A Compact Pressure-Insulated Electrostatic X-Ray Generator

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(Received April 11, 1939)

A compact, pressure-insulated, electrostatic x-ray generator has been developed for scientific and medical purposes. A major object of the work was the investigation, with a small and thus flexible machine, of the principles and design factors involved in pressure-insulated electrostatic generators with a view to the subsequent development of higher voltages in compact apparatus. The generator is housed in a steel tank 34 in. in diameter and 100 in. high. At air pressures of 11 atmospheres absolute, 1250-kv x-rays are obtained with target currents of over one milliampere supplied by the single 14-in. belt. With Freon gas the same voltages and currents can be obtained at one-third the pressure required with air. The problem of belt charge is analyzed and a method is described for controlling the electrostatic fields within the column in order to realize the high charge densities possible at high pressure. The construction of a supporting column of high breakdown strength, and other features of the design are described. At 1250 kv the x-ray intensity per milliampere of target current is about 340 roentgens per minute at 50 cm from the target in the direction of the electron beam with five mm of lead equivalent filtration.

A 1.25-MEGAVOLT x-ray generator using compressed-gas insulation has been developed at the Massachusetts Institute of Technology for scientific and medical purposes. This is a continuation of the Institute's program of developing penetrating x-ray sources, using electrostatic generators. A previous 1.0-megavolt air-insulated x-ray generator[1] has been in use at the Huntington Memorial Hospital in Boston since March 1, 1937, during which period about 700 complete treatment series totaling about 10,000 individual treatments have been given. The clinical results obtained with the Huntington generator have indicated, in a preliminary way at least, the advantage of very high voltage x-rays for certain types of malignancy.[2,3] The present development was undertaken with the object of producing a more simple and compact source of such radiation. A further object was to investigate the design factors involved in the application of pressure insulation to electrostatic generators and acceleration tubes, with a view to later developing very compact generators capable of many megavolts.

HIGH VOLTAGE SOURCE

Figure 1 shows a sectional view of the apparatus. The generator and acceleration tube are contained within a vertical steel tank 34 in. in inside diameter and 100 in. in length. The tank is divided into three sections, the upper two being completely removable for accessibility to the apparatus within. The high voltage source is an electrostatic generator of the belt type,[4] in which electric charge is continuously transferred between a high voltage terminal and ground by a rapidly moving belt of insulating material. The terminal consists of a brass spinning set on a brass casting, and is 24 inches in diameter and 19 inches in over-all height. The gap from terminal to tank is 5 inches at the sides of the terminal and about 7 inches at the top.

GENERATOR COLUMN

The high voltage terminal is supported on three Textolite pillars built up of a series of corrugated Textolite disks 3 inches in diameter with laminations horizontal. These disks are separated by thin brass sheets which extend across the column so as to define a succession of flat conducting surfaces between the high voltage terminal and the ground plane. These transverse sheets each support a brass hoop made of $\frac{3}{4}$-inch tubing so as to present a smooth exterior column surface.[5] The total potential on the terminal is divided equally between these transverse conducting members by connecting a spiral-type high voltage resistance of 400 megohms across

[1] J. G. Trump and R. J. Van de Graaff, J. App. Phys. **8**, 602 (1937).
[2] R. Dresser and J. Spenser, New England J. Med. **218**, 415 (1938).
[3] R. Dresser and J. Rude, J. Am. Med. Assoc. **111**, 1834 (1938).
[4] R. J. Van de Graaff, Phys. Rev. **38**, 1919 (1931).
[5] R. G. Herb, D. B. Parkinson and D. W. Kerst, Phys. Rev. **51**, 75–83 (1937).

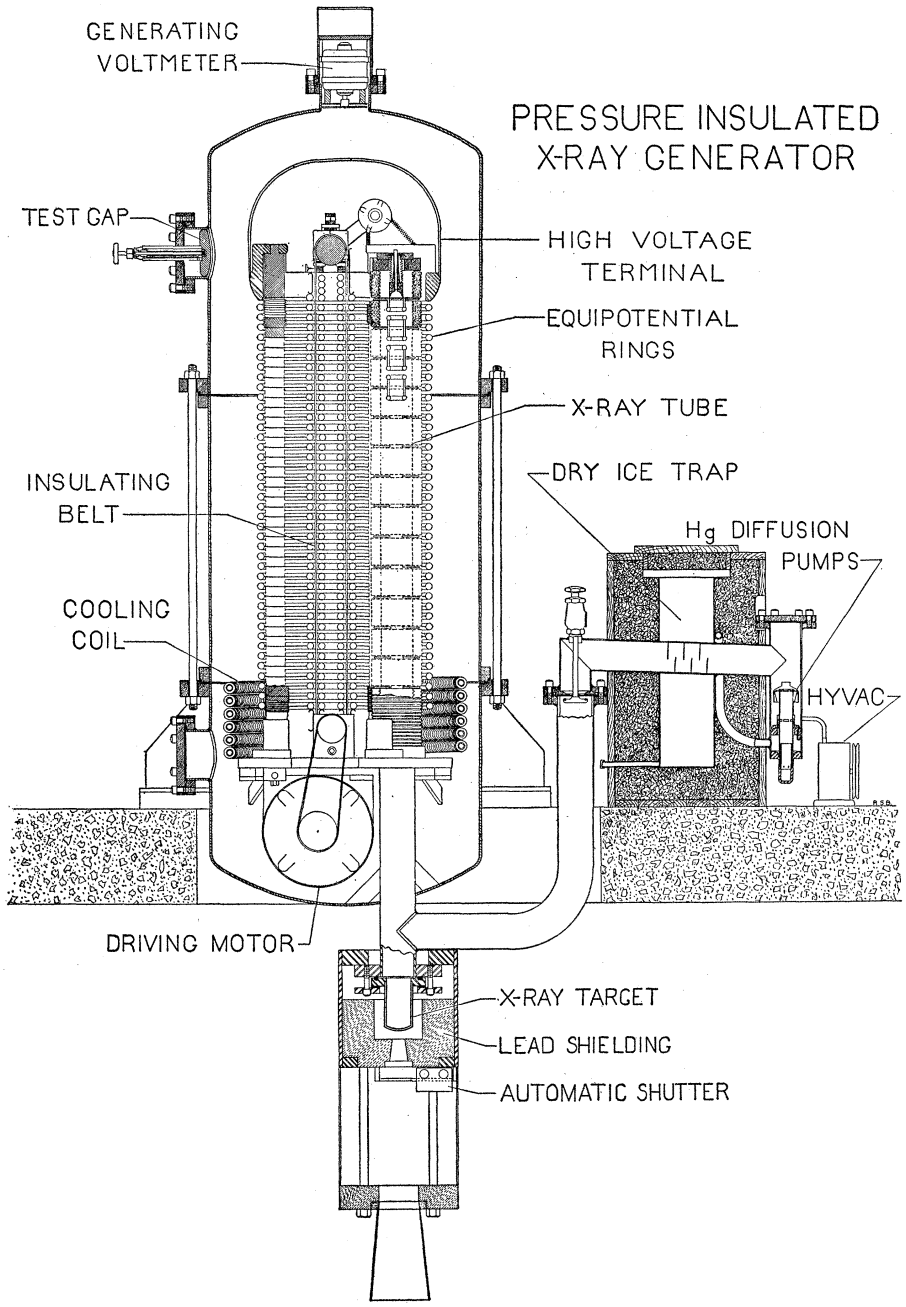

FIG. 1. Sectional view of pressure-insulated x-ray generator.

each gap, following a previously described principle.[6] The length of the column is about 50 inches. There are a total of 40 insulating sections in this distance, and the lowest of the transverse conducting members establishes the ground plane. The use of solid insulation with the laminations flatwise so as to present the direction of greatest dielectric strength to the voltage was found necessary to insulate the generator voltage in the short column length. At 11 atmospheres

[6] R. J. Van de Graaff, K. T. Compton and L. C. Van Atta, Phys. Rev. **43**, 149 (1933).

pressure absolute the flashover strength of the corrugated disk insulators between the conducting planes has been found by test to be 220 kilovolts whereas when the generator is operating at 1000 kilovolts the stress is only 25 kilovolts per insulator, thus giving a safety factor of about nine.

Charging System

The charge is carried on a single, three-ply, rubber-fabric belt 14 inches wide and running at 5000 ft. per minute. This belt is driven by a 10-horsepower, 3450-r.p.m., 3-phase induction motor. Negative electric charge is sprayed on the belt at the lower grounded end from a row of corona points directed at the pulley and supplied with power from a controllable 40-kv transformer-rectifier set. Within the high voltage terminal this charge is collected by a corona-point collector and serves to bring the insulated upper pulley to such a potential relative to the terminal that a second corona rod connected to the terminal and directed at the upper pulley sprays an approximately equal amount of positive charge on the downward run of belt.

Control of the Electric Field Due to Belt Charge

If the charge distribution is assumed to be uniform on all belt surfaces, the current of 370 microamperes which is now transferred by the 14-inch wide belt at one atmosphere pressure of air corresponds to a gradient due to the belt charge of about 12,000 volts per centimeter. This gradient is directed outward from each surface of each run of the belt. At the higher currents obtained at higher pressures this surface gradient is proportionately higher; for example, at 1.85 milliamperes, the gradient is about 60,000 volts per centimeter. The transverse gradient due to belt charge, though rarely a source of difficulty at atmospheric pressure, may cause serious sparking difficulties at higher pressure unless the problem is recognized and suitable control of the fields due to belt charge established.

In the usual arrangement[4, 6] employed in pressure-insulated electrostatic generators the electric field due to the belt charge extends the entire distance from the belt surface to the equipotential rings, and hence causes the potential of the belt to be greatly different from the potential of the ring at that same level. Moreover, since the belt looks out upon a ring which is at a varying distance due to its curvature, the potential across the width of the belt is also varying at any transverse level. On the inner surfaces of the belt, the field due to belt charge usually extends across the distance between belt runs, the lines of force from a negatively charged belt terminating on the positive charges carried by the adjacent run. Here the relatively large spacing between belt runs again results in a high difference of potential in the same transverse plane between the two runs of the belt. When the runs of belt are carrying unequal currents the variation of potential in the transverse plane is evidently even greater than with the assumed balanced charge distribution. Thus in the usual construction large potential variations exist in the transverse plane due to the charge carried by the belt, potential variations which may be of the order of hundreds of thousands of volts. This situation has been found to limit the steady current which can be carried under high pressure to a value not much greater than can be carried by a belt under normal pressure. It is evidenced by great current unsteadiness and by sparking or gliding discharges along the belt even with the terminal grounded, and it results in a limitation of the steady voltages which can be insulated by the pressure generator when an increase in current is attempted; this limitation is due to the condition of ionization and local breakdown which sets in along the belt.

These difficulties due to the charge on the belts can be substantially eliminated by localizing the resultant field by means of conducting tubes connected to the column hoops and closely spaced and parallel to each face of each belt. These tubes which are shown endwise in Fig. 1, and again in the partially assembled column in Fig. 2, evidently reduce to a relatively small value the variation in potential in the transverse plane due to the belt charge. While these parallel tubes have an important corrective effect even when spaced several inches from the belt, it has been found best to place them almost in contact

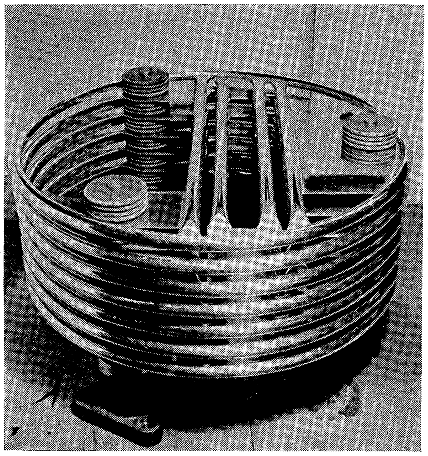

FIG. 2. View of partially assembled generator column.

with the belt surface. In this generator the spacing is one-quarter inch from the belt surface to control tube. If a surface gradient of 60,000 volts per centimeter is assumed, the potential difference between the charged belt and the column in any transverse plane is only about 40,000 volts. Without such control, the expected increase in the charge densities and current output of the belt with pressure could not be obtained.

This arrangement of field-control tubes closely spaced to each side of each run of the belt at the same time effectively divides the belt lengthwise into a series of short sections with a controlled potential applied to each, and thereby increases the breakdown strength along the belt. Since the length of the column is governed primarily by the length of belt required to insulate the desired terminal voltage, this increase in the dielectric strength along the belt is significant. Moreover, the requirement of equal charge on each run of belt, which is difficult to realize for all currents and all pressures, particularly when a self-inducing charging arrangement is used in the high voltage terminal, is eliminated by the shielding effect of the conducting tubes which pass between the two runs of the belt. The acceleration tube is likewise shielded from the electrostatic field due to the belt charge.

With this method of belt charge control the expected steady increase with pressure of the charge-carrying capacity can be obtained. This is shown in Fig. 3 for the case of air and Freon. All currents are measured with the terminal approximately at ground potential. The increase in current is nearly linear with pressure, steady currents of almost two milliamperes being obtained at 11 atmospheres of air absolute. Freon is seen to give the same currents at one-third the pressure required in the case of air. The above principle of controlling and limiting the electric field due to the belt charge appears to be fundamental to the realization of the full current-carrying capacity and full compactness of pressure-insulated electrostatic belt generators.

EFFECT OF PRESSURE AND GAS ON VOLTAGE

Figure 4 shows the variation of maximum voltage with pressure for air and Freon. In all cases the voltage limitation, as was desired in the design, was due to sparking from the high voltage terminal to the side of the tank. With air at 165 lb. per square inch absolute, maximum voltages of 1.4 megavolts can be obtained. With pure Freon at 50 lb. per square inch absolute, voltages up to 1.5 megavolts are obtained. The voltage rises nearly linearly, and insulation for a million volts is obtained at 30 lb. per square inch absolute. It is seen that with this gas the same voltage is insulated at somewhat less than one-third the pressure required with air. The use of Freon (dichlorodifluoromethane) for the time involved in these tests did not produce any injurious effect on the material, although considerable sparking and hence decomposition of the

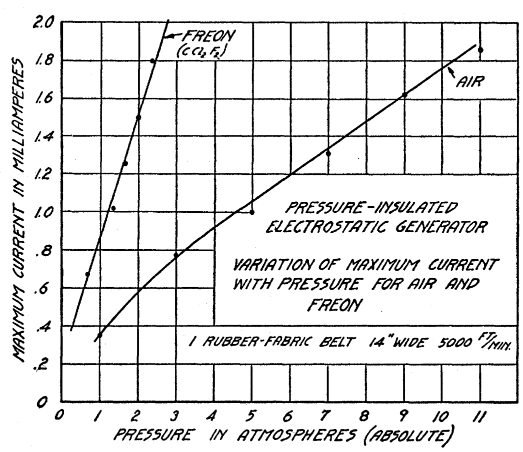

FIG. 3. Increase of generator current with pressure for air and Freon.

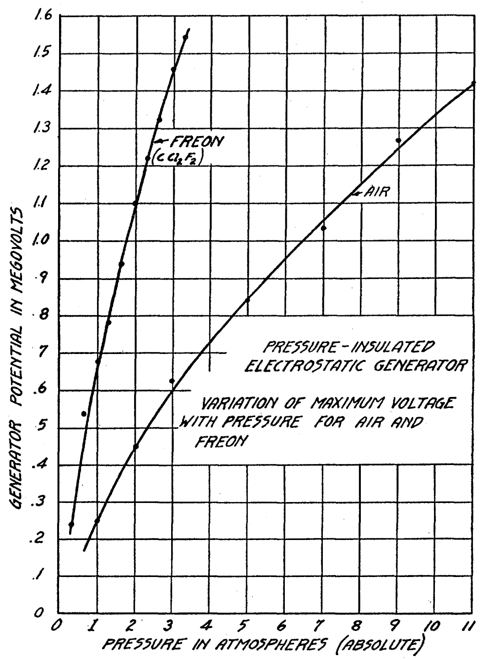

FIG. 4. Increase of generator voltage with pressure for air and Freon.

gas was permitted in order to determine the maximum voltage. The study of this and other gaseous compounds for use as the insulating medium in pressure-insulated electrostatic generators is being carried on as a separate research.

X-Ray Acceleration Tube

The x-ray tube is of the cascade type and consists of sixteen porcelain sections mounted vertically; the voltage is distributed equally between sections by connection to the transverse conducting planes of the column. The porcelain sections are corrugated inside and outside, and have an external diameter of six inches. The method of assembly differs from that used in the Huntington Hospital x-ray tube in the elimination of the tie rods, as the separate porcelain sections are permanently cemented together at assembly. Rings of wire are attached to the corrugations of the tube, both inside and outside, to improve the potential distribution. On the inside of the tube these rings have the additional effect of preventing axially unsymmetrical space charges on the tube walls, which would have a deflecting effect on the cathode stream.

Electrons are emitted from a 10-mil flat spiral filament in a hemispherical cup at the upper end of the tube, and directed in a parallel beam by electrostatic lenses which acquire their potential from the column. At the cathode end of the tube a series of annular rings are mounted on rods fixed to each of the transverse conducting planes as shown in Fig. 1. Except for these first few acceleration stages, the accelerating electrodes each consists merely of a flat metal disk with a large central hole. This general construction is simple, permits higher pumping speed due to elimination of the usual tubular electrodes, and allows excellent focusing. The electron source is mounted with a metal bellows to permit the centering of the focal spot on the target. The position of the focal spot does not shift over the entire range of voltage; the size of the spot diminishes from approximately three-quarters of an inch in diameter at 200 kv to three-eighths of an inch in diameter at 1.25 megavolts. No magnetic focusing is used. The x-ray target consists of a double copper cup between which water is circulating, the inside of which is coated with a 10-mil thickness of gold. The target is insulated from the tube extension so that the current to the target can be read on a milliammeter at the control panel. The x-rays are defined to a beam by a four-inch lead sheath with a bottom portal so that the rays utilized in treatment are those transmitted in the downward direction through the target and water-cooling jacket.

Operation

Instruments for reading the current arriving at the target, the accelerating voltage, and the x-ray intensity, are mounted on a remotely located control panel. The controls may be left at a predetermined voltage and current setting, and full voltage and current applied in about a second without injury to the tube. The generator remains stable at the same voltage and current values over long periods of time and requires only occasional adjustment to prevent slow drifting. The voltage is read with an accuracy of about one percent by means of a generating voltmeter of special design, mounted on the top of the tank.

X-Ray Output

The generator can be operated at all voltages from 200 kv to 1250 kv with a current on the target of well over one milliampere. At 1250 kv with about 5 mm of lead equivalent filtration, the x-ray intensity per milliampere in the downward direction 50 centimeters from the target is about 340 roentgens per minute. Various measurements of the physical properties of the radiation produced are now being made.

Acknowledgments

We are glad to take this opportunity of acknowledging the very able assistance in this development of Mr. Robert W. Cloud and Mr. Augustus T. Norton, Jr., as well as the help of Mr. Francis J. Safford during the summer of 1938.

In conclusion we gratefully acknowledge the generous grant of the Godfrey M. Hyams Trust which made possible the work described in this paper.

JUNE 15, 1939 PHYSICAL REVIEW VOLUME 55

Dipole-Dipole Resonance Forces

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(Received April 12, 1939)

London has shown that at fairly large interatomic distances r, the polarization energy of a molecule composed of two identical atoms varies not as the customary r^{-6}, but rather as r^{-3} in case one atom is in the ground state, and the other is in an excited state which can combine by dipole transitions with the ground level. The present paper is concerned with the size and sign of this dipole-dipole resonance energy obeying the inverse cube law. The sign has no immediate relation to the sign of the exchange and penetration forces which predominate at closer approach. This possibility of a change from repulsion to attraction results in one of the stable levels of the group of first excited states (derived from separate atom configuration $S+P$ for example) having a lip of activation energy before decomposition into atoms. There will also be a "repulsive" state having a shallow minimum at large separations. Molecules of the heavy atoms have an activation lip so large that the whole stable region is above the dissociation energy. Potential curves of this type have previously been derived empirically from spectroscopic analysis in the case of Hg_2 and Cd_2. The lip is less pronounced in lighter atoms but is none the less real, and has experimental confirmation in the Na_2 spectrum.

Introduction

It is well known that the polarization of van der Waals energy of a molecule composed of two unexcited atoms varies as the inverse sixth power of the interatomic distance r. The inverse third power, however, occurs for a molecule composed of two identical atoms when one of them is in the ground state, and the other is in an excited state which can "combine," in the spectroscopic sense, with the normal state. The mathematical origin of this anomalous inverse cube energy is quite clear. In the energy matrix the elements connecting the different approximate states are, at large distances, dipole-dipole interactions proportional to $1/r^3$. In the diagonalization of the matrix by perturbation theory such nondiagonal terms in general occur as the square, $\sim 1/r^6$, in the energy expression, corresponding to the potential of the familiar van der Waals forces. If, however, there is degeneracy, the nondiagonal elements appear to the first power, $\sim 1/r^3$ in the energy expression. Physically this kind of coupling could be described as exchange of excitation—the de-excitation of one atom with excitation of the other. The existence of a $1/r^3$ term was first pointed out by Eisenschitz and London[1] in the first excited states of H_2. Such a term, however, will occur in certain

* This work was done as a National Research Fellow, 1937.

[1] R. Eisenschitz and F. London, Zeits. f. Physik **60**, 491 (1930). See also H. Margenau and W. W. Watson, Rev. Mod. Phys. **8**, 33 (1936).

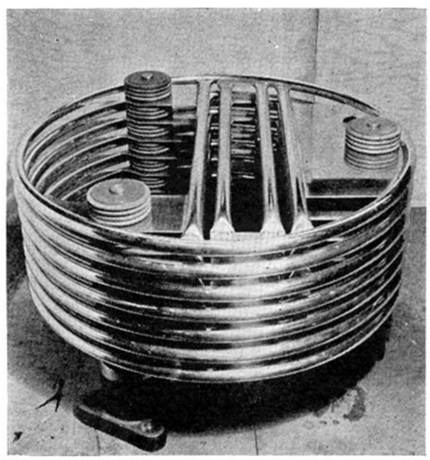

FIG. 2. View of partially assembled generator column.