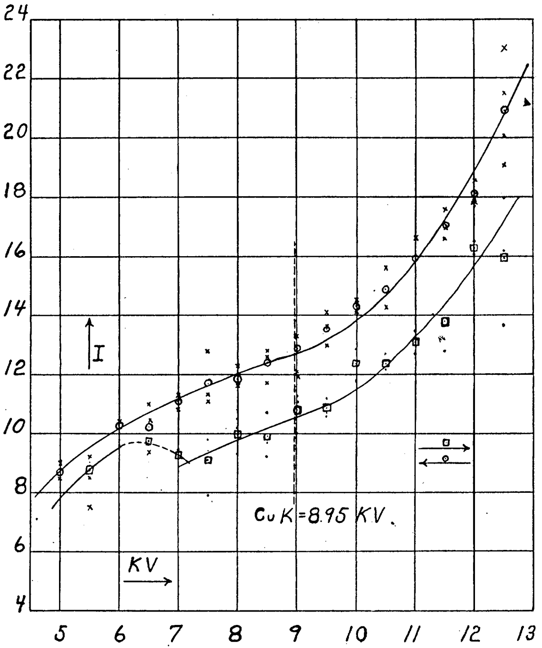

FIG. 4. The intensity of the group of Cu L is plotted against the voltage applied to the x-ray tube and shows the effect of a change of the distribution of the intensity of electron bombardment in the focal spot of the tube. The change coincides with the break in the curve.

in that the intensity is not proportional to the square of the applied voltage but to the square of the difference between the K critical potential and the applied voltage. The conditions employed in this investigation may be considered as exceptionally favorable for the determination of this relation, as the maximum in the intensity voltage curve, reported by E. Lorenz, occurs in approximately the region in which the increase in intensity begins. Hence the increase is added to a practical horizontal portion of the curve, instead of to a portion of the curve which is normally rising at a rapid rate, as was the case in the work of Stumpen.[4] These results would seem to agree very well with the predictions of the theory of Smekal,[1] concerning the return of the excited atom to its normal state.

At this point I wish to express my thanks and appreciation for the many suggestions and the continued interest of Dr. C. B. Bazzoni, under whose direction this investigation was carried out, and to the Randal Morgan Laboratory of Physics of the University of Pennsylvania, whose laboratory facilities were placed at my disposal, thus making this work possible.

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High Potential Apparatus for Nuclear Disintegration Experiments

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A 1,000,000-volt transformer and vacuum tube apparatus for nuclear disintegration work is described. The transformer consists of five 200,000-volt sections, in a cascade circuit. The tube is made of five heavy Pyrex glass sections 24 inches long and 16 inches in diameter, with hollow steel electrodes 6 inches in diameter. Each accelerating gap in the tube is connected across one of the sections of the transformer to insure uniform potential distribution. A focused ion beam of 250 microamperes is obtained at the target. Cloud chambers are operated in synchronism with this apparatus by means of a common contact system, in such a way that both the ion source and the transformers are energized for only about $\frac{1}{2}$ second, during which the chamber expansion takes place.

INTRODUCTION

SINCE the beginning of research in nuclear physics the principal technical problem has been the acceleration of positive ions, and to this end a number of different methods have been developed and used. One of the simplest and most direct, although perhaps not the most inexpensive, ways of accelerating positive ions is the application of a high alternating potential from a transformer to a vacuum tube. The high potential end of the tube will then be alternately positive and negative, and the ions will flow to the target only on the positive half-cycle. Nothing at all will happen during the negative

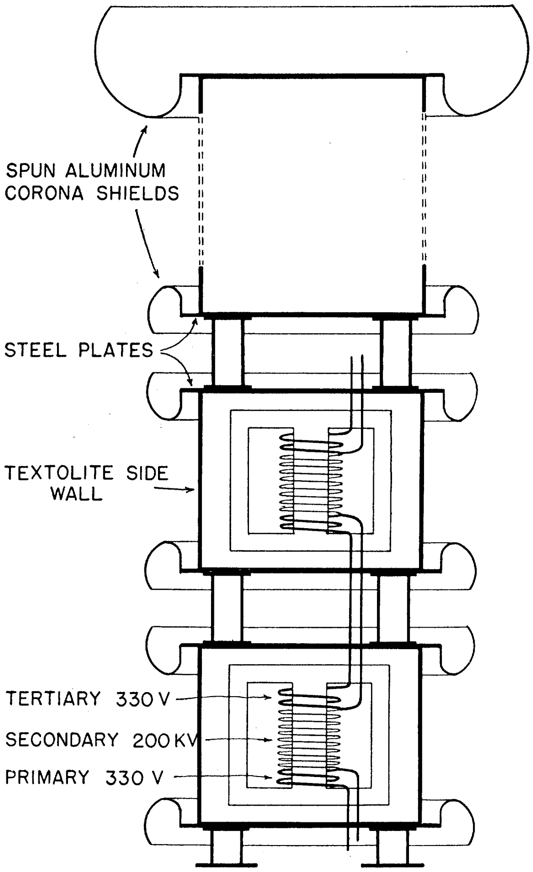

FIG. 1. Cross section of the transformer stack, with windings indicated schematically.

half-cycle, provided there are no free electrons available at the negative end of the tube. In spite of the sine variation of potential with time, an ion beam which is nearly homogeneous in energy can easily be obtained by means of a bias voltage in the source or a synchronous shutter in the ion beam itself, arranged so that ions flow only when the potential is near the peak value, say for approximately $\frac{1}{4}$ of the cycle. Even with this interrupted flow of ions, large average currents can be obtained, because of the practically unlimited power available in this type of apparatus.

The field of application of the alternating potential apparatus is not universal. There exists, however, a large and important class of problems in nuclear physics for which accurate control and measurement of the ion velocity are not essential. As examples we may mention studies of the energy spectra of gamma-rays, beta-rays, neutrons, protons and alpha-particles emitted by nuclei, and studies of the secondary effects produced by these high energy radiations and particles. In these cases the properties of the radiations studied are determined by the structure of the nuclei and are, within reasonable limits, not sensitive to the energy of the bombarding particles in the ion beam. The alternating potential apparatus is particularly suited to problems of this class. Problems such as the absolute measurement of the efficiency of disintegration, and of resonance levels for capture of particles by nuclei cannot be attacked with the apparatus to be described, but could be brought within its scope by the addition of a magnetic separator to monochromatize the ion beam. By somewhat specializing the scope of the present apparatus, valuable compensating advantages in the direction of simplicity, dependability and high ion current have been obtained, as will be evident from the following description.

DESCRIPTION

Transformer[1]

The foremost thought in outlining the requirements for a high voltage transformer was to have available a number of terminals of intermediate voltage, so that a definite distribution of potential along the tube could be maintained. The transformer set was therefore made to consist of five separate units, connected in a cascade circuit, as indicated schematically in Fig. 1. By means of air gaps in the cores of the units, the reactance of the system was approximately adjusted (at the factory) to the capacitance of the load, so as to obtain a favorable power factor in the primary feed circuit. Although the charging current flowing between the transformer and the tube is of the order of 100 milliamperes at 1,000,000 volts, the current in the primary circuit is only about 35 amperes at 330 volts. The actual power consumed by the system is mainly due to the iron and copper losses in the transformer itself; the corona and ion beam loads are both comparatively small. The total power consumed is about 6 kilowatts at full voltage.

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[1] Designed and built by the Westinghouse Electric and Manufacturing Company.

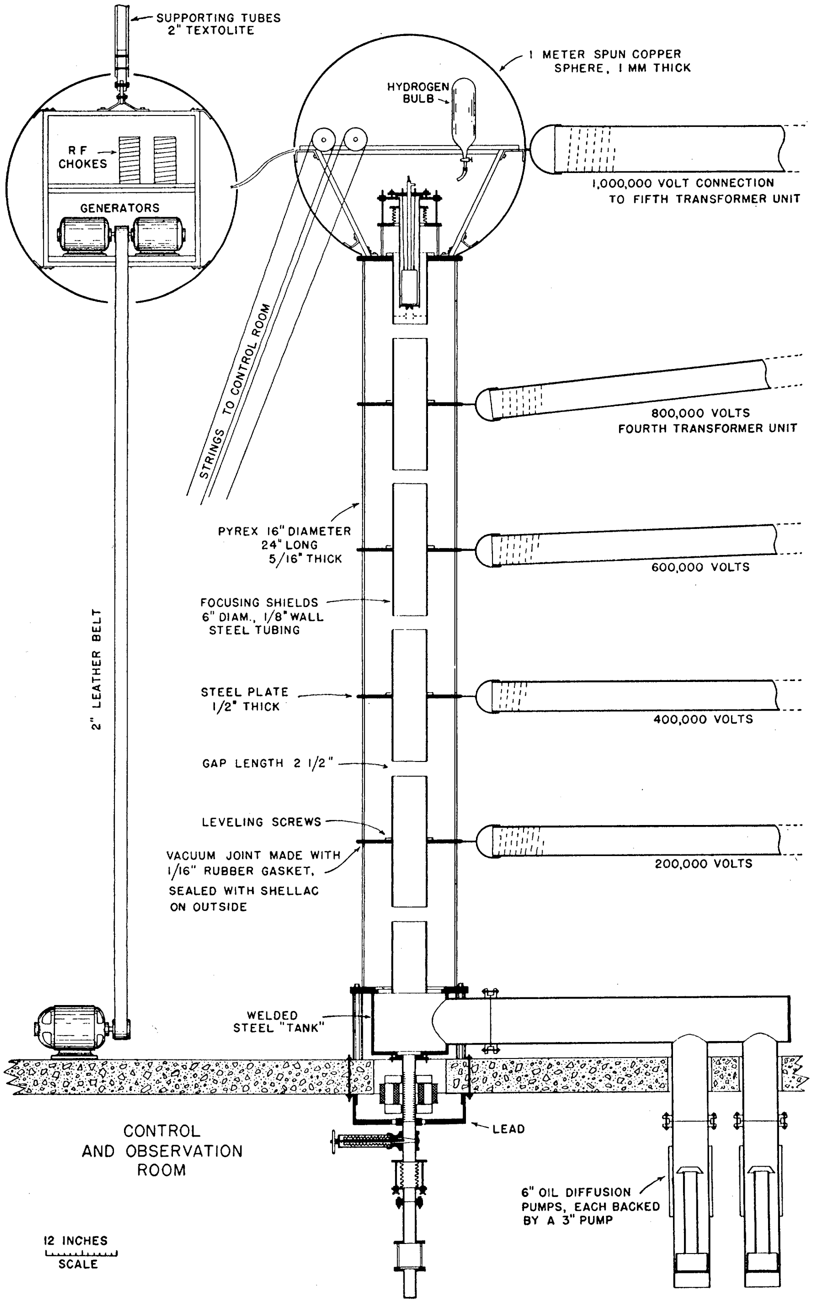

FIG. 2. Scale drawing of the entire tube.

A continuously variable voltage for exciting the primary of the transformer is obtained from a motor driven induction regulator, which supplies 10 kilowatts at any desired voltage between 110 and 330 volts. An overload relay breaks the primary circuit when the vacuum tube becomes "soft," and acts so quickly that no primary resistance is necessary for protection against excessive currents.

Vacuum tube

The vacuum tube is built of five Pyrex glass cylinders 16 inches (about 41 cm) in diameter and 24 inches (about 61 cm) long, with wall

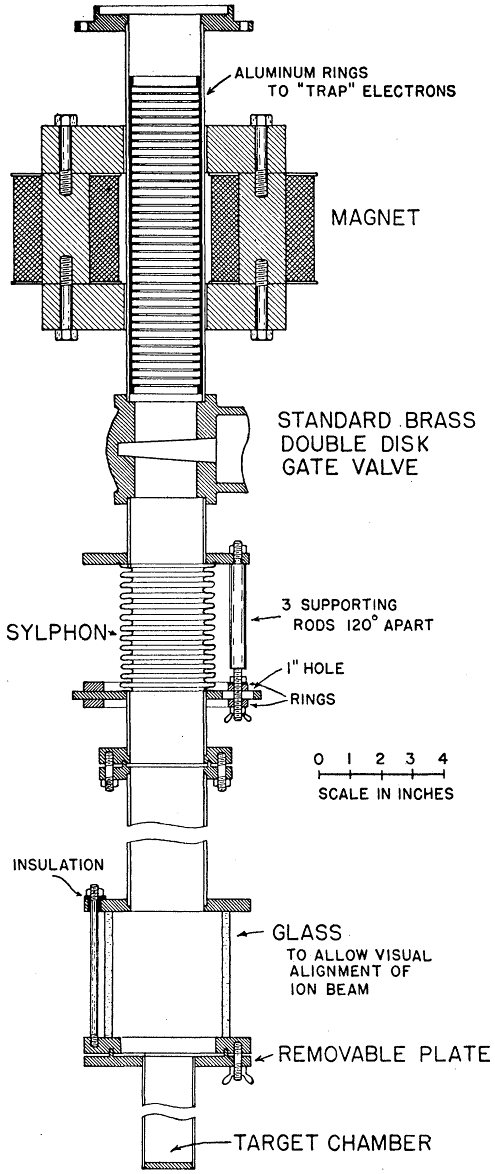

FIG. 3. Detail drawing of the ion pipe at the lower end of the tube.

thickness ranging from $\frac{1}{4}$ to $\frac{3}{8}$ inch (about 8 mm). The choice between glass and porcelain was mainly determined by availability and cost. The principal advantage which the commercially available porcelain has to offer over glass is that its outer surface is corrugated. This increases its strength against external flash-over and allows a shorter tube to be used for a given voltage. Where space is at a premium this can become an important advantage, but the height of the room in which the present tube was built was sufficient to permit the use of a straight walled tube. The fact that the ion path in a straight walled tube is necessarily as much as 50 percent longer has been found, in the author's experience, to be of secondary importance. The strength of the $\frac{1}{4}''$ glass wall against puncture due to flashes from the internal electrodes to the outside is entirely sufficient in a glass tube of the present dimensions, operated at 200,000 volts per section. For considerably higher potentials per section porcelain is undoubtedly preferable because of its thicker walls (usually $\frac{3}{4}$ to $1''$). Glass cylinders may, however, be made to withstand higher potentials by increasing their diameter in relation to the diameter of the accelerating electrodes, as well as increasing their length. The increase in diameter reduces the concentration of electrical stress in the neighborhood of the accelerating gap.

Electrode arrangement and focusing

The hollow electrodes through which the ions are accelerated are made of 6 inch (15 cm) diameter seamless steel tubing, $\frac{1}{8}$ inch (3 mm) in wall thickness. The gaps which support the 200,000 volts difference of potential are 2.5 inches (6.3 cm) long. The edges of the steel tubes are simply rounded, so that they have a radius of curvature of $\frac{1}{16}$ inch. No trouble has yet been experienced due to electron emission from these edges under the influence of the high field, so it appears that the attachment of rings of larger radius of curvature to the ends of these tubes is unnecessary up to the voltage used.

It will be noticed in Fig. 2 that the ion source is insulated from the first 6 inch electrode surrounding it, by means of an 8 inch glass cylinder inside the sphere. This was done so that an extra accelerating gap could be provided immediately below the source as shown by the dotted lines, with an adjustable potential of 5 to 10 kilovolts for focusing. This is not ordinarily used, because the system is approximately in focus without it. The focal spot obtained without the extra focusing gap is about 1 inch in diameter, and is reduced to less than $\frac{1}{2}$ inch by the use of the extra focusing gap. The small focal spot would be necessary if a magnetic analyzer were to be used.

Unsteadiness in the position or focus of the ion beam due to uneven and changing electrostatic charges on the inner glass walls of the tube seem to be small, with the length of accelerating gap used at present. The remedy for any effect of this kind would of course be to place a metal shield around the first accelerating gap so that charges on the glass could not attract the moving ions. No such shields would be necessary in the succeeding gaps, due to the higher velocity of the ions.

At the bottom of the tube (see Fig. 3) a magnet is provided for deflecting out of the beam any electrons which are accelerated on the negative half-cycle. A series of aluminum annular rings in the tube serve as traps for the electrons. Some system of baffles of a substance of low atomic number is absolutely essential to stopping the electrons: we have found that in a smooth walled brass tube a large fraction of the electrons arrive at the target in spite of a strong magnetic field. This is undoubtedly due to the efficient reflection of electrons of this energy by substances of medium or high atomic number. As an interesting experiment we have "piped" a stream of 1 Mev electrons around a corner by means of a piece of lead pipe, with surprisingly little loss.

Ion source

The ion source is one which has gradually developed out of a type already described.[2] The principal new features of the present one are that the anode is in the shape of a ring immediately surrounding the end of the canal, and that nearly all of the inside surface of the source is of glass, as shown in Fig. 4. This results in considerably larger ion currents than were obtained from the previous type, in which most of the inside surface was of metal, at anode potential. As a result of trying a number of arrangements it has appeared that the locations of the filament and anode with relation to the canal are not of great importance, probably because during operation a plasma condition exists, and the entire volume is filled with a cloud of ions. The location of the anode around the canal, however, gave the greatest yield of ions, which indicates that the cloud of ions is somewhat more dense in this region than in other parts of the volume.

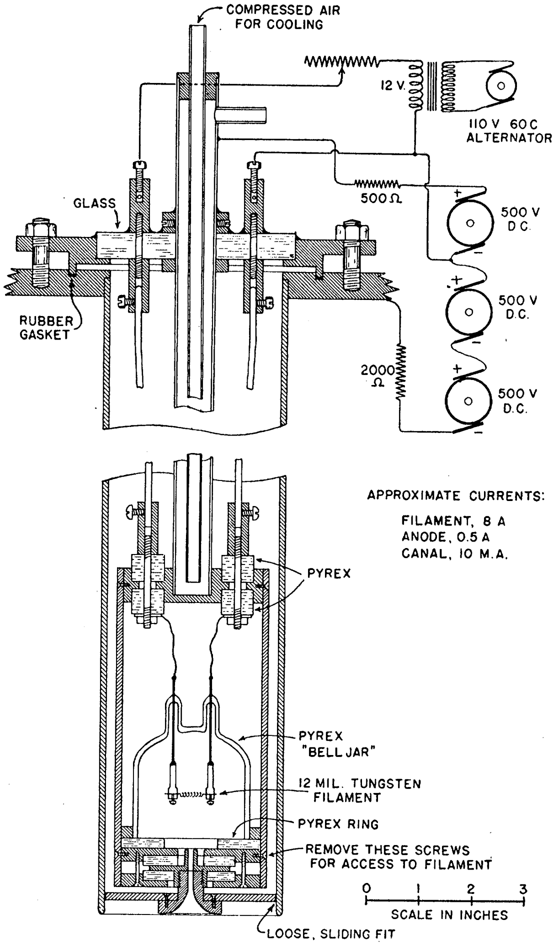

FIG. 4. Ion source assembly, with the electrical circuit shown schematically. The two 500 volt generators which supply power to the anode are sometimes replaced by a transformer, connected to the tertiary winding of the top transformer unit, as described in the text.

An important characteristic of the operation of this source is that for every gas pressure there is an optimum filament temperature, and that the ion current falls off on both sides of this value. The following explanation seems to fit the facts: The negatively charged canal causes an ion sheath to be formed around itself, which may take various forms, as indicated in Fig. 5, according to the density of ions in the discharge, which is in turn determined by the gas pressure, filament emission etc. As the filament emission is

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[2] Crane, Lauritsen and Soltan, Phys. Rev. **45**, 507 (1934).

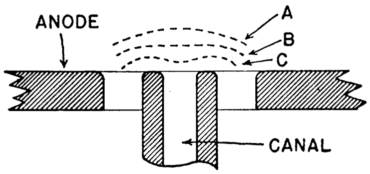

FIG. 5.

increased, the ion density in the space increases, and the sheath changes its form from A through the flat form B, to C. The ions which leave the lower surface of the sheath have initial directions perpendicular to the sheath. Therefore under conditions in which the sheath is flat across the end of the canal the ions will escape through the canal in an initially parallel beam. External focusing conditions in the accelerating tube may, however, require an initially diverging or converging beam. In this case the current received at the target will be a maximum when the filament emission is adjusted so as to fulfill those particular conditions. Thus it may be that, within narrow limits, adjusting the filament emission actually amounts to adjusting the focusing conditions. In actual operation the maximum in the ion current is easily attained and is broad enough so that frequent adjustment of the filament current is not required.

The ratio of atomic to molecular hydrogen ions has not been measured directly, but according to disintegration results it is considerably more favorable than in the previous source. This is probably due to the fact that the inside surfaces of the source are almost entirely of glass, which, if clean, reduce the rate of recombination of atomic hydrogen, and also give off smaller amounts of gases of other kinds, under heat and bombardment.

Taking advantage of the fact that the fifth unit of our transformer stack is equipped with a tertiary winding of 330 volts, we are able to supply the anode of the ion source with alternating current which is in phase with the high voltage on the accelerating tube. The 330 volts is stepped up to about 1500 volts by means of a small transformer. On the negative half-cycle (top of the tube negative) both the canal and the anode are negative with respect to the filament, so no current at all flows in the discharge space. It is therefore possible to double the power in the discharge during the positive half-cycle without greater heating effect than would be obtained normally with direct current on the anode. The total absence of discharge in the source on the negative half-cycle has the further advantage of reducing the small number of electrons which inevitably leave the region of the source and accelerate down the tube on the negative half-cycle.

The rate at which hydrogen is admitted to the source is such that the pressure in the accelerating tube rises from 10^{-5} to between 5×10^{-5} and 10^{-4} mm during operation.

The total ion current which is obtained at the target regularly and dependably is 250 microamperes. Under the best conditions about 50 percent more than this is obtained. This is measured in a Faraday cage about 3 cm in diameter and 15 cm deep, and probably includes very little current due to secondary electrons.

Protection against corona and sparking

The principal reason for enclosing the top of the tube in a sphere and enclosing the ion source generators in an elongated sphere was to prevent sparking to the walls and ceiling of the room, which are only about 9 ft. from these high voltage surfaces. Four spun copper hemispheres 50 cm in radius and 1 mm in wall thickness form the sphere on the tube and the "blimp" enclosing the generators. The five connectors between the tube and transformer consist of cardboard tubing 5″ in diameter (except the top connector, which is 8″ in diameter), space wound with fine wire and enameled. These accomplish a double purpose in that sparking between connectors is prevented because of their large radius of curvature, and electrical surges from the tube are not transmitted to the transformers because of their inductance. The distance between the transformer stack and the tube is 10 ft., which is sufficient to prevent a direct spark-over along the inductive connectors.

Corona discharge is practically eliminated by the large radii of curvature of the high potential surfaces. Therefore the external load on the transformer is almost a pure capacity (out of phase) load. In the present apparatus this causes the voltage to build up to a value somewhat in excess of that calculated from the primary voltage and the turns ratio. We have counteracted this effect by placing a resistance (heater) across the tertiary winding of the top unit, which consumes about one kilowatt and constitutes an in phase load. Thus in this particular instance the corona power loss which is so completely eliminated by the rounded surfaces has to be replaced by an artificial in phase load. The charging current which flows between the transformer and the spheres is roughly 100 milliamperes, at 1,000,000 volts. Although this circulating current is very large compared to the useful current drawn by the ion beam, it does not represent power loss.

Operation of the tube in synchronism with the cloud chamber

In operating the tube and cloud chamber in conjunction, there is no necessity for running the tube or the ion source during the time between expansions of the chamber. A central motor driven electrical contact system is used to operate the cloud chamber, transformer and tube. The primary circuit of the transformer and the anode circuit of the ion source are closed for about $\frac{1}{2}$ second at the time the chamber expands. In studying delayed activities of short life, the contacts are simply shifted so that the bombardment precedes the expansion by any desired length of time.

Discussion

Finally, some brief remarks about the possibilities of working at higher voltage with alternating potential apparatus of the type described may be of interest. At 1,000,000 volts the charging current to the high potential parts of the transformer and vacuum tube is necessarily of the order of 100 milliamperes. This current is proportional to the product of the voltage, capacity and frequency. The size of the apparatus required (and hence its capacity) is larger for higher voltages. Therefore in building apparatus for greater maximum voltage, the charging current may be expected to rise more nearly as the square than as the first power of the voltage. Although high charging current does not necessarily mean high power consumption, it does require that the transformer have a large current carrying capacity, and therefore the cost of the transformer goes up very rapidly with the voltage above 1,000,000 volts. In spite of the fact that the construction of apparatus of this type for voltages considerably higher than 1,000,000 is straightforward from the engineering standpoint, it is clear that an economic limit is reached at a point not far above 1,000,000 volts.

As a result of our experience with the present apparatus we believe that some advantage would be gained by placing the vacuum tube and transformer stack close together, eliminating the inductive connectors, and by placing the ion source generators on top of the transformer stack. The resulting reduction in the capacity-to-ground of the system would be desirable at 1,000,000 volts, and would probably be essential at higher voltages. We have found that the high frequency surges, due to cold electron emission and sudden discharges in the tube are very feeble in a multi-section tube at 200,000 volts per section, compared with the surges occurring in a single section tube at 500,000 or 700,000 volts. The elimination of inductive connectors in the case of a multi-section tube would therefore probably not place the transformer insulation in danger from the standpoint of surges from the tube, and would allow the tube to be placed closer to the transformer.

The author wishes to express his appreciation to the Rackham Endowment Fund for the financial support of this project, to Professor H. M. Randall, under whose direction this work was begun and carried to completion, to Messrs. D. S. Bayley, E. R. Gaerttner and J. J. Turin, who assisted throughout the work, and to Mr. H. R. Roemer who, as head of the physics department machine shops, deserves a large share of the credit for the successful completion of the apparatus.