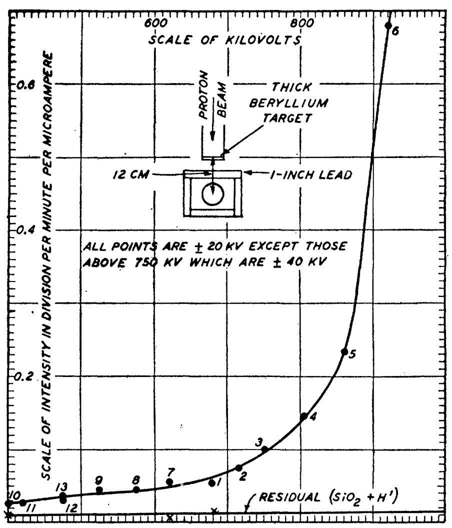

FIG. 15. Excitation function for gamma-rays from $Be+H^1$.

single sequence have proved to be dependable, any large changes in voltage depend on the absolute voltage scale and are less accurate. Thus several resonance voltages are clearly shown, although the absolute voltages for the resonance lines are not well determined.

A rough indication of the intensity can be obtained from the radium calibration cited above, namely, one mg radium at 10 cm gives 15 divisions per minute through 3 cm of lead. Note, however, that the points plotted are for a "moderately thin target," which is thick for 500-kv protons, but thin for 900-kv particles as shown by the curves.

Gamma-rays from ($Be+H^1$)

While this does not appear to be a resonance process, such observations as we have made may well be reported at this time. These are given in Fig. 15. The experimental conditions were the same as for the fluorine observations, except that a thick target was used. The beryllium was known to contain one percent iron, with other impurities under 0.05 percent.

Acknowledgment

We are grateful to Professor Lauritsen for the electroscope he very kindly sent us, which has proved to be exceedingly convenient in this work. We also wish to thank Professors Breit and Gamow for their enthusiastic interest in the problem of radiative capture, and Messrs. Brown and Dahl for invaluable technical assistance.

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High Voltage Technique for Nuclear Physics Studies

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A description is given of experiments at the Department of Terrestrial Magnetism, Carnegie Institution of Washington, during four years in which two electrostatic generators and several multiple-section high voltage tubes have been used for the production of high speed protons and deuterons, as required for studies of nuclear transmutations. A 1-meter diameter generator of the type designed by Van de Graaff reaches usable steady potentials up to 600 kilovolts (positive). A generator comprising concentric 1-meter and 2-meter shells, charging current 0.75 milliampere, reaches practical limitations at 1300 kilovolts (positive) in a special room of large size. Voltages below the maximum are steady to within several percent. Details of design and operation are discussed.

Multiple-section high voltage tubes of the Coolidge "cascade" type, giving complete focusing of positive ion currents of 20 microamperes at voltages up to 1200 kilovolts, offer no difficulties in construction or operation. No reasons have yet appeared for expecting any special troubles if this technique were to be extended to much higher voltages and currents.

A. Introduction

In response to numerous requests for a comprehensive description of the high voltage technique which has been developed during a period of years in the Department of Terrestrial Magnetism of the Carnegie Institution of Washington[1] and which has been used for studies of

[1] The development of these experiments is described chiefly in the Annual Reports of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, 1926 to date. Early work is covered by: G. Breit, M. A.

atomic nuclei, this paper presents the more important features of our past experience and the details of our present technique. Although the latter is in many ways imperfect and in process of refinement, it has proved effective and useful, and it is hoped that the concrete presentation of our experiments may be of assistance to other laboratories now initiating similar researches in this field.

With the discovery by Cockcroft and Walton[2] that various transmutation effects actually occur when particle-energies well below one million electron volts are used, the early high voltage objective here and elsewhere of obtaining true nuclear transmutations by artificial means, without special regard to the processes involved, was superseded by an increasing necessity for care in obtaining and interpreting such observations. This is particularly true in view of the importance of impurities, the complexities introduced by the discoveries of neutrons, positrons, and induced radioactivity, and the complications which result from marked differences in the excitation functions for various effects as the energy of the primary particles is altered. We feel that it is desirable, and perhaps even necessary, to work out in fair detail the nuclear reactions of a few light elements, accessible to investigation with moderate particle energies, before the more complex studies using very high voltages may safely be attempted, especially in view of the numerous reaction equations which may be written and the general failure of these to balance when using the accepted mass values.* This mitigates somewhat our initial disappointment over the failure of our equipment to actually attain the voltages indicated in our preliminary tests.

Although our equipment in its present form does not give an extremely high and steady peak voltage, it has many excellent characteristics in the voltage range up to 1000 kilovolts, and constitutes at least one approach toward the ideal of an artificial source of high energy ions, uniform in speed, direction and kind, and under control as to energy and intensity between wide limits. The ultimate desirability of such a source cannot be questioned. The initial adoption of a highly analytical experimental technique, avoiding various averaging effects which tend to obliterate critical features of the data, has led almost immediately in most of our observations to the recognition that the effects are complex and that detailed examination is required.

By reason of the exponential importance of ion velocity and of atomic numbers, and because of the great variety of processes which can and do occur, thin target results with "monochromatic" ion beams seem almost essential for the correct interpretation of thick target observations, especially if the latter are obtained with ion beams heterogeneous in speed and kind. The combination of a constant potential source and a focusing type high voltage tube with magnetic analysis at the target therefore has important advantages over some other types of equipment for this work. We can well testify to the practical aspects of the question from our experience with spark excited Tesla coils.[3] The fluctuating voltage output of the latter, and especially the extreme requirements placed on the ion source and on the time resolution of the detecting instruments (for quantitative results) by the short duration of its peak voltage caused us to abandon the Tesla coil after it had served inexpensively for the development of tubes withstanding extreme voltages and for the demonstration of artificial beta, gamma, proton and deuteron "rays" of energies above one million volts.[4] Its application to transmutation-studies was not seriously attempted, because of the obvious dangers of being misled when using such an unsuitable and erratic voltage-source, and the cost of modifying the Tesla-coil method to minimize these objections.[5] The equipment here described avoided

Tuve and O. Dahl, Phys. Rev. **35**, 51 (1930); M. A. Tuve, G. Breit and L. R. Hafstad, Phys. Rev. **35**, 66 (1930). Subsequent experiments are described in the columns of Letters to Editor of Phys. Rev., 1930, 1931, 1932, 1933 and 1934, and in the following: J. A. Fleming, Science **77**, 298 (1933); M. A. Tuve, Proc. Internat. Elec. Cong., Paris **2**, 915 (1933); M. A. Tuve, J. Frank. Inst. **216**, 1 (1933).

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

* The situation is now much more satisfactory as a result of the adjustment of the mass scale made by H. A. Bethe (see Phys. Rev. **47**, 633 (1935); also M. L. E. Oliphant, A. E. Kempton, and Lord Rutherford, Proc. Roy. Soc. **A150**, 241 (1935)).

[3] Tuve, Hafstad and Dahl, Phys. Rev. **39**, 384 (1932).

[4] Carnegie Inst. Wash., Year Books, No. 28, 214 (1929); No. 29, 256–259 (1930); No. 30, 290 (1931); No. 31, 229–233 (1932); M. A. Tuve, L. R. Hafstad and O. Dahl, Phys. Rev. **37**, 469 (1931); **38**, 580 (1931).

[5] D. H. Sloan, Phys. Rev. **47**, 62 (1935).

these difficulties and was built and installed at a moderate cost. It has its limitations, some of them both troublesome and disappointing, and we would be glad to embrace the unquestioned advantages obtainable with a well-designed and expensive constant-potential source of voltage more conventional type for the rather limited range available with our present equipment, but many investigators undoubtedly will be encouraged by the fact that this type of nuclear-physics work is possible, to a voltage limit chiefly determined by the space available, at relatively small expenditure.

B. Electrostatic Generators

(a) Preliminary tests

The limitations of the spark excited Tesla coil had been recognized from the first, but its use in this laboratory was continued until 1931 because no other form of voltage source for potentials of the order of a million volts was accessible to us on the funds available for this work. However, immediately following the construction by Dr. R. J. Van de Graaff of the first example of his simplified form of electrostatic generator,[6] cooperative tests were made in this laboratory in which his original 2-foot generators were used[7] to ascertain that a very high constant potential could be applied without difficulty to the multiple-section tubes we had been using with the Tesla coils. We then undertook here to test the prediction that the attainable voltage with such a generator should be proportional to the diameter of the conducting sphere or shell, by constructing a two-meter generator and observing its performance by means of a generating voltmeter,[8] as the next step in the development of such generators. No suitable housing was available, and the tests were carried on outdoors.[7] Because of flying bugs, lint and other debris electrostatically attracted to the sphere, difficulty was encountered in obtaining a trustworthy measure of the peak voltage and voltage steadiness attainable, but during short periods after cleaning the sphere steady potentials (± 3 percent) well in excess of 2000 kilovolts were indicated by the generating voltmeter. The latter was calibrated *in situ* by the application of a known voltage (60 kv) to the generator shell. Since the theoretical voltage limit for this two-meter sphere (giving a field strength of 30 kv per cm at the surface) is about 3300 kilovolts, these observations apparently verified the spark-gap measurements made with the original (2-foot) generators, which had indicated that 60 percent of the theoretical limiting voltage could be attained. We now know this result to be in error, as described below, because the presence of corona makes both the generating voltmeter and the spark-gap indicate higher than the true voltage, the highest actual voltage attainable in practice, according to our subsequent experience with both one-meter and two-meter generators, being only about 35 percent of the theoretical maximum when the sphere potential is positive in sign. In these outdoor experiments most of the measurements were made with the sphere potential negative, since this sign gave less trouble from unsteadiness and the peak voltage appeared to be about the same for either sign of charge. A charging current of 90 microamperes was obtained with a silk and rayon belt 6 inches wide, traveling 6000 feet per minute inside the 20-inch diameter Textolite cylinder used for support. This arrangement protected the belt from deflection by winds, and allowed humidity control by heating, as was necessary on several occasions for good belt insulation. Charge was sprayed on the belt by the corona from a 5-mil tungsten wire connected to a 40-kilovolt kenotron rectifier, and a current doubling arrangement[6] was used inside the sphere. It was interesting to find that after the Textolite support had been baked and coated with paraffin (it was supplied at our request without this customary protection) an indicated potential exceeding 1000 kilovolts was obtainable when the belt was manually operated at about 20 feet per minute. The maximum voltage attainable with this set-up was usually limited by heavy sparks down the Textolite cylinder to ground. These "lightning bolts" splintered the redwood base parts in impressive fashion. Various efforts to adjust the voltage gradient and thus prevent the violent sparking, by means of high resistance leaks

[6] Van de Graaff, Phys. Rev. **38**, 1919 (1931); Van de Graaff, Compton, Van Atta, **43**, 149 (1933).

[7] Photographs reproduced in J. Frank. Inst. **216**, 26 (1933).

[8] P. Kirkpatrick and I. Miyake, Rev. Sci. Inst. **3**, 1 (1932); R. Gunn, Phys. Rev. **40**, 307 (1932); J. E. Henderson, W. H. Goss and J. E. Rose, Rev. Sci. Inst. **6**, 63 (1935).

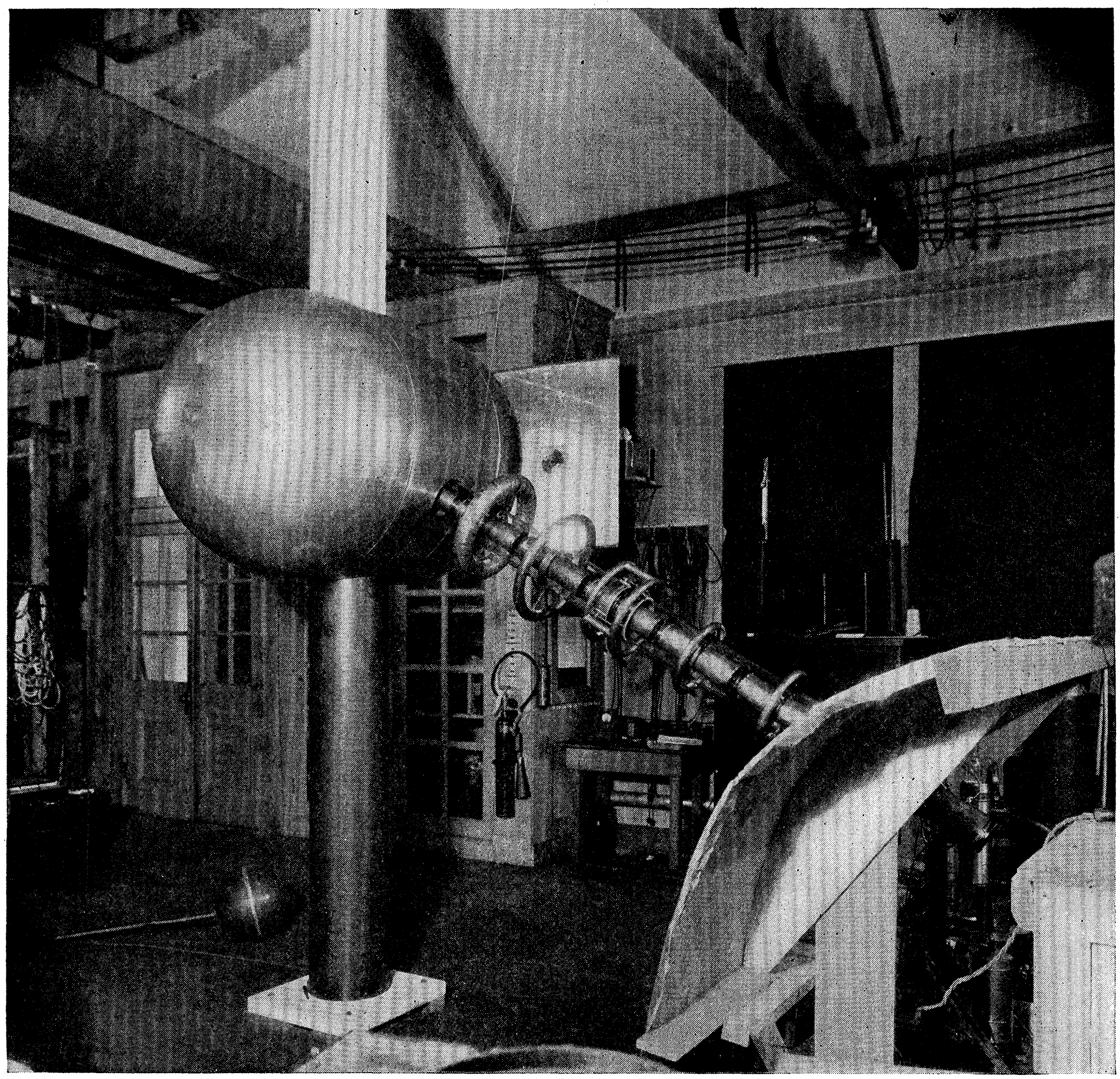

FIG. 1. One-meter electrostatic generator with six-section cascade tube.

applied to the Textolite cylinder, were unsuccessful.

Because of meteorological interference it was not feasible to attempt proton bombardment of targets with this outdoor equipment, although an indicated steady potential of 1000 kilovolts was applied without internal discharge or breakdown to a 34-section tube 9 feet long, comprised of two tubes previously used under oil with the Tesla coils, pumped to a pressure of 1/4 bar.[7]

(b) One-meter generator, construction

Lack of housing prevented further immediate use of the two-meter generator, but after some months the removal of the oil tanks used for the Tesla coil experiments gave us laboratory space for the installation (October 1932) of a smaller generator, as shown on Fig. 1. Because of the practicability of a generator of this size in almost any laboratory, a fairly detailed description of our experience with it will be given here. Two hemispherical shells one meter in diameter (drawn or spun aluminum shells are obtainable in various sizes from the Aluminum Company of America, Pittsburgh, Pennsylvania) are fitted to a short cylindrical section (see Fig. 2) which contains the pulleys, the collector

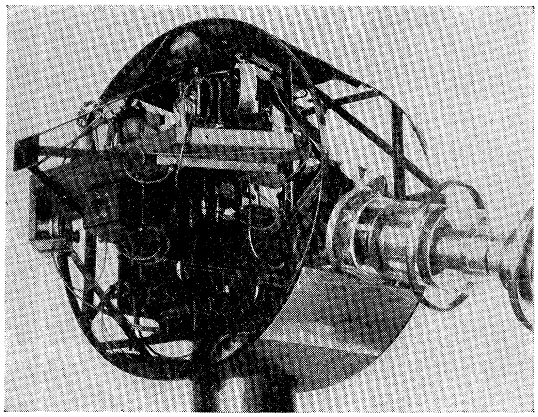

FIG. 2. Construction and interior arrangements of one-meter generator, showing equipment and controls for ion source.

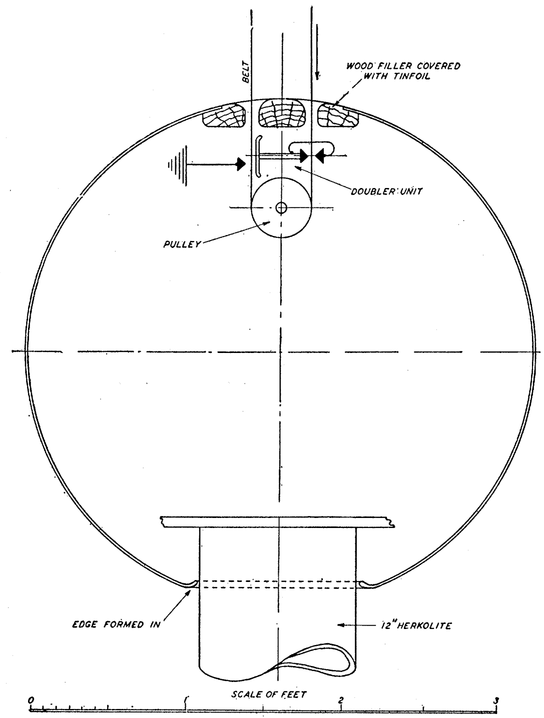

FIG. 3. Detail of openings for charging belt and support column—one-meter generator.

comb and spray wire for current doubling, and the alternating-current and direct-current generators, transformers, controls and hydrogen supply for the ion source which is attached to the high voltage end of the tube (see section C). A 12-inch silk and rayon belt running 4000 feet per minute gives 180 to 200 microamperes charging current and drives the ion source generators. To give maximum clearances with the available space the motor and the charging apparatus for the belt were placed overhead some 12 feet above the concrete floor. The 12-inch Textolite cylinder supports the generator 165 cm above the floor, and other clearances are: Belt length from shell to ground shield 150 cm, tube length 170 cm, minimum distance to grounded shields on rafters 130 cm.

Charging currents. Details of the belt charging arrangements and the shape of the belt openings in the shell are shown in Fig. 3. Numerous efforts were made to increase the charging current, especially when charging the ingoing belt only (for maximum voltage), by means of large and small shield or guard electrodes placed in various positions with respect to the spray wire, and held at either ground or spray wire potential. Temporary improvement apparently was obtained with various positions of shield, but for undetermined reasons the current would revert to the old value in a day or less, after which removing the shield made little change, and it might even appear to be of value in some new position. A theoretical maximum of 660 microamperes would be obtained if the surface charge on each side of the belt, both when entering and when leaving the sphere (four surfaces), were such as to give an electric field of 30 kilovolts per cm (5.3×10^{-9} coulomb per cm^2, for a belt charged on each side to breakdown value). The charging current was measured with the sphere at ground potential, and may be less when the sphere is at high voltages, especially because of corona to the negatively charged belt leaving the positively charged sphere. When using the "doubler" (negative charge sprayed onto belt leaving the sphere) the charging current measured 170 to 200 microamperes (usually 180), and when charging the ingoing belt only the current was usually about 65 microamperes, although in wet weather it dropped as low as 50 and for short periods (after changing shield-arrangements) it reached 85 microamperes. The fact that the "doubler" always more than doubles the current is an indication that a simple comb fails to discharge the belt completely inside the sphere, so that without the negative spray the belt still carries a small positive surface charge as it leaves.

From measurements made with the generating voltmeter at reduced charging currents (reduced spray voltage) it appears that nearly the same maximum voltage is reached as with full charging current, indicating that most of the charging current is actually available for use on the high voltage tube, except near maximum voltage, where the corona losses increase very rapidly with small changes in voltage.

Voltage limits. Much interest attaches to the maximum voltage attainable with a generator of given dimensions. During the period November 1932 to June 1933 it was found that this one-meter generator reached approximately 500 kilovolts under most weather conditions (400 kv with continued high humidity), 550 kilovolts frequently, and probably as high as 600 kilovolts in dry weather. Maximum voltage was obtainable only when the current doubling device was not used, that is, when charging the ingoing belt only. With the outgoing belt charged negatively (current doubled) very strong corona from the edges of the belt opening in the sphere, due to the increased electric field strength arising from the negative belt charge, reduces the maximum voltage by 50 to 100 kilovolts in spite of the increased charging current. If the positively and negatively charged belts were very close together, this effect should be decreased. In special tests seeking the highest possible voltages (in an effort to demonstrate conclusively the emission of neutrons from helium ions bombarding beryllium) steady potentials as high as 700 kilovolts were apparently obtained for short times, but we regard this figure as too optimistic. For these peak voltage efforts a number of paraffin coated micanite sheets were distributed over various projections and in other positions in the room to reduce the field strength (reduce or eliminate corona) in their vicinity by picking up surface charges and redistributing the field in the direction of greater uniformity. The only item of these tests retained as a permanent feature was a micanite sheet (a paraffin coating is essential) supported on four redwood sticks at the midpoint of the Textolite column. This arrangement eliminates the serious corona (with frequent "lightning bolts") down the column, which is probably due to the large hole (12 inches in diameter) in the conducting shell, and the nearness of the floor.

When the weather was dry and the doubler was not used, the maximum voltage attainable was limited by sparks from the polished spherical surfaces, out into space or toward surrounding objects, indicating that the field at many points on the generator shell reached breakdown value. Whether this was due to the building up of space charge in the vicinity of the sphere or to surface irregularities, which caused local fields three times the average (for a surface having a 1-meter curvature), was undetermined. When the humidity was high, the attainable voltage was limited by heavy sparks up the belt or down the Textolite support. A series of efforts to prevent the latter by providing a high resistance leak to grade the potential down the Textolite was again without success; a close wrapped helix of rubber tubing containing alcohol (adjusted to a leakage of about 10 microamperes at half-voltage) was effective for a few minutes, but on going to full voltage a single heavy spark split the rubber in many places. This type of failure has been true of every effort we have made toward resistance grading of the potential along an insulator; voltage grading by means of corona points between a succession of shields, as on our cascade tubes, appears to be the only reasonable method.

Exact knowledge of the voltage was not essential to the validity of the chief series of experiments for which this generator was used early in 1933 (demonstration that the apparent disintegrations of medium and heavy elements were due to contamination, probably by boron[9]), but the generating voltmeter at 550 kilovolts indicated about 15 percent higher than a rough voltage calibration by magnetic deflection of the high speed protons. Efforts to measure the range of the protons gave values in the same region, but these voltage values were open to question both because of difficulties with foils (metal foils, melted in vacuum, punctured when supported against atmospheric pressure by grids and gave evidence of thin spots; mica windows collected high surface and volume charges and

[9] M. A. Tuve, L. R. Hafstad and O. Dahl, J. Wash. Acad. Sci. **23**, 530 (1933); Phys. Rev. **43**, 942 (1933); **43**, 1055 (1933).

promptly split, etc.) and because of the uncertainty which still exists concerning the range voltage relation for protons near 500 kilovolts. Blackett and Lees[10] give 11.5 mm as the range of a 500-kilovolt proton, whereas Cockcroft and Walton[11] would place this range at about 8.5 mm. Our figures indicated a value between these extremes, and in our work to date we have tentatively the value 10 mm as the range for 500-kilovolt protons (28.5 mm for 1000-kilovolt protons).

It is thus indicated by these experiments, as well as by our later experience with the two-meter generator installation, that positive potentials exceeding 600 kilovolts should not be expected from a generator of this type which approximates a one-meter sphere. The question as to the optimum size of generator for reaching the maximum possible voltage in an available space of given dimensions cannot be answered from our experience. However, we found that this one-meter generator reached practically the same maximum voltage (550 kv) when a flat metal wall (lead foil on Celotex—far from smooth) was placed 50 cm distant from one of the hemispherical ends. This indicates that if sufficient extra length can be obtained, diagonally to a corner or otherwise, for the belts and the insulating supports (which may be cables), it is probably best to use a conducting shell which might at first thought appear too large for the given room size. How far it is profitable to go in this direction can only be determined by experiment.

(c) Two-meter generator

During the summer of 1933 a special laboratory was completed for housing the reconstructed two-meter generator, which was assembled and ready for first voltage tests early in October. A view of the installation (complete with tube) is shown in Fig. 4, and a schematic drawing of the arrangement of the laboratory is shown to scale in Fig. 5. Fig. 6 shows the construction of the generator, with the pulleys, ion source generators and controls. The advantages of a separate belt driving the ion source generators are well worth the slight additional construction involved.

[10] Blackett and Lees, Proc. Roy. Soc. **A134**, 665 (1932).
[11] Cockcroft and Walton, Nature **129**, 242 (1932).

Construction. In order to gain the numerous advantages of a vertical arrangement of the high voltage tube, a tripod support was adopted for this generator, sacrificing the easy control of the humidity of the belt which was a feature of the original outdoor installation, where the belt was run inside the large cylindrical Textolite support. It was also desirable to provide for a high charging current, and the total belt surface was designed on the basis of our experience with the one-meter generator to give 1 milliampere charging current at full speed (8-inch pulleys at 3600 r.p.m.—"four belts" 20 inches wide as in Fig. 5). It has since developed that with paper belts high humidity is a serious obstacle with this equipment, reducing the charging current by a factor of two or more and limiting the maximum voltage to 800 or even 700 kilovolts by "lightning bolts" down the belts. A more unexpected difficulty was the fact that the high lead content glass used for the tube itself (for partial x-ray shielding) adsorbed a layer of surface moisture when the humidity exceeded 50 or 60 percent (May 1934) and constituted almost a short circuit for the generator, its resistance dropping to a few megohms. A large improvement was effected by applying "Victron" varnish to the belt and tube after drying by heat (successive sections of the tube were heated by the blasts from several electric heater hair dryers), but humidity control is highly desirable and almost essential for a satisfactory installation. The whole generator room might be air-conditioned (very expensive) or the belts and tube could be surrounded by thin walled Textolite tubes to limit the volume of air requiring treatment. We have as yet made no provision for humidity control, as the limitations due to humidity are not serious during seven or eight months of the year.

The various clearances from the generator to the walls are shown by the scale drawing of Fig. 5; the ceiling of the high voltage room is 28 feet above the floor; the latter measures 32 by 36 feet and can ultimately be removed without structural alterations if a rectifier equipment or other possible future installation requires additional head room. The generator itself, shown in Fig. 6, comprises concentric one-meter and two-meter shells, with two sections of the

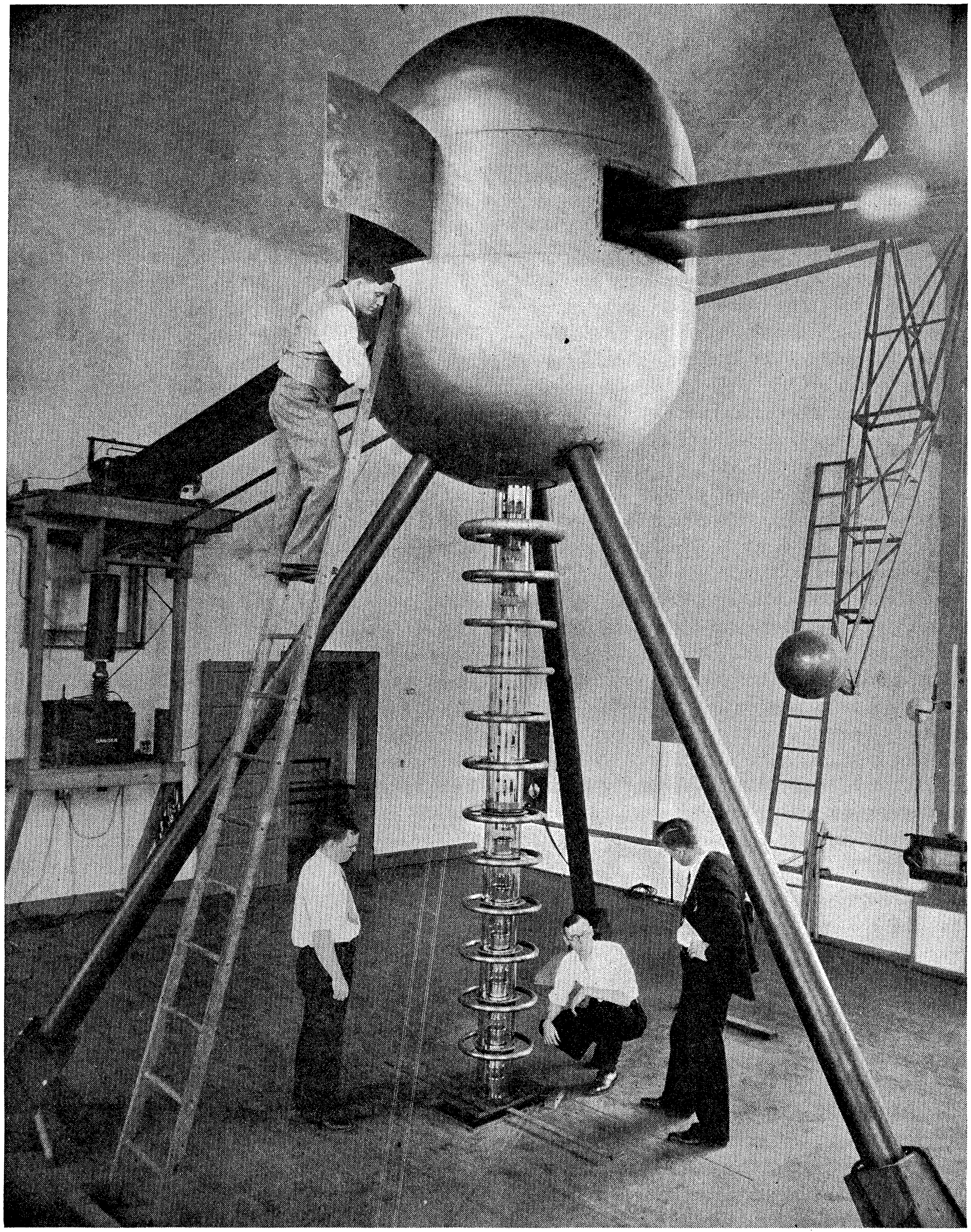

FIG. 4. View of two-meter generator and provisional cascade tube.

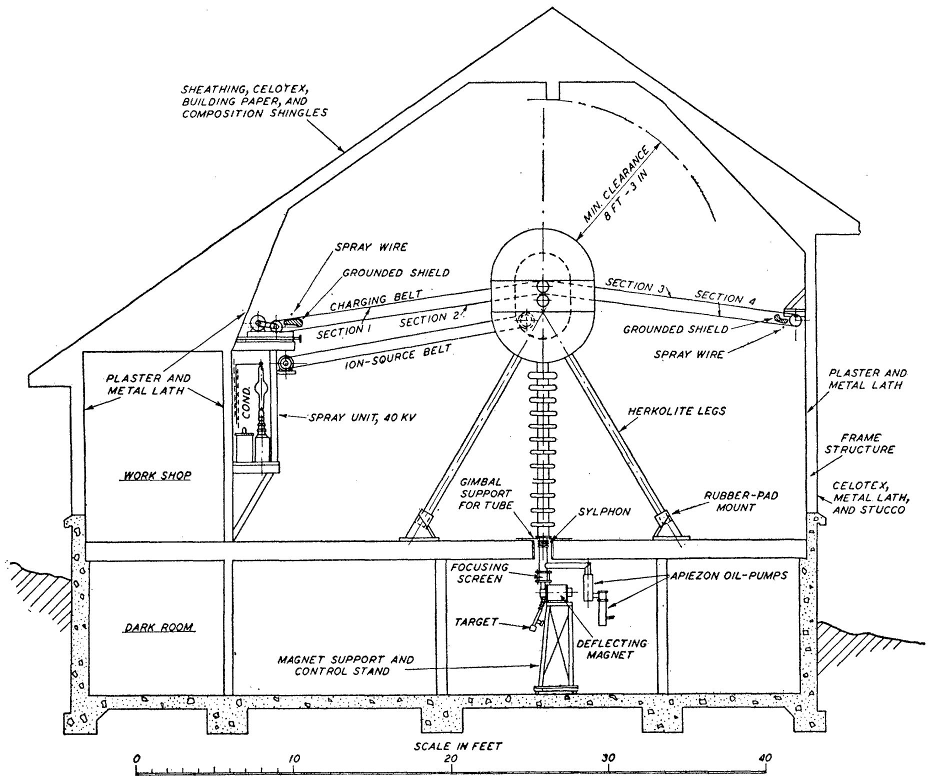

FIG. 5. Section through high voltage laboratory.

high voltage tube installed between the shells, thus giving a total voltage for accelerating the ion-beam which exceeds the maximum voltage of the two-meter shell (above ground) by whatever additional voltage is obtainable between the outer and inner shells. Theoretically, if a constant electric field strength from the outer surface to the center of a system of insulated concentric shells is arranged for by holding the shells at successively higher voltages, one might expect to attain as high a limiting voltage between the center of the system and the outer shell as from the latter to ground (at infinity). As already mentioned, we had failed to observe any large reduction in the maximum voltage on the one-meter generator when a large flat grounded conductor was brought within 50 cm (one radius) of the generator shell. Although trouble due to sparks between outer and inner shells along the belt was anticipated and encountered as a radical limitation with this concentric-shell arrangement, it appeared desirable for at least one interested laboratory to construct such a generator to test its possibilities. The chief value of the inner shell in our experience has been the convenience with which the additional voltage between the shells could be subjected to control by means of variable corona leaks across the two sections of the high voltage tube between the shells, thereby providing control of the electrostatic focusing of the ion beam down the tube and onto the targets. [See section D, below.] We cannot recommend this concentric shell design, however, since the focusing control can be attained inside the larger shell equally well and with much less constructional trouble without the inner shell. The voltage acquired by the collector combs may be utilized, or a transformer and rectifier arrangement could be provided for this purpose.

Voltage limits. The first tests for maximum steady positive potential were made with the generating voltmeter before the tube of this assembly was erected, and gave the surprising result that the outer shell reached a maximum potential of about 1800 kilovolts, steady to 1 or

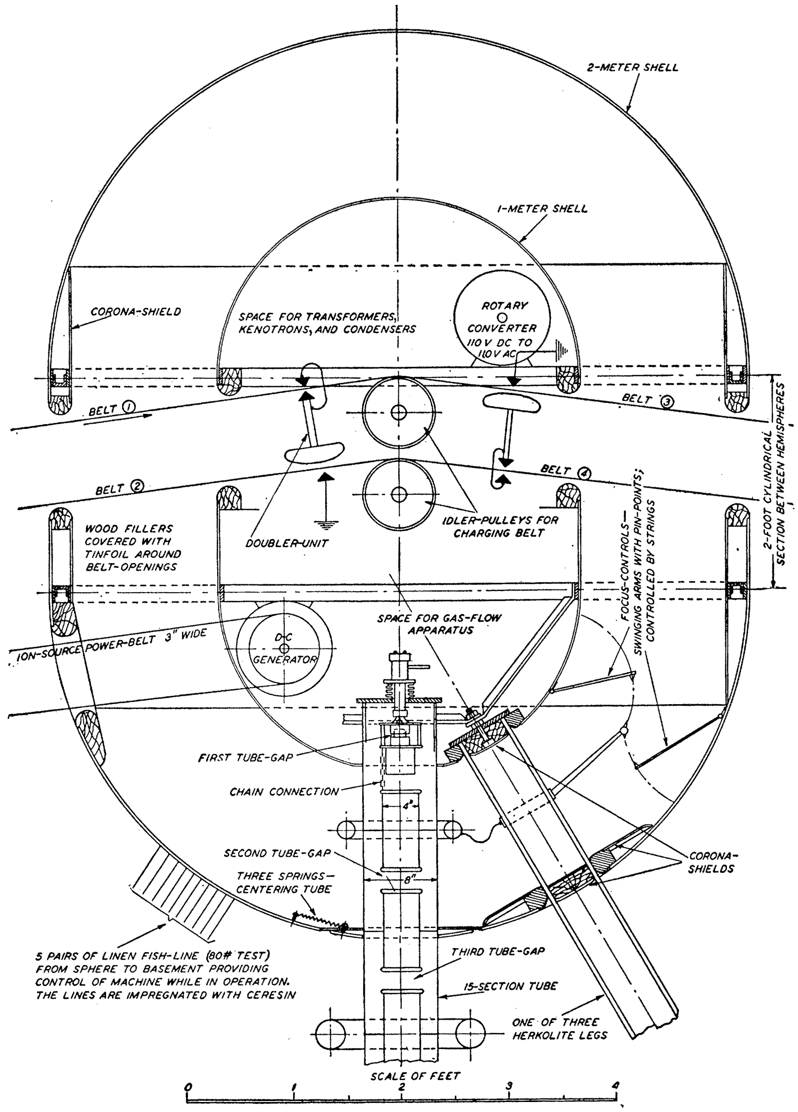

FIG. 6. Details internal arrangements—two-meter generator.

2 percent, instead of the 1200 kilovolts anticipated on the basis of our experience with the one-meter generator. This result prompted a great variety of calibrations and tests, all of which by their internal consistency, especially the proportionality of the generating voltmeter readings to the sphere gap voltages over the range of usefulness of the 50-cm sphere gap, strongly indicated the validity of this not unwelcome result. The high voltage tube was then installed, and, after several weeks spent in obtaining a properly focused and controllable ion spot at the target assembly in the observing room (see Fig. 5), voltage-determinations were made on the high speed ions themselves by their deflection in a calibrated magnetic field and by the range in air (beyond a mica or copper-foil window of measured air equivalent) of the protons in the "mass one spot" (beyond the magnetic analyzer). In spite of the simultaneous indication of a steady potential of 1700 kilovolts according to the generating voltmeter, these two more reliable measures of the voltage indicated a true potential of only about 1000

kilovolts. Since the generating voltmeter is essentially a field strength meter, subject to expected error if used as a voltmeter in the presence of corona and space charge, we accepted the conclusion that our previous measurements with this device were in error, in spite of their internal consistency and our various precautions in the conservative direction. The maximum voltage, measured by proton range, was increased to 1200 kilovolts by the reduction of corona losses and attention to other details, but in spite of prolonged efforts we have never been successful in raising the voltage limit of this two-meter generator above 1300 kilovolts as measured by proton and deuteron ranges at the target assembly. This figure is not an "absolute" upper limit for a generator of this size, but in our installation it is very definitely a practical limit, numerous features reaching their limit at this voltage value, and unless very special efforts are made the maximum voltage is in the vicinity of 1000 kilovolts even in winter.

Under good conditions, compounded of low humidity, good fortune and indefinite other ingredients, the steady voltage reaches a maximum of 1200 kilovolts or slightly higher, and no heavy sparks occur. In darkness heavy corona streamers are seen leaving the rounded edges of the belt holes near the edges of the belts, and other streamers pass between irregularities of the tube shields from section to section, and also out into space. Numerous heavy silk fish lines boiled in paraffin are strung between the controls inside the generator and the operator's position at the targets in the room beneath, and these lines have a tendency to become slightly conducting, with resultant strong corona until the offending lines are boiled again in paraffin or replaced. On a few occasions heavy sparks have passed from the rounded sphere to the slanting ceiling (see Fig. 5), but these sparks are not a major limitation, as are the sparks to the rafter shields and other grounded objects from the one-meter generator (see Fig. 1). Although both generators utilize spun aluminum hemispheres having very smooth outer surfaces, it appears from our experience that great perfection of the generator surfaces is unnecessary and a much rougher sphere can be used if it is cheaper. Decreasing the total charging current from the maximum attainable by a factor of three decreases the maximum voltage only perhaps 200 kilovolts, provided the corona points on the tube are not set so that an unusually large current passes in this way between tube shields, and with the movable "corona control" (see below) removed. Occasionally the 6-inch Textolite (Herkolite) tripod supports have given some trouble at 1200 kilovolts, long "incipient sparks" breaking from the generator shell along their surfaces. Each tripod hole in the shell presents an inward-rounded fillet of 1-inch radius where the support enters, and the metal shell is continued inside the Textolite tube by a metal disk. It appears quite definite that these smaller Textolite supports give much less trouble than the 12-inch and 20-inch holes previously used with similar Textolite supports.

Under poor conditions, which usually appear to be related to high humidity conditions (or a belt which is not thoroughly clean and dry), heavy sparks ("lightning bolts") occur along the positively charged belts to ground. This sparking can usually be reduced or eliminated, with a resultant raising of the maximum attainable voltage (from 800 to 1000 kilovolts, for example) by decreasing the kenotron voltage on the corona spray wires, thus decreasing the charges on the belt. The heavy sparks to ground have nearly always been along the belts, and hence the belt length to ground (12 feet on each side) is evidently too short for high humidity conditions. Minor irregularities in the shell, at the doors and at the joints between hemispherical and cylindrical sections, give no evidence of trouble, as was also found with the smaller generator. It appears, from the relatively infrequent occurrence of sparks over the general surface of the machine, that corona and sparks from the belt openings are the chief limitations of this larger generator, although the generalized limitation by sparks from any point on the shell, observed with the one-meter generator, apparently sets in at about the maximum voltage (1300 kilovolts) which this equipment has been made to give. With the sphere potential *negative*, different behavior obtains; prompt and continuous "lightning bolts" down the high voltage tube (shield to shield—about 5 per second) occur and have deterred us from making voltage tests with this sign of charge, although if the sphere voltage were reduced by grounded corona points undoubtedly a perfectly satisfactory behavior could be obtained.

Voltage-measurement and control. Measurement of the actual range in air of the protons and deuterons accelerated down the tube was adopted as the most convenient and reliable voltage measure, and has been used in all of our work. This method is extended to the lowest voltages (inconvenient for range measurements) by using a sphere gap as an indicator, calibrated by range measurements over the higher portion of its voltage curve (the corrections are large—the sphere gap indicates about 30 percent too high a voltage, presumably due to the presence of corona and space charges). The arrangement for making range measurements at 500 kilovolts and above is indicated in Fig. 10. A copper-foil window of 9-mm air equivalent (by weight, checked by actual air substitution) is supported by a piece of nickel gauze 100 mesh to the inch over a small hole behind the center of the target, which either can be moved in vacuum or otherwise has a 1-mm hole drilled through it to pass a portion of the bombarding ions through the window. By adjusting the current through the deflecting magnet (magnetic analysis has been used for all of our work) the mass one spot (full speed protons only) or the mass two spot (full speed deuterons and diatomic protium molecular ions) may be brought on the window and the particle ranges measured, either visually or by a shallow ionization chamber (1 mm deep, goldleaf window) connected to a string electrometer. Usually both proton and deuteron ranges are measured as a check on the voltage. A stable hydrogen isotope of mass three was found by similar range measurements[12] and is always observed in the mass three spot with sufficient deuterium flow in the ion source. In the visual range measurements the high speed particles appear as a purple colored beam in air, somewhat divergent, especially toward the end where the ions are slower, and visibly diminishing in intensity over the last couple of millimeters of path. The electrometer usually gives a range about 2 millimeters longer than the visual estimate, probably because of its too great sensitivity (10^{-12} ampere) and the well-known straggling of the particle ranges. Small rapid fluctuations in the voltage, due to corona unsteadiness, could give a similar result. Slightly larger voltage fluctuations, especially when the machine is operated at maximum voltage, show up very clearly by visual observation as a "flicker" of a millimeter or two in the total range length (23 to 35 mm depending on conditions). With high humidity the belt joints become slightly conducting (see below) causing small sparks out into space when the joint enters or leaves the generator. This or other sparking in poor weather causes a range flicker as bad as 4 or 5 millimeters at maximum voltage (voltage fluctuation ± 100 kilovolts or 10 percent), and when the fluctuations reach this we make no attempt to operate at very high voltage.

Adjustment of the generator voltage to any desired value below the maximum is accomplished by moving a grounded "comb" of many corona points (office pins) toward the sphere until the voltage drops to the desired value as indicated by direct range measurement or (at low voltages) by the settings of a 50-cm sphere set for spark over to a smooth portion of the two-meter shell (see Fig. 4). This crude sphere gap is only used as an indicator, being calibrated by range measurements from 500 to 750 kilovolts and the curve extrapolated in obvious fashion below 500 kilovolts. The voltage between the two shells of the generator is held at a fixed value ($\sim$ 90 kv for good focus of the ion beam). This voltage is separately measured and is taken as the zero point for the sphere gap curve (instead of zero voltage) when the extrapolation is made. The voltage calibration curve of Fig. 7 has been used for much of our work. An uncertainty of one millimeter in the range measurements is indicated, and this curve was tentatively adopted last year until a better absolute calibration might become available. The use of a Variac autotransformer in the primary of the 40-kilovolt transformer of the spray voltage unit provides a "vernier control" of the voltage at the operator's position near the targets; by its use the voltage is held "up against" the limit for breakdown of the sphere gap (under 500 kv) or held at the desired value when continuous range measurements

[12] M. A. Tuve, L. R. Hafstad and O. Dahl, Phys. Rev. **45**, 840 (1934).

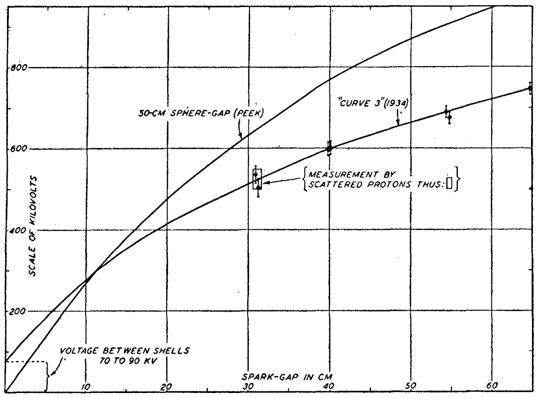

FIG. 7. Voltage scale for spark gap, as calibrated by proton range measurements.

can be made. The inherent "zero percent voltage regulation" of a constant current machine makes it necessary to guard carefully against voltage changes. It is an important characteristic of our technique that most of the ions striking the target have come from the ion source and have the full energy corresponding to the generator voltage as discussed below (sections C and E), so that improvement of the voltage steadiness of the generator is fully reflected in making the ion beam more nearly monochromatic. At voltages below the maximum (corona control in use) the voltage fluctuations of this generator are well under 20 kilovolts, and voltage changes of this amount can be made reliably, although the voltage settings cannot be repeated this closely when large changes are made, or from day to day. Observations on resonance transmutations[13] have demonstrated the steadiness of the generator voltage and will provide calibration points for ultimate intercomparisons and the establishment of an absolute voltage scale.

Belt-materials and treatment. A belt material highly suited to this specialized application still remains to be found, although a surprising degree of satisfaction and serviceability is obtained with rather ordinary materials. Pure silk or silk and rayon ribbons, with sewed joints cemented by airplane "fabric dope," were found satisfactory and long lived on the one-meter generator (also used in outdoor tests of two-meter generator), but such material cannot be obtained in widths between 8 inches and 36 inches. Following Dr. Van de Graaff and his colleagues we have been using on the two-meter generator a special paper belting supplied by the John A. Manning Paper Company, Troy, New York, specified as Electric Belting Paper, thickness 0.017 inch and usually purchased in 80-pound stock rolls 36 inches wide from which we cut both the main belt (20 inches wide, $68\frac{1}{2}$ feet endless length) and the small belt which separately drives the direct-current generator (110 volts, 1 kw, 1800 r.p.m. with belt 3 inches wide and pulleys 8 inches in diameter to prevent slipping under load) located inside the inner shell of the generator, for ion source power.

We feel that we erred in adopting the belt design shown in Fig. 5, in which side stresses on the generator tripod are (unnecessarily) avoided by letting the belt pass over idlers inside the generator, because with this four-pulley arrangement the tracking of the belt is exceedingly sensitive to the requirement that the axes of these central idlers must be accurately perpendicular to the belt motion, as would be rather obvious to a mechanic accustomed to moving heavy objects by placing rollers under them. The tracking of the belt is much less sensitive to the usual adjustments of the axes of the end pulleys. We would install two separate belts instead, if the same belt area and general design were to be duplicated. The pulleys are made from Textolite tubes 8 inches in diameter, 22 inches long, 1/2-inch wall thickness, mounted by Bakelite disks on $1\frac{1}{2}$-inch steel shafts, and they are crowned 1/32 inch over 2 inches at each end. It does not seem that crowning is necessary. A 6-inch silk and rayon ribbon belt runs satisfactorily on these pulleys and stays near the center indefinitely if started there.

Unfortunately no belt material yet tested is electrically satisfactory when subjected to 70 percent humidity at 80°F (Washington summer weather). Although during the winter (October to May) the behavior of the generator does not correlate well with the humidity (below 50 percent), there is no question concerning the ill effect of higher relative humidity on the belt insulation. Passing an unimpregnated paper belt slowly over a 10-kw electric heater for about two hours dries it sufficiently to prevent heavy belt

[13] L. R. Hafstad and M. A. Tuve, Phys. Rev. **47**, 506 (1935).

sparks for days or even weeks in winter, but this treatment lasts only a few minutes in summer humidity. Impregnating the paper with beeswax and rosin or with paraffin removes water which is essential to its mechanical strength, and the belt fails immediately. Coating the hot surface of a dry paper belt with ceresin does not prevent the growth of volume conductivity and gives slippage on the pulleys. However, a dry paper belt thoroughly soaked with Victron varnish (purchased from Dielectric Products Corporation, 63 Park Row, New York City) is relatively, but by no means completely, immune to humidity troubles and has been used to give 900 kilovolts, 750-microampere charging current, in August and behaved satisfactorily for several days after heating with 70 percent humidity at 80° to 85°F. Based on our experience with the silk and rayon belt on the one-meter generator, a charging current of slightly over 1000 microamperes might be expected on this two-meter generator, with a 20-inch belt on 8-inch pulleys at 3600 r.p.m. The theoretical maximum is 3.5 milliamperes. Untreated paper belts gave maximum currents of 620 to 650 microamperes (reduced to full width and full speed), but a Victron coated belt approaches the expected 1 milliampere, as does an untreated belt of light rubberized balloon fabric in the winter (just installed—summer tests have not been made with this material). Yellow varnished canvas, such as is used extensively for transformer insulation and other electrical construction, gives promise of being a satisfactory belt material, although the attainment of a satisfactory joint is yet uncertain; these tests are incomplete.* With the paper belts, various types of joint cements have been tested. Diagonal lap joints with a 3-inch skive are used, one end of the belt being split and the other tapered to give a joint of the same thickness as the belt. Those made with "Casco" casein glue give rise to troublesome sparking; Duco Household Cement has been the most satisfactory although this joint also requires the protection of an outside coat of Victron varnish. After some weeks of use the joint develops cracks, the paper nearest the cement tending to flake away, and after each day's run all such flakes are torn away and the belt reinforced over these areas by the application of silk cloth of light weight soaked in "airplane dope." This cloth cracks in turn, but is readily stripped off and replaced. The cracking at the joints, the collection of surface dirt, and the rough spots produced by heavy sparks are the chief limitations on the life of our Victron coated paper belts. With joint repairs and attention, our paper belts survive more than six months of hard usage (several hundred hours running time); we have used only two belts since beginning observations with this generator (although several belts were destroyed before we learned how to control the four pulley arrangement). Belt tests progress slowly since we consider it unprofitable to cut down a moderately satisfactory belt to test a new and unknown one, and we prefer to keep the generator in use.

* Since writing the above the Goodyear rubberized balloon fabric has proved admirable in all respects. It has served from February to June 1935 with no mechanical attention except adjustments for stretching, and with no trace of deterioration. It was coated with Victron varnish (now called Q-Max) as a precaution when humid weather approached, and has continued to give satisfactory results at 900 to 1000 kv even with humidity exceeding 70 percent. This appears to constitute a nearly ideal belt material.

C. High Voltage Tubes

Experiments during a period of several years in this laboratory led to the development during 1929–30 of oil immersed multiple-section high voltage tubes[14] which successfully withstood Tesla coil voltages as high as 2,000,000 volts. These tubes incorporated the well-known "cascade" principle of Coolidge,[15] which is an extension of Wien's method of "accelerated canal rays,"[16] and were characterized by the use of a large number of tube sections, each being required to withstand only a relatively small voltage, and each section being provided with external conducting shields to prevent undesired electric fields toward ground and to provide a spark gap between shields for protection against overvoltage. Sketch of a section of a tube of this type is shown in Fig. 8. After adopting in January 1930 the technique of "heat-working"

[14] Tuve, Breit and Hafstad, Phys. Rev. **35**, 66 (1930); Carnegie Inst. Wash. Year Book, No. 30, 364 (1931); Tuve, Hafstad and Dahl, Phys. Rev. **37**, 469 (1931).

[15] W. D. Coolidge, J. Frank. Inst. **202**, 693 (1926).

[16] W. Wien, Ann. d. Physik **77**, 313 (1924); **8**, 244 (1902); F. Hoffmann, Ann. d. Physik **77**, 302 (1925).

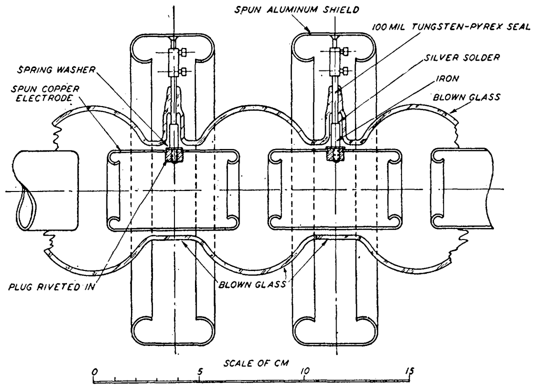

FIG. 8. Details of oil immersed cascade tube.

the Pyrex glass between the bulbs (to eliminate microscopic bubbles), which were blown at 3-inch intervals in ordinary 5-foot lengths of 44-mm Pyrex tubing, we experienced no difficulty with puncturing either on Tesla or direct-current voltages (except twice by the accidental application of grounded wires to the glass bulb of one of the highest voltage sections). These tubes were used successfully under oil with the spark excited Tesla coil for the demonstration of artificial gamma-, beta- and *H*-rays of energies exceeding a million volts,[4, 14] but further attempts to use them were abandoned in May 1931 until a more suitable voltage source of some kind could be obtained. The installation of the one-meter electrostatic generator in October 1932 gave us our first opportunity for a quantitative examination of the focusing properties of a tube of this type and its behavior when carrying appreciable currents.[17] In our work with the widely fluctuating Tesla voltages no estimate of the magnitude of the focusing or defocusing effect on the ion beam due to the curved fields between electrodes had been possible; our tubes had been originally designed solely to withstand high voltages, with the efficiency of transmission of the ions down the tube a secondary matter for later consideration to be met by modifications if necessary. Meanwhile Sloan and Lawrence[18] had found it possible to obtain 10 percent of the initial current on the target of a similar multiple-section tube utilizing high frequency voltages for the acceleration of mercury ions, and Professor Lawrence had kindly predicted to us that our tubes would be proved effective for a large percentage of ion transmission several months before we were able to satisfy ourselves on this point. As soon as we were equipped with a constant potential high voltage generator, it was found that very crude adjustment of the voltages on the several sections of the tube nearest to the generator (by adjustable points giving corona between the shields of these sections) sufficed to give a 1-cm spot on the target at two meters which measured 80 to 150 percent (with secondary emission) of the initial ion current projected from the low voltage arc ion source into the tube, provided this did not exceed 0.2 microampere. For higher currents the pumping speed of the tube itself, originally constructed for oil immersion (Archimedes' principle was our chief experimental obstacle), was too slow to handle the gas evolution and the tube "went soft." This result, that the initial ion beam was completely focused onto the target by the action of the tube itself, was of sufficient interest that it was repeatedly tested and verified; the currents were measured using very deep Faraday cages (50 cm long, 4 cm in diameter); magnetic fields showed that secondaries and slow ions were responsible for less than half of the target-currents, and the main uncertainty (a factor of 2 or less) was caused by irregular variations in the output of the ion source. The reasons why long high voltage tubes having only one or two sections in general give much less satisfactory focusing, unless very careful attention is paid to certain parameters of the problem, will be indicated in another paper, which presents a study of these factors.

To increase the pumping speed, and hence the usable ion current, a six-section tube was constructed using 6-inch moulded Pyrex tubing as shown in Fig. 1. This tube had electrodes made by rolling light gauge sheet brass into $3\frac{1}{2}$-inch cylinders 10 inches long, fitted at each end with a toroidal ring of 1/2-inch copper tubing (with an open crack at the butt joint in the ring). These parts were spot soldered together and the whole supported (in rather bad alignment) by rods passing through holes drilled in the glass wall. Spacing between the electrodes was roughly $1\frac{1}{4}$

[17] A photograph of one of these tubes being used with the one-meter generator for studies of the transmutation of Li and B was reproduced in J. Frank. Inst. **216**, 26 (1933).

[18] Sloan and Lawrence, Phys. Rev. **38**, 2021 (1931).

inches (variable because crooked). Although no parts were outgassed, this tube withstood full voltage (600 kilovolts) with target currents of 0.1 microampere within one-half hour of the first application of voltage immediately after being pumped down. Target currents up to 10 microamperes were obtainable at full voltage within several hours. Due undoubtedly to its faulty electrode alignment, although it gave a marked focusing response to the voltages on the first several sections, this tube did not focus the ions into a small diameter spot but gave an irregular "patchy" distribution over a 5- to 10-cm diameter area on the target. Most of the ions leaving the source reached this area. This tube was utilized for a series of observations on Li, B, Al, Ni and Ag.[19] The emission of rather soft x-rays from this tube in operation with 10 microamperes on the target required shielding for the observers (a pencil electroscope kindly supplied to us by Professor C. C. Lauritsen indicated 0.02 roentgen per minute at 6 feet from the tube, unshielded). This shielding was effected by installing the controls and recording oscillograph and camera in a hut outside the 12-inch concrete walls of the laboratory.

The tube which has been used with the two-meter generator from the time of its initial installation to the present date was first constructed as a temporary expedient, but it has worked well enough to cause postponement of the construction of a more permanent tube. This tube is shown to scale in Figs. 5, 6, 9 and 10, and was constructed from two 64-inch sections and one 32-inch section of moulded lead glass (Corning Glass Works, type 005 glass, 25 percent Pb) 8 inches in diameter. The voltage distribution between the sections of the tube is equalized by corona in air from section to section due to various corners and edges of metal parts inside the ring-shields. Short bent sections of wire have been added inside of each shield, giving corona to the next adjacent section, but these only serve to increase slightly the gradient control and are not essential. Only a moderate corona current passes down the outside of the tube in normal operation, as measured by the current to the bottom ring shield (30 to 110 microamperes as voltage is varied from 250 to 900 kv). At voltages below 900 kilovolts, obtained by moving a set of grounded corona-points toward the sphere, the current to these points nearly equals the total 400-microampere charging current. The corona discharges between tube sections serve the vital function of reestablishing the voltage distribution along the tube if an incipient internal discharge occurs. This safety valve action, together with the relatively low, but by no means negligible, energy which the generator will deliver into a tube flash if breakdown occurs, probably accounts for the very small amount of trouble we have experienced in applying high voltages to our tubes even when carrying the total available ion current from the source (10 to 15 microamperes). The crude type of electrode assembly described for the six-section Pyrex tube was utilized for this initial tube, which will ultimately be replaced by one

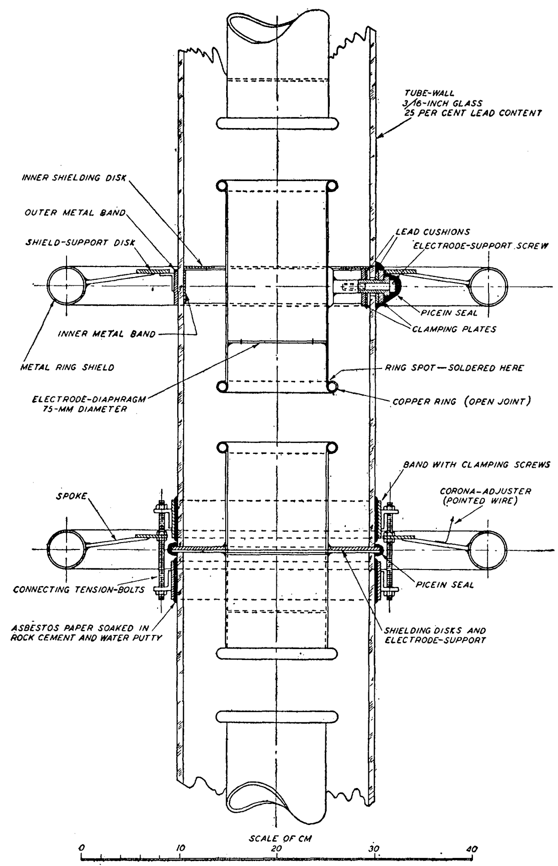

FIG. 9. Detail of tube joint and electrodes.

[19] M. A. Tuve, J. Wash. Acad. Sci. **23**, 530 (1933); Tuve, Hafstad and Dahl, Phys. Rev. **43**, 1055 (1933).

incorporating the following modifications: (a) The electrodes should be axially in alignment; (b) the electrode gaps should be of uniform width (not wedge-shaped or irregular as now) and much narrower to prevent transient deflections of the ion beam by charges on the glass wall of the tube; (c) the pumping speed of the tube itself should be increased by a factor of 10 or more by increase in the diameter of the glass cylinders and improvement (or omission) of the baffles on the outside of the electrodes. As before, no outgassing treatment was given any of the metal parts, and the tube withstood full voltage (above 1000 kv) within three hours of the first application of voltage after eliminating various air leaks. Subsequent exposure to air continues to require a "seasoning" period of the order of one-half hour before the tube will withstand full voltage and current (several microamperes).

The difficulty of applying high voltages to vacuum tubes, for positive ion currents of many microamperes (which are as large as can be used effectively in transmutation experiments at present), is only a matter of superstition if multiple-section tubes are used, as far as we can discover. Constant potentials, instead of being conducive to breakdown, are even more readily withstood than fluctuating Tesla voltages; the crudest kind of un-outgassed electrodes function without breakdown with relatively poor vacua (0.1 bar), and almost any size, shape and number of electrodes and length of tube can be made to focus practically 100 percent of the input ion current onto a relatively small area target if use is made of the focusing-parameters, especially the voltages on the various sections. It thus appears quite unnecessary to make a single section high voltage tube withstand a very high voltage because of the supposed advantage in "solid angle" of the source at the target.

The pumping system for this tube shown in Fig. 5 comprises two Apiezon oil diffusion pumps in series backed by a Hypervac. We changed from mercury to Apiezon pumps only after receiving from Professor E. O. Lawrence the complete designs for these pumps as constructed and used in his laboratory. We are exceedingly grateful to Professor Lawrence and his colleagues for the great saving of time and effort this has meant to us. The speed of the "fine" pump is perhaps 80 liters per second (air) but the overall speed is reduced to about 30 liters per second by the connecting tubes. We have had two experiences with the accidental cracking of the oil in these pumps which probably deserve mention, one of which cost us several weeks of trouble and delay. During April 1934 the pump heaters were left on continuously for two days with a leak in the tube and the Hypervac shut down. The oil in the pumps was hence greatly overheated in the presence of air, cracking to a gummy brown residue and distilling visible quantities of oil into the horizontal pump connection, and onto various surfaces in the lower part of the tube. The pumps were cleaned and refilled, and the visible oil in the pump connection and base of the tube was wiped out with benzol-soaked rags. After running the tube at moderate but increasing voltages and ion currents for a period of about five hours, the remaining oil film in the tube was converted to a noticeable carbon deposit and the tube was again usable, although the focal spot was somewhat unsteady. After several hours of use it was as good as ever.

During the autumn of 1934 we enjoyed a much less fortunate experience, however. Because of an increase in the diameter of the fore-pump connection (to realize an advantage from the "coarse" Apiezon pump) without proper baffles, nearly all of the oil from the "fine" pump diffused over into the "coarse" pump. The remaining few cubic centimeters of oil became overheated and cracked in a high vacuum (not exposed to air as before). Whether due to this cause or to some other, such as the accretion of Apiezon sealing compound Q and picein wax on the inside of the tube, due to numerous removals and repairs of the ion source at the top of the tube, a peculiar phenomenon developed at this time. The tube pressure behaved as though an "unpumpable vapor" was formed when high voltage was applied to the tube. A low pressure (0.005 to 0.01 bar) was readily attained in the tube, increased as usual by the gas flow when operating the ion source to about 0.02 or 0.03 bar, but as soon as the high voltage was applied even with ion currents as small as 0.1 microampere this pressure increased steadily (instead of the usual fixed increase of 5 to 20 percent due to gassing of tube and targets) at a rate which raised the pressure to the stalling point of the diffusion pumps (about 0.15 bar) in several minutes. If the high voltage was cut off before the pumps stalled, this pressure decreased very slowly, requiring roughly an hour to return to the initial 0.02-bar pressure, although the pumps maintained their usual high speed, as was readily demonstrated by letting in a burst of air or hydrogen. This gas was pumped away in a few seconds, the pressure returning to whatever value (between 0.10 and 0.02) it had been before the burst of gas was admitted. The tube was completely dismantled and all parts cleaned by simple abrasion with steel wool and emery-cloth (solvents uncertain for such a vague surface-impurity), and when reassembled, using picein wax for all joints and seals, all sign of trouble had disappeared. The important convenience of an ionization gauge in locating leaks and other tube troubles is worthy of mention. We use the standard Western Electric gauge, type D-79510, with oxide-coated filament, which withstands unbelievable hard usage, including operation at pressures of many centimeters and repeated "poisoning" by oil vapors. This gauge is attached at the base of the tube for indicating pressures. With 20-milliampere emission a positive ion current of 4 microamperes is taken as 0.01 bar equivalent air pressure. A single gauge has withstood more than a year of rough usage. Minute cracks or holes in picein joints are found by watching the ion current in the gauge while painting the joints successively with 90 percent alcohol, which has the property of adequately "wetting" this wax, closing such holes temporarily, as shown immediately by the gauge. To determine whether a stubborn leak was in the ion source portion of the tube or not, we have repeatedly used the device of filling the generator shells with CO_2 gas, which gives about a 15 percent change in the gauge reading when drawn through the leak in place of air.

The use of heavy lead glass for the walls of this tube has made it possible to operate this unit without any further shielding for the observers although some additional shielding would be desirable (the wooden floor of the high voltage room is negligible protection for the observing room beneath). During the first half-hour of operation after being open to the atmosphere more x-rays are produced, but the usual dosage during a four-hour run of the equipment, recorded by a Lauritsen milli-r-meter (pencil electroscope) suspended in the observing room, amounts to only 10 to 30 scale divisions; the sensitivity is such that 50 scale divisions correspond to about 0.05 roentgen, and cosmic rays give an exposure of about one scale division per day measured by the same instrument. Ten times the daily cosmic-ray exposure is certainly a conservative value to adopt as the safe daily tolerance dosage. Since the equipment is not in operation continuously for many reasons during any period of one week, the total exposure of a single observer is always kept below seven times this very conservative daily dose. The allowable daily tolerance dose for x-rays in medical practice is generally accepted as 0.1 roentgen.

A description of the focusing of this tube and the target-currents attainable will be given in a later section.

D. Ion Sources

A device for supplying high intensity positive ion beams for work of this type with reasonable costs for equipment, power, pumps and gas (deuterium) has been an auxiliary requirement for artificial disintegration experiments which has demanded attention and development in many laboratories. Our earlier work with high speed protons using Tesla coil voltages had been carried out with unsatisfactory source arrangements (various palladium and gas ionization arrangements were tested), and in the summer of 1932 as we began tests of low voltage arc devices Dr. E. S. Lamar suggested the use of a hollow anode arc to obtain high positive ion density. It was immediately found that a hollow anode does not materially increase positive ion density over that of an ordinary low voltage arc discharge, since the space potential rises above that of the anode, but with the filament and hence the discharge near to the probe this type of arrangement (Fig. 11b) gave sufficient ion current (a few microamperes into the tube under operating conditions) for our immediate needs, and in various modifications has been used for nearly all of our experiments to date. At different times during the past two years we have tried

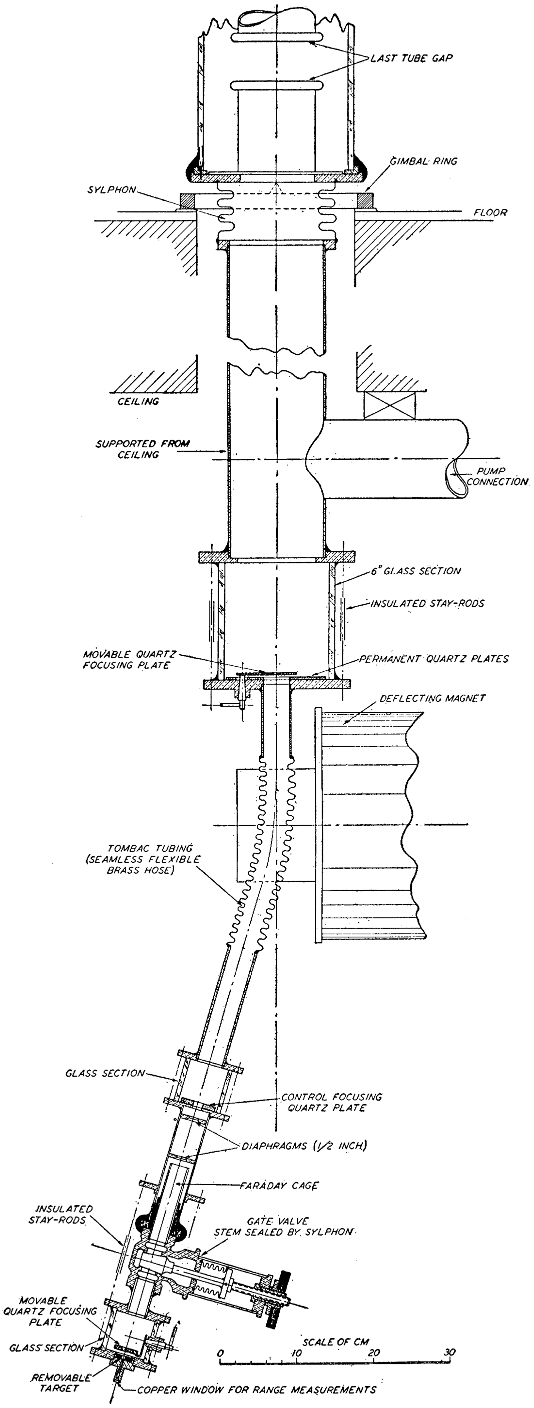

FIG. 10. Details of focus and analysis.

a great many variations of the general type of source which comprises a negative probe electrode (having a canal to pass ions into the high

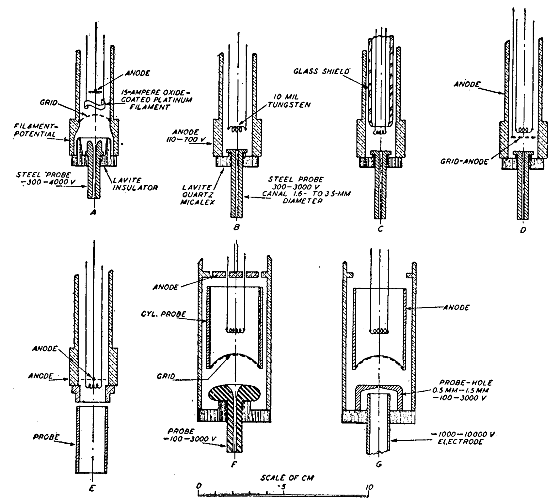

FIG. 11. Ion source arrangements.

voltage tube) immersed in a low voltage arc plasma of considerable volume extent, including the "accommodation coefficient" type (large hollow probe) recently described by Lamar and Luhr,[20] and all types tested were found unsatisfactory except for small ion currents (up to 12 microamperes) under best conditions. A few of the variants tested are illustrated by the diagrams of Fig. 11. Numerous changes of filament and probe positions, and other dimensions, of arc, grid, and probe potentials, and of arc pressure and canal size were made with each type of source design. The primary limitation of all of these arrangements was the fact that the current density to the probe face was consistently too low (10 to 65 microamperes per square mm including secondary electron emission) to counterbalance the requirement that a small area canal or diaphragm hole in the probe is necessary, with gas flowing, to give sufficient pressure for a true arc on one side of the hole and lower pressure in the high voltage tube on the other. With a full area probe hole as in Fig. 11e, ionizing the gas at tube pressure (under 0.1 bar—no true arc), the total tube current was slightly greater, 10 to 30 microamperes, but the focusing was bad or nonexistent with the large source area. This is of course to be expected, since to focus a distributed source places much higher requirements on the "optical" properties of the lens than to focus a point source. Final tests defining the

[20] Lamar and Luhr, Phys. Rev. **46**, 87 (1934).

limitations of this type of source were made with a probe in the form of a thin disk (Fig. 11g). Currents through a hole in this disk could not be space charge limited, as may be the case for a long canal, and yet the maximum ion currents through a 1.5-mm diameter hole were still only about 25 microamperes in spite of the use of curved grids and other devices in an effort to "focus" the ions on the hole in the probe. Low probe current density undoubtedly means a correspondingly insufficient ion density in the arc plasma. However, increasing the arc current (0.1 to 10 amperes) only decreased the tube current in most cases. Various sources of this general type can be made to yield several hundred microamperes through probe holes 5 mm or more in diameter with high arc pressures, but it is impracticable to provide the pump speed or the deuterium gas required if a low pressure is needed beyond the probe. To drive large ion currents through canals of great length would require voltages in excess of 10 kilovolts. Gas flow resistance increases as the first power of the canal length, and the ion current at a given voltage experimentally decreases much more rapidly than the first power after a given canal length is exceeded, perhaps due to mutual-repulsion effects on the ions.

The source arrangement with which most of our work has been done to date is similar to that shown in Figs. 11a and 12 (the grid and cylinder are connected to the filament) and has the following characteristics: Arc current 0.7 ampere; probe voltage 4500; probe current 3 to 6 milliamperes; probe canal 1.6- to 2.5-mm diameter, 26 to 48 mm long; arc pressure uncertain; tube pressure 1 to 4×10^{-5} mm; gas flow (hydrogen) 3 to 10 cc (at normal pressure and temperature) per hour; ion current into tubes 3 to 8 (15) microamperes; magnetically resolved proton current 0.5 to 12 microamperes (maximum), frequently not over 2 microamperes maximum; hydrogen ions always 55 to 90 percent atomic.

It is perhaps not flattering to ourselves but only proper to record that three separate high voltage discharge tubes intended as examples of the type of source used by Oliphant and Rutherford[21] failed to result in an ion source giving

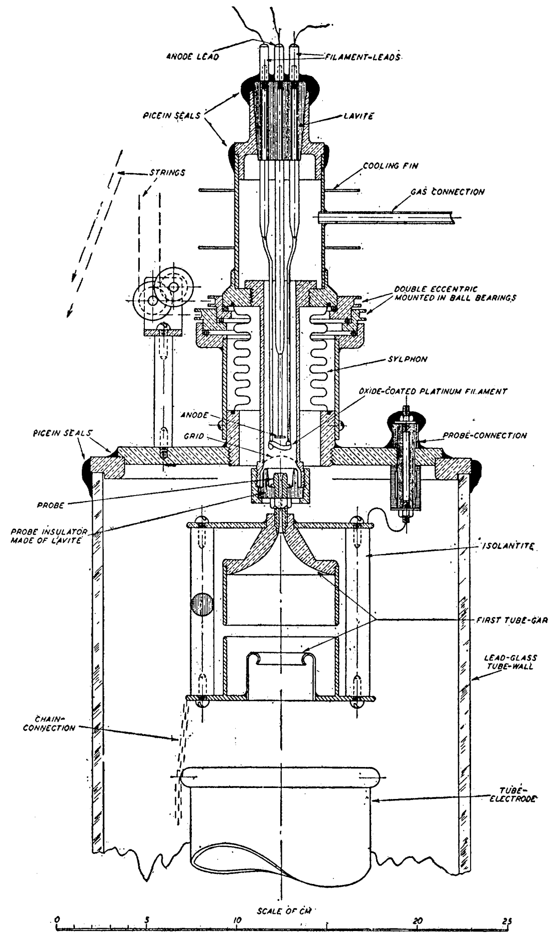

FIG. 12. Ion source.

the large currents (20 to 1000 microamperes) obtained in Cambridge. It appears from our experience and from verbal information from other workers that quite high voltages (much more than 10 kv) and large amounts of power (several kilowatts) are essential to the proper operation of a source of this type, and these requirements were difficult for us to meet. Trouble was also experienced with the insulator design at the top of the discharge tube in this design; at 10 to 15 kilovolts, 150 to 30 milliamperes, and moderate pressures only small ion currents were obtained (10 to 20 microamperes); at higher voltages and lower currents (lower available power and also lower pressures) internal sparkover gave trouble with several designs of insulators and adjoining parts. It is of course clear that this type of source gives intense ion

[21] Oliphant and Rutherford, Proc. Roy. Soc. **A141**, 259 (1933).

beams when relatively high voltage and high power are used as in Cambridge, but our experience does not encourage any belief that it might be operated with more modest equipment. Space and power, as well as artificial cooling, are at a premium inside a high voltage generator of the type we are using.

An ion source capable of supplying total currents as high as several milliamperes, with low power consumption and gas flow and with ideal flexibility of control, has recently been developed in this laboratory and is described in another paper. This new source has been used on another tube at lower voltages but has not yet been put into use with the two-meter generator since this was found to require certain minor changes in the apparatus and the original ion source was able to supply enough current for the problems immediately in hand. The original ion source and tube have been adequate for a whole series of investigations, and consequently all changes have been postponed in favor of continued operation of the present set up, although we plan to change both tube and ion source within the next several months, primarily in order to improve the steadiness of the target spot and incidentally to make available much larger currents for those problems in which they can be utilized.

E. Focusing Technique and Magnetic Analysis

A somewhat detailed description of our technique and experience in focusing the ion beam and in its analysis and steadiness on the targets may be of value to other experimentalists and also of interest in assessing the validity of transmutation results using this technique, especially in reference to the homogeneity (in energy and kind) of the ion beam bombarding the target.

Because of the dissymmetry and lack of alignment of the various tube sections, the focusing technique with this provisional tube (2-meter generator) is unnecessarily complex, as adjustment of the voltages on various tube sections (especially near the top of the tube, where the beam is slower) not only changes the size of the focal spot but also shifts its position. Major control of the focusing is accomplished by varying the voltage across each of the two tube sections which lie between the outer and inner shells of the generator. This is done by controlling the position of the two arms carrying corona points which are indicated in Fig. 6; since the charging current to the inner shell is constant (usually about 400 microamperes) and large compared to the tube current, settings of this device maintain steady controlled voltages across these two tube sections. Increasing the voltage on the first section causes the ion beam to behave exactly as a lens of variable focal length, when focused giving a spot, usually not round but with dimensions of the order of a centimeter, at some point on the quartz focusing screen shown in Fig. 10. After setting No. 1 at an underfocused voltage (divergent beam), increasing the voltage on No. 2 produces a similar behavior, but also shifts the spot to a new position perhaps 2 or 3 cm away from the position when focused with No. 1 and makes a round spot usually about 3 or 4 mm in diameter. When the tube has not been open to the air for several days and with currents of 1 microampere or less, the focal spot may be reduced to about 1-mm diameter, but with these sharp settings the spot splits into three or four adjacent spots, apparently due to a separation of ions of different mass, and these are surrounded by a diffuse spot about 10 mm in diameter. The latter aberrant ions are restored to the main spot 3 to 4 mm in diameter at the less critical settings. A third control, used to reduce the voltage and hence the arbitrary deflection produced by any of the lower sections (outside the large shell), is provided by a short length of chain inserted in a loop of silk fish-line and passing over pulleys at top and bottom so that it can be moved between any two ring shields on the outside of the tube, reducing the voltage across the selected section by corona. To facilitate the exact placing of the focal spot, in order that it shall enter the magnetic-analysis slits within 2 mm of a given position, the whole ion source is mounted on a flexible sylphon and can be shifted to any desired position in a circle 10 mm in diameter by means of a pair of eccentrics (see Fig. 12). This control has been essential also because of the slow drifts of the focal spot experienced especially during the first hour of operation with this tube, probably due to small changes in the voltages across the various sections and to charges on the glass walls influencing the ion beam through the unnecessarily wide tube gaps between electrodes. There is a slight magnification at the focal spot of the ion source motion, but this is always less than a factor of two; a great magnification undoubtedly could be obtained by moving the ion source alone, with respect to the first lens (tube gap No. 1 at top), but to avoid large distortions (with a small diameter cylinder on the first gap) it was considered safest to mount this also on the eccentrics as shown in Fig. 12.

During the first month after its erection (autumn 1933) successful focusing of ion currents up to 7 microamperes of protons after magnetic analysis was obtained using the 4-inch electrodes shown in Fig. 9 for all tube gaps including the first one (next to the ion source). The double eccentric sylphon mount was then installed on the ion source, and to reduce the focusing voltage required on the first tube gap (which was near the maximum attainable) the four electrodes on the latter were replaced by a smaller diameter cone and cylinder arrangement similar to that described by Crane, Lauritsen and Soltan,[22] and this (see Fig. 12) has been left unchanged. An empirical investigation of the various parameters important to the focusing of a beam of ions down a high voltage tube has just been completed and is presented in a separate paper.

The arrangement of the magnetic analysis apparatus at the bottom end of the high voltage tube is shown to scale in Fig. 10. The magnet[23] gives a maximum field of 5500 gauss with a pole face separation of 3.5 cm, and this just suffices to bring the mass 5 spot (protons = mass 1) onto the target at full voltage. The focal spot is reproduced (usually with some distortion toward a linear form, due to the nonuniform edges of the magnetic deflecting field) on the quartz focusing disk in the target position, the desired ions (protons, deuterons, tritons, helium ions) being selected by adjusting the magnet current. The virtual separation of the various spots at the target distance is 4 to 7 cm; hence, there is no overlapping, and only ions of the specified mass can strike the target. The high degree of purity of resolution (absence of high speed in ions having directions other than that of the main beam, lack of scattering from slits, etc.) is clearly demonstrated by the fact that when a mixture of ordinary hydrogen and deuterium is used in the tube, whereas bombardment of carbon or quartz by the mass 2 spot gives rise to a count of several hundred particles per *second* actually recorded by a linear amplifier adjacent to a mica window near the target, shifting the magnetic field to bring the mass 1 spot on the target (roughly equal current), promptly reduces the count to the residual value (frequently 0 counts in 2 minutes, but arbitrarily assigned as 4 counts per minute to be as conservative as possible). A similar test of the purity of resolution is afforded by experiments on the induced radioactivity of carbon, where the effect at 1000 kilovolts due to deuterons is approximately 10,000 times as large as that due to a similar current of protons and the latter has been proved (by excitation functions) due to the protons alone. Tests made when 95 percent deuterium gas was flowing through the ion source showed likewise that the contamination of the mass 1 spot by deuterons was not detectable, and hence was less than one part in several thousand. When 98 percent deuterium gas flows into the ion source the mass 2 spot measures about 10 times the current of any other spot up to mass 6. A similar condition holds for the mass 1 spot when using ordinary tank hydrogen. The gas flow is usually set at a value which approximately doubles the ionization manometer reading of the residual tube pressure (1 to 5 microamperes on the ionization gauge).

It is to be pointed out that magnetic analysis (or even crossed electric and magnetic fields) for a given particle energy can only select ions of a given value of e/m, hence the mass 1 spot is the only one which is not a mixture. The mass 2 spot contains H^2 nuclei and H^1H^1 molecular ions; mass 3 spot contains H^3, H^2H^1, and $H^1H^1H^1$ ions, and the mass 4 spot contains He^4, H^3H^1 H^2H^2, $H^2H^1H^1$ and $H^1H^1H^1H^1$ ions. Thus a

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

[23] A copy of a magnet built by Dr. L. F. Curtiss to whom we are grateful for the design details. This magnet utilizes a one-piece yoke cut from the billet by acetylene torches, kindly supplied by the American Rolling Mill Company, Middletown, Ohio.

subtractive technique, based finally on the purity of the mass 1 spot, must be followed in ascribing given results to given types and energies of ions. Since the various ions have different *velocities*, although the same energies, a separation by *range* can be effected if a homogeneous medium, air, for example, is used for stopping power. This procedure has been used for the identification of stable hydrogen atoms of mass 3 in numerous electrolytic deuterium samples.[12] The simple assumption that the composition of the ion beam from a high voltage tube is the same as the composition of the gas flowing into it is a highly erroneous practice, due to the large numerical ratios between the effects of different ions and the consequent importance of very small percentages of impurities (such as H^2 diffusing from the electrodes after use, etc.). The general effect of the input gas composition on the ion ratios is of course obvious.

The homogeneity in voltage distribution of the ion beam striking our targets is another factor of great importance, and is best demonstrated by our measurements on various resonance processes.[24] Suffice to say here that the ion beam has a spread of less than 20 kilovolts (probably considerably less) due to all causes, including both tube and generator, except at the highest voltages (above 900 kv—corona control removed) where the voltage fluctuations of the generator itself may be considerable because of small sparks to the belts, supports, control strings and out into air. A fluctuation exceeding about ± 50 kilovolts is not tolerated, even at peak voltage, the belt and strings then being dried to prevent sparking or the voltage reduced slightly by a weak corona control to give a steadier voltage.

The analytical virtues of a homogeneous ion beam are not fully realized, of course, if thick targets are bombarded, since ions of all velocities down to zero are then present in the target. For the numerous cases in which the effect under observation changes rapidly with voltage, including both the effects which show an exponential increase with voltage and those which show the familiar characteristics of a resonance response, observations with thin targets are almost essential since the thick target curve is an integral one and differentiation of an experimental curve is a procedure having a long history of defaults, valuable as an indicator when no other procedure is possible but to be avoided otherwise.

The authors take pleasure in recording their great obligation to Dr. John A. Fleming, Director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, for his sustained interest in these experiments. Without his vision of its ultimate significance and without his hearty support, this work could never have been carried out.

[24] L. R. Hafstad and M. A. Tuve, Phys. Rev. **47**, 506 (1935).

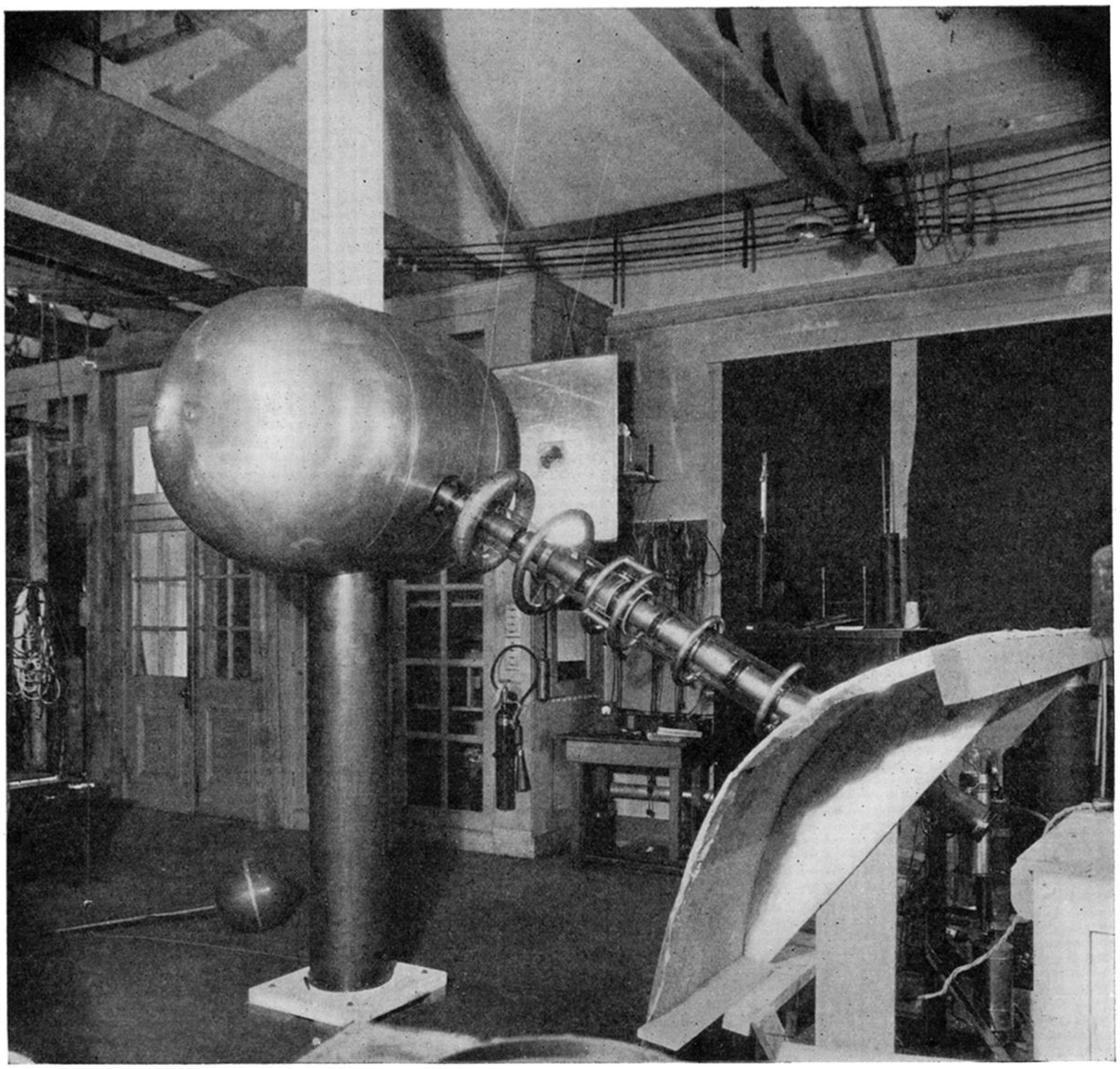

FIG. 1. One-meter electrostatic generator with six-section cascade tube.

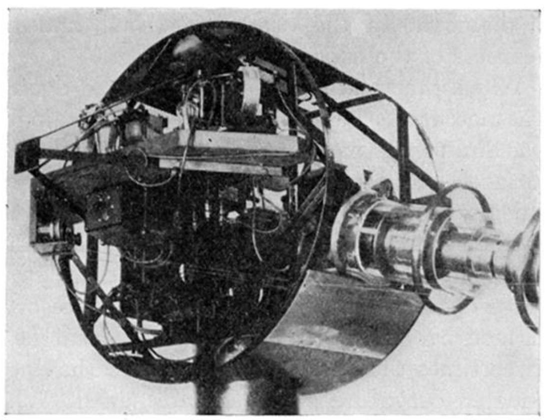

FIG. 2. Construction and interior arrangements of one-meter generator, showing equipment and controls for ion source.

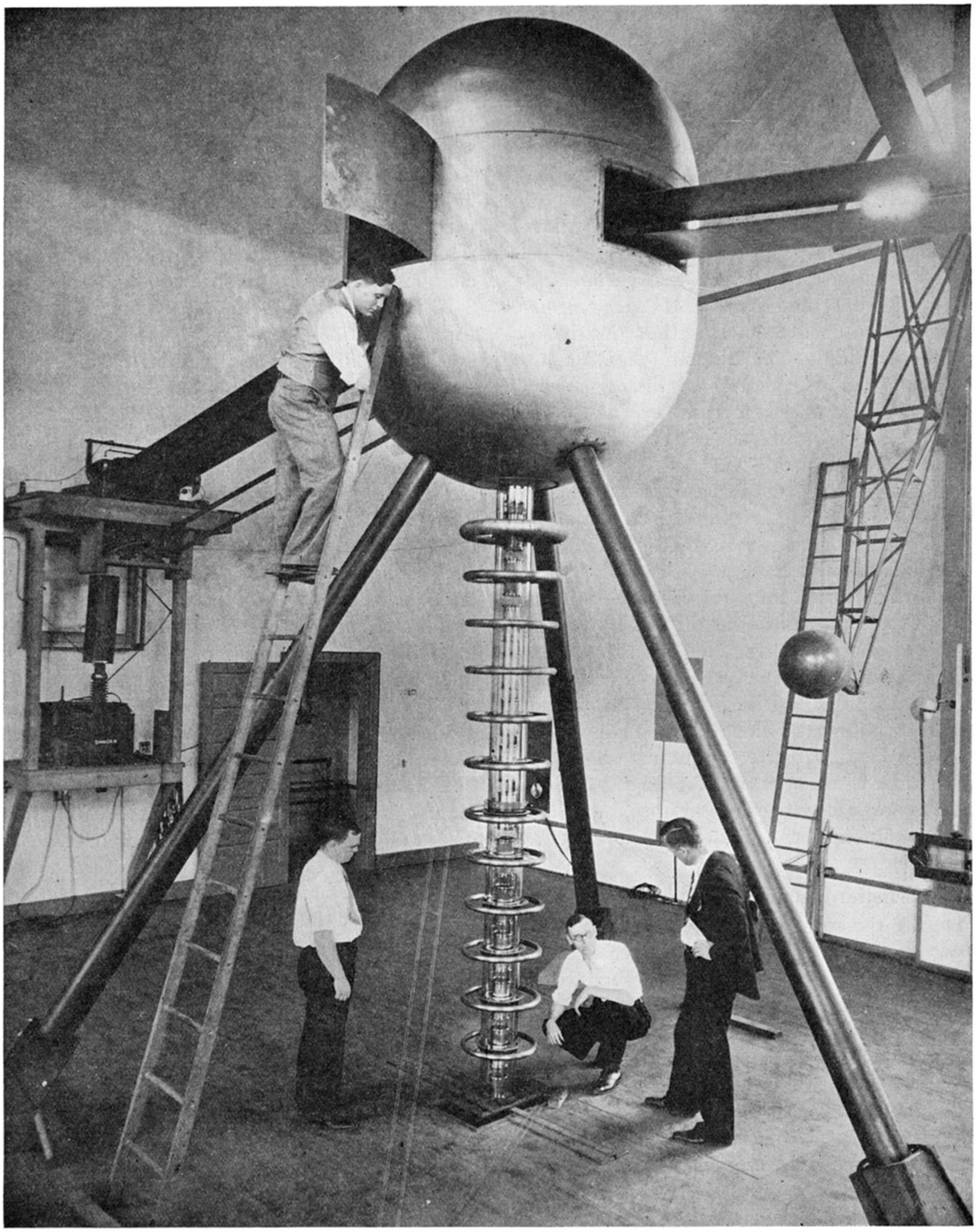

FIG. 4. View of two-meter generator and provisional cascade tube.