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Compact Electrostatic Generator for the Production of Positive Ions*

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The design and operational characteristics of a compact pressurized electrostatic generator are described. The machine is operated in a pressure vessel with an over-all height of 13 feet, and positive ions have been accelerated to energies up to 1.75 Mev through a tube 5 feet long. The potential gradient thus achieved along the tube is 350 kv/ft., which is considerably greater than the average value achieved by other positive ion accelerators thus far reported. It is believed that even the present voltage limitation can be extended.

I. INTRODUCTION

IN the summer of 1939 plans were formulated for the construction at the Bartol Foundation of a compact electrostatic generator ("statitron") for the acceleration of positive ions. The basic design was completed by one of us (WED) after a consideration of published reports,[1] supplemented by discussions with persons who have had experience with high voltage machines. By 1941[2] the machine had been assembled in rudimentary form, but the beginning of the war forced us to abandon this work temporarily. In August, 1946, the work was resumed by the three last named authors toward further development of the machine, and, in particular, of those features having to do with the acceleration of positive ions.

Difficulty was encountered in maintaining, during summer weather, a humidity low enough so that the insulating material of the generator, if exposed for a few hours or days to moist air, would dry out again in a reasonable time when the pressure vessel was put over the machine and dry air circulated through it. (Humidity control equipment was not available at the time.) The insulation problem became progressively more acute, and was aggravated by such sparking as did occur during operation; our voltage limitation dropped to about 800 kilovolts. It was decided, therefore, to change insulating materials and to make other rather extensive improvements which our experience indicated as desirable, and in the summer of 1947 two of us (ELH and CPS) accordingly began this work.

The results reported in this paper represent the total of the effort which has been made to develop this generator to its present operating condition.

* The work reported herein has been assisted by the Office of Naval Research since June 1946. The basic parts of the machine were fabricated through the use of Bartol funds.

[1] R. G. Herb, D. B. Parkinson, and D. W. Kerst, Phys. Rev. **51**, 75 (1937); J. G. Trump and R. J. Van de Graaff, Phys. Rev. **55**, 1160 (1939); W. H. Wells, R. O. Haxby, W. E. Stephens, and W. E. Shoupp, Phys. Rev. **58**, 162 (1940); I. A. Getting, J. B. Fisk, and H. G. Vogt, Phys. Rev. **56**, 1098 (1939); T. Lauritsen, C. C. Lauritsen, and W. A. Fowler, Phys. Rev. **59**, 241 (1940); J. H. Williams, L. H. Rumbaugh, and J. T. Tate, Rev. Sci. Inst. **13**, 202 (1942).

[2] W. E. Danforth and E. L. Hudspeth, Phys. Rev. **60**, 170 (1941).

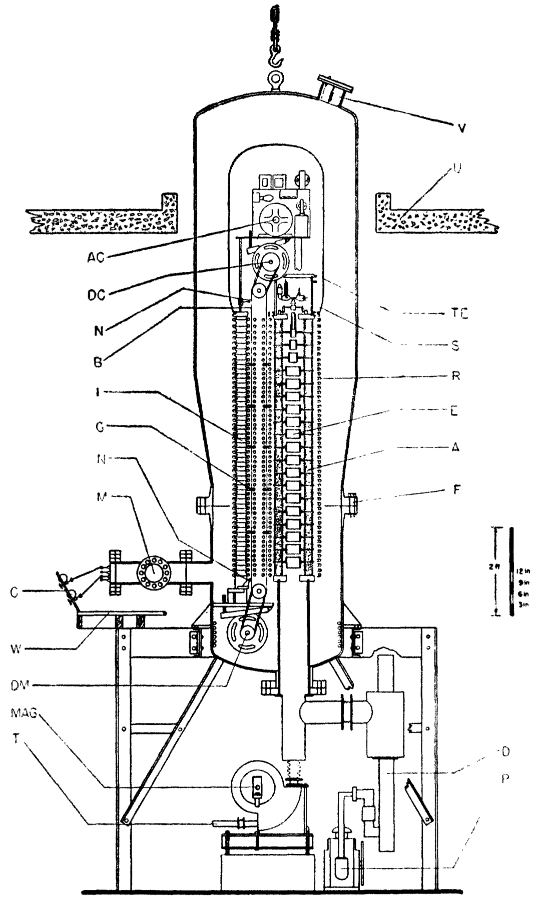

FIG. 1. Sectional view of the Bartol generator. The belt B is driven by a 10-horsepower motor DM. Charge is sprayed on and subsequently removed through corona needles N, N. The upper pulley is coupled by a V-belt to a 1.5-kw d.c. generator which supplies current for the arc of an ion source S and also drives an a.c. converter. The upper assembly is covered by a terminal electrode, TE, which was spun from copper. The belt itself is centered by guards G. The supporting structure consists of 52 equipotential rings R, separated by Textolite insulators I. The accelerating tube is built up of porcelains, A, which support electrodes, E, and which are evacuated through pumps D and P. The positive ion beam is resolved by use of the magnet MAG and the selected component impinges on target T. The energy of the bombarding particles is measured by the voltmeter V (which is at present of the generating type). The controls C pass from the outside of the tank to the terminal electrode through suitable shafting and insulating rods. Internal leads are brought in through the manifold M. The pressure vessel is separable at flange F, and the equipment inside the tank is then accessible from platform W. The tank, when raised, may be moved along the upper floor U, thus permitting use of the hoist for disassembly and replacement of other component parts of the generator.

II. GENERAL NATURE OF THE DESIGN

It was our purpose to build a pressure-insulated generator of compact design, utilizing a low voltage arc to produce positive ions which are homogeneous in energy to a hundred volts or so. The space available indicated the desirability of constructing a vertical machine in a pressure chamber which would occupy the lower floor of our building, with provision for removing the pressure cap through a hole in the ceiling (see Fig. 1). The vertical dimensions of the machine were therefore set by the distance from the floor of the first story of the building to the ceiling of the second floor. After allowing room for removal of the pressure cap as a single unit and additional room beneath the vessel for the analysis of the emergent ion beam, it appeared that the over-all height of the tank should be about 13 feet. The apparatus at the terminal electrode was to be housed in a spinning of vertical height of about four feet, clearance for the belt drive-motor and associated equipment was nearly two feet, and the space required for insulation between the terminal electrode and the wall of the pressure vessel was estimated to be something over one foot. This left approximately five feet for the maximum length of our accelerating tube, and it was hoped that it would withstand a potential difference of at least 1.5-million volts between its ends. Using 1.5-million volts as a rough working limit for the generator, the remainder of the dimensions were adjusted and a final design was formulated. The various components of the generator and something of the operation of the completed unit will be described in the following sections.

III. PRESSURE VESSEL AND STORAGE TANKS

The pressure vessel was constructed in two parts, separable at a flange which accommodates 36 $1\frac{1}{4}$ in. bolts. Removal of the upper section exposes nearly all of the internal parts of the generator. This section can be lifted by an electric hoist in about five minutes, and provision is made for rolling it along the second floor for storage; the hoist may then be used to raise the terminal electrode assembly, or, if necessary, the entire column or bottom motor plate. The general dimensions of the tank may be gauged from Fig. 1; it is 44-in. in maximum diameter and has a wall thickness of $\frac{7}{16}$ in. The tank may be evacuated completely, and it has an internal working pressure of 200 pounds per square inch. Its volume is 110 cubic feet.

Since we planned originally to use compressed air in the generator, no provision was made for gas storage. One fire and the danger of additional fires proved to us the desirability of using gases which would not support combustion, but the cost of likely gases (nitrogen and freon) was too great unless storage could be provided. We accordingly made use of four tanks (of the type used for oxygen storage on submarines) for gas storage; the generator tank may be exhausted into these tanks, and the stored gas subsequently pumped again into the generator.

IV. SUPPORTING COLUMN AND EQUIPOTENTIAL RINGS

We adopted the design of Herb and his collaborators[3] as regards the use of equipotential rings for controlling voltage gradients. Fifty-two rings, made of $\frac{3}{4}$-in. brass tubing and 24 in. in diameter, are built up with three insulators made of corrugated Textolite between adjacent rings.[4] The potential difference between the rings is established by placing a 500-megohm resistance between them, and the total resistance of our column is hence approximately 2.5×10^{10} ohms.

The insulating Textolite supports for the rings snap into place as the rings are placed on top of one another, and each ring also supports a removable belt guard of the type described by Trump and Van de Graaff.[4] These guards have effectively shielded the belt up to our maximum operating voltage. Because of the importance of keeping the belt well centered between the guards, we have installed guides on both the inside and outside of the belt; these are placed on every tenth ring, the design of which was copied from Trump. Each guide consists simply of a glass rod set in a machined groove in an aluminum rod. The belt just touches the surface of the rods, and many hours of running have shown no appreciable wear. Guides of Textolite and hard rubber tubing were also tested, but the glass guides were much more satisfactory.

[3] R. G. Herb *et al.*, reference 1, and subsequent papers from the University of Wisconsin.

[4] J. G. Trump and R. J. Van de Graaff, reference 1.

V. ACCELERATING TUBE

The accelerating tube was made up of 20 corrugated porcelains, each of which was $3\frac{1}{8}$ in. high, $6\frac{1}{2}$ in. I.D., and 11 in. O.D. It would doubtless be worth while to use more[5] procelain sections—probably one should be associated with each equipotential ring. However, these porcelains were available at the time and it was felt originally that the upper limit of voltage on the generator would not be set by tube breakdown. The porcelains were heated and cemented to stainless steel electrode supports with Apiezon W (mixed with a small amount of pump oil). The column has been quite vacuum tight except for a slight amount of initial difficulty. The electrodes inside the accelerating tube are made of cylinders, rounded on the ends, and each $2\frac{3}{4}$ in. in height and $4\frac{1}{2}$ in. in mean diameter. The electrodes nearest the ion source, however, are graded in diameter from about 1 in. to this maximum size.

VI. BELT, DRIVE MOTOR, AND CHARGING SYSTEM

The charging belt is driven by a 10-horsepower motor which is placed in the bottom of the pressure vessel. Charge is sprayed onto the belt from a series of corona needles which are fed by a 50,000-volt adjustable supply. The lower pulley is insulated from ground through a microammeter, and we are thus able to measure leakage of the belt and to observe direct sparking to the pulley. The belt runs at 3800 ft./sec. over balanced pulleys, each 4 in. in diameter, and drives a belt which is 13 in. wide.

Both rubberized fabric belts and a Tilton endless woven cotton belt have been tried. The Tilton belt is much smoother in operation, as others have also observed, and is now used. The cotton belt does not now constitute a fire hazard (in a nitrogen-freon atmosphere), but we understand that coated cotton belts which are fire resistant can be obtained.

The spray-on voltage required to attain a given potential on the terminal electrode is, of course, a function of the pressure and nature of the gas in the tank, the distance from the needles to the surface of the belt, and the value of the tube current. Charge from the belt is drawn off

[5] Lauritsen *et al.*, reference 1.

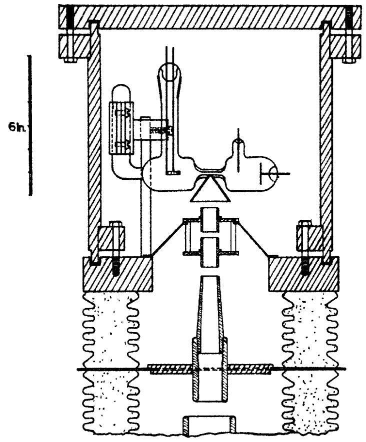

FIG. 2. This drawing shows the ion source, which was constructed of glass, in position at the top of the accelerating tube. The focusing electrodes are shown beneath the cone-shaped electrode which protrudes into the glass capillary. Electrical leads are brought in through tungsten rods set in glass grinds.

at the terminal electrode by a set of needles similar to those used for spray-on; return charge can be drawn from the terminal electrode by charging still another set of needles by induction (the upper pulley being insulated), but the voltage has not been as steady under these conditions and this plan was abandoned. In neither case is the upper limit on voltage which the generator will achieve set by any lack of charge carrying capacity of the belt, since a single run of belt will carry several hundred microamperes.

VII. TERMINAL ELECTRODE AND ION SOURCE

All equipment at the high potential end of the column is housed inside a large copper spinning. This equipment includes a 120-volt, 2-kw d.c. generator, driven from the upper pulley of the generator. This furnishes d.c. power for a low voltage capillary arc (see Fig. 2) and also drives a 1-kw d.c.-a.c. converter. The 110-volts a.c. from this converter supplies, through Variacs and suitable associated circuits, the power for (a) a "tickler" voltage of 800-volts a.c. for initiating the discharge in the ion source, (b) a variable voltage—300 volts negative to 100 volts positive—which may be applied to a cone-shaped (see Fig. 2) electrode for the purpose of obtaining initial focusing of the ion beam, (c) a focusing voltage of 0 to 4000 volts negative on the electrode just beneath the cone, and (d) another focusing voltage of 0 to 15,000 volts negative on the next electrode. Power is also supplied for (e) heating a palladium leak which regulates the flow of hydrogen, and (f) the cathode of the ion source. Both oxide-coated cathodes and thoria-coated cathodes have been used; either is satisfactory, although the former are subject to "poisoning" and the latter dissipate considerable heat. About 15 watts are required for the oxide-coated cathode and nearly 50 watts for the thoria-coated cathodes, with an emission in each case in excess of 500 milliamperes.

It was observed, with compressed air in the pressure tank, that the d.c. generator often failed to deliver current. Various types of brushes were tried, but no reliable performance was attained under pressure. This trouble vanished, however, when the gas in the tank was changed to a nitrogen-freon mixture, and it has not recurred.

VIII. CONTROL SYSTEM

The circuits enumerated in the previous section may be controlled as follows: Steel rods pass through suitable glands in a pressure-tight manifold. These rods are then individually connected through flexible shafting to a gear box located at the bottom of the lowest equipotential ring. Control is then carried to the terminal electrode through lengths of Pyrex rod; these rods terminate in another gear box which connects flexible shafting to the Variacs or potentiometers which must be adjusted. The system has been quite reliable, and calibrated dials on a panel outside the generator enable us to determine the settings of the circuits inside the terminal electrode. Flashlight bulbs associated with various circuit elements were used, together with a suitable lens system and photoelectric cells at the base of the column, to determine the actual functioning of the circuits. These were not found to be necessary, however, and their use was discontinued before the system was really perfected.

The Pyrex rods which are now used in our control system were installed after Textolite tubes had caused a fire in the generator when it was operating in compressed air. The fire melted solder on some of the equipotential rings and we were forced to recement our accelerating tube. No really major damage was inflicted, but the control rods were changed to Pyrex. Pyrex tubes were also tested, but were not satisfactory because of the discharges which occurred inside the tubes, and which limited the voltage which the set could generate.

IX. COOLING SYSTEM AND DRYING OF GAS

During operation of the set the power dissipated in the pressure vessel amounts to about 8 kilowatts, most of which is expended in driving the belt. In order to prevent excessive heating of the equipment, water is circulated through eight coils of copper tubing which are wound around the inside of the tank at about the height of the motor.

It is, of course, necessary to maintain a low relative humidity inside the tank. When air was used in the vessel, it was pumped in through a drying agent, and the air could be further dried by use of a blower which pulled it over potassium hydroxide sticks. At present the tank is dried by simply evacuating it, then admitting dry gas.

The relative humidity rises to values around 80 percent or more in the Philadelphia area during the summer, and if the tank is open to room air for a few hours during such weather, it may be several days before it can be dried out sufficiently to operate at high voltages again. In any case, humid air on the outside of the tank has caused trouble with spray-on leads and with other equipment which is used with the generator. It is highly desirable to provide suitable control of humidity. As a temporary measure we have, on occasion during humid weather, simply blown the room air over calcium chloride crystals (used commercially as ice cream salt), thus lowering the humidity to a point where tests and preliminary adjustments on the machine could be conducted in the air (without putting on the pressure cap).

X. OPERATION OF THE GENERATOR

The generator has been operated with a positive ion beam from 150 kev to 1750 kev. The beam is analyzed by means of a magnet (see Fig. 1) which bends the selected component through a right angle, sending it onto a target about 20 in. above the floor of the room. The total positive ion current has been as great as 40 microamperes or more, but in such cases focusing has been poor and operation of the set correspondingly erratic. This condition was improved by placing a small diaphragm in one of the focusing electrodes. Although the current was considerably diminished, operation of the set was quite steady. We obtain about 0.1 to 2 or more microamperes of resolved beam; the atomic beam is sometimes nearly as intense as the molecular beam, but the latter is more often 50 percent greater. It is known that we could substantially increase our beam current, but it has not thus far proved necessary to have greater currents. It would seem, from the reported experience of others, that we should extend our focusing control to at least one more accelerating electrode, and this can be readily done.

Voltage on the terminal electrode is measured by a generating voltmeter (which replaced the electrostatic instrument shown in Fig. 1) of a previously tested design.[6] Current from this voltmeter is balanced by a calibrated cell and a decade resistance box, and fluctuations are observed as a galvanometer deflection. Within observational limits imposed by a 3-second galvanometer period, our set is steady to somewhat less than $\frac{1}{4}$ percent for periods of half a minute or so; a fine-control adjusts spray-on current to compensate for voltage fluctuations on the terminal electrode, and a system of highly stabilized voltage control will be installed when experiments requiring it are undertaken. Magnet current is held constant during a run by a highly accurate control system which will be suitable in its present form for high resolution of the ion beam. The low voltage spread of our beam as it emerges from the ion source should be of particular advantage for this type of work.

Current may be drawn from the terminal electrode through a small metal rod (probe) which passes through the pressure vessel and whose distance from the electrode is adjustable. This probe may be used for voltage changes, and it serves to stabilize the set when large currents are drawn down the tube. Its function in this respect is apparently not so important as in the case of generators which utilize corona discharge instead of resistors between equipotential rings.

[6] J. G. Trump, F. J. Safford, and R. J. Van der Graaff, Rev. Sci. Inst. **11**, 54 (1940).

Incidentally, the current flowing through these resistances can be observed, and gives an indication of the voltage on the terminal electrode. This current, at a given set voltage, appears quite steady after the generator has become well dried out, but we rely on the generating voltmeter for voltage measurements.

The maximum voltage at which we can operate at present is limited by sparking inside the accelerating tube; with about 10 pounds of freon and 70 pounds of nitrogen inside the pressure vessel, sparking from the terminal electrode and between equipotential rings was eliminated. No difficulty with sparking down the cotton belt has yet been observed, although a temporary difficulty was once experienced with a rubber fabric belt.

Although tube breakdown limits the maximum voltage which we can obtain with this generator, the potential gradient which has been achieved with the present tube is substantially larger than has been generally achieved heretofore. Breakdown occurs at 350 kilovolts per foot of tube in this generator, whereas 200 kilovolts per foot is an approximate average of performance thus far reported in the literature of positive-ion generators. Several generators reported were not limited by tube breakdown, however, and hence no direct comparison of limiting tube gradients is possible.

It would seem advisable to increase the number of porcelain sections in order to establish smaller potential drops per section, and this will probably be done in the future. The ultimate voltage should exceed 2 Mev, and this limit will probably be again set (judging also by experience of the M.I.T. group) by the accelerating tube.

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