the belt to obtain maximum voltage. Raising the spray voltage on one run of a belt above this best value causes sparking on this run of the belt near the high voltage electrode. This seems to imply that at maximum voltage the charge density is the same on each run of a belt. At this balanced condition a lower voltage is necessary for negative corona points spraying charge on the belts than is necessary for positive points.

The first belt material tried was Goodyear Zeppelin fabric, which gave, at a speed of 5000 feet per minute, a charging current including both belts of about 500 microamperes, measured from the electrode to ground through a microammeter at atmospheric pressure. To eliminate the lap joint of these thin belts, a commercial belting of fabric and latex, called brown Tontex[10] was tried with a vulcanized smooth splice of thickness the same as the rest of the belt. These gave a lower charging current of about 300 microamperes. They were injured by sparks along the belts. A series of aluminum tubes was then installed, as described later in this paper, giving an increase in the maximum voltage obtainable, but rips due to sparking at these higher voltages soon necessitated removal of the Tontex belts. The next belts tried were a commercial black latex coated belting of the kind used by Professor J. G. Trump.[11] They have a smooth spliced joint. These belts were also injured by sparks and one of the charging belts was split down the center line for one-half of its length. Next, Balata[12] belts were tried. These have two of the fabric layers on the outside surface, with the Balata material and one fabric layer between them. The charge transported was about 300 microamperes again. All types of belting take many hours in dry air to dry out after exposure to humid air. We have found that a somewhat higher voltage can be obtained near 45 lb./in.$^2$ air pressure after running these belts for about a hundred hours, than was the case with any of the other kinds of heavy belting used.

## AIR-DRYING SYSTEM

Air for the pressure vessel is dried by two activated alumina[13] drying beds in series. Valves are arranged with a blower whose capacity is about 200 cubic feet per minute at 3 lb., so that the air initially in the pressure vessel can be circulated through the towers and back into the vessel. The towers also dry the incoming air at a rate of about 250 cubic feet per minute, with no change in the relative humidity in the pressure vessel that is not explainable as a temperature effect.

It is necessary to reduce the relative humidity in the pressure vessel to about 40 percent to obtain high voltage on the electrode. No apparent

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[10] Tontex belts are obtainable from Tontex Corporation, Grand Rapids, Michigan.

[11] Private communication from Professor Trump.

[12] Balata belts are obtainable from Victor Balata and Textile Co., New York, New York.

[13] Design information can be obtained from the Aluminum Ore Co., East St. Louis, Illinois.

gain in maximum voltage was obtained in one series of tests when the relative humidity was below 10 percent for several days.

### CORONA RING SYSTEM

A system of metal rings surrounding the support tower was provided as in the design of R. G. Herb and associates.[2] A set of gaps between adjacent rings, consisting of four negative points opposite a plane, act to produce corona current down the ring system. One hundred rings of 1.25 inch diameter Al tubing held by brackets in the corrugations of the bushings are spaced at about one inch average clearance. This clearance varies somewhat because of the flexibility of mounting. At the ends of the porcelain bushings the clearance from the bushing caps to the nearest ring is somewhat larger. One corona ring is attached to the center of the flat steel rings of the support tower to shield their surfaces. The corona rings have a mean diameter of 108 inches.

With this choice of corona rings, the average axial field strength at the surface of a ring was estimated to be about one-half of the field strength at the spherical surface of the high voltage electrode. This seemed sufficient to prevent the ring system from being a limitation to the maximum voltage of the generator.

### VOLTAGE CONTROL

As a control for voltage on the electrode, a "poker" is mounted on a nozzle at one side of the pressure vessel, as is shown in Fig. 1. It can be made to approach the electrode or recede back into the vessel wall by a reversible drive controlled from the control panel for the generator. A friction drive is used to avoid damage to the apparatus. A set of points on the end of the "poker" controls the voltage by varying the corona-current drain from the high voltage electrode. The position of the "poker" is indicated on the control panel by means of Westinghouse Type ADS position indicator motors. The direction chosen for the poker is at about 45° upward, so that corona from the points would affect the generating voltmeter as little as possible. There has, as yet, been no indication of such an effect.

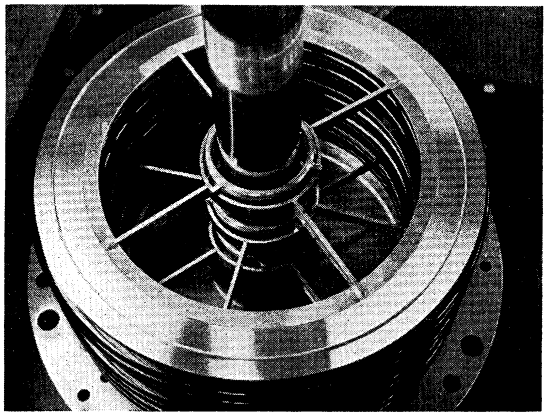

FIG. 6. Photograph taken during assembly of a section of the accelerating tube.

The voltage is also controlled by adjustment of the spray voltages used for the charging belts. An increase in the voltage on the ion-source probe decreases the voltage on the high voltage electrode since this increases the output of the ion source.

### ACCELERATING TUBE AND VACUUM SYSTEM

The accelerating vacuum tube occupies a central position inside the support column as shown in Figs. 1 and 2. It is made up of 130 flat porcelain rings, 15 inches mean diameter, 1 inch minimum wall thickness, and $2\frac{1}{8}$ inches in height.[14] Two flanges 1 inch in depth were made on both inside and outside walls, to increase the surface creepage path. The rings were ground flat and then coated with a platinum alloy glaze giving a metallic end surface in intimate contact with the porcelain to prevent concentration of electrical stress where the porcelain joins the gasket.

The structure of the tube is shown in the photograph (Fig. 6). Flat rings of $\frac{1}{8}$-inch brass, extending about $\frac{1}{2}$ inch inside and outside of the porcelain ground surfaces, hold a 5-inch outside diameter ring of $\frac{1}{8}$-inch wall, one inch in height in the center, by means of 4 radial webs. All joints were silver soldered. The majority of the electrodes which form the focusing gaps of the tube are $2\frac{1}{8}$ inches in height made from $\frac{1}{4}$-inch wall brass tube with 4-inch outside diameter.

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[14] Made at the Derry Works of the Westinghouse Electric & Manufacturing Company.

The electrodes are supported from the 5-inch diameter brass ring by four steel Allen screws forced into the brass at time of assembly. The tube was assembled with $\frac{3}{32}$-inch diameter tin wire gaskets and aligned on a mandrel in sections consisting of 18 porcelains with the associated brass electrode structures. Steel end rings which remained with each section were used to transport and to compress the section by means of tie rods. The end rings were doweled to insure correct alignment of the tube in final position. The upper lens ring in each section was made longer to preserve the lens gap of about $\frac{3}{8}$ inch between successive electrodes.

With cover plates and rods to prevent overloading of the gaskets, each section was tested to 180 lb./in.$^2$ external pressure. The tin wire gaskets have an elastic limit on short time tensile test of 1300 lb./in.$^2$. The full pressure load on the top of the tube at 120 lb./in.$^2$ could probably be supported without much more flow by the gaskets when they reach a radial width of $\frac{3}{16}$ inch due to friction gripping of the thin gasket by the ground porcelain surface. It was decided, however, to provide a large jack screw to increase the compressive force on the tube when necessary, and also to provide four tie rods opposing the action of the jack screw to prevent most of the extra compressive force due to pressures above atmospheric from being applied to the gaskets. This arrangement can be seen in Fig. 5. The tube is braced laterally to the support column at three places, $\frac{1}{3}$ and $\frac{2}{3}$, and at the upper end of its height since calculation showed that the unbraced structure would be close to the buckling limit.

In the assembly of a section of the tube, the gasket seals were compressed to about one-half their final thickness, painted with thinned glyptal by means of hypodermic needles, and the remainder of the compression was then taken up. The vacuum system contains over 1000 feet of this type of seal, and can be pumped down with our present pumping system to below $2\times10^{-5}$ mm Hg. The lower end of the vacuum tube rests on the top of a flanged pipe which forms the seal from inside the pressure vessel to the space outside. This has a thick lead gasket which was compressed eccentrically to compensate for final misalignment of the tube with respect to the support column. The gross adjustment due to misalignment of the lower nozzle axis was taken up by welding together the flange and the outlet pipe with their axes at a small angle.

As shown in Fig. 1, the vacuum pumps and analyzing magnet are located in the second floor room of the laboratory building. The analyzing chamber with nozzles for attachment of targets is at the center of the first floor room. A four-inch all-metal diffusion pump with a speed of 240 liters per second backed by a Hypervac 20 is used. The diffusion pump is of the self-fractionating type supplied by the Distillation Products Corporation, Rochester, New York. When first attached by means of a 12-inch length of straight 4-inch pipe to the main vacuum tube and without a baffle, trouble was experienced due to back streaming of the pump oil into the main tube, causing the oil to run down to the target position. This back streaming was not eliminated by insertion of the baffle, which came with the pump, but was eliminated by inserting a 12-inch vertical section of 4-inch pipe between the diffusion pump and the main vacuum tube. This cuts down the pumping speed approximately half, but the pipe attached to the main vacuum tube has remained dry for the last several inches before entering the main tube. After continuous pumping for several months, about $\frac{1}{3}$ of the oil in the diffusion pump disappeared. It did not appear to be condensed in either the main vacuum system so as to impair its ability to stand high voltage, nor did it appear in a buffer tank used between the diffusion pumps and the mechanical pump, and so probably had been pumped away as volatile products formed from the oil.

## CONTROLS

The controls necessary to operate the generator, excepting the belt motor controls, have been put on two relay rack panels mounted on a wheeled table. About 100 control wires from the panel are connected to the panels in the form of 22 prong plugs, so that the controls can be moved to another part of the building when necessary. Seven position indicator motors[15] are

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[15] Type ADS position indicator motors made by Westinghouse Electric and Manufacturing Company.

mounted on the panel and connected to seven others inside the pressure vessel. Strings go up from these to the high voltage electrode to adjust Variacs on spray voltage, ion source filament, ion source high voltage supplies, and a needle valve controlling the gas flow for the ion source. The panel also contains the lower spray voltage control for the charging belts. Controls are also provided for the deflecting magnet and for the generating voltmeter, voltage control "poker," and main tube vacuum measurements.

An illuminated meter panel in the high voltage electrode shows the ion source performance and upper spray voltage for the belts. A telescope is used to view this panel from the first floor of the laboratory through a sight glass in the lower manhole.

## Voltage Tests and Belt Performance

The maximum voltage obtainable at atmospheric pressure is about 1.4 Mv. This is limited by sparking from the electrode to the pressure vessel wall and down the corona ring system. A beam of particles can be maintained for hours at 1.25 Mv.

When first operated at pressures above atmospheric, the maximum sparking voltage was limited by sparking along regions of the charging belts, vacuum tube, and corona rings. A representative set of values is given by the points for curve *A* in Fig. 7. As the pressure was increased, a region was reached in which the maximum voltage obtainable began to fall with increasing pressure. A similar effect at a somewhat higher pressure has been reported by Herb and Bernet.[16] This region was characterized by shorter and more frequent sparks along the belts and corona ring system than occurred at lower pressures. During these tests the belts were damaged in many places by sparks which ripped out fabric and latex, and in some cases, split the belts.

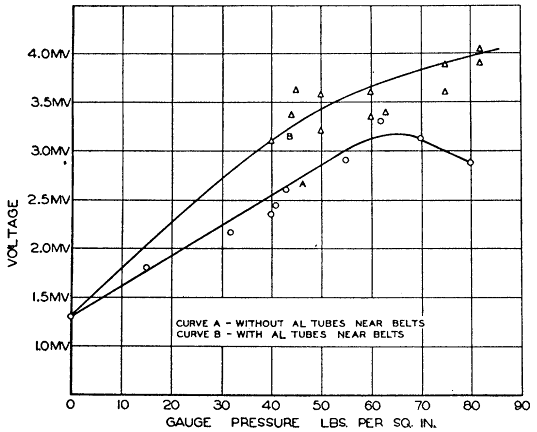

Fig. 7. Maximum sparking voltage of the generator as a function of air pressure, with and without aluminum tubes near the belts.

The charging belt surfaces have a minimum clearance of about 10 inches from the vacuum tube and parts of the support column. Trump and Van de Graaff[17] have made a small belt machine operating in air under pressure, in which a series of metal tubes was placed parallel to and near the surfaces of the belts to reduce the horizontal voltage difference between a point at the belt and a nearby point on the vacuum tube or high voltage electrode supports. Following this idea, we inserted a series of aluminum tubes of $\frac{3}{4}$ inch diameter placed on each run of the belts every 3 feet. It was also necessary to place these tubes along the power belt, after which the maximum obtainable voltage at a given pressure was higher as given by the points for curve *B* in Fig. 7. The limitation was still sparking of the same general character as before.

The corona gaps between the corona rings along the support tower each consist of four negative points opposing a positive plane. The maximum voltage obtainable with the generator occurs for gap spacing of about $\frac{3}{4}$ to 1 inch. In general, it is possible to maintain an ion beam focused on the target at voltages a few hundred kilovolts below the maximum voltage at which sparking occurs. The highest sparking voltage obtained is 4 million volts, as shown in Fig. 7. The highest voltage at which an ion beam has been maintained is 3.7 million volts.

## Ion Source

The ion source now being used is shown in Fig. 8. It is an adaptation from one described by Tuve, Hafstad, and Dahl[18] with changes in

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[16] R. G. Herb and E. J. Bernet, Phys. Rev. **52**, 379 (1937).

[17] J. G. Trump and R. J. Van de Graaff, Phys. Rev. **55**, 1160 (1939).

[18] M. A. Tuve, L. R. Hafstad, and O. Dahl, Phys. Rev. **48**, 315 (1935).

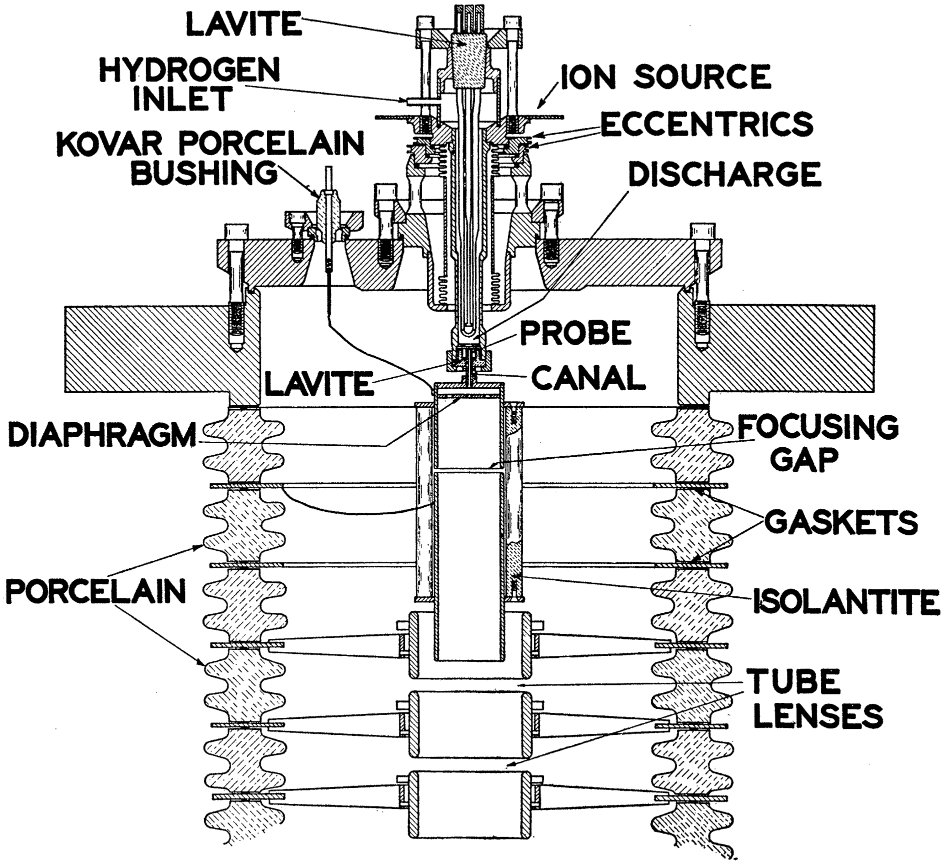

FIG. 8. Ion source and first few accelerating gaps of vacuum tube.

the probe mounting and in the first focusing gap. Satisfactory filament life of several hundred hours is obtained at about 200 milliamperes discharge current. The filament is made of 10-mil tungsten wound with 5-mil nickel, coated with a BaO and SrO mixture and a binding agent. The discharge voltage drop is between 50 and 100 volts with hydrogen pressure of 2 to $3\times10^{-2}$ mm Hg. With voltage of about 2 kv on the probe, an output current of 50 to 80 microamperes of ions was obtained as measured below the probe to the rest of the tube as a Faraday cage.

To get some idea of the total effective focusing action of the large number of electrostatic lenses which make up the main part of the tube, calculations were made by the method of Hansen and Webster.[19] From the general theory of lens action together with the experimental potential distribution found by Kirkpatrick and Beckerley[19] the formula for the focal length of each individual lens is

$$f=16.5R(V/\Delta)^2.$$

Here $R$ is the radius of the cylindrical electrodes, $V$ is the potential in volts of the first cylinder of a lens relative to the potential of the ion source, and $\Delta$ is the potential difference between the two cylinders constituting the lens. In deriving the formula, it is supposed that the gap between the cylinders is small compared to $R$, that the length of each cylinder is long compared to $R$, and that $\Delta$ is small compared to $V$. Actually in our case the length of the cylinders is not long compared to $R$ so the actual focal length will be much greater than that given by the formula. If $Z$ is the coordinate of a particle measured along the tube axis and $r$ is its distance

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[19] W. W. Hansen and D. L. Webster, Rev. Sci. Inst. **7**, 17 (1936). (See especially fine print paragraphs at end of paper.) P. Kirkpatrick and J. G. Beckerley, Rev. Sci. Inst. **7**, 24 (1936).

from the axis, then the method of Hansen and Webster gives the following equation for the average trajectory of a particle through a succession of lenses spaced a distance $l$ apart, using the above approximation for the focal length of each lens and assuming that $\Delta$ is the same for each lens (uniform voltage distribution along tube),

$$d^2r/dz^2 = -(l/16.5R)r/z^2.$$

This differs slightly from the formula as printed by Hansen and Webster because of some numerical misprints in their paper. Although this equation may have solutions of oscillatory type (corresponding to a succession of focal points along the length of the tube) if $l/R > 4.1$, with our dimensions $l/R = 1.25$, so the non-oscillatory case is the one that applies here. This is even more the case when it is remembered that the formula for $f$ overestimates the power of the individual lenses.

With the method indicated, it appears that the aggregate focusing action of the tube is such that a beam that is parallel 1/13 of the tube length from the ion source end will be brought to a focus at the target ten feet beyond the end of the lens system. This is such a weak contribution to the focusing that it is evident that the first few lenses near the ion source must be relied upon to do the focusing. This result from theory is in accord with our experience and that of other workers with whom we have discussed the question.

The first focusing gap must be considered as a thick lens since the increase in voltage between the cylinders is not small compared to the voltage on the first, or probe, cylinder. Useful data giving the constants for such a lens over a considerable range of voltage ratios are given by Klemperer and Wright.[20]

That a large fraction of the ions had a spread in direction after coming from the probe so that they were not focused by the present lens arrangement was shown by inserting a diaphragm 5 mm below the probe canal with a 1 mm diameter central opening and several side openings for gas flow. The current from the probe canal measured as before was now about 5 microamperes, and total ion currents of the same order of magnitude are obtained at the target in a well-focused spot. The currents obtained in the beams of different masses are about 0.3, 0.5, 0.5 microamperes of $H^+$, $H_2^+$, $H_3^+$, respectively, and commercial tank hydrogen is used, the hydrogen supply line being kept at a pressure of 15 lb./in.$^2$ above that used inside the pressure vessel. Between successive electrodes of the accelerating tube 1000-megohm IRC resistances are connected. These resistances are connected electrically to the corona ring system only at the two lateral places where there are braces to insure mechanical stability of the tube as already mentioned. These are located at points $\frac{1}{3}$ and $\frac{2}{3}$ of the way along the length of the tube. It is necessary to keep the vacuum at the lower end of the vacuum tube below about $10^{-4}$ mm Hg in order to maintain high voltage on the tube.

## VOLTAGE MEASUREMENT AND STEADINESS

Voltage on the high voltage electrode is measured with a generating voltmeter installed in the 12-inch nozzle at the top of the pressure vessel. The voltmeter was calibrated by using the value of 0.862 Mv for one of the prominent resonances for gamma-ray production from fluorine bombarded by protons. This value was determined by Bernet, Herb, and Parkinson.[21] By bombarding a thin tantalum fluoride target with the $H^+$, $H_2^+$, and $H_3^+$ beams, the generating voltmeter was shown to be linear using the voltages at which the 0.862-Mev resonance was a maximum as 1.724 Mv for the $H_2^+$ beam and 2.586 Mv for the $H_3^+$ beam.

The generating voltmeter is used as a null instrument.[22] A measured voltage is applied to an adjacent sectored plate of the voltmeter until the field due to this plate is the same as the field produced by the high voltage at the pick-up plate. The induced voltage produced on the pick-up plate is amplified and viewed on an oscilloscope. The wave form for the balance point is easily reproduced. The voltage on the high voltage electrode remains constant at a

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[20] Klemperer and Wright, Proc. Phys. Soc. London **51**, 296 (1939).

[21] E. J. Bernet, R. G. Herb, and D. B. Parkinson, Phys. Rev. **54**, 398 (1938).

[22] G. P. Harnwell and S. N. Van Voorhis, Rev. Sci. Inst. **4**, 540 (1933).

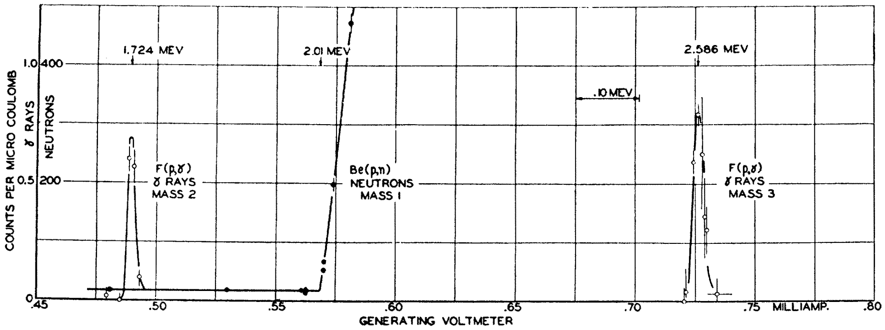

FIG. 9. Curve showing fluorine gamma-ray resonances used for voltage calibration and a typical run to determine the $(p,n)$ threshold for beryllium.

given voltage to within 0.5 percent for observing times of several minutes. Sometimes the voltage remains constant to within 0.2 percent for one-half minute or so.

The generator is especially suitable for the investigation of nuclear reactions in which it is desirable to know the homogeneity in energy at a given energy to within limits of a few tenths of a percent. It is possible to vary the voltage of the generator from below 1 Mv up to 3.7 Mv and at different voltages within these limits to obtain focused ions which are homogeneous in energy to within 0.2 percent.

The apparatus is being used for accurate measurements of the thresholds of several light elements for emission of neutrons under proton bombardment. This work is now being completed and will be published soon in another paper. As an indication of the steadiness of the apparatus, Fig. 9 shows the gamma-ray resonances from a thin tantalum fluoride target with $H_2^+$ and $H_3^+$ ions and also the yield of neutrons obtained on proton bombardment of beryllium. The threshold value, 2.01 Mev,[23] is obtained by linear interpolation between the two fluorine resonance peaks. Although the fluorine resonance peaks seem narrower than the widths previously reported by Herb, we do not feel entirely sure of this until it is checked again. Critical discussion of this threshold value and others obtained on proton bombardment of lithium, boron, and carbon will be presented later.

We wish to express our appreciation for the cooperation and assistance given to this work by many members of the staff of the Westinghouse Research Laboratories, and in particular to Dr. L. W. Chubb, Director, and Drs. E. U. Condon and J. Slepian, Associate Directors of the Laboratories. The technical assistance of Mr. J. W. W. Ow in the drafting work connected with the generator has been an important contribution to its successful construction and operation.

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[23] This value, given by a sample run, is not to be taken as our final result. This generating voltmeter scale could be read only to $\frac{1}{4}$ or $\frac{1}{2}$ percent. Hence the error in this comparison is approximately one percent.

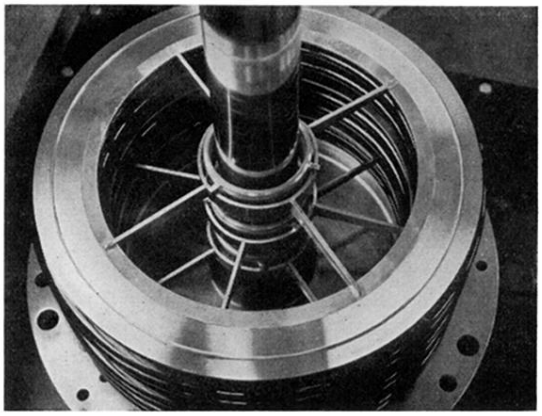

FIG. 6. Photograph taken during assembly of a section of the accelerating tube.