Title
The Berkeley Electrostatic Generator

Permalink
https://escholarship.org/uc/item/06h1h526

Authors
Turner, C M
Hudgins, A J
Fillmore, F L
et al.

Publication Date
1949-06-01

Copyright Information

UCRL 352
cy 2

UNIVERSITY OF CALIFORNIA

Ernest O. Lawrence Radiation Laboratory

BERKELEY, CALIFORNIA

UNIVERSITY OF CALIFORNIA

Radiation Laboratory

Contract No. W-7405-eng-48

THE BERKELEY ELECTROSTATIC GENERATOR

C. M. Turner, A. J. Hudgins, F. L. Fillmore,
M. R. Jeppson, J. D. Gow

June 16, 1949

Berkeley, California

INSTALLATION	NO. COPIES
Argonne National Laboratory	10
Armed Forces Special Weapons Project	1
Atomic Energy Commission, Washington	2
Battelle Memorial Institute	1
Brookhaven National Laboratory	10
Bureau of Ships	1
Carbide & Carbon Chemicals Corporation (K-25)	4
Carbide & Carbon Chemicals Corporation (Y-12)	4
Chicago Operations Office	1
Columbia University (Dunning)	1
Columbia University (Failla)	1
General Electric Company, Richland	7
Hanford Operations Office	1
Iowa State College	1
Kellex Corporation	2
Knolls Atomic Power Laboratory	4
Los Alamos	6
Massachusetts Institute of Technology (Gaudin)	1
Massachusetts Institute of Technology (Kaufmann)	1
Mound Laboratory	8
National Advisory Committee for Aeronautics	2
National Bureau of Standards	2
Naval Radiological Defense Laboratory	2
NEPA Project	1
New York Operations Office	8
North American Aviation, Inc.	2
Oak Ridge National Laboratory	12
Patent Advisor, Washington	1
Sandia Base	2
Technical Information Branch, ORE	15
UCLA Medical Research Laboratory (Warren)	1
University of California Radiation Laboratory	6
University of Rochester	2
Western Reserve University (Friedell)	4
Sylvania Electric Products, Inc.	1

INFORMATION DIVISION
Radiation Laboratory
Univ. of California
Berkeley, California

OUTLINE

THE BERKELEY ELECTROSTATIC GENERATOR

C. M. Turner, A. J. Hudgins, F. L. Fillmore,
H. R. Jeppson, J. D. Gow

Radiation Laboratory, University of California,
Berkeley, California

....

ABSTRACT

A pressure-insulated electrostatic generator has been built to serve as an injector of 4 Mev protons into the linear accelerator. This machine is of the Wisconsin horizontal type and is housed in a pressure vessel eight feet in diameter and 27 feet long, designed for a maximum operating pressure of 200 p.s.i.g. A length of 15 feet is provided for the insulating support structure, including charging belt and accelerating tube. The air gap between the high potential electrode and tank wall is 20 inches, with a second electrode operating at one-half the total voltage subdividing this gap into two 10-inch gaps. Dependable operation at the 4 million volt level is realized with 100 p.s.i.g. nitrogen with about 5 percent by weight of Freon 12 (CCl_2F_2). Proton pulses at 4 Mev of up to one milliampere height and 500 microsecond duration at a normal repetition rate of 30 per second are now available focused into a spot diameter of 1/16" - 1/8". The pulse repetition rate can be increased to give an average proton beam current of about 50 microamperes.

THE BERKELEY ELECTROSTATIC GENERATOR

INTRODUCTION

The Berkeley electrostatic generator[1] was designed and built primarily to serve as the injector or ion source for the proton linear accelerator in this laboratory[2]. The basic requirements for linear accelerator injection are: (a) To have the injected beam current as large as possible, and (b) to have the energy above a certain minimum value which is set by considerations of drift tube design and focusing.

The drift tube array in the accelerator is 40 feet long, with a 3/4" diameter opening through which the beam passes. Neglecting the focusing forces, this sets the order of magnitude of the angular divergence which can be tolerated in the injected beam without excessive loss at 10^{-3} radians. It appeared that an electrostatic type accelerator could deliver a larger current into this acceptance angle than could a cyclotron, due to the inherent ability of an electrostatic machine to deliver a beam of small diameter, together with small and controllable angular spread.

The injection energy of 4 million volts chosen for the present machine was arrived at from the following considerations: (1) It was initially planned to use thin conducting foils to close the drift tube opening on the high energy side of each gap to secure first order focusing. This required an injection energy high enough to avoid prohibitive scattering in the early stages where the proton energy is low. (2) It was desired to have

---

[1] This article is intended to describe only the essential features of the machine. See U. C. Radiation Laboratory Report UCRL-323 for greater detail.

[2] "Berkeley Proton Linear Accelerator," (University of California, Radiation Laboratory Report No. 236, dated 11/30/48.)

a machine with a high enough operating voltage to make it a useful research instrument in itself. (3) The art of electrostatic generator design indicated that 4 million volts was a safe design figure and 4 million volts appeared adequate to fulfill the first two requirements.

BASIC DESIGN

The Wisconsin horizontal machine[3,4,5] was chosen as the basic model for the Berkeley machine because of its satisfactory performance and because its extrapolation to give dependable operation at the 4 million volt level appeared to be a safe undertaking. A horizontal machine was also preferred for linear accelerator injection, since it avoids the problems of defocusing and sensitivity of beam position to energy associated with the 90° deflection that is required with a vertical machine.

Experience with the Wisconsin machine showed that the highest voltage at which it would operate steadily and dependably on a production basis was near 3.5 million, although intermittent operation with frequent sparking at voltages as high as 4.5 million was attained in early test work. The basic limitation in the 3.5 million volt region was air gap breakdown, although in the highest voltage test work, some damaging sparks occurred along the charging belt near 4.5 million. The changes that appeared necessary in order to insure satisfactory operation at the 4 million volt level were: (1) Increasing the strength of the air gap against direct sparkover; (2) Increasing the strength of the charging belt against flashover; and

---

[3] R. G. Herb, C. M. Turner, C. M. Hudson, R. E. Warren; Phys. Rev. **58**, 579, (1940).

[4] C. M. Turner; University of Wisconsin, Ph.D. Thesis, 1943.

[5] R. G. Herb, C. M. Turner, A. O. Hanson; to be published.

(3) Increasing greatly the mechanical strength of the insulating support structure to accommodate the considerably greater weight of equipment involved. Figure 1 illustrates the general features of the Berkeley machine, and the photograph of Figures 2, 3, 4, and 5 show the general appearance of the machine.

The air gap was strengthened by the following changes: (1) The diameter of the pressure vessel was increased from 5-1/2 feet to 8 feet, and a simultaneous increase in the diameter of the high voltage electrode from 34 inches to 56 inches gave an air gap length of 20 inches compared to 15 inches in the Wisconsin machine. (2) The maximum operating pressure of the tank was increased from 100 p.s.i.g. to 200 p.s.i.g. (3) Provision was made, if the necessity arose, to use a total of three equipotential shells (in addition to the high potential electrode) to subdivide the air gap, although it was felt that one would be sufficient and only one is in use.

The danger of sparking along the charging belt was reduced somewhat by the following two provisions. (1) Three equally-spaced sheet metal partitions or diaphragms, D_1, D_2, and D_3, subdivide the insulating column into four equal lengths. The belt runs through rounded slots in these diaphragms so that electrically it is effectively divided into four equal short lengths. This helps to maintain the proper distribution of potential over the length of the belt and thereby reduces the likelihood of failure due to effects which are dependent on belt length. (2) Provision was made for a complete system of belt shields as developed by Trump and Van de Graaff[6], although experience has shown that they are unnecessary for satisfactory operation at 4 million volts.

---

[6] Phys. Rev. 55, 1160 (1939).

The strength of the tripod support structure used in the Wisconsin machine was marginal[5]. Since we had the problem of supporting a considerably greater weight of equipment in the high potential electrode, as well as a greater weight of equipotential shells and vacuum tubes, it was imperative that the support structure be made much stronger. This was accomplished by the following changes, although the same material[7] was used: (1) The number of tubes was increased from 3 to 6 to form what we may call a hexapod. (2) The size of the tubes was increased from 3-3/4 inches outside diameter by 3/8 inch wall in the Wisconsin machine to 5 inches outside diameter by 13/32 inch wall. (3) The tubes are arranged in groups of 3 above and below, at 30° angular separation (Figure 1). An increase of vertical rigidity is gained with this method of grouping without sacrificing too much lateral rigidity and at the same time the accessibility of vacuum tubes and belt from the sides is greatly increased. (4) The base diameter of the hexapod was increased over that of the tripod to give an included angle at the apex of 14-1/4°, while the corresponding angle for the tripod is 9.5°. (5) The apex of the hexapod is made considerably more rigid than that of the tripod. The tubes are anchored rigidly to the large dural casting, C, at the front of the high potential electrode, while the middle tubes above and below are effectively continued almost to the point of intersection by means of steel-lined Textolite tubes inside the high voltage terminal. (6) While it was not initially planned to do so, it was later found desirable to install diagonal braces from the ground end to the midpoint of the machine. These braces contribute greatly to the rigidity and straightness of the support structure.

---

[7] Grade 1824 Textolite (Herkolite) manufactured by General Electric Company.

GENERAL DISCUSSION

The main body of the tank is mounted on a carriage and rolls back on a track to give easy access to the generator mechanism. The process of disassembly consists of: (a) Removal of the bolts in the main flange: (b) Releasing the intermediate shell onto a special cradle placed in the tank; (c) Removal of the high voltage electrode with an overhead traveling crane. The whole procedure of disassembly can be accomplished in about 3/4 hour, but reassembly takes about twice as long, due to the careful cleaning that is required.

The hexapod support structure is anchored to the rigid steel framework, F, which in turn is attached to the tank at three points where provision for adjustment permits accurate centering of the hexapod within the tank. The diaphragms, in addition to breaking the machine up into shorter lengths electrically, serve to hold the textolite tubes at the correct separation at these intermediate positions and provide support for the vacuum tube (or tubes), and belt guide bars. The stiffness of the hexapod, including the braces to the midpoint, is such that 100 pounds gives a deflection of about .08 inches. To prevent the structure from overturning due to its overhang when the tank is withdrawn, the short end of the tank is supported by a framework which extends well beyond the center of gravity.

In order to provide adequate space for mounting of equipment necessary for operation of a high current ion source, a relatively large (6 feet long by 56 inches diameter) high voltage terminal is used. The extensions into the high voltage terminal of the middle textolite tubes top and bottom provide a convenient means of supporting and insulating the ion source equipment. The intermediate electrode divides the overall 20-inch air gap equally into 10 inch gaps, and it is supported entirely by attachment to the hexapod at the open end of the shell, thus avoiding the complications associated with the use of an auxiliary support for the outer end.

The charging belt[8] is 20 inches wide and is driven at a speed of 90 feet per second. It is kept properly centered on the pulleys (6 inches in diameter by 22 inches long) by a 0.9° taper extending over a distance of 4 inches from each end, together with a mechanism by means of which the rear pulley can be tilted. A pneumatic cylinder (Figure 1) keeps the belt under a constant tension of about 800 pounds to take up stretch, eliminate sag, and avoid pulley slippage in transmitting power to the generator inside the high voltage terminal. Zircon[9] guide rods keep the belt accurately positioned where it passes through the diaphragms. The charging system consists of a spray comb with needles spaced 1/4 inch apart and about 1/4 inch from the belt connected to a 0-60 kv voltage doubler. Negative charge can be applied to the outgoing belt run by means of a standard charge doubling system in the high voltage terminal.

Provision is made in the design for two identical vacuum tubes side by side beneath the belt (Figure 1), with the second tube being originally planned for differential pumping on the ion source. This plan was later abandoned in favor of the differential pumping system described later in connection with the ion source, so only one tube is being used in the machine at the present time. The accelerating tube design is

---

[8] Four-ply, endless woven cotton, manufactured by Arthur S. Brown Co., Tilton, N.H.

[9] High dielectric strength ceramic containing zirconium oxide.

practically identical to that used in the Wisconsin machine[3,4,5] except that 1/32 inch gaskets are being used instead of .01 inch. The tube is assembled in four subsections, each consisting of 17 porcelain sections and spinnings, which join at the diaphragms. A jack screw and gimbal ring assembly at the ground end pushes the assembled tube against springs at the high voltage end with a force of about 5,000 pounds to hold it together and maintain the vacuum seals.

Hoops made of 3/4 inch diameter dural tubing spaced 1-1/4 inch apart enclose the hexapod structure and negative point-plate corona gaps give the required uniform gradient of potential along them. In the plane of each hoop, shield rings made of 1/2 inch dural rod are situated both inside and outside each textolite tube (Figure 6) to insure a uniform gradient along them.

The beam from the Van de Graaff generator must be injected into the linear accelerator accurately along the axis of the drift tube assembly to minimize losses. Proper alignment is secured by means of the steering magnets shown in Figure 1 which are about 3 feet apart and which are constructed so that each magnet can deflect the beam in either the horizontal or vertical plane. This permits correction for both displacement and lack of parallelism between the axes of the two machines.

In order to minimize the danger of damage to the machine by fire, nitrogen gas is used with about 5% by weight of Freon 12 added to increase the breakdown voltage. Nitrogen gas is supplied from a high pressure storage system[10] which stores 20,000 ft.^{3} of nitrogen (NTP) at 2,000

---

[10] Installed and kept charged by the local Linde Air Products Company.

p.s.i.g. which is sufficient to fill the Van de Graaff tank about three times. Freon is introduced into the tank by means of a standard refrigeration compressor. The gas charge is vented to the atmosphere when it is necessary to open the tank. Moisture and oxygen present in the atmosphere are removed when the tank is closed after servicing by evacuation for a few hours by means of a 750 c.f.m. Beach-Russ pump. Since the gas admitted to the tank is extremely dry, further drying equipment has been found unnecessary.

ION SOURCE SYSTEM

Basic Problem

An instantaneous RF power input of 2.5 megawatts is necessary to operate the linear accelerator resonant cavity at the required voltage level. This means that pulse techniques must be employed to keep the average power level at a value such that the cavity walls can be kept cool and such that the power costs are not prohibitive. A pulse length of 300 microseconds and a pulse repetition rate of 15 per second giving a duty cycle of about 1/200 have been employed until recently when the maximum available duty cycle was increased to about 1/50 by doubling both the pulse length and repetition rate. During each pulse, stable acceleration takes place over only about 10°/o of each RF cycle, and the focusing grids which are now used in the drift tubes in place of the originally planned foils intercept about 50°/o of the beam. These factors combine to give an efficiency for utilization of a steady injected beam of only about 10^{-3}. Since the instantaneous current that can be handled by the linear accelerator without excessive loading is of the order of 10 milliamperes, the beam available from the injector will clearly be the limiting factor on the output of the machine. This makes it not only desirable but essential to get as large beams as possible from the injector.

The production of high current, high energy ion beams with a Van de Graaff electrostatic generator presents first the problem of generating, by means of a suitable ion source, an ion current of the desired magnitude; and second, the problem of acceleration of this ion beam to high energy through a suitable accelerating tube. Inasmuch as the basic requirements for a satisfactory high current ion source are determined almost entirely by processes occurring within the accelerating tube, the latter will be reviewed first.

Accelerating Tube Processes

Difficulties are encountered when an attempt is made to accelerate large ion beams through the moderately long accelerating tube required for high voltage acceleration due to the presence of residual gas in the tube. Ions traversing the tube make ionizing collisions with the molecules of residual gas, creating further ions, and free electrons which in turn lead to the following additional processes. (1) Positive ions formed in the tube create further positive ions. (2) Secondary positive ions can collide with the tube electrodes causing emission of secondary electrons, as well as outgassing which contributes further to the pressure of residual gas. (3) The electrons liberated in the ionization process and possibly by secondary emission from the electrodes are accelerated toward the high voltage end of the tube and can in principle multiply further in transit by striking the tube electrodes and by producing ions in the gas. They will in general acquire sufficient energy before striking either the tube electrodes or the high voltage end of the tube to produce penetrating X-radiation for which adequate shielding must be provided.

A limit to the current-carrying capacity of a tube can in principle be set by either of the two following mechanisms. (1) Secondary ionization occurring inside the tube can increase the ion loading to the point where it exceeds the charging capacity of the system which maintains the voltage. (2) Ion and electron drain to the accelerating electrodes can distort the distribution of potential along the tube to the point where breakdown is initiated. The relative importance of these two mechanisms depends entirely on what happens to the secondary ions and electrons formed in the tube. If most of them traverse the full length of the tube and arrive at the ends without striking the electrodes, we may expect the first process to be the more important; but if a substantial fraction of them reach the electrodes, we can expect trouble when this current becomes comparable to that flowing along the bleeder system which maintains the uniform distribution of potential along the machine.

Irrespective of which of these two processes is the more important, it is apparent that the successful handling of large beams is dependent on minimizing the secondary ionization. The dependence of secondary ionization in the tube on residual gas pressure can be expected to be exponential since the multiplication process is qualitatively similar to that of electron avalanching in a gas. If N_o is the number of ions per second entering the tube from the ion source, N_x is the number crossing a plane at distance x down the tube, and λ is the average free path between ionizing collisions, then the following relation should apply:

$$(1) \qquad N_x = N_o \, e^{\frac{x}{\lambda}} .$$

For x = L, where L is the length of the tube,

$$(2) \qquad N_L = N_o \, e^{\frac{L}{\lambda}}$$

where N_L is the number of positive ions per second arriving at the ground end of the tube, assuming no loss to the electrodes in transit. The back electron current should be essentially equal to N_L also (assuming $N_L \gg N_o$), since each ionization process liberates equal positive and negative charges. For a given voltage, the X-ray background from the machine should be directly proportional to the back electron current and hence it provides a means of checking equation (2). X-ray measurements show a linear dependence on primary beam current and an exponential dependence on pressure as predicted.

Differential Pumping

Since ionization in the tube is exponentially dependent on residual gas pressure, it is clearly of primary importance to minimize this pressure. Positive ions are generated in an ion source by ionization of a suitable gas, and it is some of this gas which enters the accelerating tube, along with the ions, that causes trouble. The quantity of gas entering per microampere of ion beam depends on the efficiency for conversion of gas to ions, but in the best sources, this is only a few percent. The residual pressure in the accelerating tube due to this flow of gas varies inversely as the pumping speed of the tube, so it is desirable to use a tube with as high a pumping speed as is practicable. However, the best solution to the gas problem appears to be that of differential pumping on the ion source. By suitably arranging the electrodes of the ion source, the ion beam can be made to pass through a small opening which offers relatively high impedance to the flow of gas prior to its entrance into the accelerating tube. If S_1 is the speed for flow of gas through this opening and a pumping system with speed S_2 is connected to the space ahead of this opening, then the fraction of gas leaving the ion source that gets into the accelerating tube is S_1/S_2. This arrangement is known as differential pumping, and it is possible to make S_1/S_2 of the order of a few percent so a large reduction in the amount of gas entering the tube can be attained in this manner.

Differential pumping can in principle be accomplished by a variety of methods,[11] each of which has certain advantages and disadvantages. The most common method is that of a pumping tube similar in construction to the ion accelerating tube serving as a conduit for gas from the ion source to pumps at the ground end. We are using an alternative method described later in which a complete pumping system is operated inside the high voltage terminal.

Ion Source Pulsing

Since the linear accelerator is pulsed, the beam from the injector can likewise be pulsed in synchronism, and it turns out to be advantageous to do so for the following reasons. (1) For a given instantaneous injection current, pulsing cuts the average ion load on the machine by a factor equal to the duty cycle (about 100). This permits acceleration of beams of the order of a milliampere which would far exceed the capacity of the machine on a steady basis. (2) Experience with both pulsed and steady beams has indicated that it is the average current through an accelerating tube that sets the limit on what it will handle rather than the instantaneous current. This means that a tube limited to 5 microamperes in a steady beam will give satisfactory performance with a 500 microampere pulsed beam at a 1% duty cycle. For these reasons, most of our effort has gone into development of pulsed ion sources.

It should be noted that the capacity between accelerating tube electrodes is sufficient to provide a stabilizing effect for pulsed operation,

---

[11] See UCRL-323.

since the stored charge opposes any change of the potential distribution by charges collected on the electrodes.

PIG Ion Source

A Zinn type ion source was employed until recently when it was replaced by another source using a PIG (Phillips Ion Gauge) type discharge, which has proved to be better in every respect. This source uses no filament, operates at a hydrogen pressure about one-tenth that required for the Zinn arc, and delivers into a more sharply focused beam greater currents than were available from the Zinn source. Figure 7 illustrates the essential features of this source. The two soft aluminum cathodes C_1 and C_2 and stainless steel anode A are situated in a uniform axial magnetic field generated by coil S. The volume defined axially by the cathodes and radially by the hole in the anode is a region in which electrons are trapped. They cannot escape axially because they are in a potential trough, and they can escape radially across the magnetic field only after making many collisions with gas molecules. Upon application of the anode voltage, the discharge is initiated by a free electron from some source and it is built up and maintained by secondary electron emission from the cathodes due to positive ion bombardment. A much larger percentage of the power in a discharge of this type goes into creation of ions than in an ordinary discharge where each electron traverses the gas only once. A small hole in the center of one of the cathodes permits those ions to emerge that would otherwise have struck it. The presently used source is designed only for pulsed operation, although adequate cooling of the cathodes would permit steady operation if desired. Normal operating parameters for this source are about 20 microns hydrogen pressure, 1-2 amperes pulsed arc current and 800 gauss magnetic field.

The normal running voltage of the arc is about 300 volts, but varies some depending on the condition of the cathodes. In order to permit the arc to seek its own running voltage, the arc current is supplied by a high impedance or essentially constant current source. It was found that maximum beam currents were obtained using a 90° cone and probe geometry.

Figure 8 shows a schematic of the complete ion source system. Ions produced in the discharge are accelerated and focused into a small diameter beam by the probe and lenses L_1 and L_2. The focus of the beam at the ground end of the accelerating tube depends principally on the voltages across L_1 and L_2, as well as the voltages across the first two gaps of the accelerating tube which can be varied by means of adjustable corona gaps. The probe voltage has only a small effect on beam focus. With the machine operating at 4 million volts, the best beam and focus are obtainable with a probe voltage of about 10 kilovolts negative, L_1 at 2 kilovolts negative, and L_2 at 50 kilovolts negative. The first two accelerating tube gaps are estimated to have about 1/2 the normal voltage of 60 kilovolts across them. If the voltage of the machine is reduced below 4 million volts, a focus can be maintained principally by varying the voltages across L_1 and L_2.

Differential pumping is accomplished by means of a 4" diameter, 3 stage gas cooled diffusion pump which has a speed for hydrogen of about 100 liters/second. The speed for escape of hydrogen into the accelerating tube is about 30 liters/second, which means that about 75°/o of the gas that would otherwise enter the accelerating tube is removed by the pump. Cooling gas for the pump is forced up through the Textolite tubes by a centrifugal blower, from a water cooled heat exchanger at the ground end.(Figure 1). The diffusion pump is backed by a Cenco hypervac mechanical pump, which together with its driving motor is enclosed inside a small steel pressure vessel to protect it from the high pressure atmosphere in the main tank. A pressure of one atmosphere of hydrogen is maintained inside the hypervac tank to provide a closed circulating system which operates as follows. Hydrogen from the tank passes through the oil vapor filter and palladium leak into the arc chamber. The hydrogen removed by the pumping system is discharged back into the tank. With a .03"(No. 70 drill) hole for escape of ions, the gas flow is about 20 cc/hour at NTP.

The voltages required for the probe and the two accelerating and focusing gaps are furnished by separate and independently adjustable power supplies.

Pulsing is accomplished by applying a positive signal to the grid of a series control tube (Figure 8). The timing signal which starts the oscillators on the linear accelerator resonant cavity also triggers a pulsed light source which projects a beam of light through one of the textolite support tubes to a photomultiplier tube in the high voltage terminal. The signal from the photomultiplier and its amplifier operates a multivibrator which drives the grid of the series control tube positive for the desired length of time. The time delay in starting of the arc (about 10 microseconds), plus the transit time of protons through the accelerating tube is small compared to the time required for buildup of the accelerator cavity to full voltage.

Ion Source and Accelerating Tube Performance

The best performance realizable with the Zinn source installation was about 50-100 microamperes of protons in a pulsed beam and 5-10 microamperes in a steady beam.

With the PIG source, proton pulses at 4 Mev of 1 milliampere have been realized dependably, focused into a spot of 1/16" - 1/8" diameter. While the PIG source cannot be run steadily, the pulse repetition rate can be varied and it has on occasion been increased to the point where an average proton current of 50 microamperes has been attained. The relative yield of protons, diatomic and triatomic ions from the source, is approximately 2:2:1. This means that total beam pulses of 2.5 milliamperes have been accelerated and average currents of about 125 microamperes.

Our experience with the acceleration of large pulsed beams has led to the following conclusions and points of interest regarding accelerating tube behavior.

(1) Measurements of the total ion loading on the accelerating tube (made by noting the difference in charging current required to hold a given voltage with and without an ion beam), and the distribution of bleeder current along the potential distributing corona system with and without a beam, have shown that total ion loadings many times greater than the bleeder drain can be tolerated. This indicates that only a small fraction of the ions and electrons formed in the tube get to the electrodes. Estimates of momentum transfer and scattering in the process of ion formation[12] indicate that it is unlikely that either an ion or a free electron formed near the axis of the tube will acquire sufficient radial velocity to carry it out to the electrodes before it reaches the end of the tube.

(2) Only small changes are noted on the meters along the bleeder system with and without a beam even when the total ion load is several times the bleeder drain. This shows that any secondary electron multiplication occurring on the

---

[12] See UCRL-323.

electrodes is small.

(3) The fact that it is possible to accelerate large pulses through a long accelerating tube indicates that ionization of the gas by electrons traveling up the tube is negligible compared to that of the positive ion beam, as is to be expected on the basis of relative velocities. Comparable cross sections for ionization by the two methods would provide a mechanism for a Geiger type discharge which would occur in a time of the order of the positive ion transit time, which is short compared to our pulse length of 500 microseconds.

(4) X-rays from back electron current vary linearly with ion beam current, and exponentially with residual gas pressure. Measurements with an X-ray telescope show that most of the X-rays originate at the ion source.

(5). The successful acceleration of large ion beams to high energy appears to be materially aided by injecting into the tube a well-collimated beam of small diameter which is produced entirely by power supplies within the high voltage terminal. Focusing potentials obtained from taps on the electrostatic system are too easily altered by ion and electron drains.

The principal difficulty encountered with the use of a gas-cooled oil diffusion pump in the high voltage terminal has been that of keeping the vapor pressure of oil sufficiently low. Excessive oil vapor in the differential pumping region causes scattering of the ion beam and any oil vapor which gets into the accelerating tube aggravates the problem of ion multiplication. Silicone oil (DC-703) which was originally highly recommended for this application was later found to be far inferior to ordinary Litton oil. The use of an activated charcoal trap and ice water cooling of the heat exchanger has aided materially in reducing the oil vapor. The installation of a freon refrigerated baffle in the manifold between pump and ion source is planned for the near future. The factor of 10 reduction in the hydrogen gas flow gained by the installation of the PIG ion source reopens the question of the best method of differential pumping. At the present time it appears that a pumping tube provides the best ultimate solution, unless some unforeseen difficulties are encountered with the operation of such tubes in other installations now being built.

The overall ion optical system of the ion source and accelerating tube must be such as to permit focusing the beam at the ground end of the tube over the range of voltage for which the machine is to be used. For the sake of simplicity it was desired to avoid the use of specially shaped focusing electrodes at the beginning of the accelerating tube as is customarily done. With the Zinn source installation, the geometry was not quite correct to satisfy simultaneously the requirements of getting maximum beam through the differential pumping baffle and getting a good focus at the ground end. This difficulty was corrected on the PIG installation so it is now possible to get both good beam focus and maximum beam over the full useful voltage range of the machine.

Power and Controls

Electrical power to energize the ion source circuits is supplied by a permanent magnet field, 400 cycle generator[13] having a capacity of 5 kilowatts at 115 volts. This machine uses no slip rings or brushes and has given reasonably trouble-free performance since its installation about 9 months ago. Prior to this, we used a pair of 400 cycle generators with a DC component for field excitation with which a prohibitive amount of trouble was encountered from rapid brush and commutator wear.

---

[13] Manufactured by Kober Electric Co., Arlington, Virginia.

Controls of two types are required for operation of the ion source equipment: (1) On-off controls, and (2) Mechanically driven devices, consisting mostly of variacs. Relay circuits are used to operate on-off control functions, while small 28 volt DC actuator motors are used for all mechanically driven devices. All control circuits are connected into a 21-position multideck selector switch in such a way that each position of the switch permits operation of one control function (Figure 9). This switch is itself actuator operated with its position being shown by a selsyn driven indicator visible to the operator through a viewing port at the ground end of the tank. Communication between the ground end and high voltage terminal is accomplished by means of a loop of nylon fishline which operates a 4-position switch inside the high voltage terminal. Two points on this switch give forward or reverse rotation to the 21-position selector switch which permits the selection of the desired control function, while the other two points activate the selected control to give on or off, increase or decrease, as the case may be.

In order to facilitate operation of the ion source and associated apparatus, 14 meters are provided in the high voltage terminal. These are readily visible through two viewing ports which are equipped with 6 power monoculars.

General Performance

Dependable operation at the 4 million volt level required for linear accelerator injection is readily attained with 100 p.s.i.g. of nitrogen to which is added about 30 pounds by weight of freon which gives a concentration of about 5% by weight. Due to the excessive drain along the corona systems that occurs in a pure nitrogen atmosphere, it is impossible to build up appreciable voltage without the addition of some freon. This makes it impossible to get a curve of sparking voltage vs. pressure of pure nitrogen. It is possible, however, to get a curve of sparking voltage vs. pressure of N_2 + k °/o freon where k is a constant (about 5 °/o) by taking the curve as gas is released from the tank after the normal amount of freon has been added to 100 p.s.i.g. nitrogen.

One intermediate electrode for subdivision of the air gap has been found adequate for 4 million volt operation. Experience has shown that the belt shield system is not needed for satisfactory operation at 4 million volts if the belt charging current is kept below 400-500 microamperes. Sparks along the belt occurred on several occasions during the early life of the machine when this value of charging current was exceeded.

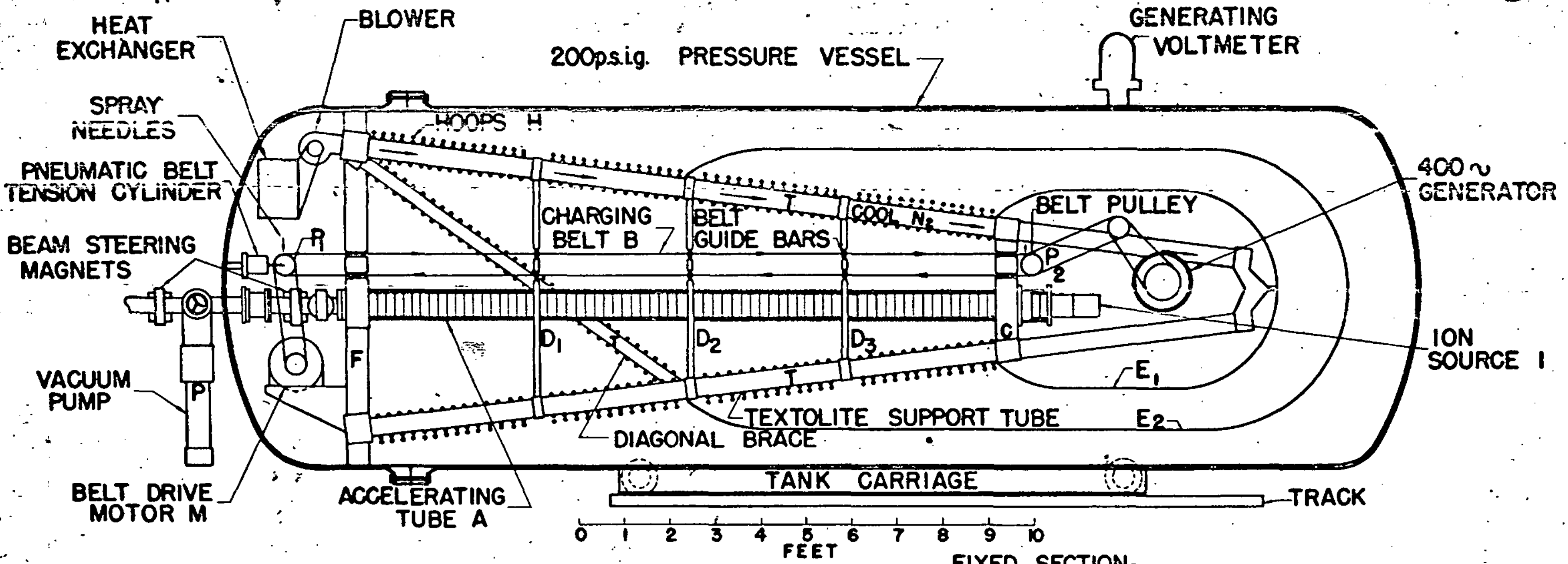
The ultimate voltage limit of the machine has not been explored with any degree of thoroughness as yet, primarily because adequate voltage for the purpose for which the machine was designed is attainable at only 100 p.s.i.g. There is some difficulty at higher pressures with overloading of the belt drive motor and instability of the spray system, but these can be eliminated if desired. Eventual reconstruction of the accelerating tube using vinyl seal assembly is contemplated in order: (a) to obtain greater pumping speed, (b) to avoid the large amount of rubber at present required for gaskets, and (c) to get accelerating electrodes made to closer tolerances than our present ones.

The overall operational reliability of the machine was initially poor, due largely to the greater than normal amount of equipment in the high voltage terminal, but it has improved steadily until at present it averages 80-90 °/o on a 16 hour day operating schedule. No difficulty has been encountered from sparks damaging the nylon control line. No undue deterioration of V belts occurs in the oxygen-free atmosphere. Charging belt life now averages about 1,000 hours.

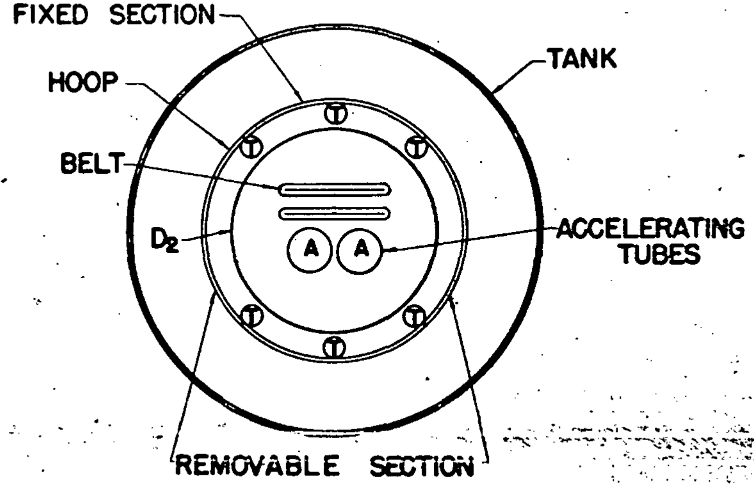
ACKNOWLEDGMENTS

We wish to express our indebtedness to Professor L. W. Alvarez for continued advice and encouragement during the course of this work; to members of the Engineering Department, particularly Mr. Hayden Gordon, Mr. A. W. Chesterman and Mr. Edward Day for contributions to the mechanical design; to Dr. R. G. Herb for valuable advice and assistance during initial testing and debugging of the machine; to Mr. Joseph Ballam and Mr. Bruce Cork for extensive assistance; to Mr. John Foster for aid in the development of the PIG ion source; to Mr. Saul Lissauer, now in charge of operations, and to Mr. Robert Clack, former operator, and to Mr. Albert Bartlett and Mr. Wendell Olson, present principal operators of the machine; to the many service groups of the laboratory whose facilities and assistance have been extensively used, particularly the machine shops, the electronics maintenance and installation groups and the inspection and accelerator technician groups; and finally to Miss Velma Turner for valuable secretarial assistance. This work was financed by the Atomic Energy Commission under Contract W-7405-eng-48.

vt



COMPARATIVE DATA ON UNIVERSITY OF WISCONSIN & BERKELEY MACHINES	WISCONSIN	BERKELEY
TANK DIAMETER	5 1/2 ft.	8 ft.
TANK LENGTH	21 ft.	27 ft.
MAXIMUM PRESSURE	100 p.s.i.g.	200 p.s.i.g.
AIR GAP	15 in.	20 in.
ACCELERATING TUBE LENGTH	159 in.	176 in
NO. SUPPORT TUBES	3	6
NO. SHELLS	3	2 or 4



CROSS SECTIONAL VIEW AT D_2

FIG. 1

GENERAL SCHEMATIC OF BERKELEY VAN DE GRAAFF GENERATOR

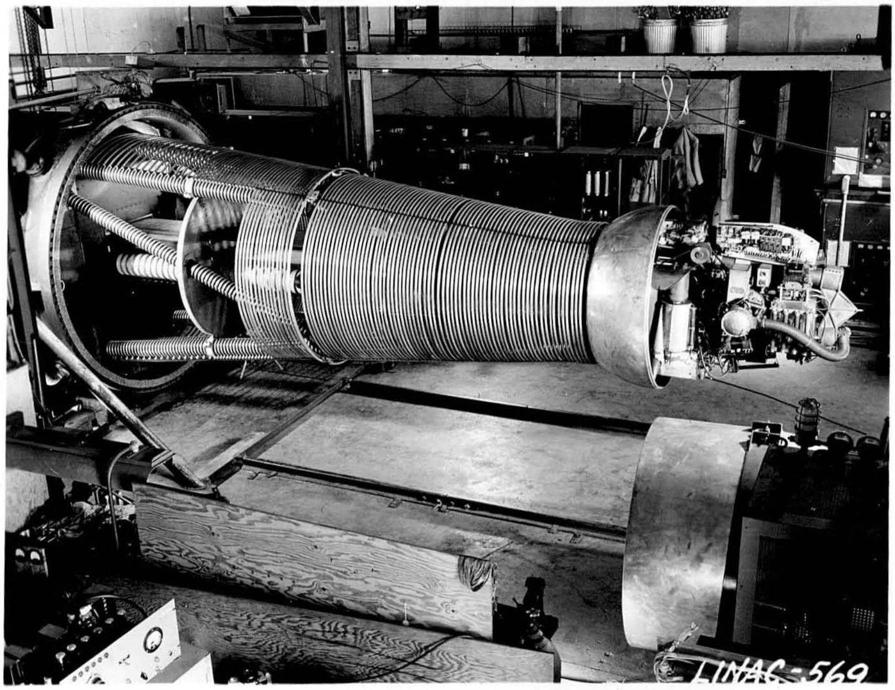


Fig. 2

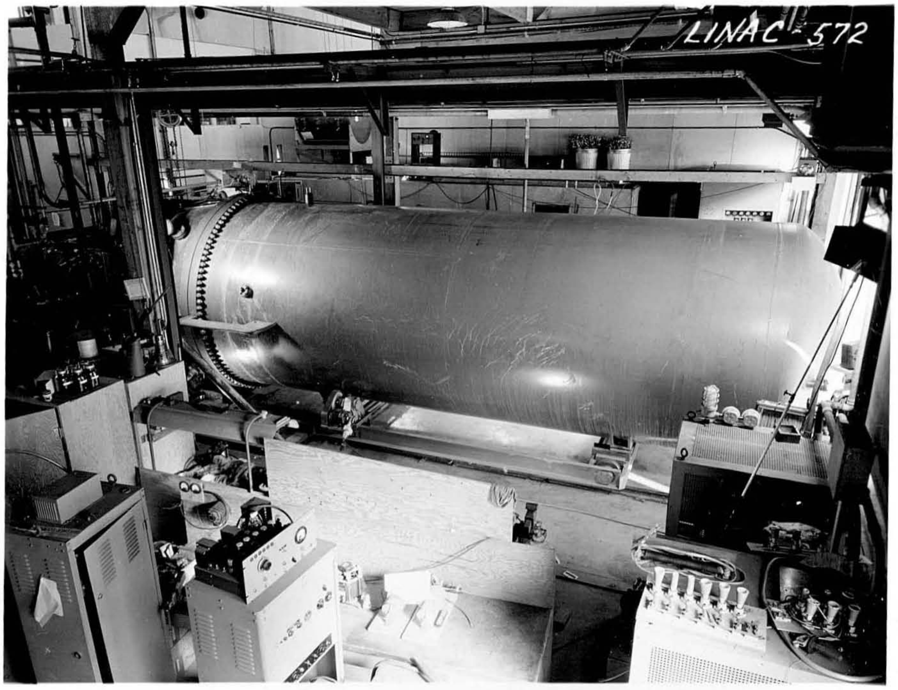


Fig. 5

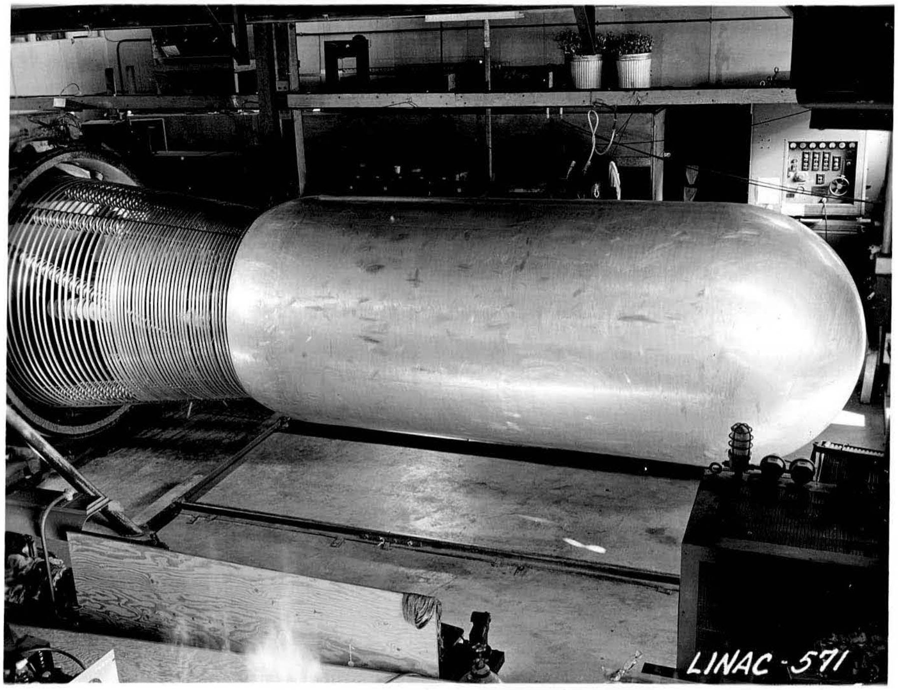


Fig. 4

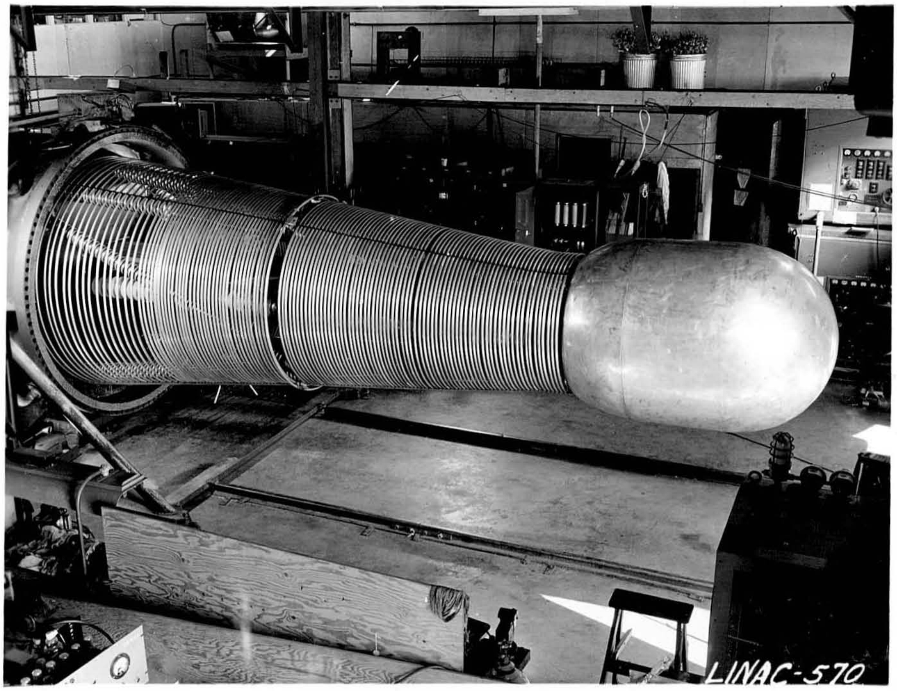


Fig. 3

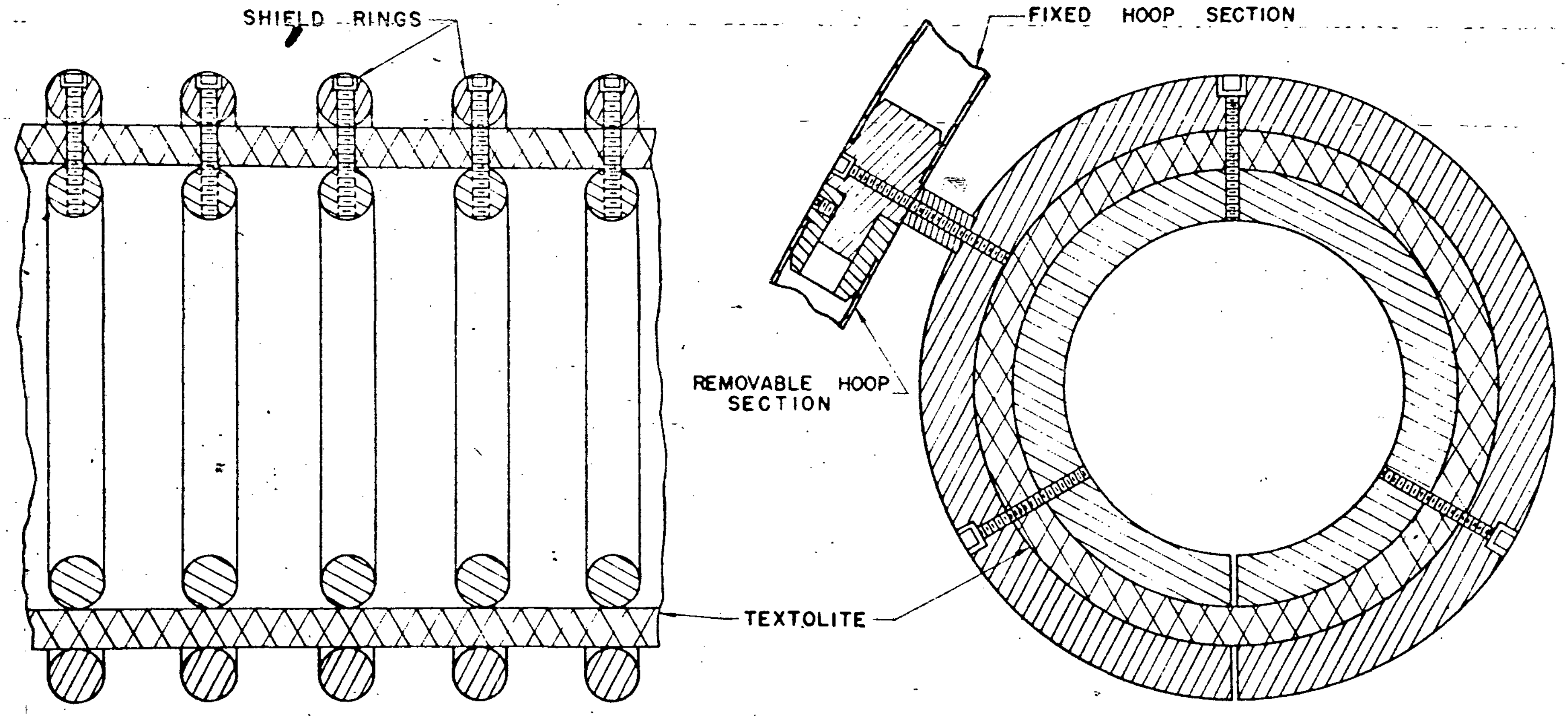
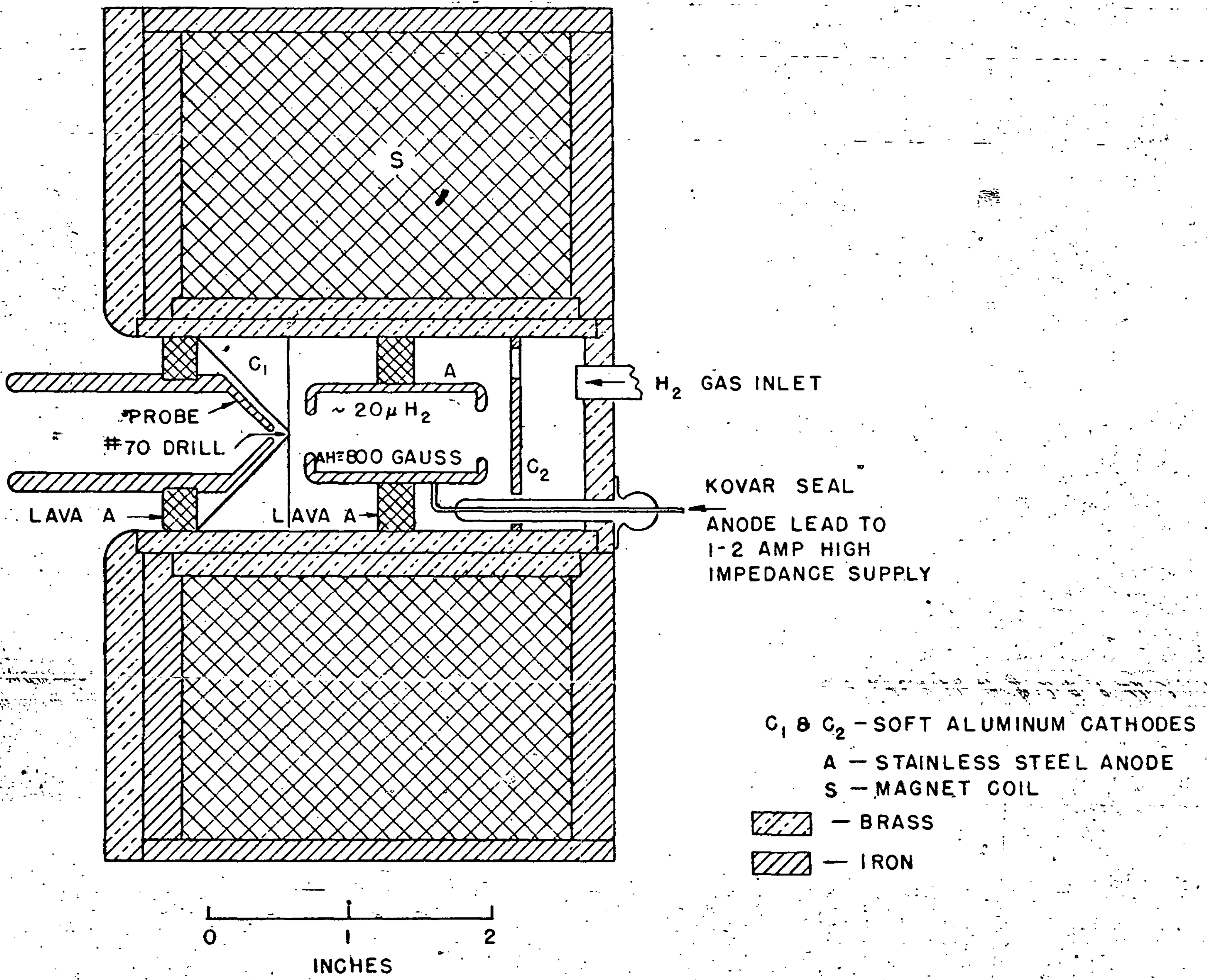


FIG 6

SHIELD RING SYSTEM FOR TEXTOLITE TUBES

OZ 484


S
C_1
A
~ 20μ H_2
ΔH=800 GAUSS
PROBE
#70 DRILL
LAVA A
LAVA A
C_2
H_2 GAS INLET
KOVAR SEAL
ANODE LEAD TO 1-2 AMP HIGH IMPEDANCE SUPPLY
C_1 & C_2 — SOFT ALUMINUM CATHODES
A — STAINLESS STEEL ANODE
S — MAGNET COIL
▨ — BRASS
▨ — IRON
0
1
2
INCHES

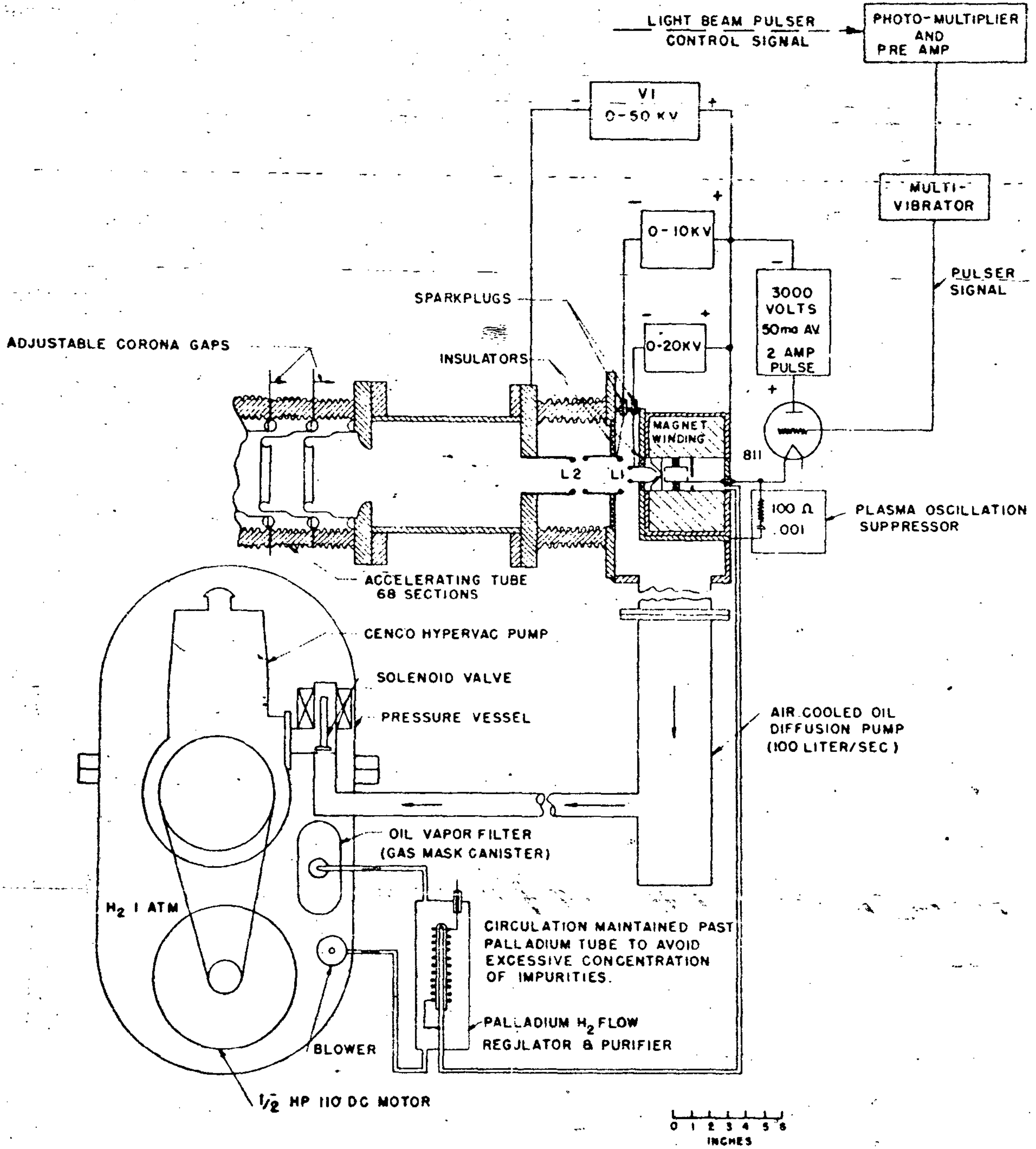
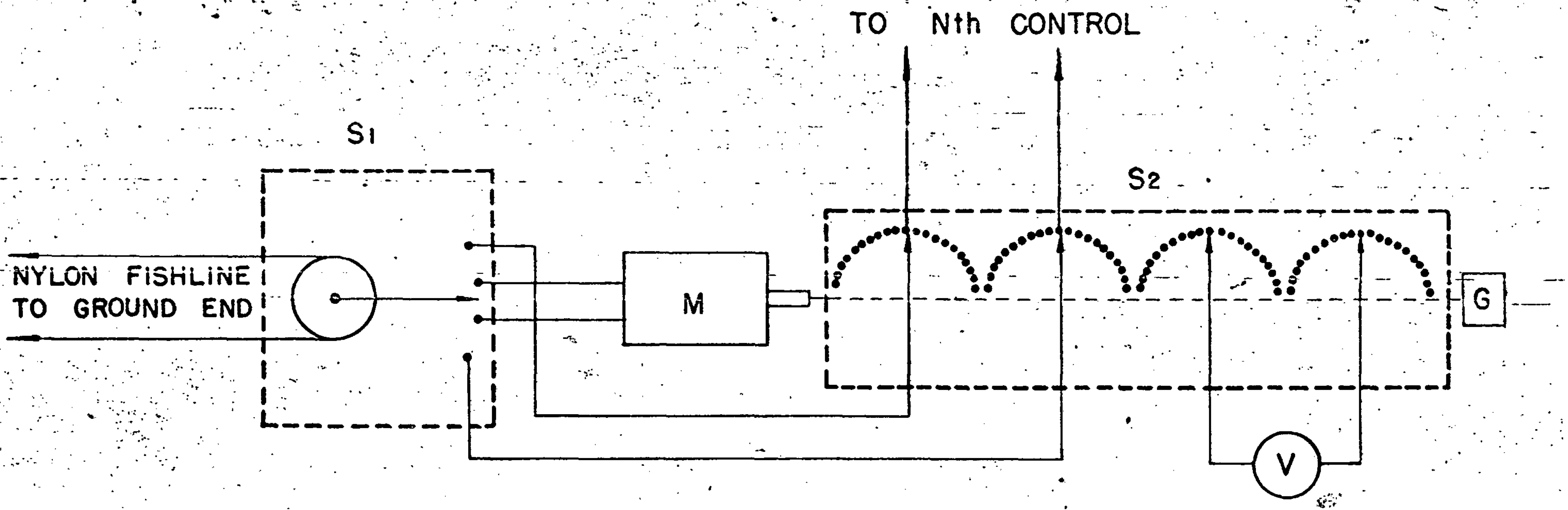


FIG. 8

GENERAL ION SOURCE SCHEMATIC

07 483



S1- SINGLE POLE, 4 POSITION SWITCH

S2- 4 DECK - 21 POSITION SWITCH

M - POSITIONING MOTOR FOR S2

V - GENERAL PURPOSE VOLTMETER

G - SELYSN GENERATOR WHICH DRIVES POSITION INDICATOR

FIG. 9

CONTROL SYSTEM SCHEMATIC