

# Lawrence Berkeley National Laboratory

## Recent Work

### **Title**

DESIGN CONSIDERATIONS FOR HIGH-INTENSITY NEGATIVE ION SOURCES

### **Permalink**

<https://escholarship.org/uc/item/4gz1d0jw>

### **Author**

Ehlers, Kenneth W.

### **Publication Date**

1964-07-08

**University of California**

**Ernest O. Lawrence  
Radiation Laboratory**

DESIGN CONSIDERATIONS FOR  
HIGH-INTENSITY NEGATIVE ION SOURCES

**TWO-WEEK LOAN COPY**

*This is a Library Circulating Copy  
which may be borrowed for two weeks.  
For a personal retention copy, call  
Tech. Info. Division, Ext. 5545*

**Berkeley, California**

## DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory  
Berkeley, California

AEC Contract No. W-7405-eng-48

DESIGN CONSIDERATIONS FOR  
HIGH-INTENSITY NEGATIVE ION SOURCES

Kenneth W. Ehlers

July 8, 1964

DESIGN CONSIDERATIONS FOR  
HIGH-INTENSITY NEGATIVE ION SOURCES\*

Kenneth W. Ehlers

Lawrence Radiation Laboratory  
University of California  
Berkeley, California

July 8, 1964

ABSTRACT

An attempt has been made to improve the output of negative hydrogen ions, which are extracted directly from a hot-cathode Phillips-ion-gauge type of discharge. The discharge chamber has been modified to accord with assumptions made as to the probable formation mechanism of the negative ions observed. Negative hydrogen ion currents in excess of 5 mA have been obtained. Ion source operating parameters, as well as considerations for the utilization of this discharge geometry by negative ion cyclotrons, are discussed.

It has recently been shown that the difficult problem of extracting the beam from an isochronous or sector-focusing type of cyclotron is simplified by the acceleration of negative ions.<sup>1</sup> By stripping two electrons from accelerated negative hydrogen ions by means of a thin foil located near the final radius of the machine, the UCLA sector-focusing cyclotron has produced an external beam of 50-MeV protons.<sup>2</sup> Under such conditions, the magnetic field of the cyclotron, which constrains the negative ion while it is accelerated, will cause the ion to deflect in the opposite direction, or out of the machine, as the ionic charge is made positive. By stripping but one of the electrons from the negative ion, an external beam of energetic neutral atoms can be had. Moving the stripper foil closer to the center of the cyclotron will result in a lower-energy neutral beam, thus making the negative-ion cyclotron, in essence, a variable-energy machine.

To realize the attractive features of negative-ion acceleration, it is first necessary to generate adequate beams of the negative ions to be accelerated. In general, these will be beams of hydrogen, and hydrogen isotopes, with intensities (we hope) in the milliamperere rather than the microampere region. It is also required that this be done in a manner that does not add intolerable complication to the machine.

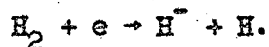
Previous work<sup>3</sup> has shown that substantial beams of negative ions can be generated by ion sources similar in many respects to those already employed in many cyclotrons. A complication, however, is that to obtain these currents rather high gas flow rates are required. The resulting high background pressure, particularly in the immediate region of the source,

can in turn act as the stripping medium for the weakly bound (0.755 eV) electrons.<sup>4</sup> Thus a good vacuum is essential if one hopes to accelerate an appreciable percentage of the available negative ions to full energy, and any large increase in gas flow through the source must in turn be accompanied by additional vacuum-pumping capability.

Because of the rather encouraging results of this work,<sup>3</sup> however, an attempt has been made to determine if the source geometry could be altered so as to allow the generation of sizable negative ion beams at reduced gas flow rates. In machines such as the proposed UCLA 625-MeV  $H^-$  cyclotron, where axial injection of an ion beam can be employed, considerably higher gas flow rates can be tolerated at no expense to the main system vacuum. Thus the characteristics of source operation under conditions such that the gas flow rate is not a limitation were also investigated.

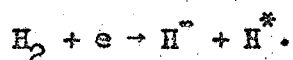
Previous experience has indicated that the method of formation of the negative ions observed probably involves the collision of electrons with neutral gas molecules. The cross sections for reactions of this kind have been measured by Schulz,<sup>5</sup> and his results are summarized in Fig. 1.

The solid curve at less than 13.6 eV is associated with the reaction

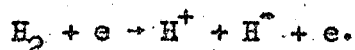


The formation of negative ions indicated by the dashed curve with a peak at about 6.8 eV is observed when reagent-grade hydrogen is introduced without a liquid nitrogen trap. It is interpreted as the production of  $H^-$  from water vapor present in the gas. It seems unlikely that this effect could be adequately amplified by using gas mixed with water vapor, because of

the extreme narrowness of the energy spectrum of electrons that take part in the reaction. The sharp peak with a maximum at 14.2 eV is attributed to the reaction



In addition to the negative ion, this reaction results in an excited hydrogen atom. Above 17.2 eV the electron has sufficient energy for the production of both a positive and a negative ion, and this energy is thus the threshold for the reaction



This reaction shows a rising cross section at the highest electron energies used by Schulz. Measurements at higher energies by Khvostenko and Dukel'skii<sup>6</sup> show the cross section is still rising linearly at 38 eV, the highest energy for which these measurements are available. These data, which are included as the dashed line in Fig. 1, indicate a cross section in excess of  $3.5 \times 10^{-20} \text{ cm}^2$  at this point.

Each of the reactions discussed in connection with Fig. 1 can contribute to the  $\text{H}^-$  production; however, it is the simultaneous production of  $\text{H}^-$  and  $\text{H}^+$  above 17.2 eV that would seem by far the most important. Here the cross section remains high over the broad spectrum of electron energies available in the ion source. It is perhaps more important, however, to recognize that the basic unit with which each of these reactions starts is the hydrogen molecule. Any of the many competing processes within a discharge which results in ionization or dissociation of this basic molecular



unit is detrimental to negative ion production.

If the reactions described are important for the production of the negative ions observed, it would seem that special attention should be given to maintaining an abundance of molecular gas in the immediate region of the arc where the negative ions are to be extracted. In the previously reported work with hot-cathode sources<sup>5</sup> the gas was fed into the arc chamber near the cathodes, and as with most ion sources, the arc plasma column was located immediately behind the ion exit slit. In line with the above reasoning neither condition would seem ideal.

The attempt to incorporate these considerations into an ion source geometry is illustrated in Fig. 2. Gas is fed into the arc chamber directly in the region of the ion-extraction slit. In addition, the plasma column has been defined so as to be recessed from the ion-exit slit. This allows the incoming molecular gas to completely surround the discharge column in the region where any negative ions formed can be extracted from the discharge chamber. The arc-defining hole, located directly below the heated cathode, is  $3/32$  in. in diameter. The remainder of the arc chamber is  $3/16$  in. in diameter, and thus the edge of the arc column is recessed from the metal wall by  $3/64$  in. in the region of ion extraction. Aside from these major changes, the arc geometry is essentially the same as that previously described. Among the parameters that remained unchanged was the filament. The filament, cut from 0.150-in. tantalum sheet, has a potential emitting area that is more than  $4-1/2$  times the area of the arc-defining column.

Although the filament would appear much larger than needed, a large

filament is essential for arc operation at high gas flow rates. Under these conditions the majority of the filament heat is supplied by ion bombardment of this cathode, and the added filament mass serves as a heat sink which allows the arc to be run in a controlled manner.

The water-cooled tantalum reflector cathode is electrically insulated from the source structure and can be connected externally to either anode or cathode potential, or electrically isolated so as to allow this electrode to assume its own potential.

Attempts were made to minimize gas leaks from the arc structure so that the chamber pressure would be largely a function of the size of the ion exit slit. Figure 3 shows the test source structure equipped with a  $0.5 \times 3/64$ -in. ion exit slit.

Figure 4 shows the ion source installed in operating position. The source is pictured inside the vacuum vessel, which is between the pole tips of an 18 x 36-in. magnet. It is operated in a mass spectrometer arrangement with the extractor electrode at ground potential and the source structure biased negatively in order to extract the ions. With these polarities, a sizable electron current is also removed from the plasma in the slit region. These electrons migrate in small trochoids along equipotential lines normal to the magnetic field. Unless these electrons are intercepted, they will make their way to the high-voltage insulator on which the source structure is supported, thereby causing breakdown. They are removed by providing a component of electric field in line with the magnetic field. This electric component, provided by a carbon block (F in Fig. 2), causes these electrons to be dumped into the water-cooled copper

cup shown in Fig. 4. As these electrons are dumped at full ion extraction potential, the cup was designed to dissipate several kilowatts of power. This eliminated the gas bursts caused by local heating, and the source could be operated continuously for long periods of time with no great difficulty, even at the higher system pressures.

Two ion-beam-monitoring Faraday cups were used. One was located at the 180-deg focal plane of the spectrometer and was used for mass analysis. This cup was movable, its position being determined by a lead screw which could be controlled from outside the vacuum system. The other cup, which could be positioned closer to the extractor electrode, was used when higher magnetic field operation would not allow the extracted ions to reach to the minimum position of the analysis Faraday cup. The size of this cup was such as to allow changes in ion Larmor radius without the necessity of changing cup position. This cup could be raised out of the beam, thus allowing the ion beam to be read by the traveling Faraday cup. In that both cups operate within the magnetic field no difficulty with secondary-electron effects was encountered. Faraday cup bias, though available, was not necessary to obtain reliable readings, and both cups repeatedly gave identical ion-current readings. These Faraday cups are both shown in Fig. 4.

Vacuum was provided by a 14-in. oil diffusion pump. The system was equipped with single  $-80^{\circ}\text{F}$  mechanically refrigerated baffle, resulting in an effective pumping speed for hydrogen of approximately 5000 liters/sec. The base pressure of the system during these operations was  $2 \times 10^{-7}$  mm/Hg.

Initial operation was with deuterium gas so that the performance of

the modified arc geometry (Fig. 2) could be compared with the previously reported data.<sup>3</sup> It was immediately apparent that the output of the modified source, under similar operating conditions, had improved. The diode and FIG-type methods of source operation were compared and the results for one gas flow rate are shown in Fig. 5.

In the diode type of operation, the lower electrode (B in Fig. 2) is returned to anode potential. Electrons from the cathode thus make only a single transit through the arc chamber before striking this lower electrode. The electrons are therefore not efficiently used, and a higher arc current is required. In this style of operation, the arc voltage is quite critical, with a definite peak occurring for the gas flow rate shown in Fig. 5 at about 100 volts. The modifications improve the diode style of operation by about a factor of two.

In the Philips ion gauge type of operation (FIG), where the lower cathode becomes an electron reflector by being connected to the same potential as the upper cathode, the comparative improvement is greater. Where a peak negative ion current of 0.2 mA was previously available at 1 A of arc current, now an output of nearly 1 mA is available, or improvement by a factor of 5. It is interesting to note that the ion current decreases, in this style of operation, at the higher arc currents. If the electron density, for a given gas density, becomes too high, the competing processes which reduce the molecular gas content can increase owing to multiple collisions. The result is an increase in dissociation and ionization. This process would not be detrimental for positive ion production, and for a source designed to produce protons a similar fall-off with increasing

arc current would not be expected.

With the arc recessed from the ion exit slit, a higher arc current can be tolerated before these competing processes become dominant.

The diode type of operation, though effective for producing high negative ion currents, requires a high arc current. As the electrons make a single transit through the gas, their energy must be optimized in the region of the ion exit slit. In meeting that requirement in this geometry, the electrons are left with considerable energy when they strike the lower electrode, and the cooling of this electrode becomes difficult. In these tests it was not uncommon to melt the lower tantalum electrode at the arc currents required to maximize the negative ion output. Because of this difficulty, work concentrated on the use of the more efficient FIG style of operation, with the lower electrode serving as an electron reflector.

Operation with hydrogen showed the  $H^-$  output to be as high as the  $D^-$  current. The  $H^-$  output of the source at a number of arc currents and gas flow rates is shown in Fig. 6. It can be seen that the optimum arc current is a function of the gas flow rate. As the gas flow rate is increased the optimum arc current also increases, and at the higher gas flow rates this optimum has not been fully attained. The optimum arc voltage also increases with gas flow rate. At lower gas flow rates an arc voltage of  $\approx 250$  V is best. At the higher gas flow rates shown, an arc voltage of 350 V is required. Ions bombarding the heated filament at this energy provide considerable filament heat, and it is at this point that the use of a large filament becomes important.

The maximum current obtained at each of the various gas flow rates

in Fig. 6 is replotted in Fig. 7 along with the vacuum system pressure. It is rather interesting to note that the points fall on a line with a slope indicating that the negative ion current available is directly proportional to the gas flow rate. From the slope of this curve one could expect to determine the magnitude of gas flow rates that would be required to obtain higher negative ion currents than the 5.3 mA obtained with a rate of about 30 cc/min (STP). At this gas flow rate the test system pressure was  $6 \times 10^{-5}$  mm Hg, and nearing the pressure at which high-voltage sparking would become intolerable. In addition, either a larger filament or additional filament cooling capacity would be required. At this point the filament power had been reduced nearly to zero in order to maintain the required arc potential.

The ion beam outputs shown in Figs. 6 and 7 were emission limited. Although the arc was operated with an extraction potential of 12.5 kV, the arc was essentially emission limited at about 8 kV, and no additional ion current was extracted as the voltage was increased beyond that point. With the output being emission limited, one could expect the size of the extraction slit to be an important parameter. Decreasing the slit size should reduce the ion output available accordingly--however, this decrease in the slit area also increases the arc chamber pressure at a given gas flow rate. This in turn should result in an increase in the number of negative ions available. To check the effect of slit size on ion output, the arc slit length was reduced from 1/2 in. to 1/4 in.; these results are also plotted in Fig. 7. The 50% decrease in slit area resulted in beam current that averaged 65% of that previously available. The resultant increase in ion current density indicates a higher arc pressure for a given

gas flow rate.

In an attempt to obtain a higher total ion current, the length of the ion exit slit was increased to  $3/4$  in. The ion currents obtained are not plotted in Fig. 7, but the points obtained were only slightly higher than the ion outputs from the  $1/4 \times 3/64$ -in. slit. In this case the loss of ions by the pressure reduction is proportionately larger than the ions gained through the increase in extraction area. The original slit geometry thus seems to provide the best compromise for the geometry tested.

Electron drains, which closely approximate a space-charge-limited condition, were directly proportional to slit area. With the longest extraction slit, in fact, the increased electron drain was effective in promoting premature high-voltage breakdown at the higher gas flow rates.

Operation of this basic design as a source of negative ions inside a cyclotron would require that it operate efficiently in the presence of high magnetic field intensities. To determine the effect of high magnetic fields on the beam properties in the test spectrometer arrangement is difficult, however. As the magnetic field is increased, the Larmor radius of the extracted ion decreases so that for the levels of extraction potential that can be maintained, beam monitoring is impossible. Aside from beam monitoring, no difficulty in source operation was experienced with magnetic fields as high as 20 kG. Beam characteristics for the monitoring geometry (pictured in Fig. 4) at several magnetic field levels are shown in Fig. 8. As the magnetic field is increased, more voltage is required for the beam to reach the beam-monitoring Faraday cup. The beam current, however, reaches the point of emission limitation with no change in

intensity. Beam currents were monitored in magnetic fields as high as 9 kG and no large decrease in ion current was observed.

Electron drains as shown in Fig. 8 decrease with increasing magnetic field. Recessing the arc column from the ion exit slit greatly reduces the electron drain. For example, under comparable conditions of magnetic field and extraction potential, recessing the arc column reduced the electron drain from 200 mA to 30 mA, nearly a factor of 7.

Additional work, using deuterium in fields as high as 10 kG, indicated there was some decrease in ion output with increasing magnetic field. As the magnetic field was increased, extraction potentials in excess of those calculated were required to obtain the full emission-limited ion output. As the magnetic field is increased, the arc plasma column can be more constricted with less diffusion of the plasma normal to the field. Thus higher extraction potentials may be needed to provide sufficient electric gradient at the effective plasma surface to remove the ions. It is possible that for operation at high magnetic field levels less physical recession of the arc column than the  $3/64$  in. used here would be required. In this study, this parameter remained unchanged.

Many cyclotron ion sources use a floating reflector cathode (B of Fig. 2). During these tests, this electrode, which was normally connected electrically to the heated cathode, was allowed to float. In each case there was a noticeable decrease in negative ion output. The amplitude of this decrease varied somewhat with arc conditions, but in general ranged from 20 to 30%.

For cyclotrons with the usual internally located ion source, the



maximum negative ion current that can be made available for acceleration will be a function of the pumping speed of the vacuum system. In general, the gas flow rate that can be accommodated before ion loss by residual gas scattering becomes excessive will limit this current to small fractions of a milliampere. Should the ion source be externally located, however, so that differential pumping can be employed, this limitation can be removed and the full output of the source can be made available.

Ions have been injected axially through the center of the magnet of the University of Birmingham's radial-ridge cyclotron.<sup>7</sup> A similar method is illustrated in Fig. 9, in which the beam enters the machine through a hole in the magnet and is deflected into the dee aperture by means of an electrostatic beam deflector. The ion source, which utilizes a separate magnet and vacuum system, is operated in the manner successfully employed in the injector of the Berkeley heavy-ion accelerator.<sup>8</sup> Here the converging ion beam enters the axial beam tube after traveling approx 110 deg in the source magnet.

Because the beam emerges from a slit and is then subjected to a focusing force normal to but not in line with the source magnetic field, some astigmatic correction is required. In the diagram (Fig. 9) this correction for astigmatism is provided by the box-type lens.

The largest deterrent to easy beam control is usually the space-charge (or Coulomb) repelling forces within the ion beam itself. In the negative ion beams observed in this work, these forces seem extremely weak and should present little difficulty in beam control.

Figure 10 is a time exposure of the light created by a 5-mA beam of

negative hydrogen ions as they emerge from the ion source and are deflected by the magnetic field. As can be seen, the beam effectively preserves its ribbon-like characteristic as it is bent through 180 deg.

#### ACKNOWLEDGMENTS

I sincerely appreciate the interest expressed in this work by Dr. J. R. Richardson and Dr. B. T. Wright of UCLA. It was through their support that this work was possible. The continued interest and consideration of Dr. C. M. Van Atta of this Laboratory are also gratefully acknowledged.

FOOTNOTE AND REFERENCES

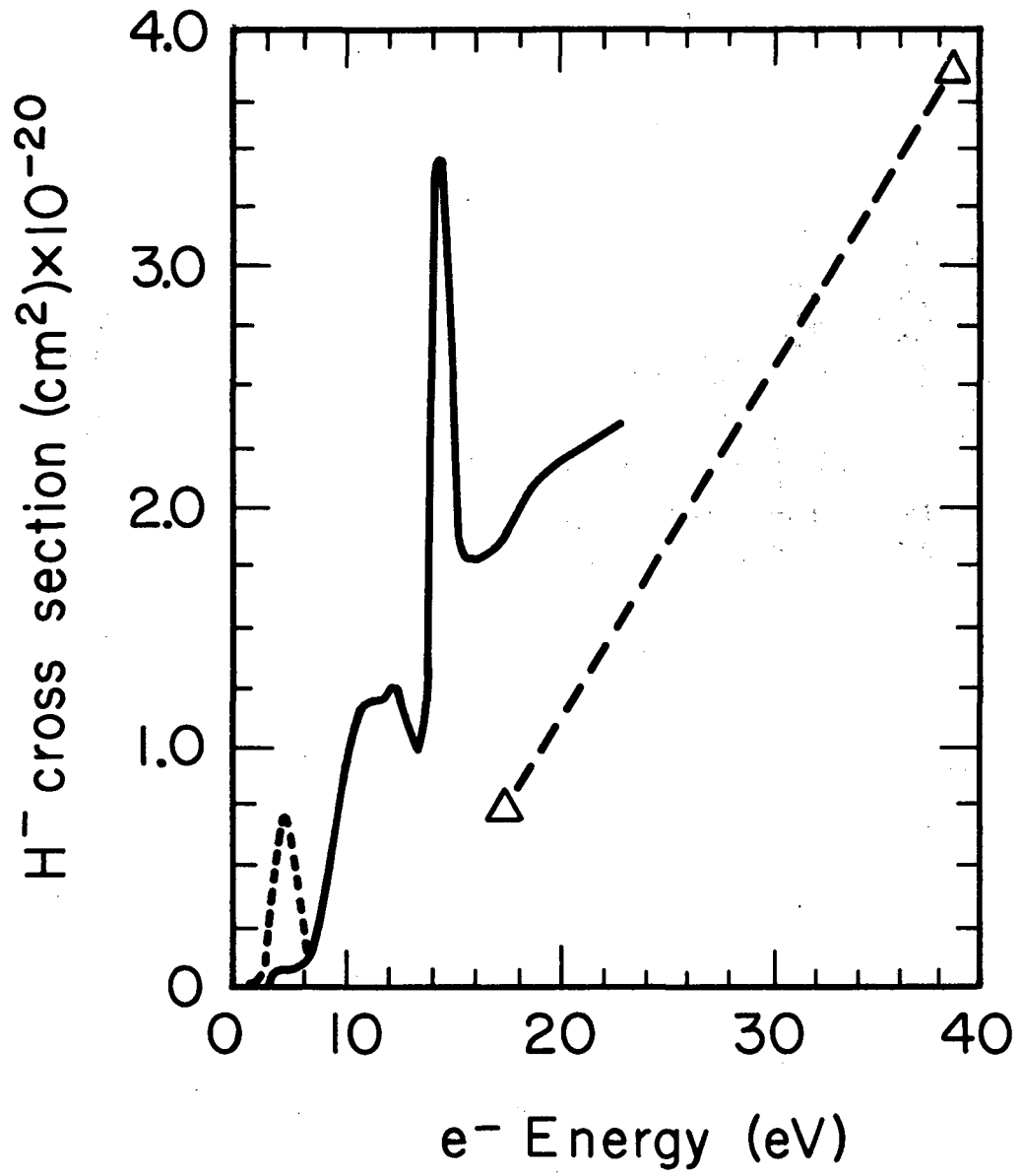
\*Work done under the auspices of the U. A. Atomic Energy Commission

1. M. E. Rickey and R. Smythe, Nucl. Instr. Meth. 18, 66-69 (1962).
2. J. R. Richardson, J. Verba, and B. T. Wright, Bull. Am. Phys. Soc. 7, 431 (1962).
3. K. W. Ehlers, B. F. Gavin, and E. L. Hubbard, Nucl. Instr. Meth. 22, 87-92 (1963).
4. B. T. Wright, Archiv. Matematik og Naturvidenskab, Liv. B, Nr. 2, 9-18 (1957).
5. G. J. Schulz, Phys. Rev. 113, 816-819 (1959).
6. Khvostenko and Dukel'skii, Zh. Eksperim. i Teor. Fiz. 33, 851 (1957)  
JETP (English transl.) 6, 657 (1958) .
7. A. J. Cox, D. E. Kidd, W. B. Powell, B. L. Reece, and P. J. Waterton, Nucl. Instr. Meth. 18, 25-32 (1962).
8. E. L. Hubbard et al., Rev. Sci. Instr. 32, 621-634 (1961).

FIGURE CAPTIONS

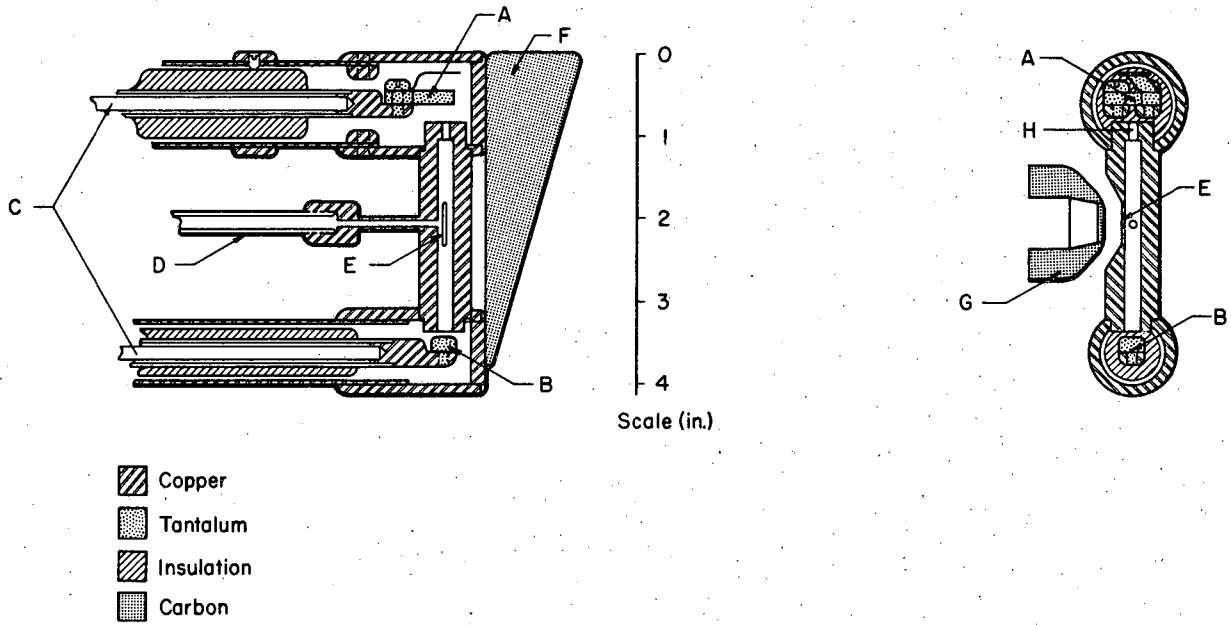
- Fig. 1  $H^-$  cross section as a function of electron energy.  $\Delta$ : data from reference 6.
- Fig. 2 Cross-sectional drawing of the modified ion source geometry.
- A: heated filament
  - B: cold reflector cathode
  - C: water-cooled squirt tubes
  - D: gas feed line
  - E: ion exit slit
  - F: trochoidal electron dump block
  - G: ion-extracting electrode
  - H: arc-defining hole.
- Fig. 3 Negative ion source assembly.
- Fig. 4 Ion source in operating position.
- A: ion-extracting electrode
  - B: water-cooled electron receiver
  - C: traveling Faraday cup
  - D: test Faraday cup.
- Fig. 5 Increased negative ion current as a result of modification of arc geometry. Original geometry:  $\bullet$  - diode,  $\Delta$  - PIG type; modified geometry:  $\circ$  - diode,  $\nabla$  - modified.
- Fig. 6 Beam current of  $H^-$  ions obtained from the PIG-type discharge with changing arc current and gas flow rate. Extraction potential, 12.5 kV; magnetic field, 3.5 kG.

- Fig. 7 Relation between negative ion current output and system pressure as a function of gas flow rate.  $\nabla$ : system pressure;  $\square$ : ion current, larger slit;  $\circ$ : ion current, smaller slit.
- Fig. 8 Electron drain and ion output as functions of magnetic field.
- Fig. 9 Axial injection of negative ions into cyclotron from an externally located ion source.
- Fig. 10 3-mA  $H^-$  beam in mass spectrometer. System pressure,  $4 \times 10^{-5}$  mm Hg.



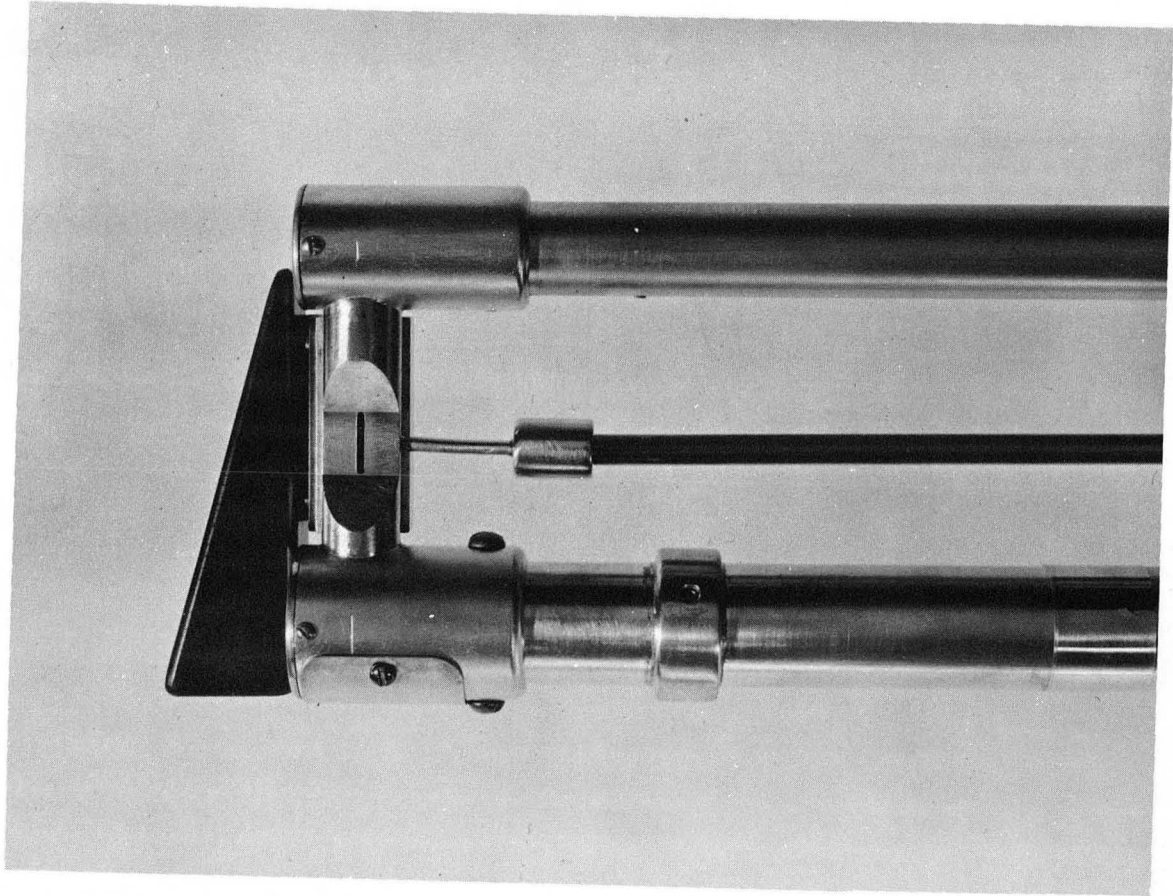
MUB-3232

Fig. 1



MUB-3233

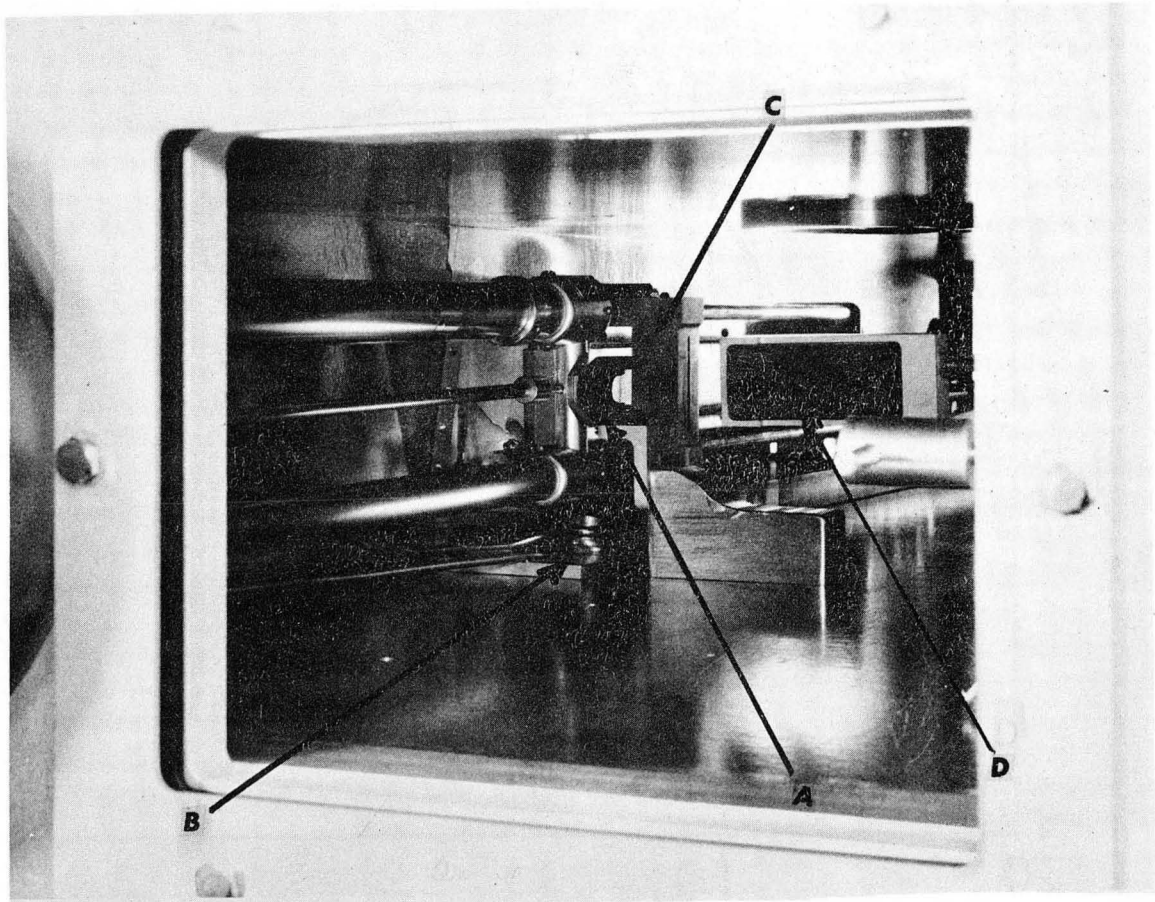
Fig. 2



ZN-4383

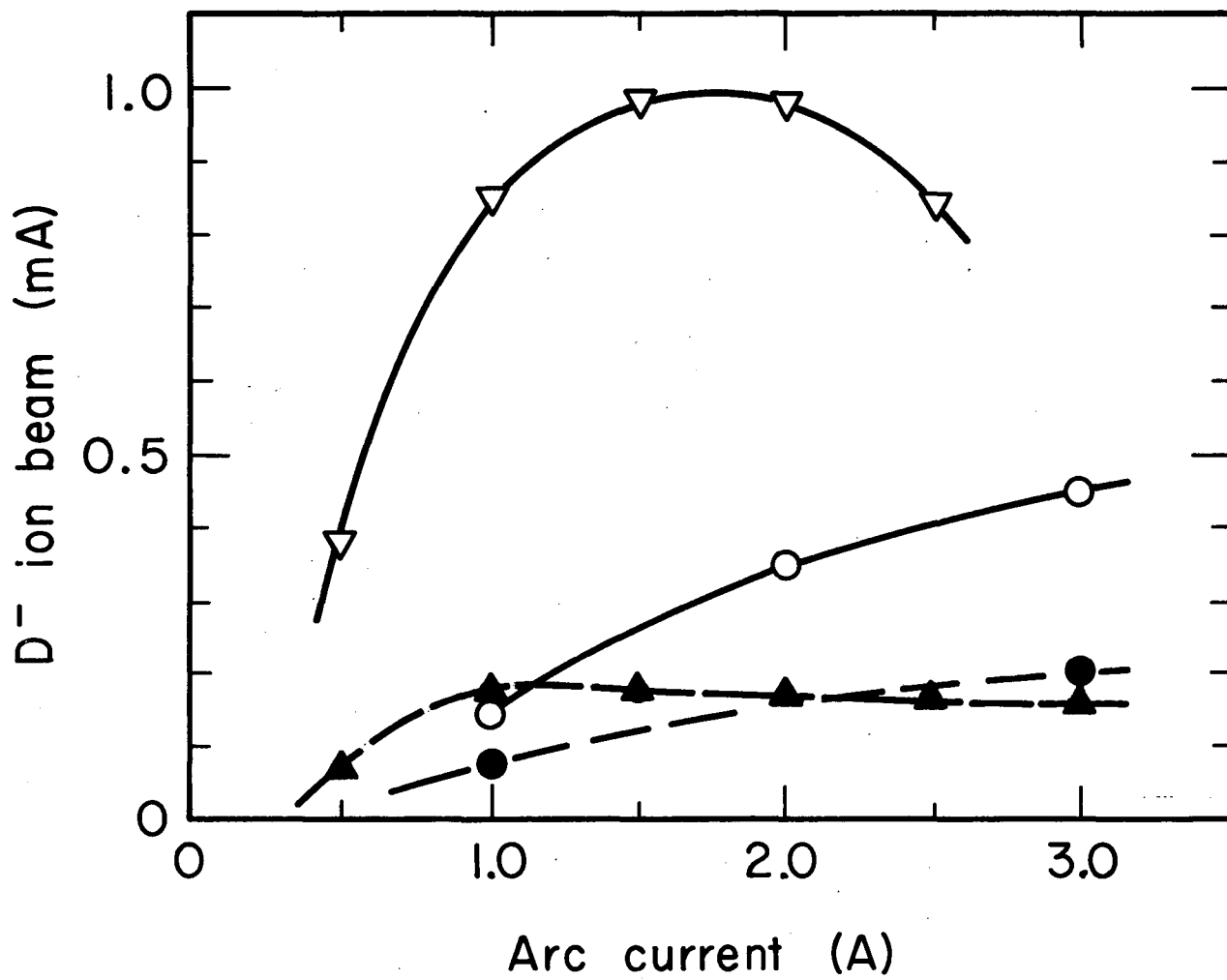
Fig. 3





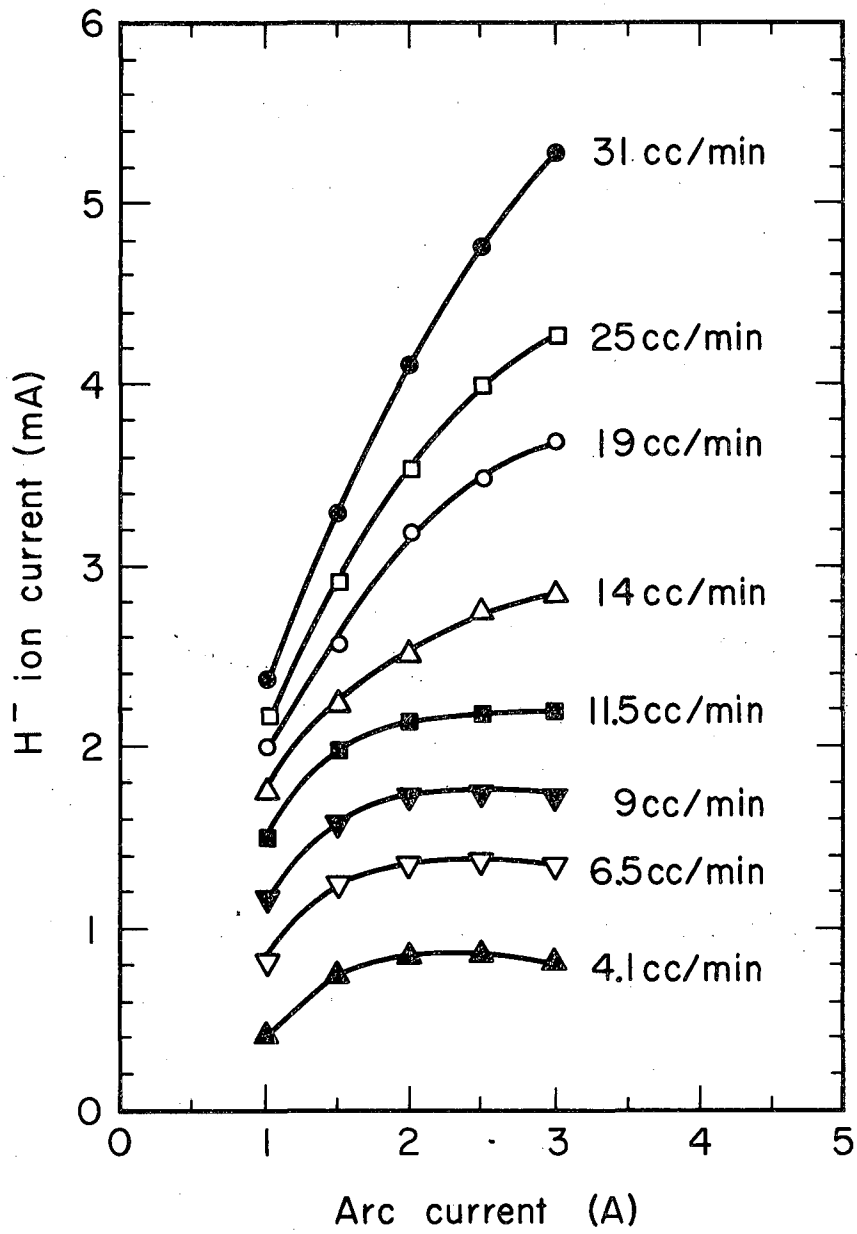
ZN-4345

Fig. 4



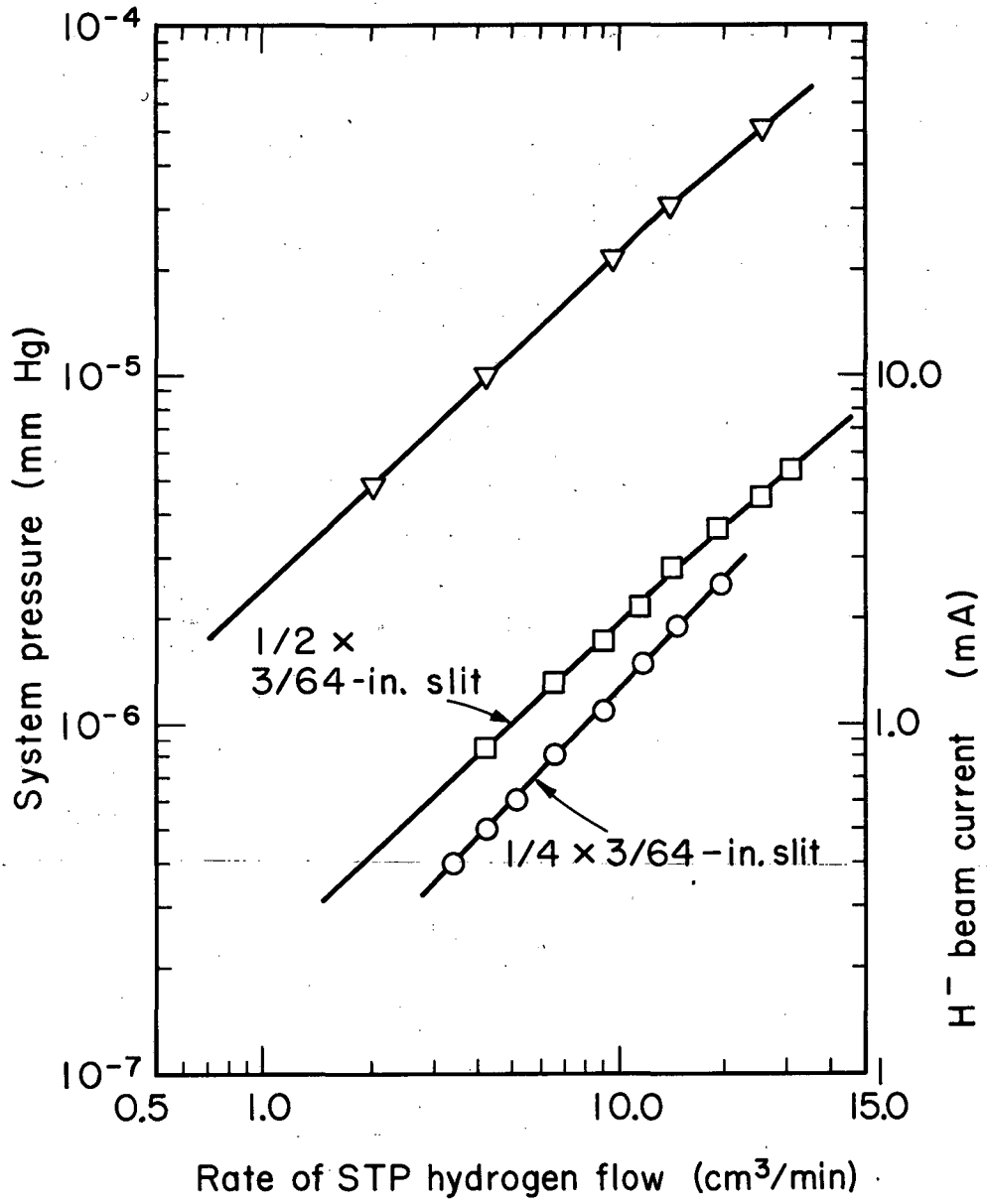
MUB-3234

Fig. 5



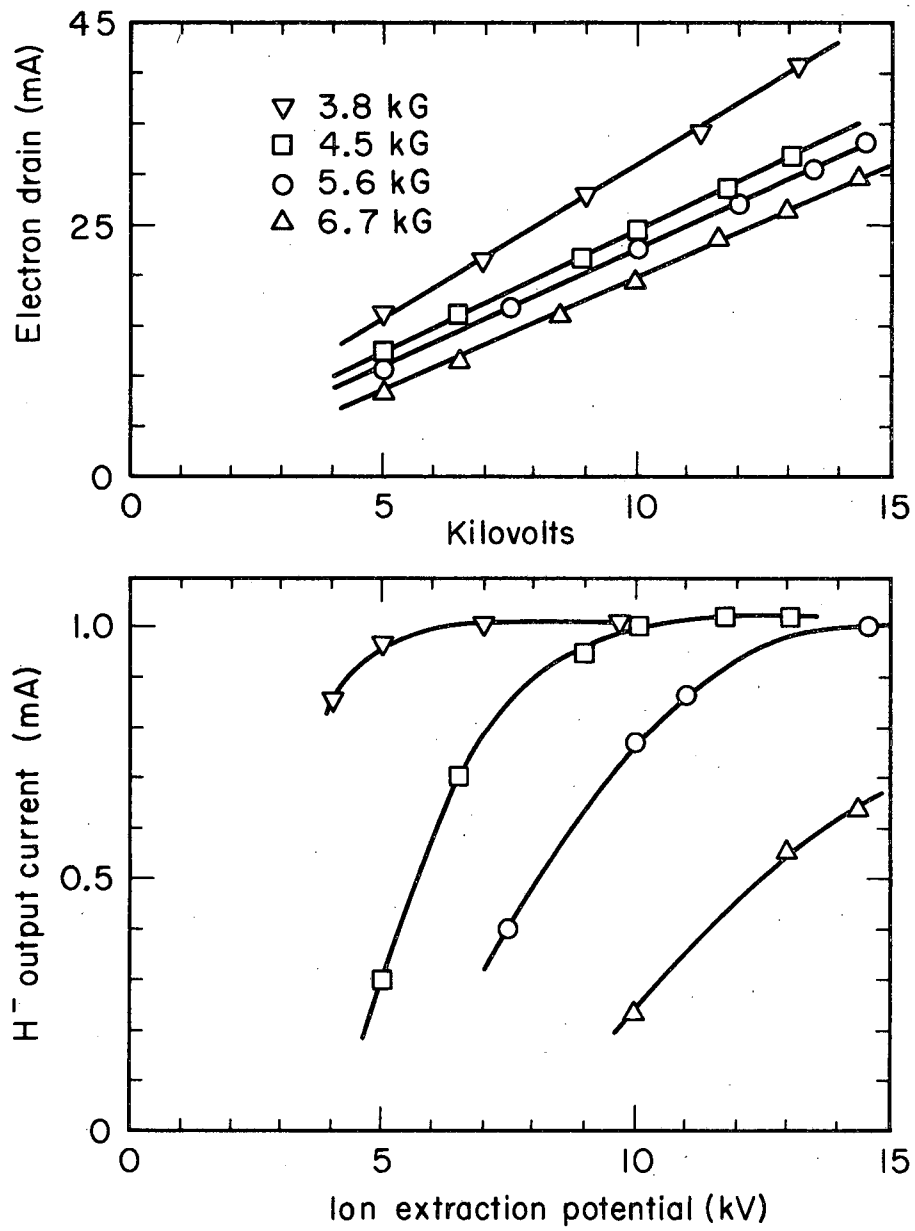
MUB-3235

Fig. 6



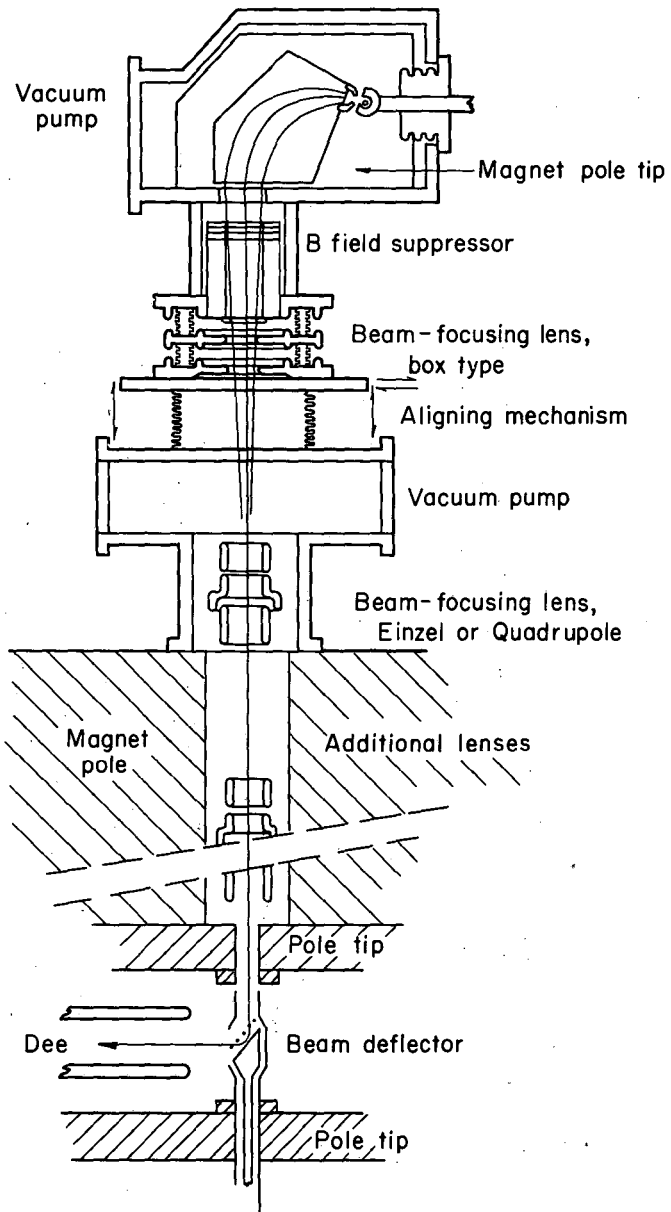
MUB-3236

Fig. 7



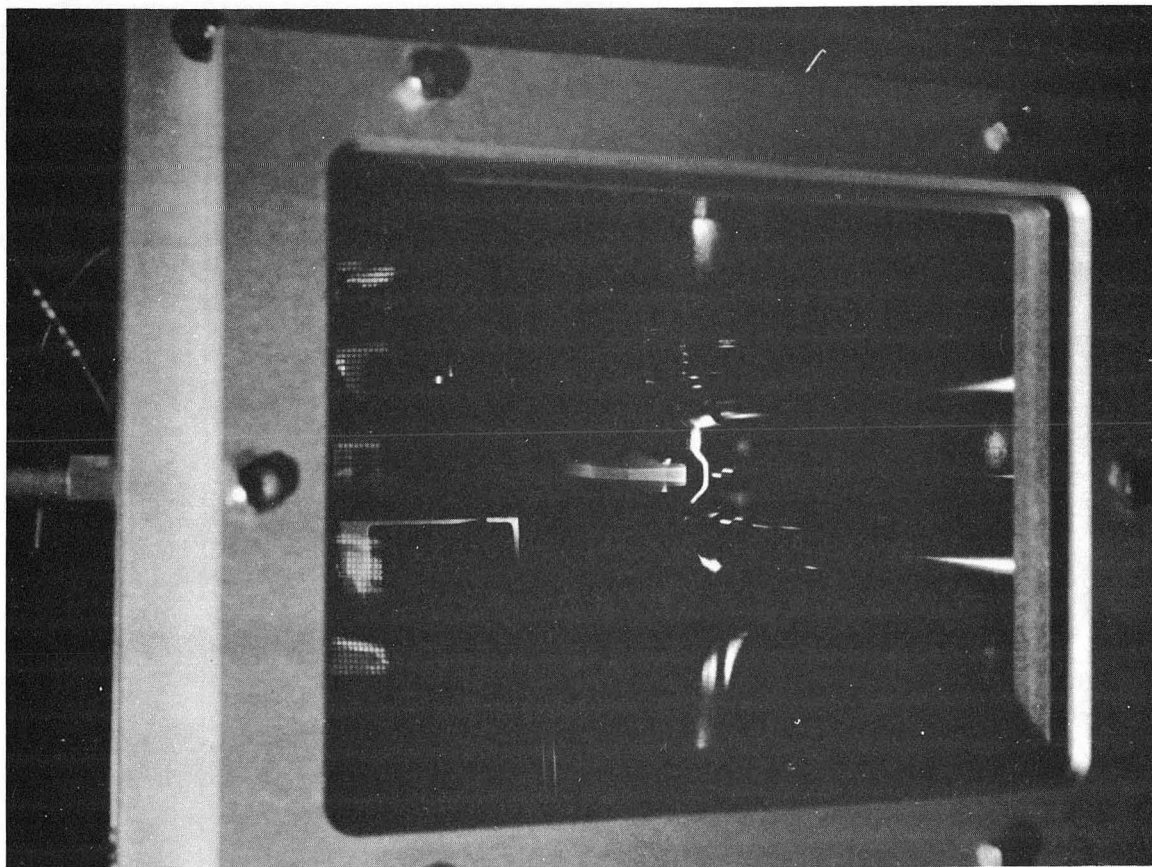
MUB-3245

Fig. 8



MUB-3237

Fig. 9



ZN-4382

Fig. 10

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.



