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Citation: Review of Scientific Instruments **38**, 467 (1967); doi: 10.1063/1.1720740
View online: http://dx.doi.org/10.1063/1.1720740
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/38/4?ver=pdfcov
Published by the AIP Publishing

THE
REVIEW OF SCIENTIFIC
INSTRUMENTS

VOLUME 38, NUMBER 4 APRIL 1967

Technology of Intense dc Ion Beams*

O. B. MORGAN, G. G. KELLEY, AND R. C. DAVIS
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831
(Received 6 October 1966; and in final form, 12 December 1966)

The present status of a program directed toward the improvement of ion sources and the technology of intense dc ion beams is described. The work is in the energy range of from 20–600 keV at currents of up to 1 A. Several factors have differentiated the approach from that existing in some other areas of ion beam research. There are severe cooling problems in the ion source and in beam targets. Grids cannot be used in the electrode system, and many of the techniques which have been used to study detailed emittance shapes are very difficult to utilize because of these thermal problems. On the other hand, it is possible to accumulate electrons in these dc beams to eliminate the dispersive effect of space charge. Pulsed beams with on-times of less than a few hundred microseconds ordinarily are completely unneutralized. Ion sources are described which are especially suited to proton production and to molecular ion production at source arc currents of up to 50 A. Single gap accelerating and focusing arrangements are described. A special configuration prevents electron trapping and subsequent breakdown in the combined electric and magnetic fields.

INTRODUCTION

THIS paper gives the present status of a program directed toward the improvement of ion sources and the technology of intense dc ion beam production. The work is in the energy range of from 20 to 600 keV at currents up to 1 A. It has been motivated by the high energy injection approach to controlled nuclear fusion research. Because these fusion experiments have simple phase-space acceptance characteristics for the ion beams, the approach has been different from that existing in some other areas of ion beam research. The usual criterion is to obtain as much beam as possible through a simple arrangement of limiting apertures. The aperture sizes are dictated by such parameters as vacuum and the ability to shield the beam from transverse magnetic fields. Other conditions also have influenced our approach. It is possible to accumulate electrons in these dc beams to eliminate the dispersive effect of space charge. On the other hand, pulsed beams with on-times of less than a few hundred microseconds ordinarily are completely unneutralized. The problem of power dissipation with intense dc beams calls for special features in the design of the ion source and accelerator. In addition, many of the techniques used for the study of detailed emittance shapes of pulsed beams are very difficult to utilize because of these thermal problems. There are areas of our work, however, that are of interest in pulsed beam applications, and in addition, the applications of intense dc beams are becoming more numerous.

ION SOURCES

The ion sources available at the beginning of this program which had most of the characteristics thought to be desirable could not be operated continuously at high current because of power dissipation problems. The modifications which have been made to eliminate this problem are described in the following sections of this paper. Work concerning optimization of extraction geometry, ion species production, prevention of current drain and discharges produced by electron trapping regions, external design for high gradient accelerator columns to eliminate voltage breakdown in air, and power dissipation in the beam system are discussed in later sections.

The plasma necessary for the extraction of 100 mA to 1 A ion beams can be obtained from any of several types of ion sources: the calutron,[1] Penning discharge (PIG),[2] Lamb–Lofgren,[3] radio-frequency (R.F.),[4] and duoplasma-

* Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

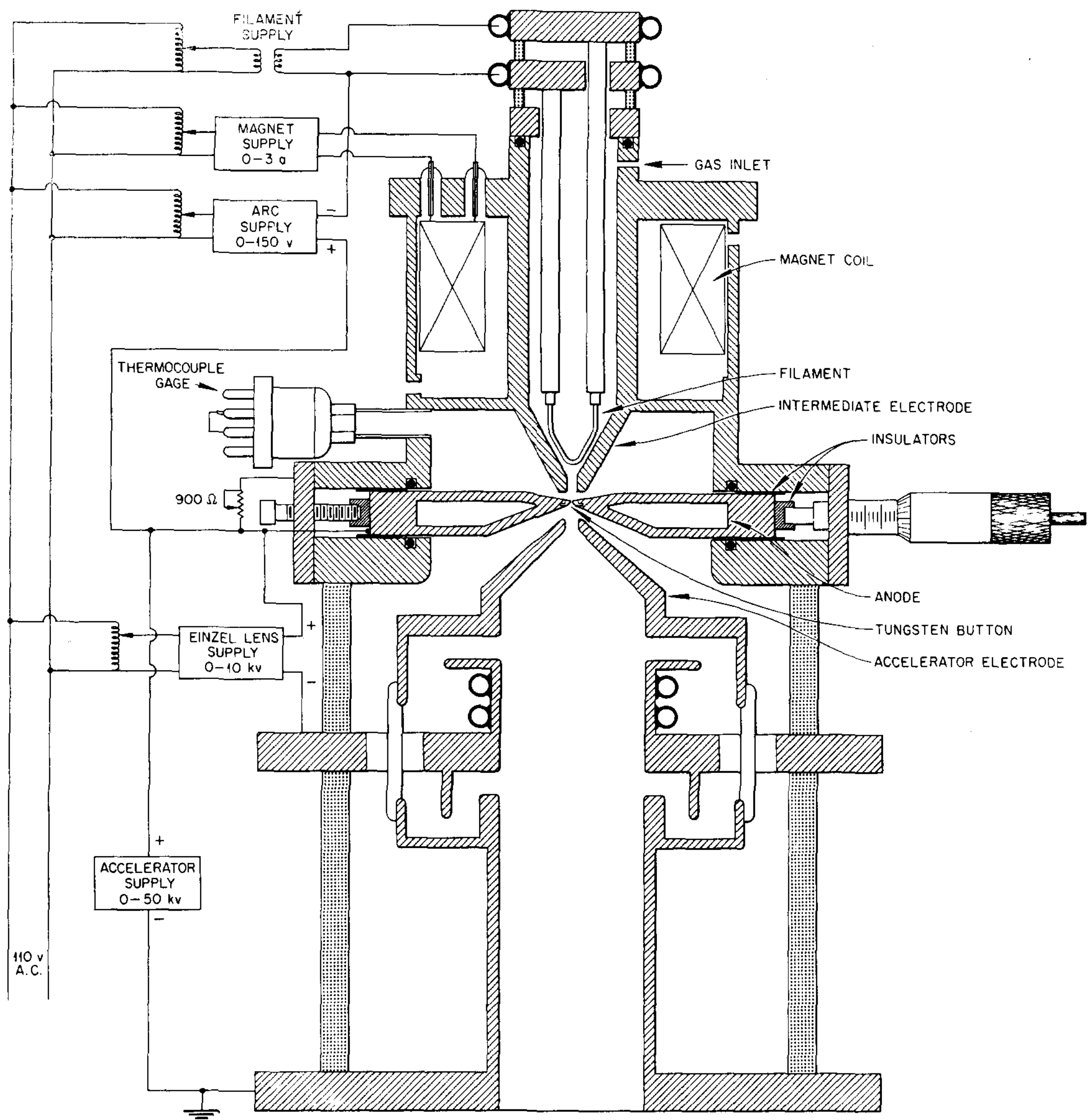


FIG. 1. Cross section of a duoplasmatron ion source and electrostatic lens.

tron.[5,6] The primary reasons for choosing one of these ion sources for a particular application are the detailed requirements of the extracted ion beam—the emittance, brightness, energy spread, and the desired ion species—and the physical limitations—for example the size, available electrical power, and pumping speed of the equipment. The family of ion sources described in this paper probably come closer to satisfying some of the more stringent requirements for intense, bright, dc ion beams than any of the above mentioned types. Our sources evolved from those developed by von Ardenne and his co-workers. They used the names uniplasmatron and duoplasmatron, with the prefix indicating constriction of a discharge either by a simple aperture or by both an aperture and shaped magnetic field. This distinction is not always possible or very meaningful for some of the sources described in this paper. These sources could be referred to simply as plasmatrons.

The first source used in this work is shown in Fig. 1 and was based on an earlier development by a group in the Physics Division of the Oak Ridge National Laboratory.[7] The source consisted of a filament, ferromagnetic intermediate electrode, ferromagnetic anode with a tungsten "button," magnet coil, and a beam extraction region with "Pierce" geometry.[8]

[1] R. S. Livingston and R. J. Jones, Rev. Sci. Instr. **25**, 6 (1954).
[2] M. D. Gabovich, L. L. Pasechnik, and L. I. Romanyuk, Z. Tekn. Fiz. **31**, 87 (1961).
[3] W. A. S. Lambi and E. J. Lofgren, Rev. Sci. Instr. **27**, 907 (1956).
[4] C. S. Taylor, "*Proceedings of the Dubna Accelerator Conference, 1963*" (Atomizdat 1964), p. 475.
[5] M. von Ardenne *et al.*, *Tabellen der Elektronenphysik, Ionenphysik and Übermikroskopie*, M. von Ardenne (VEB Deutscher Verlag der Wissenschaften, Berlin, 1956).
[6] H. Fröhlich, Nukleonik **1**, 183 (1959).
[7] C. D. Moak, H. E. Banta, J. N. Thurston, J. W. Johnson, and R. F. King, Rev. Sci. Instr. **30**, 694 (1959).
[8] J. R. Pierce, *Theory and Design of Electron Beams* (D. Van Nostrand Co., New York, 1954), 2nd edition.

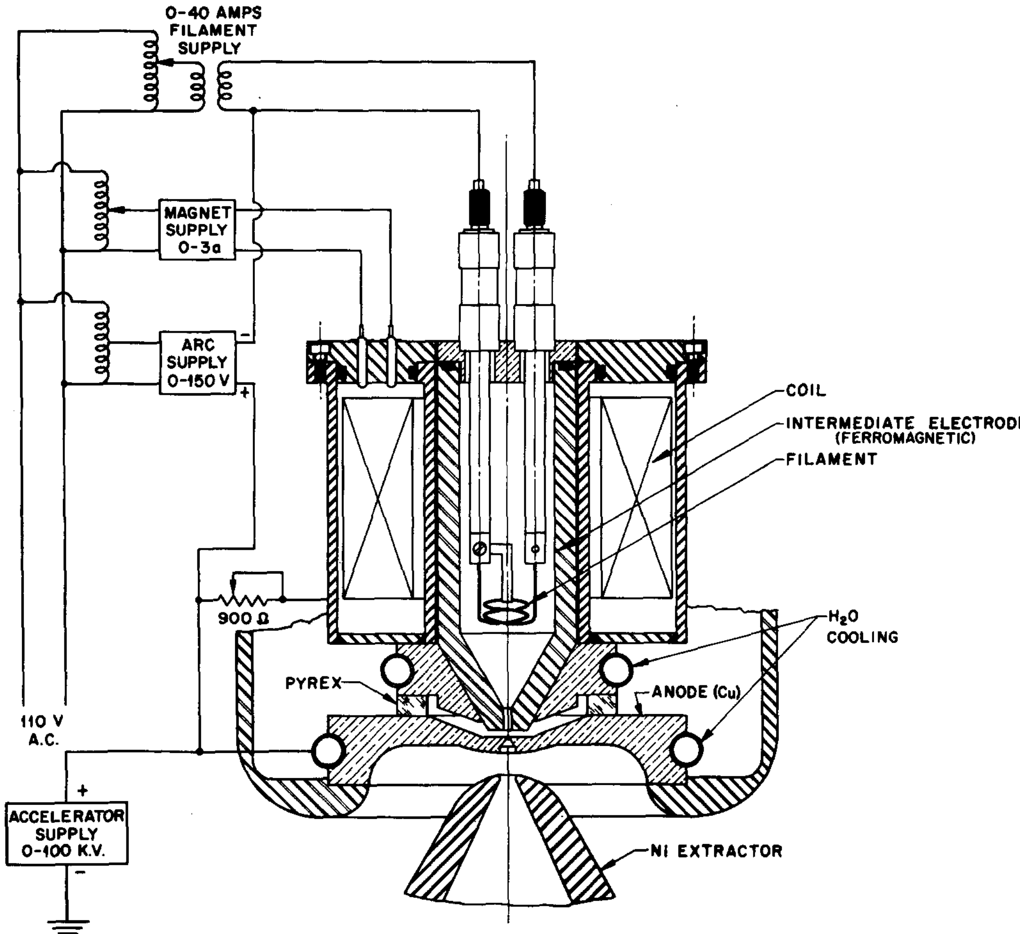


FIG. 2. Duoplasmatron with improved cooling for high current dc operation.

For intense dc ion beams, this source and lens have the following serious problems:

(1) The intermediate electrode and anode are not adequately cooled, especially for the 10–50 A of arc current necessary for 1 A dc H^+ ion beams.

(2) With a "Pierce" geometry in the extraction region electrical breakdown problems are unnecessarily severe due to the high electric fields in regions not needed for beam acceleration.

(3) Space charge severely limits the magnitude of beam current that can be handled in the electrostatic lens. For example, with H_2^+ ion beams in the energy range of 60–80 keV, the current is limited to $\sim$100–150 mA.

The ion source now being used for injecting H_2^+ ions into the thermonuclear experimental device DCX-2 is shown in Fig. 2. This source was developed to eliminate the thermal problems mentioned above. The intermediate electrode is furnace-brazed to a surrounding section of water-cooled copper, and the anode is made entirely of copper. This type of construction allows dc operation of the source for arc currents of up to 50 A. The change in the magnetic field shape in the beam extraction region caused by the removal of the ferromagnetic anode does not adversely affect the performance of the source. When a ferromagnetic (usually nickel) extraction electrode is used, the beam divergence and high voltage stability are actually improved.

There are many references describing the operation of the duoplasmatron[5,6,9] including a discussion of an earlier version of the source shown in Fig. 2.[10] The ion source section of this paper is restricted to a discussion of a group of specialized sources now being used extensively in this program.

The first modification of the source shown in Fig. 2 to be discussed is the incorporation of a large plasma expansion "cup," Fig. 3, in the beam extraction region. This expanded plasma type source has been used by other investigators, and especially for pulsed ion beams where the use of grids in the "cup" is feasible. The source shown in Fig. 3 has been evaluated on the 600 keV DCX-2 injector to be described later in this report. This configuration

[9] R. A. Demirkhanov, H. Freulich, U. V. Kursanov, and T. I. Gutkin, "A Collection of High Energy Accelerator Papers from U.S.S.R.," BNL Report 767 (C-36), (1962), p. 224.
[10] G. G. Kelley, N. H. Lazar, and O. B. Morgan, Nucl. Instr. Methods **10**, 263 (1961).

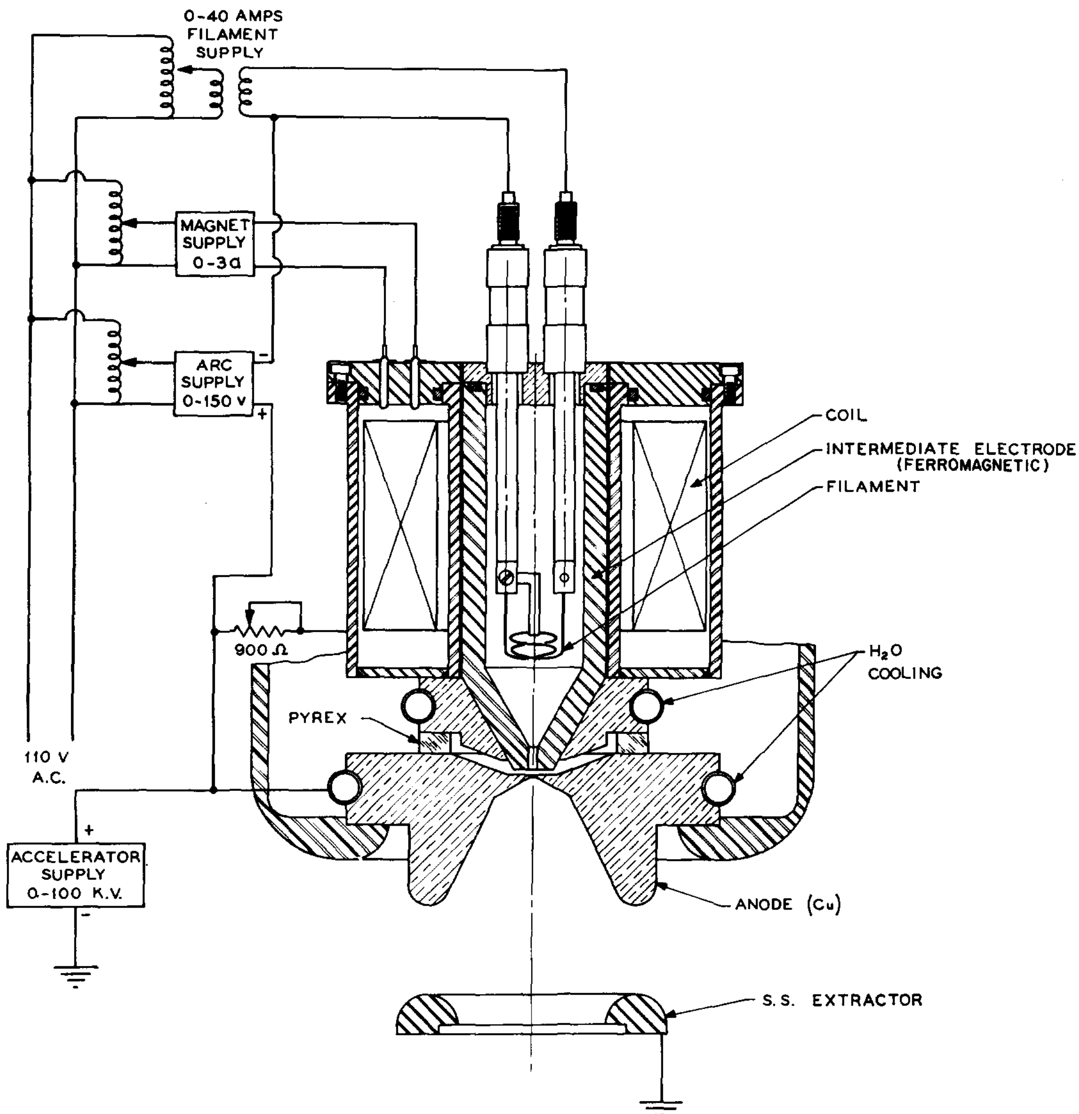


FIG. 3. Modified duoplasmatron ion source with large plasma expansion "cup."

results in a lower value of beam brightness than the source shown in Fig. 2. The results possibly would have been better with gridded extraction apertures to shape the electric field, but with intense (>100 mA) dc ion beams with 40–150 keV extraction energy this has been found to be impractical. For applications where total ion current with stable dc operation is the primary goal, rather than the brightest beams, this type source has an advantage because of the reduced electric field in the extraction region. For example, we are now using the source shown in Fig. 3 for a 0.5 A 150 kV dc neutron generator in a joint project with the O.R.N.L. Health Physics Division, the Armed Forces Radiobiological Institute, and the Edgerton, Germeshausen and Grier Corporation.

For the production of bright dc ion beams, the source shown in Fig. 4, which includes an auxiliary coil around the expanded anode "cup", has proven very successful. This source has been used primarily in the energy range of 20–100 keV in conjunction with a magnetic solenoid lens to produce very bright dc ion beams. This system is discussed in detail in a later section of this paper. The auxiliary coil prevents excessive plasma losses to the walls of the anode cup and is used to shape the magnetic field in the ion extraction region. Best results are obtained when it approximately cancels the stray field from the magnetic lens at the surface of the plasma.

Two specialized ion sources using the same beam extraction geometry as described for the source shown in Fig. 4 are shown in Figs. 5 and 6. The source shown in Fig. 5 is an all-copper source (including the intermediate electrode) that is used with 30–50 A arc current with dc operation for the production of intense (~1 A) hydrogen ion beams that are composed of more than 80% atomic ions. Figure 6 is a source used for the production of intense H_2^+ ion beams. This source is based on work done by Demirkhanov and associates in the U.S.S.R.[9] An additional electrode, the target cathode, is used in this source, and like the intermediate electrode, it is connected to the anode through a variable impedance. The source could be called a plasma fed "PIG" source and operates stably at a very low pressure, $\sim$50–70 μ, with 9 mm apertures in the electrodes, and produces a 200–300 mA dc hydrogen ion beam that is $\sim$65% H_2^+. A second version of this four electrode source is shown in Fig. 7 without an expansion "cup" and auxiliary coil and with a nonferromagnetic target cathode. This source is used for H_2^+ ion production with the 600 kV injector to be described in detail in a later section. There have been other sources developed for very special projects in this program that are not included in the above group.

The capabilities of the above sources are evident from later sections where their performance is discussed on either a 100 or 600 kV test stand. The construction of the sources has been kept as simple as possible without sacrificing performance. The earlier sources, Fig. 2, were assembled with an alignment "jig" by using vinyl acetate to attach the electrodes to the insulator. The present technique is to assemble the sources with self-aligning insulators and O-rings. The filaments are identical to those described earlier[10] and have been used for tens of hours of operation in some of these sources with dc operation up to 50 A arc current. The source magnet is filled with oil and has an expansion chamber. The coil housing and the rest of the source are water-cooled through brazed-on copper tubing.

ION EXTRACTION

The family of sources described above produce the plasma from which the ion beams to be described later are extracted. The suitability of a particular ion source for a given application depends primarily on the properties of this plasma. For most applications, it is important that

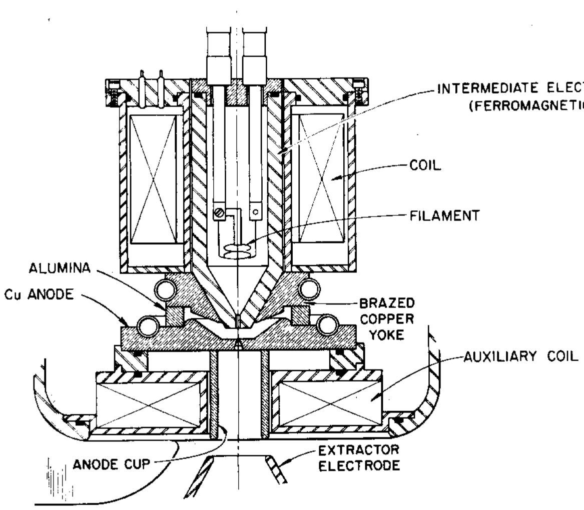


FIG. 4. Ion source with auxiliary coil.

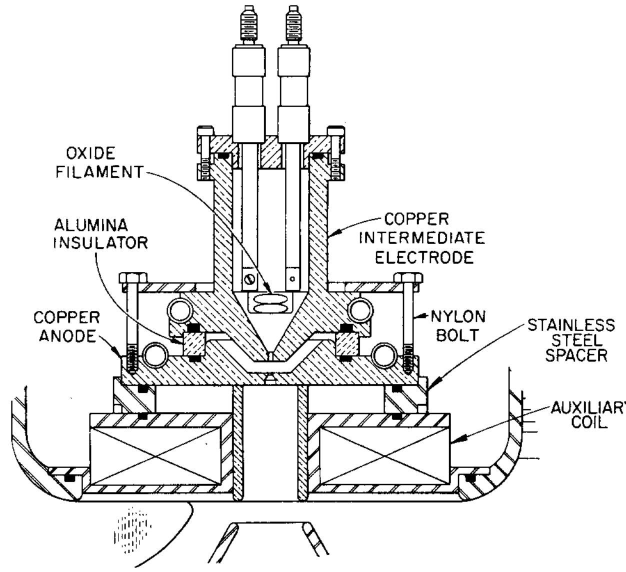


FIG. 5. H^+ ion source with auxiliary coil.

there be very little neutral gas present, and random thermal motions of the ions should be small. Directed motion of the ions, however, can be desirable. The source should provide an adequate plasma density so that ions reach the surface in sufficient numbers to provide the current density desired. The ions should be of the desired mass species insofar as possible. The other properties are determined by the configuration of the extraction and acceleration regions.

When an electric field is applied to the surface of a plasma, the surface retreats from the source of field until the space charge of the ions leaving the plasma cancels the field at the surface. The ion current is space charge limited at all times, but the size and shape of the surface depend on the plasma density, the shape of magnetic fields in the region, and the shape of the electrodes which are involved in producing the electric field. The shape of the plasma surface is an important factor in the ion-optical characteristics of the beam system, and its control is one of the most difficult problems in the design of an ion accelerator.

The space charge limited current density between plane electrodes is given by

$$j=(5.44\times10^{-8}\Phi^{3/2})/A^{1/2}z,$$

where j is the current density in A/cm^2, Φ is in volts, z is the electrode spacing in centimeters, and A is the mass in atomic mass units. This formula also applies in the case of "Pierce" geometry. We have found in fact that it also gives the correct result within 10% over a wide range of electrode shapes (for axially symmetric systems), if an empirical adjustment of the spacing is made to take into account the effect of the aperture in the accelerating electrode. The spacing is replaced by an effective spacing Z where $Z=z+r$, r being the radius of the hole in the accelerating

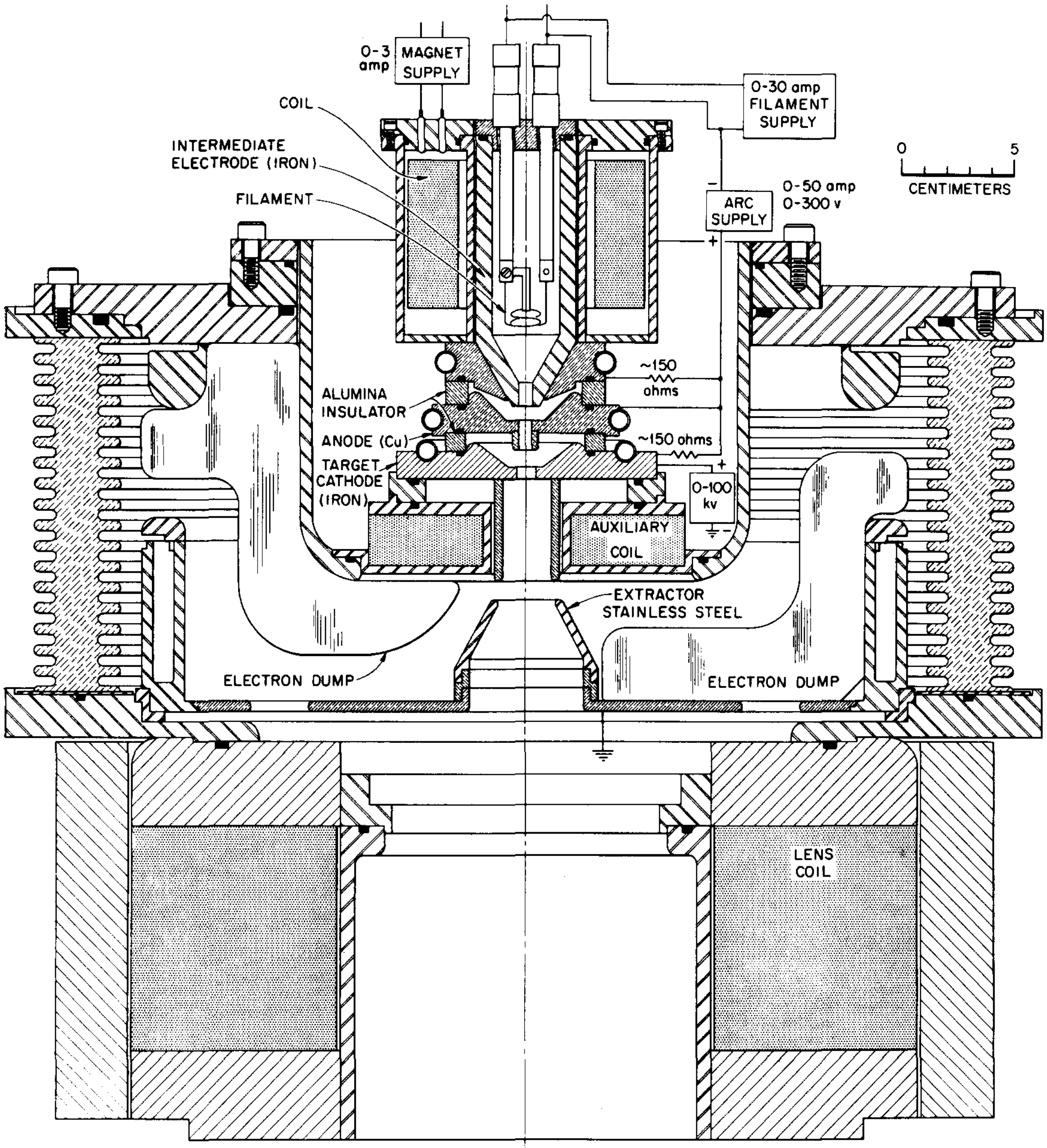


FIG. 6. System used for producing intense H_2^+ ion beams in the energy range of 50 to 70 keV.

electrode. It may be seen that the total current,

$$I=\pi r^2 j=\frac{1.71\times10^{-7}}{A^{\frac{1}{2}}}\frac{\Phi^{\frac{3}{2}}}{(Z/r)^2}$$

of a given ionic species depends only on the three-halves power of the accelerating voltage and the square of the ratio of beam radius to extractor spacing. Since there is an optimum value for this ratio in a given situation, depending on the beam divergence which can be tolerated, the total current is prescribed by the value of the accelerating voltage. A particular maximum current can be obtained using a fixed voltage with small spacing and high current density or with a larger spacing and correspondingly reduced current density. In the first case the object size is smaller, but the radial space charge forces in the beam are much greater. Whether there is an improvement in beam "quality" by going to lower fields and larger spacings depends on how well the shape of the plasma surface can be controlled.

The quantity which best describes the "quality" of a beam, i.e., how well a given volume in phase space can be filled with current, is its brightness. This quantity is defined by van Steenbergen.[11] According to his definition, the normalized brightness of a symmetrical beam is

$$B_4=\frac{9.4\times10^8 A}{\Phi}\frac{I}{\alpha^2}$$

[11] A. van Steenbergen, IEEE Trans. Nucl. Sci. **NS-12**, No. 3, 746 (1965).

for nonrelativistic particles. Here I is in milliamperes, Φ is in volts, A is the mass in amu, and α is the conventional phase area obtained by plotting the angular spread of the beam in radians against radius in centimeters. A complete description assuming that the beam is axially symmetric in velocity and configuration space would require the brightness to be given as a function of current or radius for the fractional part of the beam included in the measurement. For example, a particular beam might have a small over-all brightness, but a sizable fraction of the current might be included in a very intense core. In some applications it might be desirable to increase the brightness in this case by excluding all but the core.

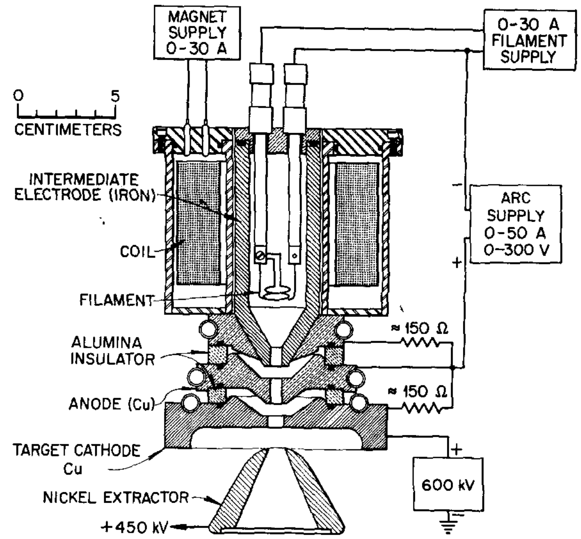


FIG. 7. H_2^+ ion source.

LOW AND INTERMEDIATE BEAMS

One of the two test stands used for ion beam studies in this program is shown in Fig. 8. The system uses a 3.5 A 100 kV dc power supply and has an $\sim$250 cm beam drift space. The vacuum system consists of three 25 cm oil diffusion pumps with silicone 705 oil, Freon-cooled chevron baffles, and filament type titanium evaporators for extra pumping when desired. The system is not bakeable and has a base pressure of $\sim 1\times 10^{-7}$ Torr. The beam drift space is accessible from eleven 20 cm diam ports and allows the incorporation of a wide variety of beam collimation apertures and neutral forming cells for energetic neutral beam work. A magnetic lens is used which is a short solenoid with up to 200 000 ampere turns and an iron yoke. This solenoid focuses the beam and analyzes it (by the mass dependence of its focal length) through the use of a series of limiting apertures to remove the unwanted beams. It also reflects strongly the electrons which are made by the beam in the field free region beyond the lens. This magnetic "trap" provides automatic space charge neutralization of a beam after the first few hundred microseconds unless an electric field is incorporated to drain off the electrons.

The use of a magnetic lens following a short single or multistage column is in keeping with the general approach of this program since the first accelerator was built in 1959. We feel that the ion beam should be accelerated very rapidly to full energy to minimize space charge problems in the accelerating region where space charge neutralization is impossible. For this reason the beam is not pre-analyzed and is passed through the magnetic lens as soon as feasible after accleration. It is then space charge neutralized throughout the drift space.

The desire to have the accelerator column very close to the magnetic lens means that the column is immersed in the stray field of the lens. This stray magnetic field combined with the electric fields within the column makes the design of the column electrodes to eliminate regions subject to "PIG" discharges very difficult. The single stage column in Fig. 9 controls these PIG discharges by incorporating electron "dumps." This technique makes it possible to operate a system over a range of voltage and magnetic field in which it was unstable without the "dumps," but complete elimination of the problem requires an arrangement which is described later. After optimization of some parameters in the beam extraction region (anode cup diam and length, auxiliary coil size and location), the system can be used successfully for intense dc ion beams. There are many interrelated variables involved when one tries to determine the best extraction geometry. For example, for every size of anode "cup" there is a corresponding optimum length that allows the plasma from the source to fill the cup but prevents large plasma losses to the cup walls. For the ion source and lens arrangement shown in Fig. 9, the source coil was found to be unnecessary, and in fact was generally detrimental to the beam quality and magnitude when energized. This point is illustrated in Fig. 10 where the H^+ current through a 3 cm diam aperture located 120 cm from the lens is shown as a function of the amp turns in the source coil. Another point illustrated in Fig. 10 is that the available beam is greatest when the auxiliary coil is used to oppose ("buck") the stray field of the magnetic lens.

With the above parameters optimized, the system shown in Fig. 9, with the source coil removed, can be used very successfully up to a total hydrogen ion beam of $\sim\frac{1}{2}$ A in the energy range of 60–100 keV and with total source arc currents of 25–30 A. When even higher total dc ion currents are desired, and especially where up to 50 A arc current is used to produce beams composed primarily of H^+, there is again a problem of properly cooling the ferromagnetic intermediate electrode. For this very high current (>500 mA) application, the source shown in Fig. 5 can be substituted for the source shown in Fig. 9. This is an all-

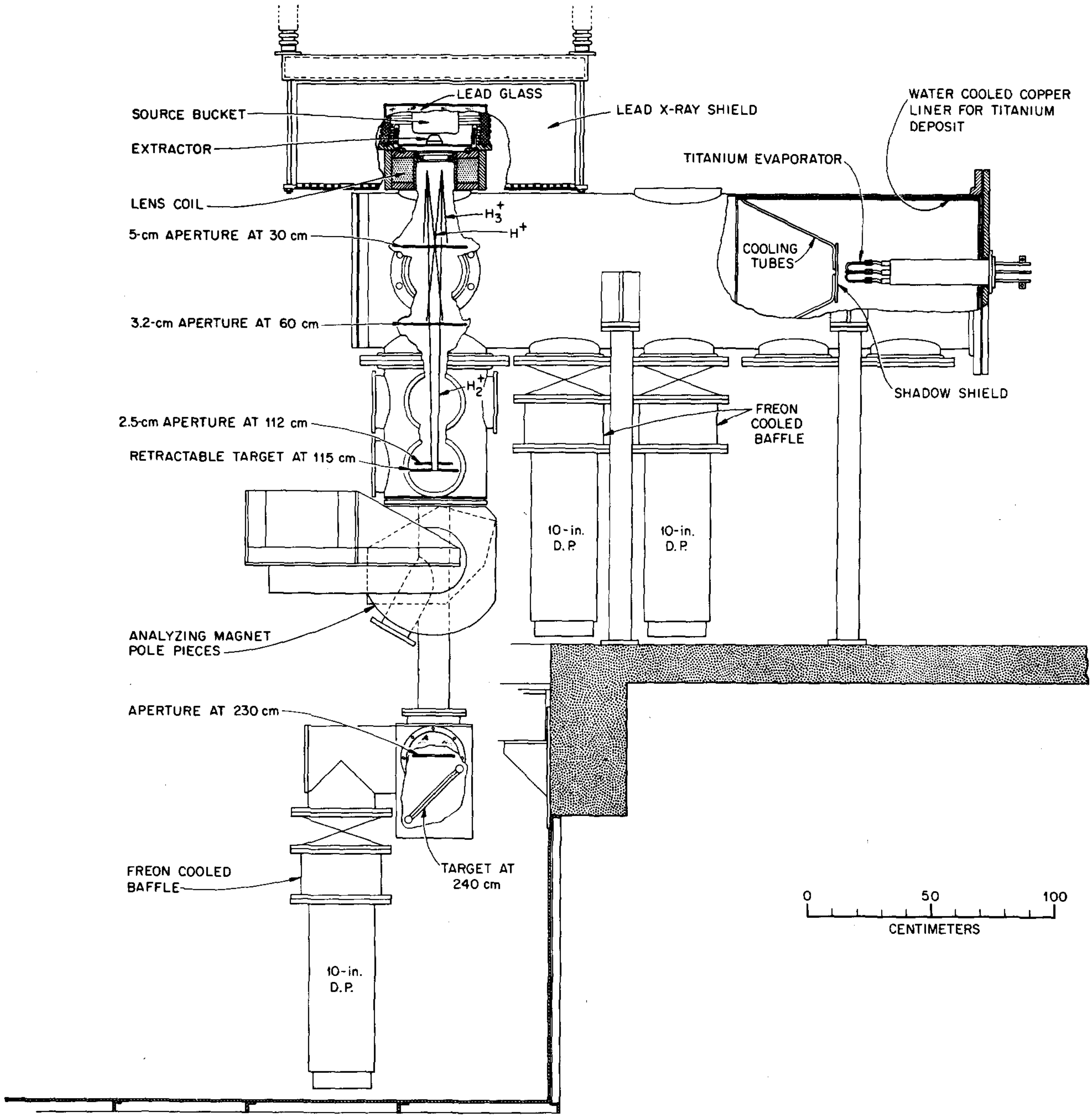


FIG. 8. 100 kV test stand.

copper source, including the intermediate electrode, and will operate with dc source arc currents up to 50 A and produce total hydrogen ion beams up to 1 A in the energy range of 80–100 keV. Figure 11 shows a plot of the H^+ current available on a target 120 cm from the lens after passing through a 3 cm aperture located 60 cm from the lens. The source actually produces more than the $\sim 80\%$ H^+ beam indicated here since some of the H^+ beam is lost on the 3 cm aperture. For total beams of 500 mA and above the source appears to produce 85% or greater H^+ ions.

The column shown in Fig. 12 completely eliminates the electron trapping problem. The insulator for this column is an epoxy plate transverse to the beam axis instead of the more typical coaxial ceramic cylinder. The electric equipotential surfaces are convex as viewed looking from positive to negative in the 0–100 kV accelerator region. This geometry permits a wide variation in magnetic field shape without permitting electron trapping. As shown, this system also includes a second epoxy plate that allows a negative potential to be applied to the extractor electrode. Incorporation of a ground plane after this electrode results in an accel-decel electrode combination that traps electrons between these electrodes and the magnetic lens and allows space charge neutralization in this region.

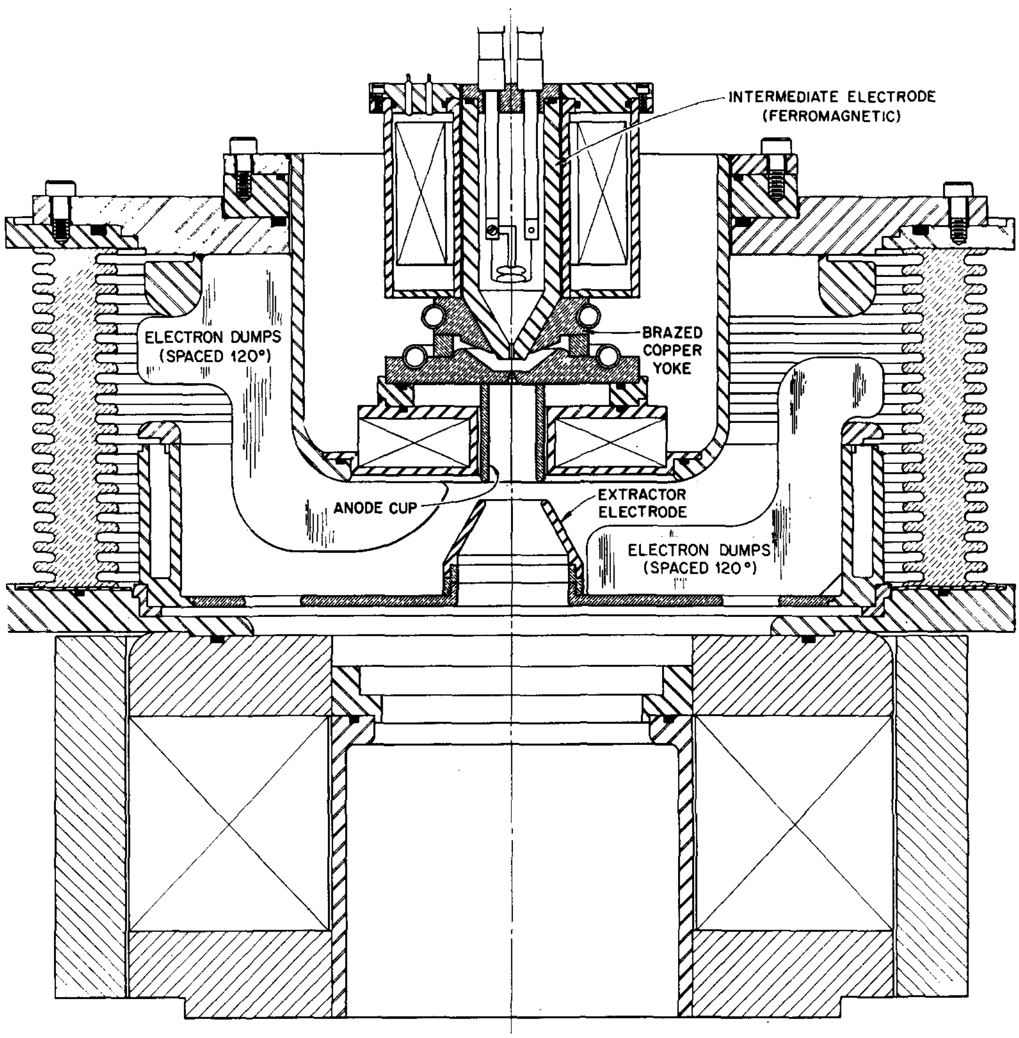


FIG. 9. Zero to 100 kV ion-beam assembly with electron "dumps."

The epoxy used for the above insulators and the epoxy used in the "skirts" to be discussed in a later section is Shell Epon 815 with Versamid 014 (General Mills) hardener. The mixture is 100 parts by weight of Epon 815 to 40 parts by weight of hardener. After very thorough mixing, the material is cured at ~20°C for some 48 to 96

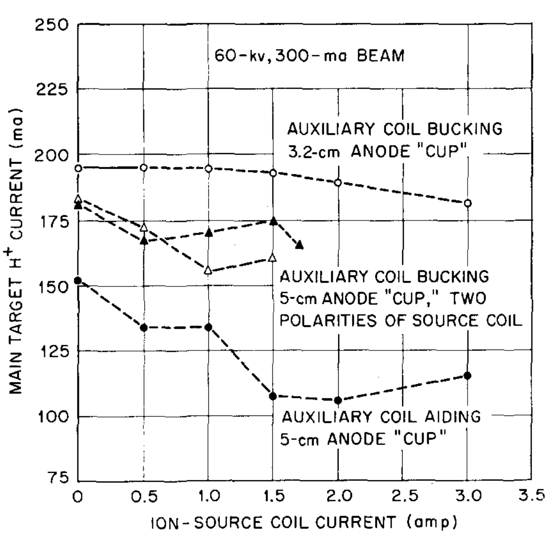


FIG. 10. H^+ beam to main target (120 cm from lens) as a function of current in ion source coil. The coil has 3000 turns.

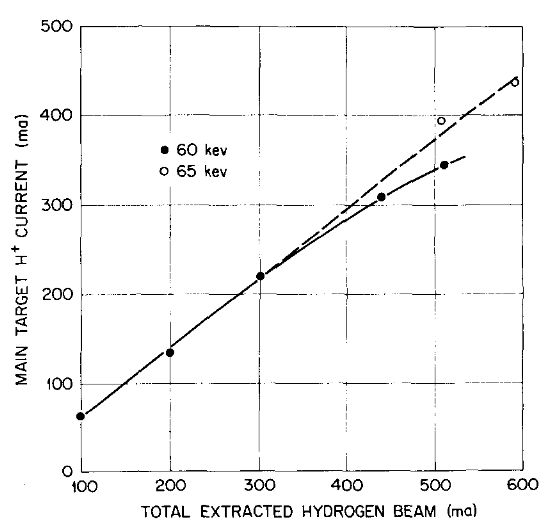


FIG. 11. H^+ current to main target (120 cm from lens) as a function of total extracted hydrogen current.

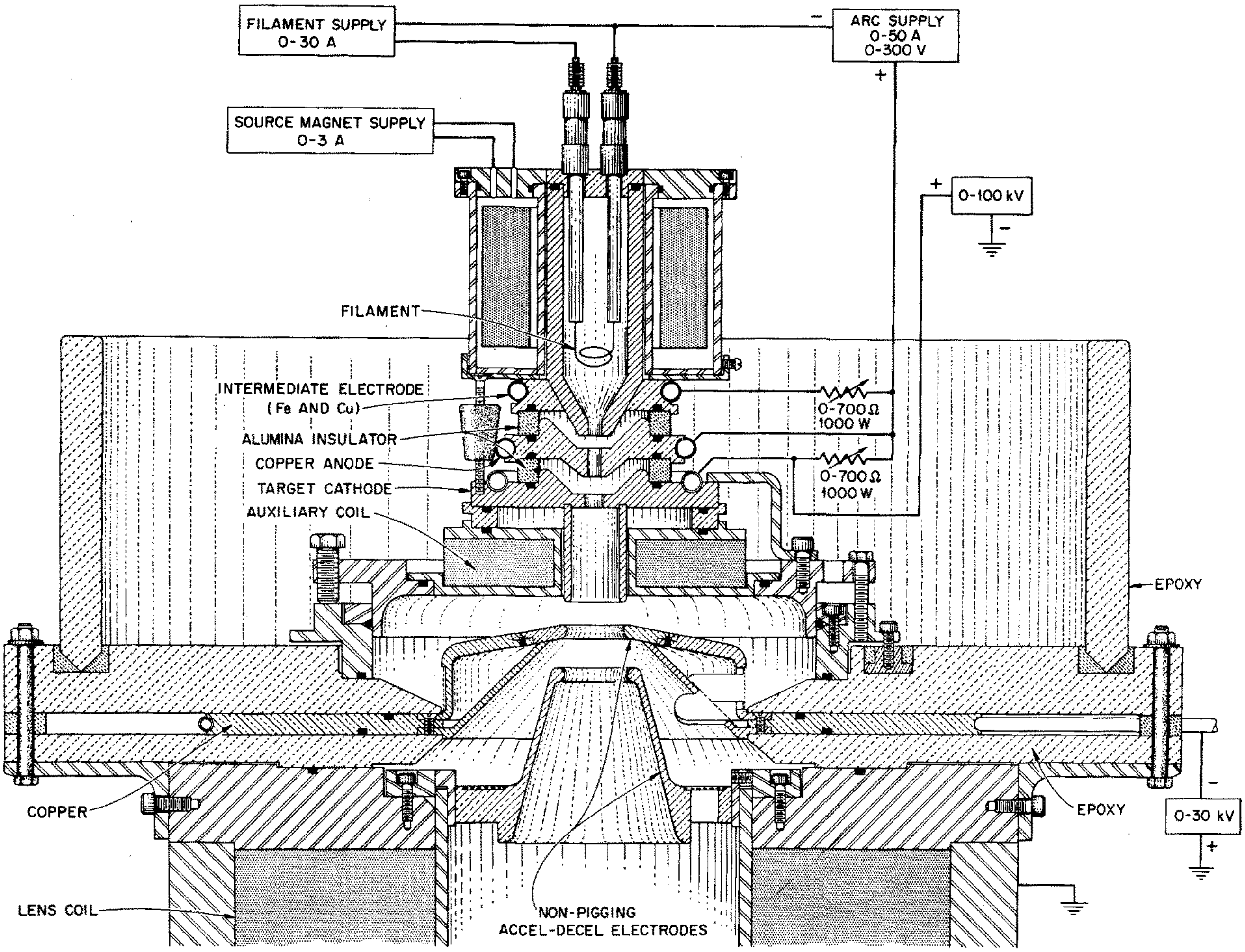
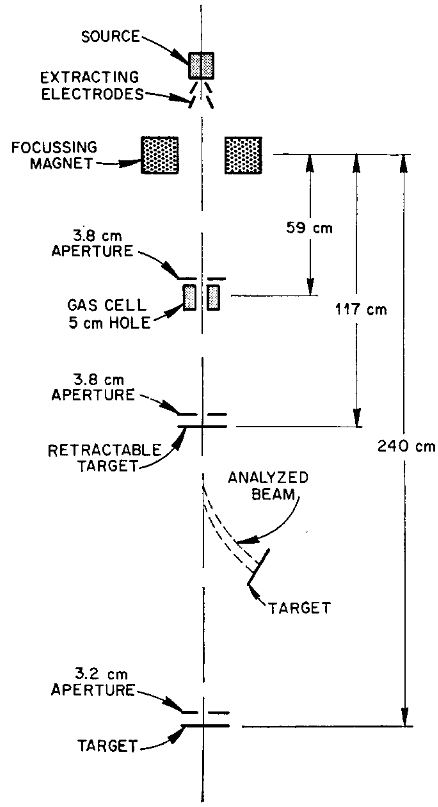


FIG. 12. Modified intense ion beam assembly with non-PIG design. Four-electrode H_2^+ ion source.

h (varying with the quantity of material). The material can be either molded or machined to the desired configuration. In machining, the proper tool and cutting rate for this type of material is necessary. The strength of this unfilled material is adequate for the type of insulators described in this paper. The material has been used extensively to insulate 100 kV through a 3 cm thickness with various geometries of the supported electrodes. A vacuum surface path length of only 4 cm is used for 100 kV insulation. For beam test stands as described in this paper with large pumping speeds, there has been no evidence that this material either contaminates the electrodes or increases the base pressure of $\sim 1\times 10^{-7}$ Torr. While we have made no basic studies of the properties of this material, and certainly no detailed investigations to indicate there are not better materials, it provides an inexpensive, convenient, and highly satisfactory insulator for this type of application.

The column shown in Fig. 12 has been used primarily to produce 40 keV H_2^+ ions which are injected into a magnesium vapor cell developed by H. Postma and R. G. Reinhardt of the ORNL Thermonuclear Division. The resulting 20 keV H^0 beam is then to be used for injection into the DCX-3 and INTEREM experimental facilities. The performance of this system for ion and neutral beams with the indicated amount of beam collimation is summarized in Table I. The accel-electrode is operated at ~ -12 kV so the beam is extracted at ~ 52 kV and de-accelerated to 40 kV. These results will probably improve when better lens and auxiliary coil are incorporated. The present coils have some asymmetries that cause undesirable perturbations in the magnetic field in the region where the beam is extracted from the source plasma. Since the coils are operated in opposition to produce an essentially field free region at the plasma surface, any nonuniformities in these fields are certainly detrimental to the resulting ion beam. As indicated in Table I, for equilibrium conditions the magnesium cell converts about 90–92% of the 40 keV H_2^+ ions into 20 keV H^0 neutrals. The cell is 3.8 cm i.d., 10 cm long and performs very satisfactorily with these intense beams. The DCX-1 group of the ORNL Thermonuclear Division is now preparing to study the excited state population of the H^0 beam produced by this system.

TABLE I. Performance of system for producing charged or neutral beams. A magnesium vapor cell is used for producing neutrals. The results at 117 cm and 240 cm represent the currents which will be obtainable through the injection ducts in INTEREM and DCX-3, respectively.



ACCELERATED mA	TARGET LOCATION	NEUTRALIZATION	mA ON TARGET
200	240 cm	OFF	66
200	240 cm	ON	92 mA EQUIVALENT OF 20 keV H_0
200	117 cm	OFF	126
220	117 cm	ON	222 mA EQUIVALENT OF 20 keV H_0
200	H_2^+ ANAL	OFF	90
200	H_2^+ ANAL	ON	7
200	240 cm*	OFF	83
214	240 cm*	ON	102 mA EQUIVALENT OF 20 keV H_0

*5 cm APERTURE AT 234 cm

Because of our interest in molecular ions, the accelerator shown in Fig. 8 has been used almost exclusively for the production of 30–60 keV H_2^+ ions. However, from brief investigation it is evident that, as expected, this accelerator can also be used just as satisfactorily with the source shown in Fig. 4 for the production of 20–100 keV H^+ ions. The increased stability of the system plus the addition of the space charge neutralization between the accelerator region and the lens will certainly improve the results for H^+ ion beams shown in Figs. 10 and 11.

HIGHER ENERGY ION BEAMS

The test stand shown in Fig. 13 and equipped with a 600 kV 1 A dc power supply is used primarily for the production and evaluation of 600 keV H_2^+ ion beams. The vacuum system is similar to that described for the 100 kV test stand with the exception of liquid nitrogen rather than Freon traps for the oil diffusion pumps. The beam drift space can be as long as 5 m, but most work has been done with a 2.5 m distance. The lens is again a magnetic solenoid with a throat diameter of 15 cm and with $\sim$250 000 ampere turns producing approximately a 10 kG central field. The accelerator, Fig. 14, is a short high gradient column with no pre-analysis. It immediately precedes the magnetic lens and since it is immersed in the stray magnetic field of the lens, electron trapping regions can exist. The accelerator consists of four sections of porcelain, 37 cm i.d.$\times$15 cm high, with epoxy "skirts" cast around the porcelain to extend the external air gap. These skirts have been in use for approximately 4 years with no failures. The interior of the column is made of stainless steel electrodes that are designed to minimize electron trapping regions. This design is adequate for the present ion source and accelerator, but does not allow the incorporation of distinctly different ion sources with more intense and differently shaped magnetic fields as is indicated in the following section. The ion beam is accelerated in four 150 kV stages over a distance of $\sim$30 cm, with the first 150 kV of acceleration being in 7.6 mm.

This accelerator is used to produce H_2^+ ions for injection at 600 keV into the thermonuclear experimental device DCX-2 using the ion source shown in Fig. 2. Total dc hydrogen ion beams of up to 350 mA at 600 kV can be obtained with the system. However, only about 100 mA of this beam is available as H_2^+ ions through 4 cm diam apertures located at 178 and 250 cm from the lens, representative of the DCX-2 injection channel. The primary problem is the inability to produce more H_2^+ ions with this source. Using the ion source shown in Fig. 7 which will produce more H_2^+ ions, we are still limited to $\sim$100 mA of H_2^+ ions through the 4 cm diam apertures. The limit in this case is caused by a reduction in brightness from the beam obtained from the source in Fig. 2. With the ion source shown in Fig. 7, the 600 kV accelerator would not operate stably until a copper instead of a ferromagnetic target cathode was used.

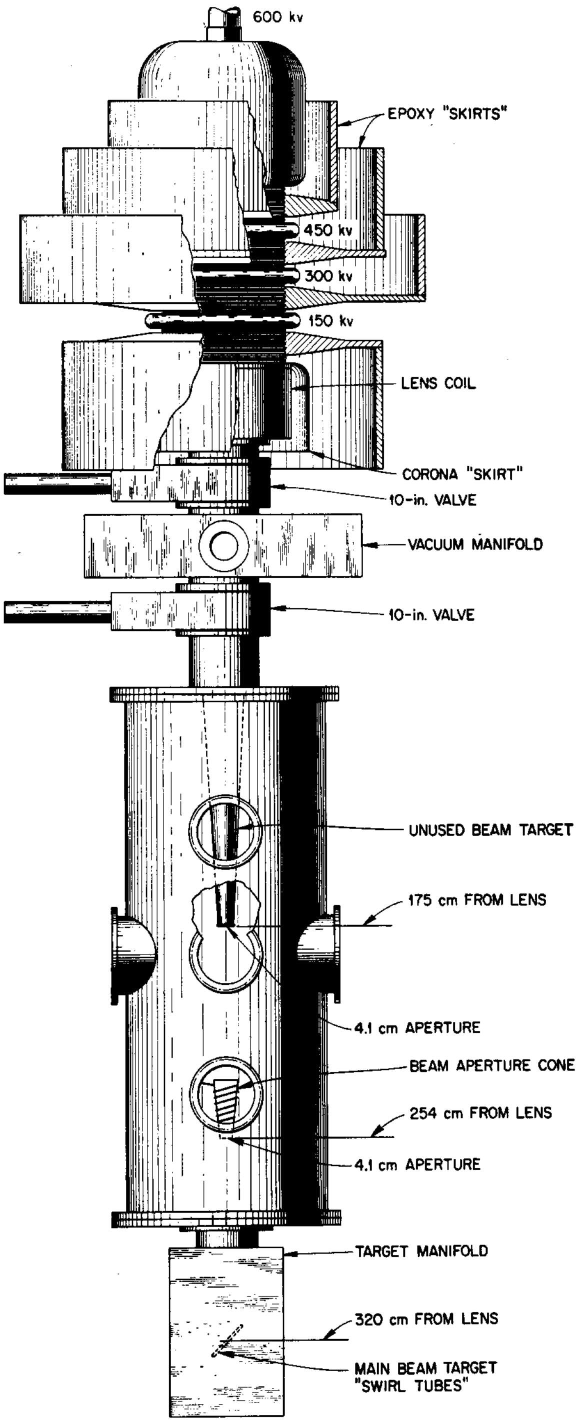


FIG. 13. 600 kV test stand.

From 100 kV test stand results, the source shown in Fig. 6 produces a less divergent, brighter beam than either of the sources shown in Figs. 2 or 7. However, when we attempted to incorporate the source shown in Fig. 6 into the 600 kV accelerator, the column was unstable because of new electron trapping regions created from the stray field of the auxiliary coil. This again emphasizes the necessity of a column that is free from potential electron trapping regions for intense dc ion beams. This problem is now being pursued based on the successful results of the single stage column shown in Fig. 12.

PROPERTIES OF ION BEAMS

As we have said, under proper conditions electrons can accumulate in ion beams and neutralize the radial forces due to the space charge of the beam itself. Loss of electrons from the beam is prevented by keeping all surfaces in the drift region at approximately the same potential and by preventing electrons from flowing along the beam toward the region where the ions are accelerated. The electrons can be stopped either by the use of a solenoidal focusing lens, by a transverse magnetic field,[12] or by an electrostatic field strong enough to overcome the field produced by the unneutralized beam.[13] The beams under consideration here require potential differences of a few kilovolts in an accel-decel arrangement. For best results the exit electrode must be at the same potential as the walls of the drift region. We have used an electrostatic field electron trap arrangement with an einzel lens and have gotten a factor of 5 increase in beam brightness.

Using the above electron accumulation techniques, space charge neutralization is apparently almost complete at all pressures down to the lowest we can maintain in the drift region (about 2×10^{-6} Torr) for beams of greater than about 60 keV. At lower energies there is a pressure dependence, and a pressure of greater than about 2×10^{-5} Torr is required for the greatest possible degree of neutralization. When a vapor cell is used to produce a neutral beam, however, neutralization apparently is complete at all pressures, even at low energy.

We suspect that perfect neutralization of the beam space charge does not occur even under the best conditions. It is difficult, however, to separate the effects of space charge and of lens aberrations when the effects are small, and we have not attempted to do so. The failure of neutralization becomes obvious, however, when the beam is brought to a focus in the drift region.[12] The beam has been studied in some detail under this circumstance both visually and with a small differential calorimeter. The outer region of the beam begins to diverge well before the point at which the rays leaving the lens would be expected to cross. The rays more nearly on axis continue toward the focus but are deflected outward before they reach this point. The beam appears by eye to come to a very sharp focus but at a very much smaller intensity than would be expected from the appearance of the beam as it leaves the lens. Beyond the focus at 600 keV the beam is so diffuse that it can no longer be observed visually. At lower energies it is seen to be a

[12] G. G. Kelley and O. B. Morgan, Phys. of Fluids 4, 1446 (1961).
[13] W. Herrmann, Report No. IPP2/13, Institut für Plasmaphysik, Garching bei München, Federal Rep. Germany (1963).

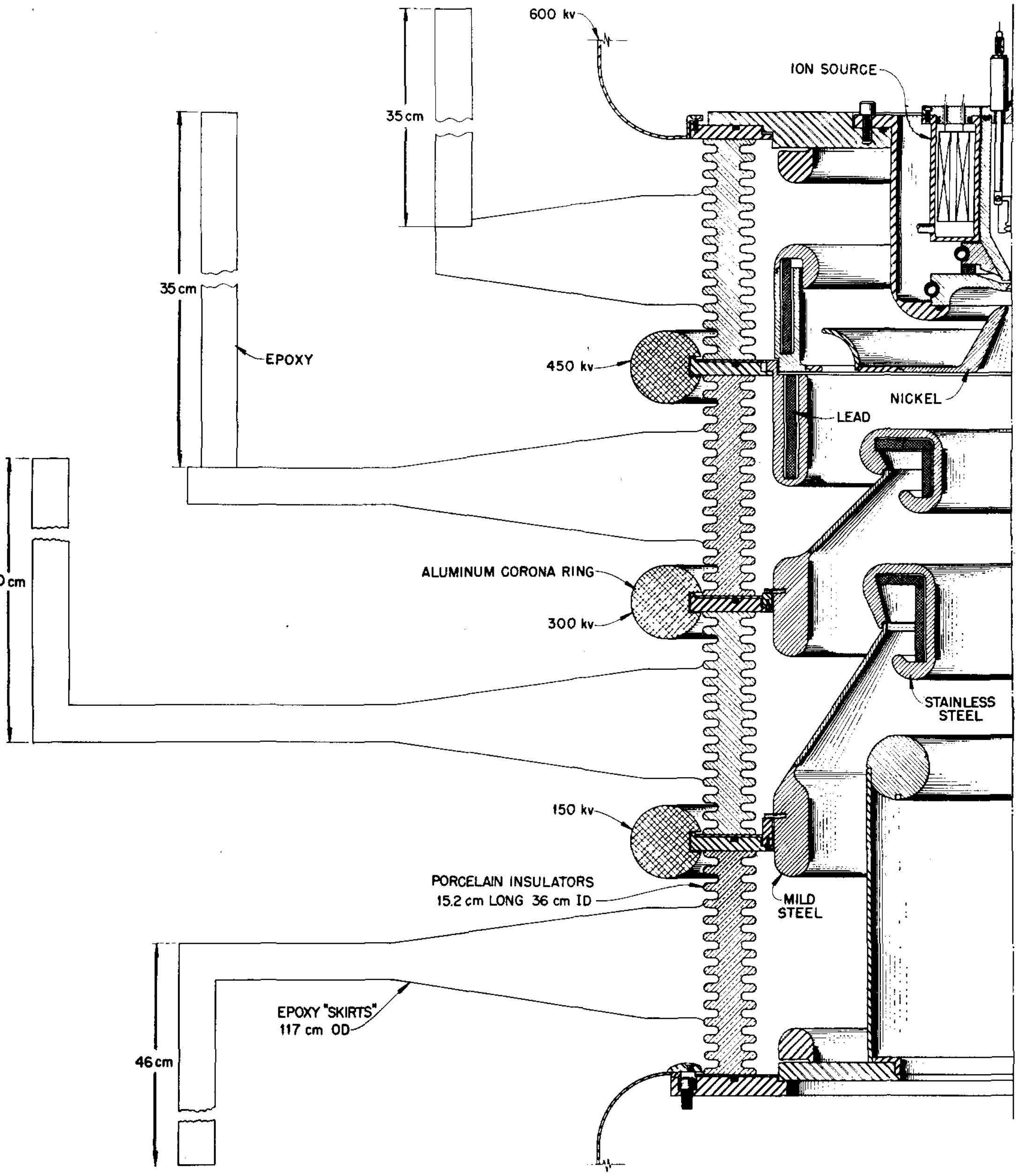


FIG. 14. 600 kV accelerator column.

hollow cone having a much greater angle with respect to the axis than the greatest angle of the rays before the focus. There is also a very narrow pencil of rays of considerable intensity consisting of ions apparently trapped in a region of negative space charge. The current density in this pencil is found calorimetrically to be much greater than the current density in the cone. The failure of neutralization and the resulting angular dispersion puts a severe constraint on the ion-optical design of a beam system. In particular, it means that a parallel beam cannot be produced which is any smaller than the largest diameter of the beam anywhere in the system. It should be remembered that there are no diverging electric or magnetic lenses.

An important characteristic of an ion beam for some applications is its steadiness. We usually do not monitor the "noisiness" of our beams, but have looked at the current fluctuation in most systems. In some cases, particularly in the DCX-2 application, we check the amount of intensity modulation more or less continuously. We find that over a current range of about a factor of more than three, depending on the size of the anode aperture, the rf noise produced in the beam current can be held below about 4% rms by the proper choice of source magnet current. Current fluctuations associated with the power line frequency are not present when the filament is heated by direct current, and the magnet and arc supplies are well filtered.

The beam currents discussed in this paper are all determined calorimetrically. Since the beams are space charge neutralized, a biased target is not desirable and usually does not provide an accurate measurement of current. The calorimeters use piles consisting of ten series thermocouples to measure temperature.[14] They are mounted in stainless steel fins in the inlet and exit water lines of the target. We have found these devices to give more reliable results than are obtained with thermistors because of the dependence of calibration of the latter on inlet water temperatures. Since 100 mA 600 kV dc beams with an $\sim$3 cm diam must be dissipated on these targets, special construction techniques are required. A parallel array of copper tubes with swaged-in spiral ribbons to produce a thin high velocity sheet of water on the inner surface is used for these targets. They are a development of the O.R.N.L. Reactor Division.[15]

PROTECTION OF EQUIPMENT AGAINST DISCHARGES

At the beginning of our work with high voltage, high current power supplies, we were afraid that spark-overs would ruin the accelerating electrodes or the source. We were careful to provide very fast devices to sense an over-current and to turn off the supply. In addition, on the 100 keV 3.5 A test stand we had a vacuum-switch "crowbar," which was capable of much faster action than the ac disconnects. We also added "softening" resistors (6000 Ω) between the power supply and the source terminal equipment. It has turned out, however, that sparking has not been a serious problem as far as the components in the vacuum are concerned. The fast "crowbar" has been found unnecessary. On the other hand, the external effects of sparking have been much more troublesome, particularly when using the 100 kV supply. In this case our terminal equipment is connected to the supply and to a 3-phase 440 V isolation transformer through four approximately 30 m lengths of RG-19/U cable. This cable has a capacitance of 100 pF/m and a characteristic impedance of about 50 Ω. A spark to system ground in the accelerator can produce a momentary difference of potential of as much as 50 kV between the ends of these lines and the terminal ground. In order to prevent this voltage from producing ruinous current surges in the terminal power supplies, we have had to use chokes and terminating resistors to provide short-time isolation of the line from the table and to dissipate the energy stored in the lines as quickly as possible. In addition, it was necessary to terminate the input ends of the cables to prevent damage to the cables themselves. The 600 kV power supply has an internal impedance of about 80 000 Ω and a small energy storage. It has caused no trouble due to sparking.

[14] Delta-T Company, P. O. Box 473, Santa Clara, California.
[15] W. R. Gambill, R. D. Bundy, and R. W. Wansbrough, "Heat Transfer, Burnout and Pressure Drop for Water in Swirl Flow through Tubes with Internal Twisted Tapes," Chem. Eng. Symp. Series 57, No. 32 (1961).