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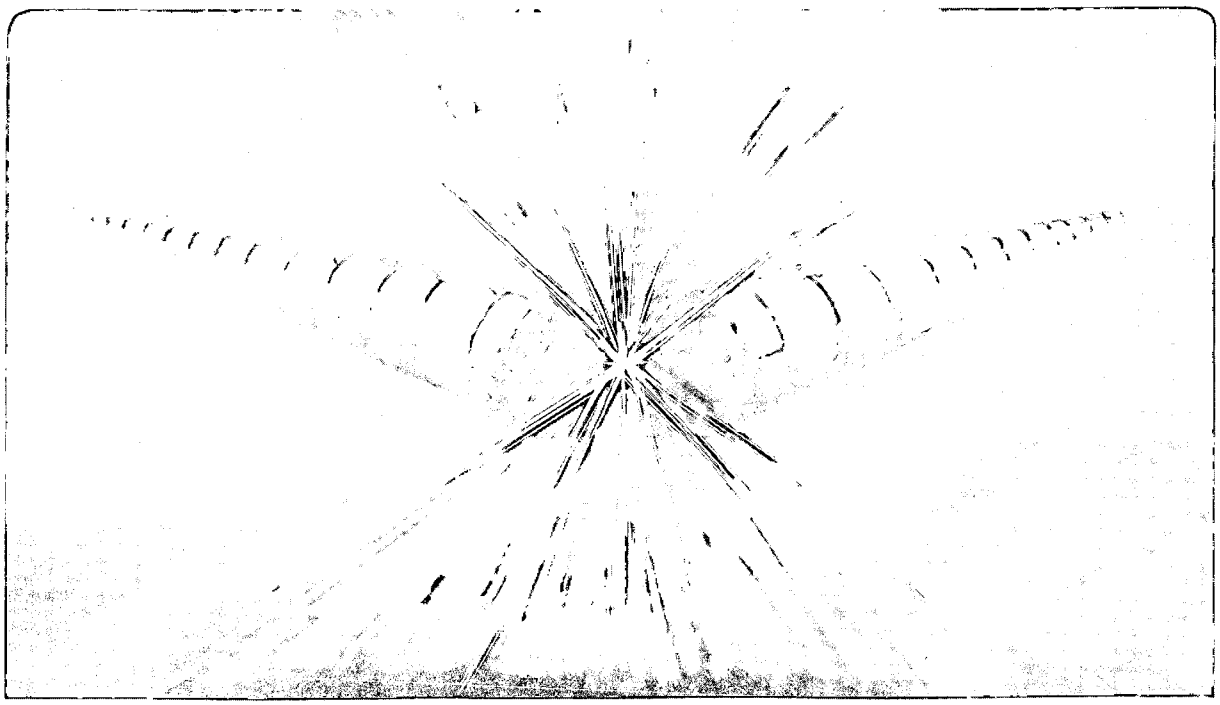

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# NEGATIVE ION SOURCES FOR NEUTRAL BEAM SYSTEMS*

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Neutral beams to heat the plasmas of controlled fusion experiments are generated by neutralizing the charge of positive ions after they have been focused and accelerated. The efficiency of this system decreases with ion velocity and, for $D^+$, the system is practical only at ion energies of less than about 150 keV, which is less than the energies expected to be required in the future. However, the use of negative ions, where neutralization is accomplished by removing, rather than by adding electrons, allows much higher ion energies to be efficiently employed. Programs to develop sources of large currents of $H^-$ and $D^-$ are therefore under way. There are three principal methods of generating negative hydrogen ions, and sources using one or another of these methods are being investigated at fusion laboratories in the U.S., Europe, and Russia. The goal is to produce practical sources which can supply ampere beams of continuous, impurity-free, negative hydrogen ions in geometries that can be extended to even larger currents. This paper briefly describes the three main methods of producing negative ions and the advantages and disadvantages of each.

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Negative Ion Sources for Neutral Beam Systems

## 1. INTRODUCTION

The plasma parameters needed to provide a sustained controlled nuclear fusion reaction are extremely difficult to attain. The plasma must first satisfy the Lawson criterion,[1] which states that the product of the ion density times the plasma confinement time must be greater than $10^{14}/cm^3$. Then, before a reaction can be obtained, the ions in the plasma must be extremely hot. For a deuterium-tritium plasma, ion temperatures must exceed about $10^8$ C. Only in the last decade have plasma temperatures of this magnitude been obtained in magnetically confined fusion experiments, and this has been accomplished by injecting large equivalent currents of energetic neutral atoms into the plasma. Neutral atoms are required as they can pentrate the sizable magnetic fields needed to confine fusion plasmas. To date, these neutral beams have been obtained by accelerating very large currents of positive deuterium ions which are generated in large-area plasma sources.[2] These accelerated ions are then converted to energetic neutrals in a single charge-exchange reaction by passing through a deuterium-filled gas cell. The neutralization efficiency of this process is a function of the ion energy.(Fig. 1.) For the atomic $D^+$ ion, this charge exchange process peaks at approximately 20 keV and then decreases steadily as the ion energy is increased. The practicality of the process begins to fail when the required neutral beam energy exceeds about 150 keV.

When these energetic neutral atoms penetrate the reacting plasma volume, they are reionized. The position within the plasma where the reionization occurs is energy senstive. If an atom is reionized near the edge of the plasma, it may be thrown out of the plasma and onto the containment wall by the magnetic field. Thus the velocity of the injected neutrals is an important consideration for plasma penetration and plasma profile control.

The need for higher neutral atom velocities will be even more important as reactor sizes and plasma densities are increased. These are some the reasons why designers of the next generation of controlled fusion experiments have determined that neutral beams with energies considerably in excess of 150 keV will be required.[3]

Fortunately, as shown in Fig. 1, there is an alternative approach: accelerate negatively charged hydrogen or deuterium ions. A gas cell similar to those employed in present positive ion technology, can raise the conversion to neutrals at 150 keV from about 30% to 60% by using negatively charged deuterium ions. But, more important, this efficiency does not decrease even at very high energies. For the negative ion, a number of other charge-neutralizing processes become possible. The use of a high density plasma rather than a gas cell has been shown to convert nearly 85% of a 500 keV $H^-$ ion beam into neutrals.[4] Both of these processes suffer from the fact that an entering negative ion can have two electrons removed, and this results in the production of unwanted $D^+$ ions. Recently, a third process, namely the photon or laser neutralizer has received careful attention.[5] In this case, a large flux of photons with a frequency at or near the peak of the photon stripping cross-section ($h\nu$=1.5eV, $\lambda \cong$8,000 A) is required. The laser neutralizer is particularly appealing as it provides a number of important system advantages. In principal, it would permit neutralization efficiencies close to 100%. In addition, the finite photon energy will not produce $D^+$ ions, nor will it neutralize heavy mass impurity ions as these in general have higher electron attachment energies. The use of a laser neutralizer would also eliminate the need to introduce gas near the entrance to the fusion plasma, thus eliminating the stringent pumping requirements which a gas cell would require.

Because of the probable need for higher neutral beam injection energies,

fusion laboratories in the U.S., France, England, and Russia have started programs to develop negative-ion-based neutral beam systems. The first problem of course, is to generate the large currents of $D^-$ ions that are needed, and to make such a source compatible with other beam line considerations. In general, the goals are to generate and accelerate continuous or very long pulse, multi-ampere beams of contaminant-free hydrogen or deuterium negative ions. These are sizable goals, particularly since it was not too long ago that a few milliampere beam of $H^-$ was quite impressive. The problems of beam generation are compounded by the sign of the charge. The potential that accelerates $H^-$ ions also accelerates the ever-present electron, and the problem of electron rejection must be considered from the very start.

There are three main methods now used to produce negative hydrogen ions: charge exchange, volume production, and surface production. This paper will describe these three systems and the advantages and disadvantages of each as part of a total neutral beam system.

## II. CHARGE EXCHANGE METHOD

In this method, focused beams of fast positive hydrogen ions are changed into a beam of negative ions by passing the beam through a gas or vapor cell (Fig. 2). The initial part of this system is similar to the present positive-ion neutral beam systems, except that the first gas cell is altered to produce a double-charge exchange reaction, adding two electrons to the incoming positive ion instead of just one. If this cell contained hydrogen or deuterium, as in positive-ion systems, about 2% of the incoming $H^+$ positive ions, if accelerated to about 10 keV, would be converted into negative ions. As this reaction is velocity-dependent, a $D^+$ ion would have to be accelerated to 20 keV to reach the same velocity (Fig. 3). At these same energies, according to Fig. 1, about 90% of the incoming ions

would leave as neutral atoms, the remainder leaving as positive ions. Both the neutralizing and double-charge exchange reactions are reversible and thus one needs only enough gas in the cell to equilibrate the final charge state distribution. The required line density for most neutralizer or charge exchange cells is on the order of $2 \times 10^{15}$ $cm^{-2}$, where line density is the product of gas density in molecules per $cm^3$ times the length of the cell.

For a practical double-charge exchange cell at such densities, a more efficient-cell medium is needed. Figure 3 shows the conversion efficiency for a number of elements holding the most promise. A vapor of cesium or strontium, for instance, yields conversion efficiencies ($F_-^\infty$) of 30% to 50%. There is a price to pay, however: in materials that produce a higher $F_-^\infty$, the peak occurs at a much reduced ion energy. The maximum for strontium, for example, is only 500 electron volts for $D^-$ ions (250 eV for $H^+$). At this reduced potential, the extraction of reasonable ion current densities from a plasma source becomes difficult. The extraction current density, is a function of the 3/2 power of the extraction potential ($j^+ = K V^{3/2}/x^2$), where x is the electrode gap. The gap can be reduced, but it in turn is sensitive to the aspect ratio of the extraction apertures. Thus accel-decell electrode structures are usually employed.[6]

The first use of the double-charge exchange process to form negative hydrogen ion beams for accelerators occurred about 1950. Beams of $H^-$ ions were needed to utilize the "Swindletron" method of ion acceleration proposed by Alvarez.[7] Negative hydrogen ions, accelerated from a source at ground potential, were converted to positive ions by losing two electrons when passing through a thin foil mounted in the positive high-voltage terminal. The positive ions were then reaccelerated back to ground potential, resulting in a final energy that was twice the power supply potential. Although it was known that small currents of $H^-$ ions (.02 μA) could be extracted

directly from a plasma, particularly if water vapor was added to the gas,[8] the double-charge exchange process was employed to obtain larger currents as well as to reduce the problem of extracted electrons.

These early sources,[9] which used hydrogen gas in the conversion cell, were very rich in molecular positive ions; if these positive ions were extracted at voltages near 20 kV, higher $H^-$ currents were obtained. The extracted molecular ions were dissociated in the gas cell, leaving two atomic atoms or ions traveling near the optimum velocity to charge exchange to $H^-$, in a 1- or 2- step process. These sources produced negative hydrogen beams of 10 to 30 μA. In 1964, a single-aperture source that achieved nearly 1 mA of $H^-$ was developed at High Voltage Engineering.[10] Since this source, which was developed for use with tandem Van de Graaff accelerators, had a large $H_3^+$ content, these positive ions could be accelerated into the conversion gas cell with three times the optimum potential shown in Fig. 3.

To generate much higher $H^-$ currents than those available for accelerators, two developments were needed. The first was the introduction of very large area plasma sources with large currents of positive ions extracted from many apertures; the second was the realization that high conversion efficiencies were available with cesium instead of hydrogen in the conversion cell. In 1966, Drake and Krotkov reported that cesium vapor was an efficient converter of incident deuterons into negative ions. They observed that at 1 keV, 25% of the positive current could be converted to negative ion current if they used ~10 mTorr centimeters of cesium vapor.[11] Using these techniques, Osher et al.[12] obtained a $D^-$ beam of 50 mA with a mean density of several $mA/cm^2$. This was extended to 300 mA by Hooper et al.,[13] who accelerated about 100 mA of this beam to 60 keV.

Today, only Geller et al.[14] in Grenoble, France, use double-charge

exchange in cesium to generate $D^-$ ions for neutral beams. This program, jointly sponsored by the French and Swedish governments, uses a gas-efficient ECR source to generate the positive ions. Because the source requires a magnetic field to operate, ($\sim$4 kG), the field is lengthered to include the ion accelerator, the cesium vapor cell, and the stripper neutralizer. In the most recent results[15] 80 mA of $D^-$ were observed at the exit of the cesium cell, with 30 mA accelerated to 30 keV in 4-second pulses.

The work with cesium, while demonstrating that conversion efficiencies of over 30% can be realized, has also shown that it is very difficult to obtain good beam optics with the very low energy ions needed to obtain this efficient conversion. Attention has thus turned to the conversion of large-area beams by charge exchange in sodium. The maximum conversion efficiency of sodium is less, but the cross section remains relatively high up to about 10 keV for deuterium (see Fig. 3). This permits operation at energies where beam optics can be better, and where angular scattering of the beam in the charge exchange cell can be reduced. Thus a better quality beam with a reduced current density should result.

In 1977, Semashko et al.,[16] using a sodium conversion cell, obtained $H^-$ beam currents as high as 1.4 A, with a peak current density of several $mA/cm^2$. They obtained an unexpectedly high conversion efficiency of 18% with hydrogen at 10 keV. This they credited to the conversion of the diatomic and triatomic positive ions. This 10 ms $H^-$ beam was accelerated to 40 keV, resulting in the co-acceleration of about twice as many electrons as negative ions. This work is continuing, but the results of the past several years are not known.

In 1980, Hooper et al.,[17] using double-charge exchange in sodium, obtained a 2.2 A beam of $D^-$, with a current density of about 12 $mA/cm^2$

at 10.5 keV. The conversion efficiency was about 8.5%, close to the predicted values. Angular scattering was much reduced at this energy, and the optimum line density of the sodium cell was $10^{15}$ $cm^{-2}$, less than that used by Semashko et al. ($5 \times 10^{15}$ $cm^{-2}$). It is possible that the higher line density allows full dissociation and conversion of the molecular components of the beam, which might explain the difference in two conversion efficiencies. It is not known if this increased line density increases the angular scattering.

Large-area charge-exchange systems require very large area charge-exchange cells. Figure 4 is a cut-away drawing of the sodium charge-exchange cell used by Hooper et al.[17]. This cell had an available aperture of 20 by 50 cm, but was apertured down to 7.5 by 36 cm, the size of the positive ion beam. The geometry is recognizably similar to a standard vacuum diffusion pump; In fact, Semashko et al. reported that their sodium cell, which operates continuously, was capable of pumping hydrogen at 6000 l/sec. The cell can thus be used to reduce the gas pressure downstream, where the negative ions would be accelerated. Reducing the pressure in this region is extremely important due to the ease of distruction of the negative ions by charge exchange in the background hydrogen gas. Indeed, it is this cross-section which is our public enemy #1 ($H^- + H_2 \longrightarrow H + H_2 + e^-$). Figure 5 shows this cross section versus negative ion energy. For example, if a 10 keV beam of $H^-$ were to exit the cell into a region where the pressure is $10^{-4}$ mm, one would suffer a 30% loss per meter of length. Thus, sources with good gas efficiency are required along with considerable cryo-pumping capability.

In summary, the double charge-exchange method can produce multi-amperes of $H^-$ and $D^-$. The ion current densities are not high, so to attain large currents one must use large areas. The process has two advantages: it

uses large-area ion sources and the experience gained in the positive-ion neutral beam program.

It also has disadvantages: the charge-exchange media that give the greatest conversion efficiencies require very low positive-ion energies, which increases beam optics problems as well as scattering. Also, large-scale experiments to date have not fully faced up to the electron problem. This problem is related to the exit region of the charge-exchange cell, where electrons exist, and a practical method of eliminating the acceleration of electrons at this point has not been demonstrated.

A final problem involves the otherwise beneficial vacuum pumping capability of the charge exchange-cell, where a second pumping action is created by the directed energy of the positive ions and hot gases emerging from the ion source. The magnitude of this problem, has yet to be determined, but the result is to pump sodium or cesium from the cell chamber into the ion accelerator electrodes. This can be expected to result in voltage holding difficulties.

## III. VOLUME PRODUCTION

Within the plasma environment of conventional ion sources, the cross sections of the fundamental processes that can destroy $H^-$ or $D^-$ ions exceed those of known processes that can create these ions by about $10^4$ (Ref. 19). It would thus seem unlikely that negative ion currents could be directly extracted from a plasma. Experiments have shown however, that more negative ions are available from this process than theory would imply. By using several clever diagnostic techniques, experimenters in France[20] determined that, under certain conditions, more than 20% of the ions in the central portion of a hydrogen discharge may be $H^-$. These results have not yet been extended to very high plasma density conditions, nor has it been shown that this high population of negative ions can be extracted. If

confirmed, however, these results would indicate that unknown formation processes exist. One possibility, now receiving theoretical treatment,[21] is that $H^-$ ions are formed from vibrationally excited hydrogen molecules.

The direct extraction of volume produced negative ions from a discharge would allow the large-area ion sources and accelerators that already exist to be used merely by reversing the sign of the extraction and acceleration potentials. This in turn would eliminate the need to use low-work-function alkali metals in a double-charge exchange region or within the source, which may be important for systems required to maintain very high ion acceleration potentials. The big disadvantage of this system, even if adequate extraction current densities of $H^-$ or $D^-$ can be generated, is that the potential which accelerates these ions will also extract and accelerate large currents of electrons. Thus, prior to high voltage acceleration, some provision must be made to remove or separate the negative ions from the electrons.

In 1965, I developed a modified Penning-type ion source to generate $H^-$ for cyclotrons.[22] This source is shown in Fig. 6. Continuous $H^-$ currents in excess of 5 mA could be extracted from this source, with an emission current density of 40 $mA/cm^2$, a surprisingly high $H^-$ current density and the geometry is in use today with a number of isochronous cyclotrons and tandem accelerators. The extractable ion current also increased sizably with increased source pressure, as shown in Fig. 7.

Electrons were also extracted, but because the extraction was E X B and the magnetic field was high, the electrons did not reach the extractor electrode. Instead, they migrated in small trochoids along equal potential lines to where they could be intercepted. They were removed by aligning part of the electric field with the magnetic field, which caused the electrons to be dumped at full extraction potential onto a water-cooled block mounted below the electron dump block. The main source modification

was to relieve the discharge column so that the incoming molecular gas could completely surround the discharge-plasma column. This action was designed to amplify formation reactions that involve molecular hydrogen:

In 1972, in Russia, Bel'chenko, Dimov and Dudnikov[23] introduced a magnetron-type plasma source. (Fig. 8) $H^-$ ions were extracted from the E X B produced plasma from a slit in the anode elongated perpendicularly to the magnetic field. Because of the small size and the very high arc power, pulse lengths of only a few milliseconds were allowed. $H^-$ currents up to 22 mA, with the exceedingly high ion current density of 220 $mA/cm^2$, were extracted. As can be seen in Fig. 8, this source also incorporated a relief between the main body of the plasma and the extractor electrode, but, even though the source pressure was very high (0.2 Torr), the extracted $H^-$ ion current substantially exceeded that expected from known $H^-$ formation and destruction cross-sections.

Scaling up these small volume-production sources to obtain amperes of $H^-$ ions,presents difficulties. The gas efficiency is very poor (<1%). In addition, discharges of this type operating within a magnetic field are often noisy. This noise which is characterize by a variation in ion current density, results in a degradation of ion optics. Although the electron problem is easily solved for a single slit aperture, when one adds longer parallel apertures, the solution is not so simple. And finally, one is required to design optics where the beam is extracted in a magnetic field region, and must then pass to a field free region to be accelerated.

If indeed the negative ion concentration in existing large-area plasma sources is as high as indicated by Bacal et al.[24], these sources could be considered as candidates to produce large negative ion beams. If, for example, the $H^-$ concentration were 10%, large sources producing positive hydrogen ion beams of 65 A could be used to generate 6.5 A of $H^-$, provided, of

course, that some new method could be developed to separate or sizably reduce the extraction of electrons by methods that would not destroy the beam optics.

A recent development termed the "magnetic filter" has shown some promise toward meeeting this objective. Figure 9(a) is a diagram of a small multi-line cusp plasma source of the type used to produce multi-amperes of positive ions. Under normal operating conditions, the potential of the plasma in such a geometry is several volts positive with respect to the chamber wall, which is the anode electrode. The beam-forming electrode floats negative relative to the anode. Thus, while positive ions can drift freely to this extraction electrode, negative ions are electrostatically trapped within the plasma volume, as there is not a more positive electrode for them to be lost to. Although this trapping could account for the unexpectedly large percentage of $H^-$ ions observed in some discharges,[24] it would also make it exceedingly difficult to extract these ions from the discharge. So, before any negative ions can be extracted from the source geometry shown in Fig. 9-A, the beam forming electrode must be connected to anode potential. When this was done for the small test source shown, a small $H^-$ ion current could be extracted, but it was, of course, accompanied by a large electron current, 9000 times the negative ion current and about 100 times as large as the number of postive ions that could be extracted. This is approximately the values expected (Fig. 10).

The addition of a magnetic filter is shown schematically in Fig. 9-B. The filter consists of rows of tailored permanent magnets mounted inside the source chamber, with their housings connected to the anode potential. These magnets effectively divide the chamber into two parts: a source chamber and an ion extraction chamber. The filter magnetic fields are made strong enough to prevent primary electrons from leaving the source discharge chamber. Positive ions, because of their larger mass, can penetrate the filter

magnetic fields. The interesting feature of this filter geometry is that the electrons accompaning these ions to form the plasma in the extraction chamber are very cold. This temperature--which may be as low as a few tenths of an eV means that these electrons are unable to generate additional positive ions in the region of ion extraction. The use of this filter geometry for positive ion sources has been investigated[25] to improve the plasma density profile and increase the atomic ion component of a hydrogen discharge.

The magnetic filter geometry inherently reduces the positive ion extraction current density, and this reduction can be enhanced by applying a positive bias to the beam-forming electrode. The effect of this bias is to control the potential of the plasma in the extraction chamber relative to the plasma potential in the discharge chamber. This net reduction of positive ions near the extractor is matched by a similar reduction of cold electrons in this region. The final result is to open the door for the flow of negative ions into the extraction chamber. That this indeed happens is shown in Fig. 10. The use of a weak filter and a positive bias produces a factor of 10 increase in the number of $H^-$ ions extracted (Fig. 10-A) plus a factor of 3 decrease in the number of electrons extracted (Fig. 10-B). The use of a stronger filter and the proper bias results in a slight increase in $H^-$ plus an additional factor of 2 decrease in electrons extracted. The net result of the filter geometry is that the extracted $H^-$ current has been increased by more than one order, and the electrons have been reduced by nearly the same amount, giving an $Ie^-/IH^-$ ratio of 100, an improvement of nearly two orders of magnitude. This ratio is still too high but is a step in the proper direction, and further refinement and innovation may yet solve this difficult problem.

In summary, large area plasma sources utilizing volume production will not receive active consideration for negative ion beam lines until the

electron problem can be resolved. It will also have to be demonstrated that adequate $H^-$ an $D^-$ current densities can be obtained from such sources without excessively high source pressures.

## IV. SURFACE PRODUCTION

In 1973 workers in Russia added cesium to the discharge of a magnetron source similar to that shown in Fig. 8, raising the $H^-$ output from 5 mA to 20 mA.[26] Further refinements to the geometry resulted in $H^-$ ion currents of nearly 200 mA, and with the very small extraction slits employed, the resulting ion current density was greater than 3 $A/cm^2$. These small sources operated with a high source pressure (100 to 200 milli-Torr), and as the required arc power was high (150 V and 100 A), operation was limited to very short pulses (~1 milli-sec). The 200-mA beam was accompanied by ~300 mA of electrons, but since the ion extraction was E X B, these electrons were mass-separated from the ion beam.

Studies of the energy spectra of the resulting $H^-$ ions (27,28) have determined the approximate surface-plasma mechanisms producing these intense $H^-$ ion beams when the cesium is admitted. The cathode of the gas discharge is bombarded by fast ions of hydrogen and cesium. Reflection of the hydrogen ions and sputtering of adsorbed hydrogen from the cathode surface by the impinging cesium and hydrogen ions result in hydrogen atoms leaving the cathode surface with some finite energy. If the work function of the surface is reduced, some of these atoms can capture an electron as they leave the surface. If its departure from the surface is fast enough to escape the image forces of the surface barrier, an atom can then maintain the additional electron in the n=1 shell and depart as a negative ion. The required atom exit velocity for $H^-$ survival is not fully determined but is believed to be ~3 to 5 eV (Ref. 29). The low work function of the cathode surface is provided by a partial monolayer of adsorbed cesium, and, for

reasons not yet understood, molybdenum seems to be the best substrate.[30]

By 1974, short beam pulses of nearly 900 mA at 3 A/cm$^2$ current density had been obtained from larger sources at Novosibirsk and their operation confirmed at Brookhaven.[32] Since then, a variety of similar source geometries, including the "planotron" and others with multiple apertures, have been tested in Russia. The "planotron" geometry confines the discharge to the front cathode surface which faces the extraction apertures only, considerably improving the source power efficiency.[33] In 1979, Fermilab converted its accelerator to operate with $H^-$ ions generated by a surface-production source similar to that shown in Fig. 8.[34]

In 1979, we began a program in Berkeley to develop a surface production $H^-$ source that would meet the difficult neutral beam requirements. The goal was to develop a source that could generate a continuous, self-extracted $H^-$ ion current of 1 A or better, and then to accelerate this beam to ~40 kV. Because of ion optics considerations, we did not desire a high ion current density; thus, to obtain multi-ampere beams, a large exit aperture would be needed, and this in turn would require the source operating pressure to be low.

Figure 11 shows the source geometry, a multi-line cusp, with rows of permanent magnets placed on all sides of the well-cooled chamber wall. The wall also serves as the anode for the plasma generator. Eight tungsten filaments are the cathodes for the discharge which operates well at 1 milli-Torr or less at 80 V and arc currents of ~100 A. To produce negative ions, a water-cooled concave molybdenum converter (8 cm high and 25 cm long) is inserted into the plasma through two feedthrough insulators. By biasing the converter negatively (~200 V) with respect to the plasma, positive ions from the plasma are accelerated across the sheath to strike the converter surface. Negative ions formed at the converter surface are then accelerated back through the sheath by the same potential, and the bias voltage on the

converter thus becomes the negative ion extraction potential. The converter surface is curved to geometrically direct the negative ions through the plasma to the exit aperture. The B field in this region is tailored to be strong enough to reflect all energetic primary electrons but weak enough to produce only a small lateral displacement of the trajectories of the energetic self- extracted $H^-$ or $D^-$ ions. The electrode defining the exit aperture is electrically isolated so that a small positive bias can be applied, which is essential for complete electron suppression.[35] The cesium vapor is introduced into the discharge from an external oven through an ohmically heated, coaxial tube located below the exit aperture. Figure 12 shows the source chamber together with the oven and cesium jet assembly.

After emerging from the source exit aperture, the ions are accelerated to higher energies by the four-electrode accelerator shown in Fig. 11. The results to date have been encouraging. With the discharge operating at 80 volts and 100 A and a hydrogen pressure of about $8 \times 10^{-4}$ mm, a continuous self-extracted beam of $H^-$ of 1.1 A has been routinely obtained. The converter electrode, biased at -160 V, draws a total current of about 20 A, and spectrometer signals indicate a high mass impurity of less than 1%. The self-extracted beam has been accelerated to 34 keV for periods of about 7 sec, the time being limited by the thermal capacity of the beam stop. The measured electron component in the beam is directly related to the pressure in the accelerator gap; this indicates that the observed electrons are produced in the accel gap. (See Fig. 5) By utilizing the maximum pumping capability of the system, $I_{e^-}/I_{H^-}$ was reduced to 0.038, where the gas efficiency of the source was approximately 13%.[36]

With neutron-activated foils, we determined that the amount of cesium escaping from the discharge chamber is exceedingly small; thus only small amounts of cesium need be admitted to the source chamber. The magnitude of

$H^-$ production is very sensitive to cesium coverage of the converter as well as to the amount of cesium ions in the discharge. Is is therefore important to control the recycling of cesium in the source chamber in the presence of a continuously operating discharge. In a pulsed discharge the converter can be covered with cesium atoms during the off-time between pulses. The electrode temperature is then an important parameter, an it should be just warm enough to insure the desired coverage, approximately 0.7 monolayers. In a dc discharge, however, few un-ionized cesium atoms exist, and the proper coverage must be obtained with energetic cesium ions rather than with thermal atoms.

The shape of the source is designed to be scalable in both the vertical and horizontal dimensions in order to obtain negative ion currents larger than a single converter can produce. By increasing the height of the source chamber and maintaining the magnet spacing shown, additional ion exit apertures could be placed above and below the original single aperture.

Little has been said thus far of deuterium operation with surface sources. To avoid the neutron problem, much of the experimental work is done with hydrogen. But, in general, the $D^-$ yield under similar operating conditions is from ~2 to $\sqrt{2}$ times less than that of $H^-$ ions. Although the data are limited it seems that the same production ratio exists for volume-produced negative ions.

Work has been under way at Brookhaven National Laboratory to develop a dc magnetron source.[37] This work has recently been delayed in order to persue a new method of providing the plasma. This method, shown in Fig. 13, could, in principle, supply a dense plasma to the surface of the converter at a source pressure much less than that required by the magnetron geometry. Two hollow cathodes, are mounted in a 200-gauss axial magnetic field to provide a wide, thin plasma. The discharge can be operated as a diode, with the beam dump acting as anode or as a Penning discharge, with the beam dump

connected to cathode potential and the anode cover at anode potential. Negative ions created at the biased converter plate are then extracted across the magnetic field from an array of slots. $H^-$ beams in excess of 0.100 A have been extracted. Ion optics and methods to provide the desired amount of cesium to the discharge are two problems currently being studied.

At Oak Ridge National Laboratory, a Penning source, somewhat similar to the volume-production source shown in Fig. 6 has been used to supply the plasma for a surface converter. A biased molybdenum converter is aligned along magnetic field lines (Fig. 14). Because the source is operated at a low pressure ( 3 milli-Torr), few volume-produced $H^-$ ions are observed. Operting with 5-sec pulses and with the converter biased to -150 eV volts, the source has produced 23 mA of $H^-$ at an extraction current density of 56 $mA/cm^2$.[38] This source incorporates a method of intercepting the E X B extracted electrons on a +1.5 keV electrode, thus considerably reducing the power dissipation that results when these electrons are collected at full extraction potential.

## V. SUMMARY

Of the three methods discussed for producing $H^-$ and $D^-$ ions, surface production seems to offer the most promise for obtaining the high currents needed to meet the neutral beam requirements. However, future developments in sources employing the change-exchange and volume-production methods will be watched with great interest. It must be recognized that we are still in the early stages of high-current negative ions source development, and many problems remain to be solved. Nevertheless, the record to date is impressive: in just the last 20 years, steady state beams of $H^-$ ions have increased steadily from less than 1 mA to more than 1 A, an improvement of nearly four orders of magnitude.

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## Figures

Fig. 1 Neutral beam efficiency versus energy.

Fig. 2 Components of a charge-exchange negative ion neutral beam system.

Fig. 3 Equilibrium fraction ($F^{\infty}$) of $H^-$ and $D^-$ versus energy for hydrogen, sodium, cesium, and strontium.

Fig. 4a Charge exchange cell.

Fig. 4b Geometry of nozzle used to form the sodium jet.

Fig. 5 $H^-$ loss cross-section by stripping in hydrogen gas vs energy.

Fig. 6 Cross-sectional drawing of a modified Penning $H^-$ ion source.

A = heated filament;
B = cold reflector cathode;
C = water-cooled squirt tubes;
D = gas feed lines;
E = ion exit slit;
F = trochoidal electron dump block;
G = ion-extraction electrode;
H = arc-defining hole.

Fig. 7 $H^-$ ion current vs gas flow.

Fig. 8 Magnetron negative hydrogen ion source.

Fig. 9a Multi-line cusp plasma source geometry.

Fig. 9b Source modified to include a magnetic filter.

Fig. 10a $H^-$ ion current vs beam-forming electrode bias;

Fig. 10b Extracted electron current vs beam forming electrode bias;

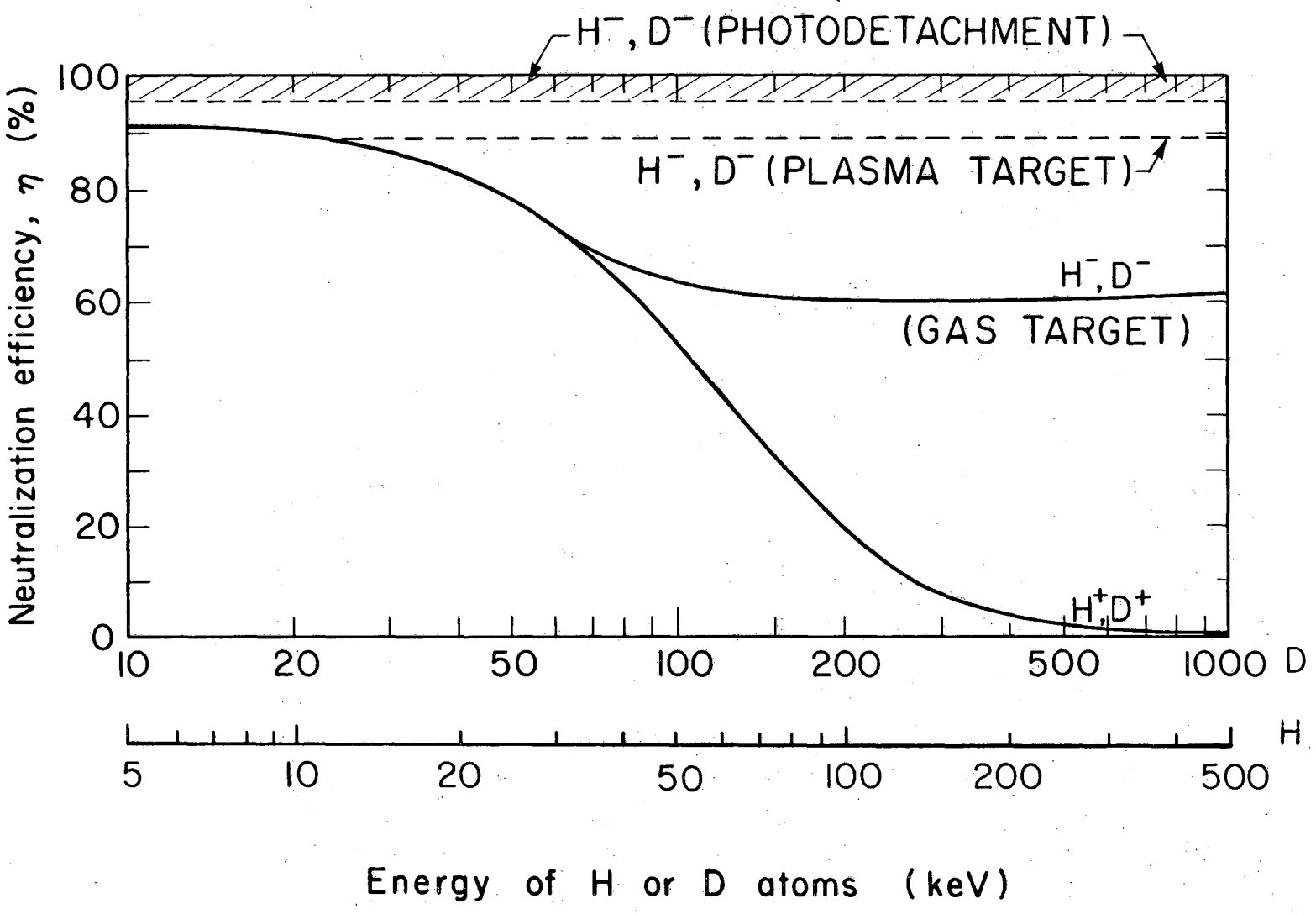
Fig. 10c Extracted positive ion current vs beam forming electrode bias.

Fig. 11 Schematic diagram of the LBL self-extraction negative-ion source.

Fig. 12 The source chamber and the cesium over and jet assembly.

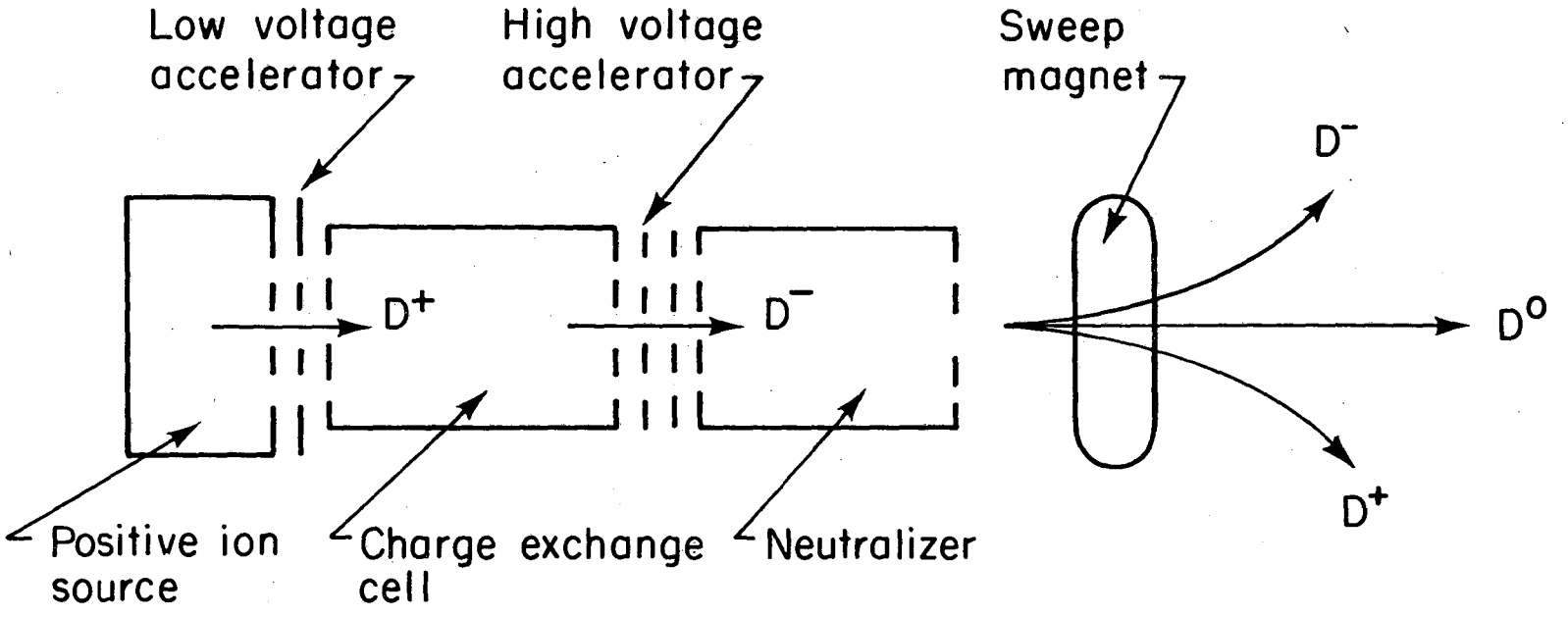
Fig. 13 Drawing of the hollow-cathode discharge experiment.

Fig. 14 Cross-section of Penning source with surface converter.



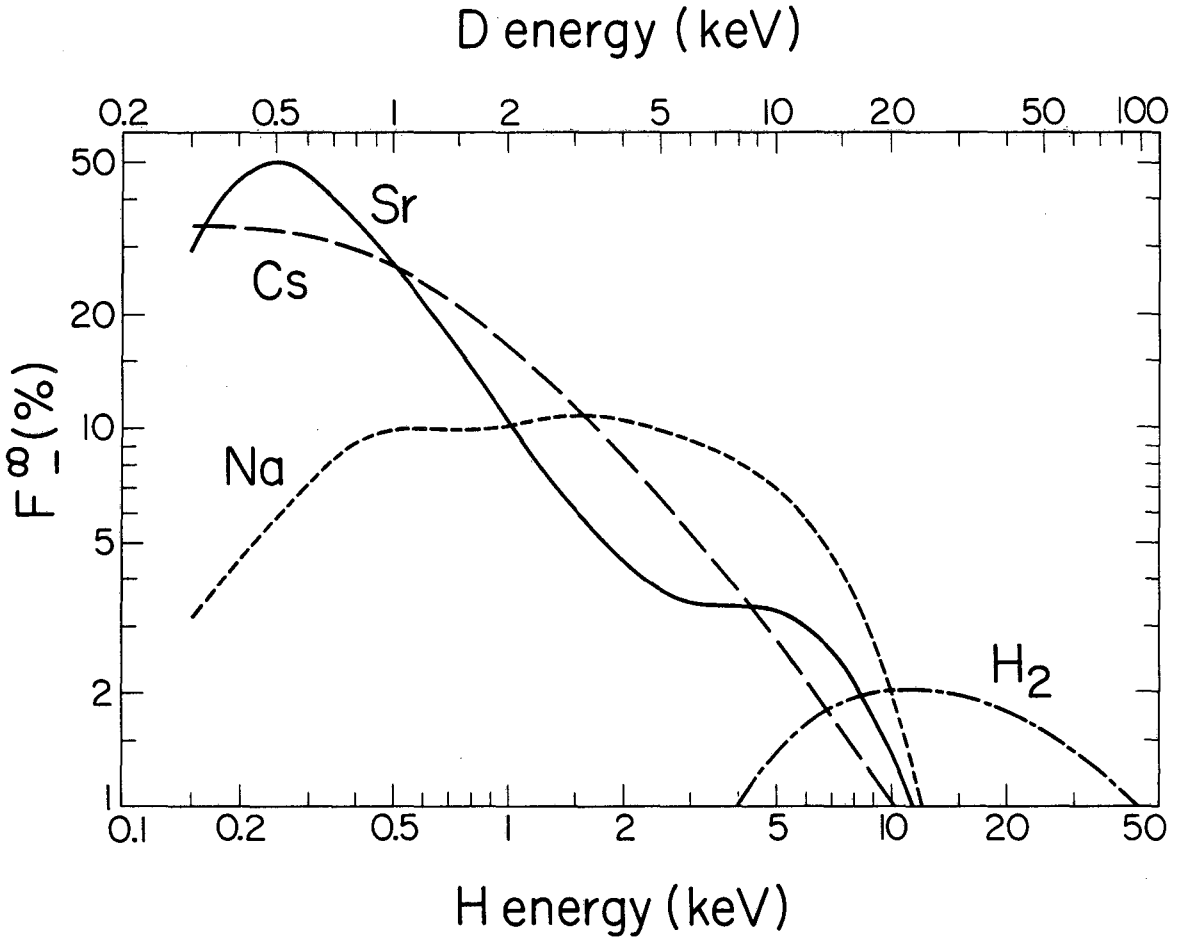

XBL 827 – 933

Fig. 1



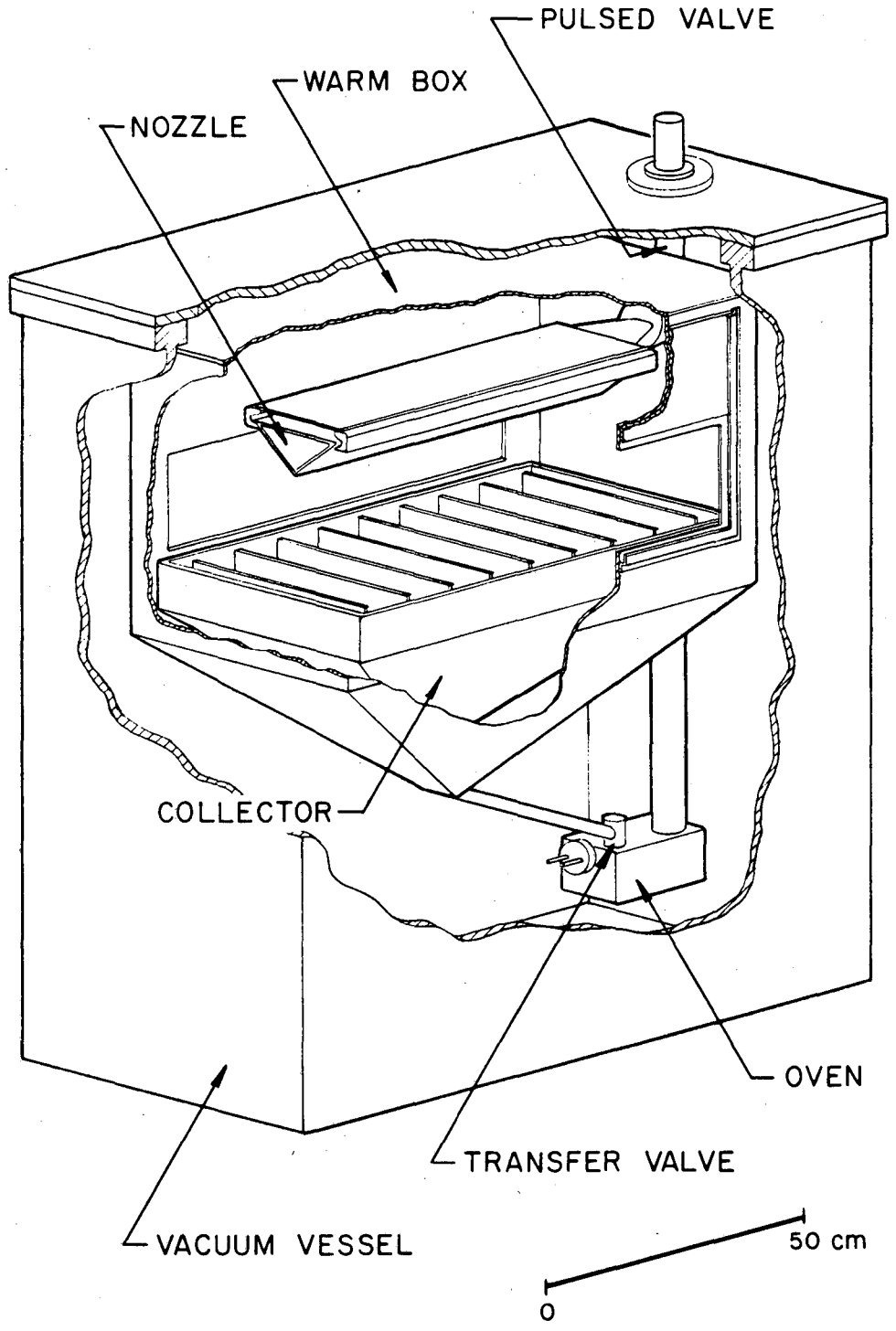

XBL 827 – 931

Fig. 2




XBL 824-303

Fig. 3




XBL 809-11826

Fig. 4A

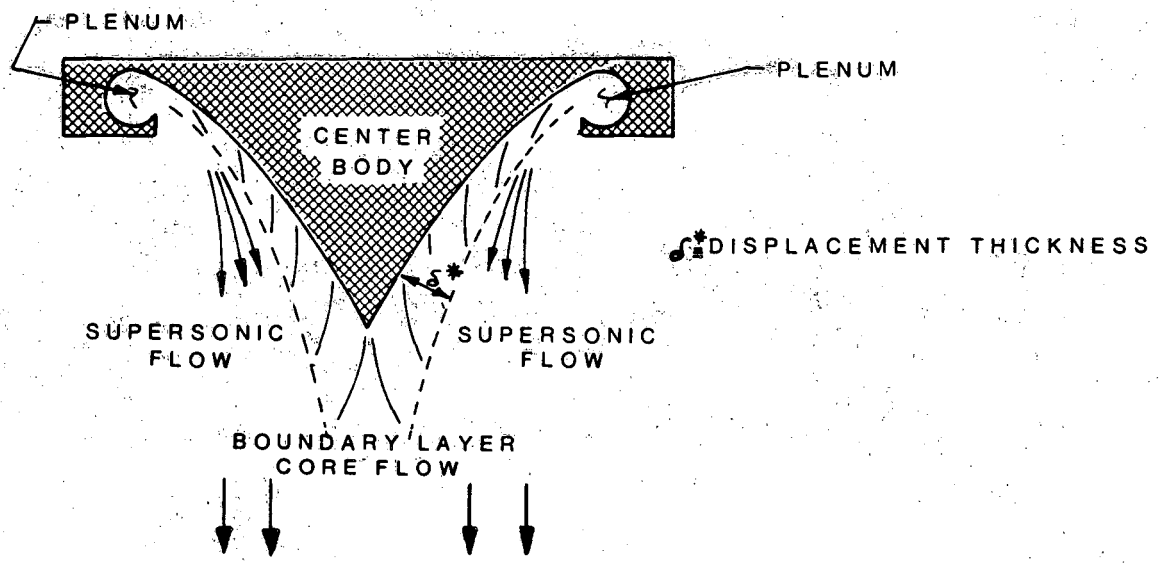
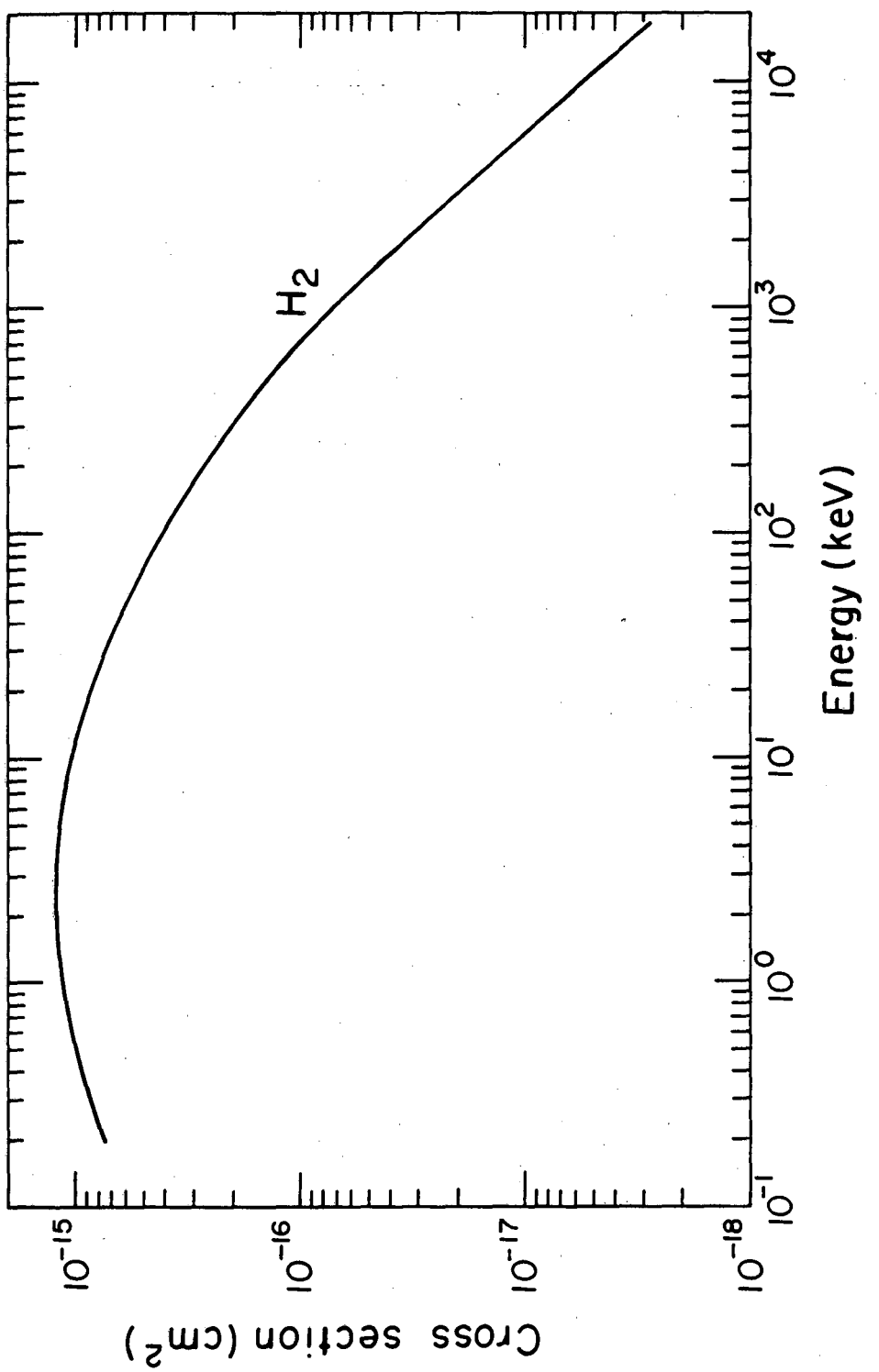
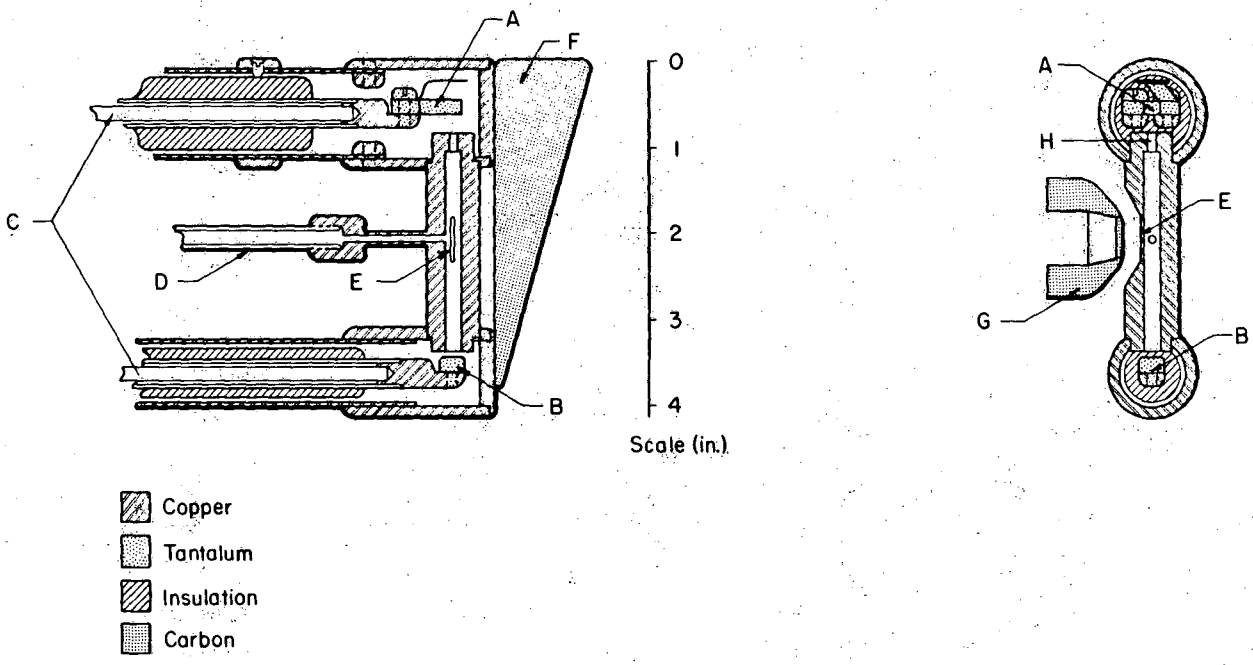

PLENUM
PLENUM
CENTER BODY
DISPLACEMENT THICKNESS
SUPERSONIC FLOW
SUPERSONIC FLOW
BOUNDARY LAYER CORE FLOW
XBL 812-8085

Fig. 4B




XBL 827 – 932

Fig. 5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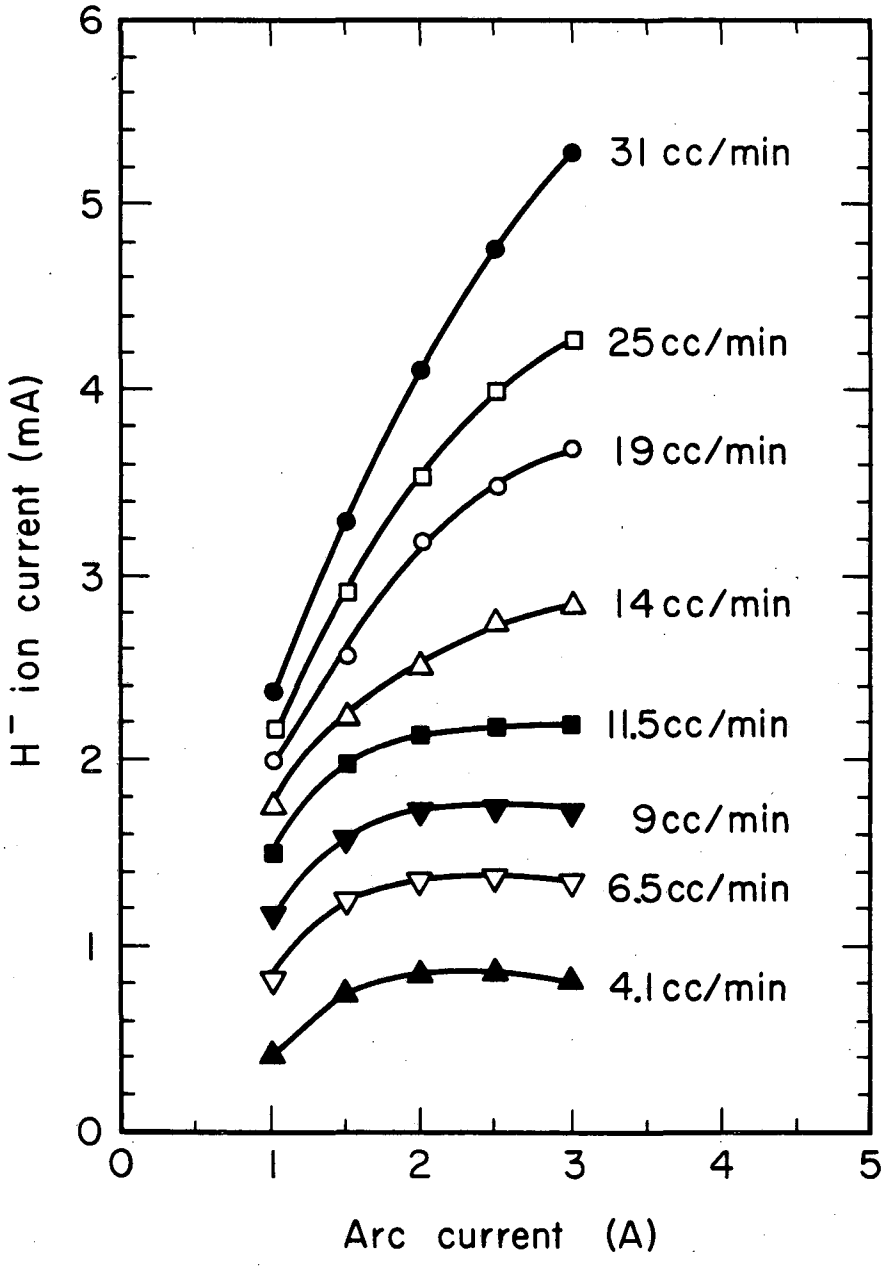
F
C
D
E
B
0
1
2
3
4
Scale (in.)
Copper
Tantalum
Insulation
Carbon
A
H
E
G
B

Fig. 6


6
5
4
3
2
1
0
0
1
2
3
4
5
H⁻ ion current (mA)
Arc current (A)
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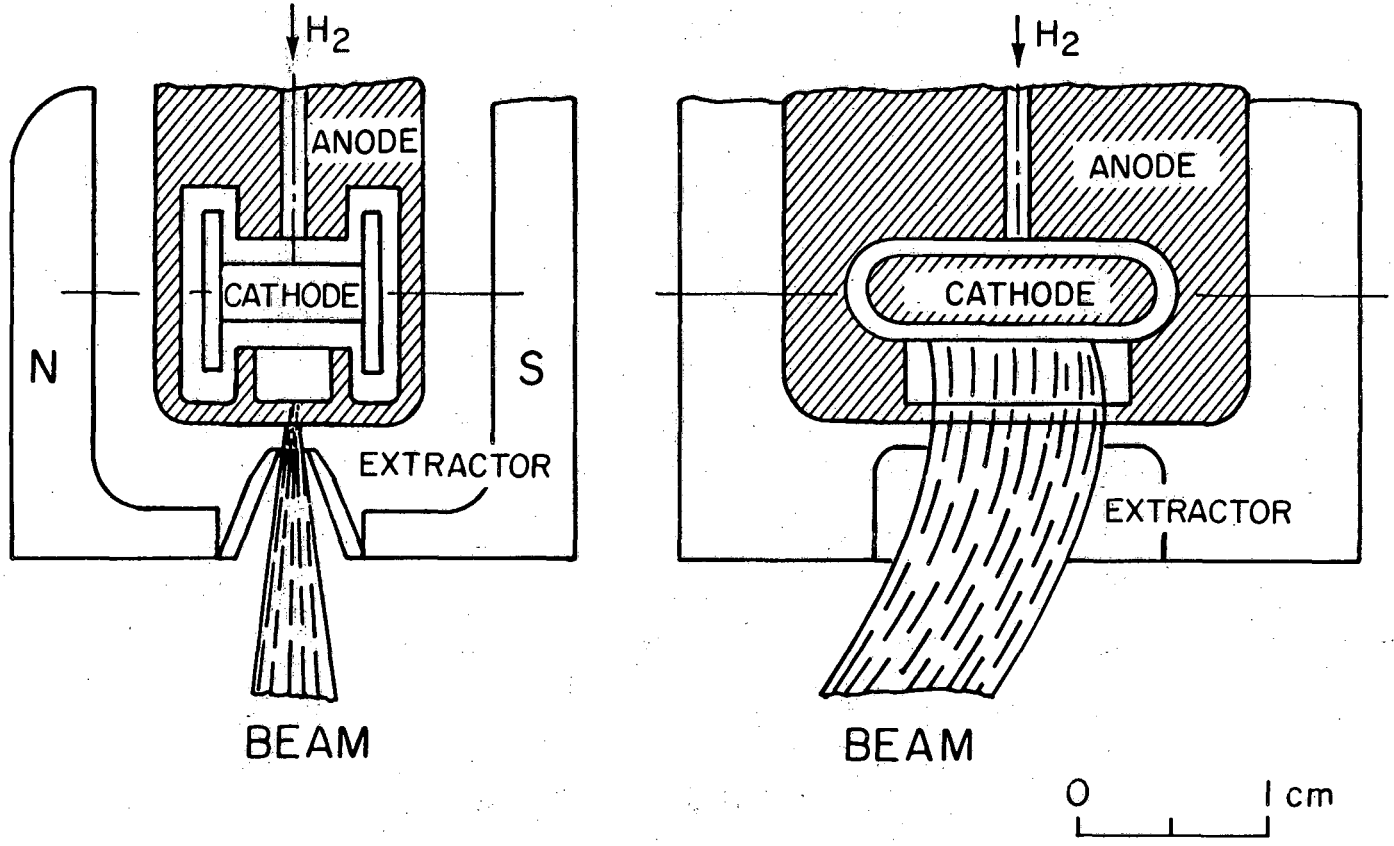
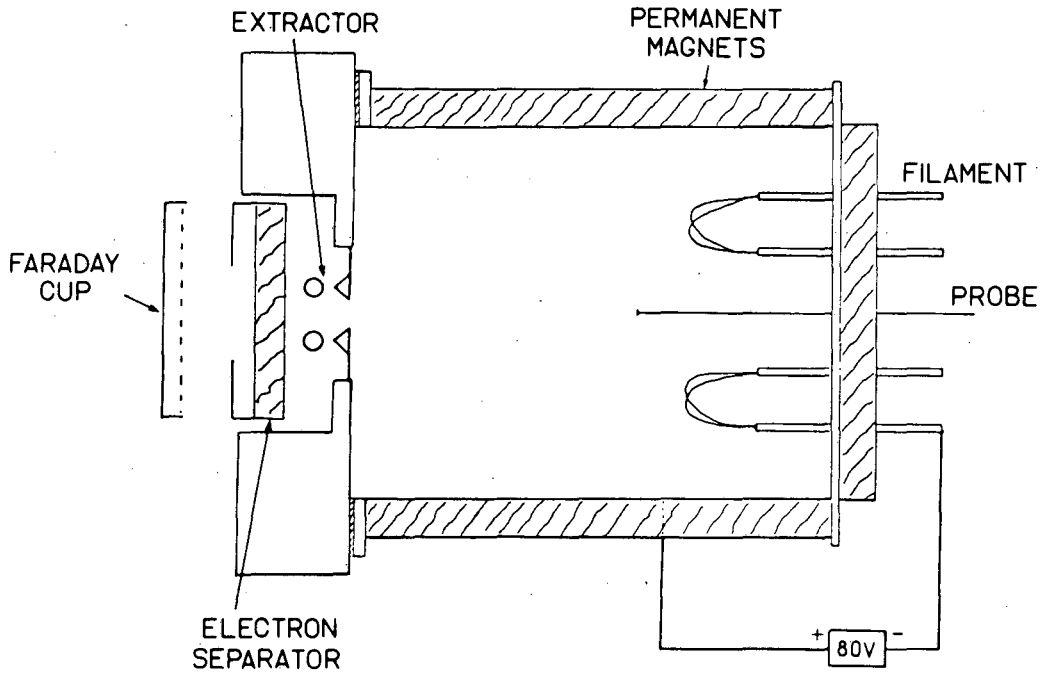
25cc/min
19cc/min
14cc/min
11.5cc/min
9cc/min
6.5cc/min
4.1cc/min

Fig. 7

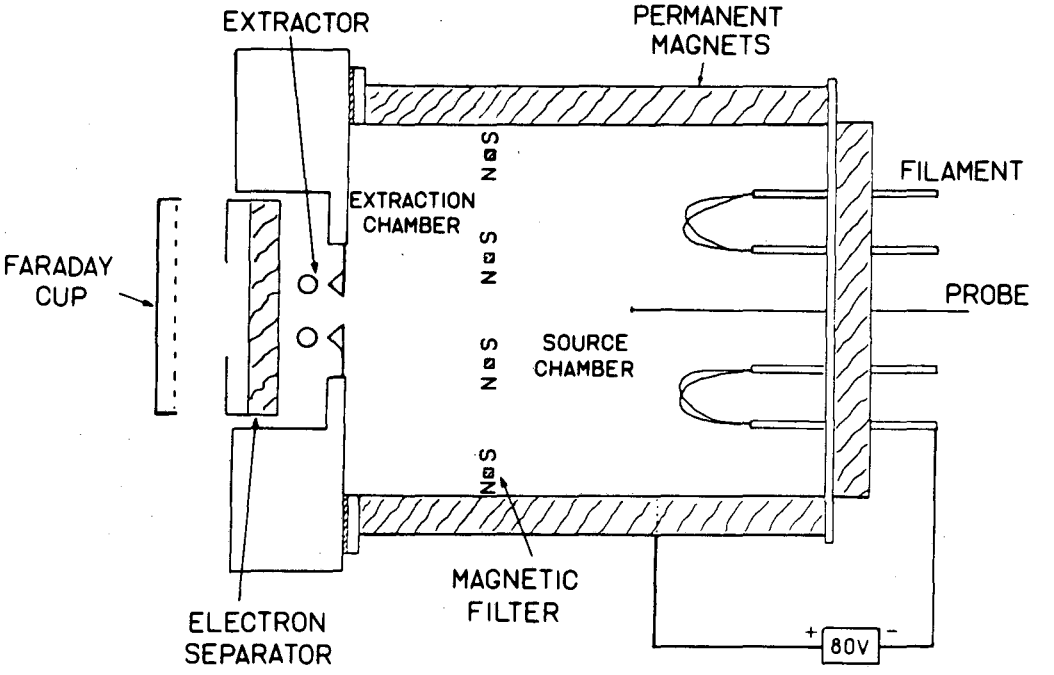



XBL 827 –934

Fig. 8




(a)




(b)

XBL 824-9254B

Fig. 9

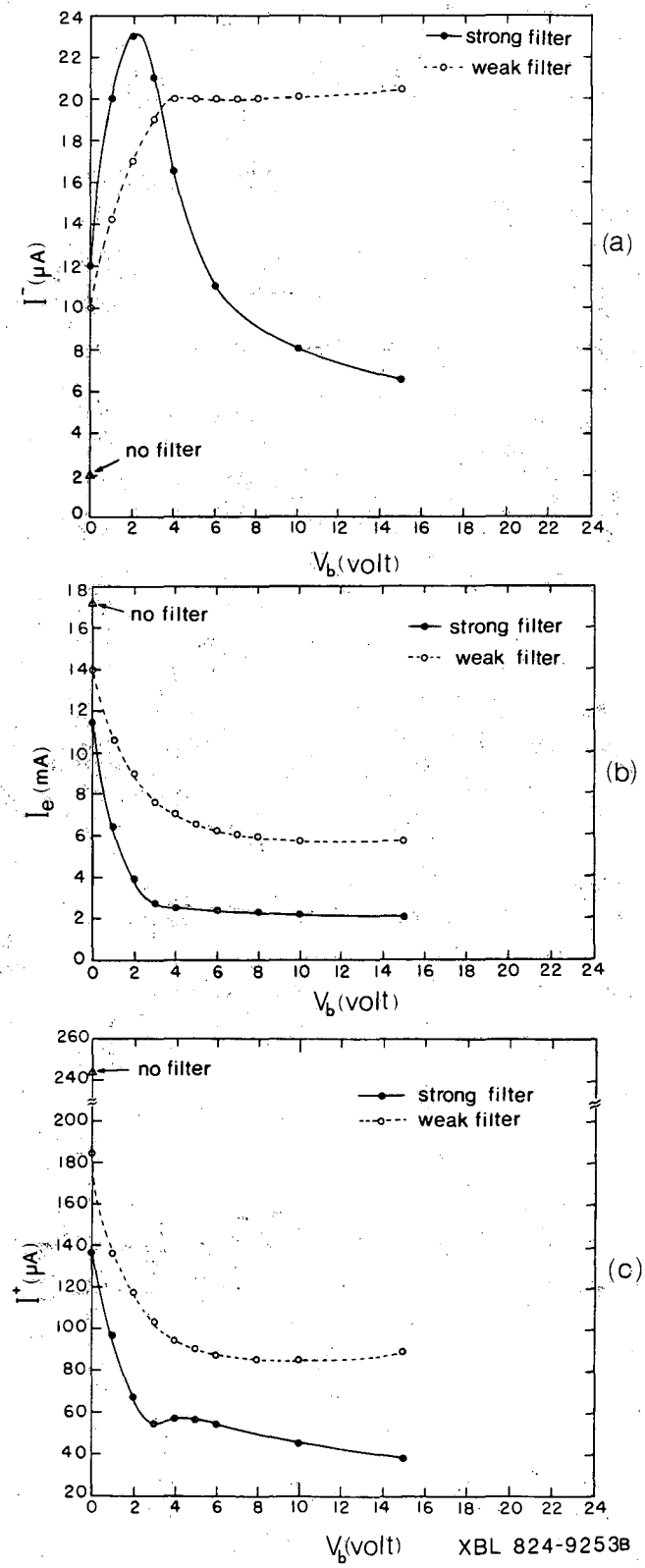
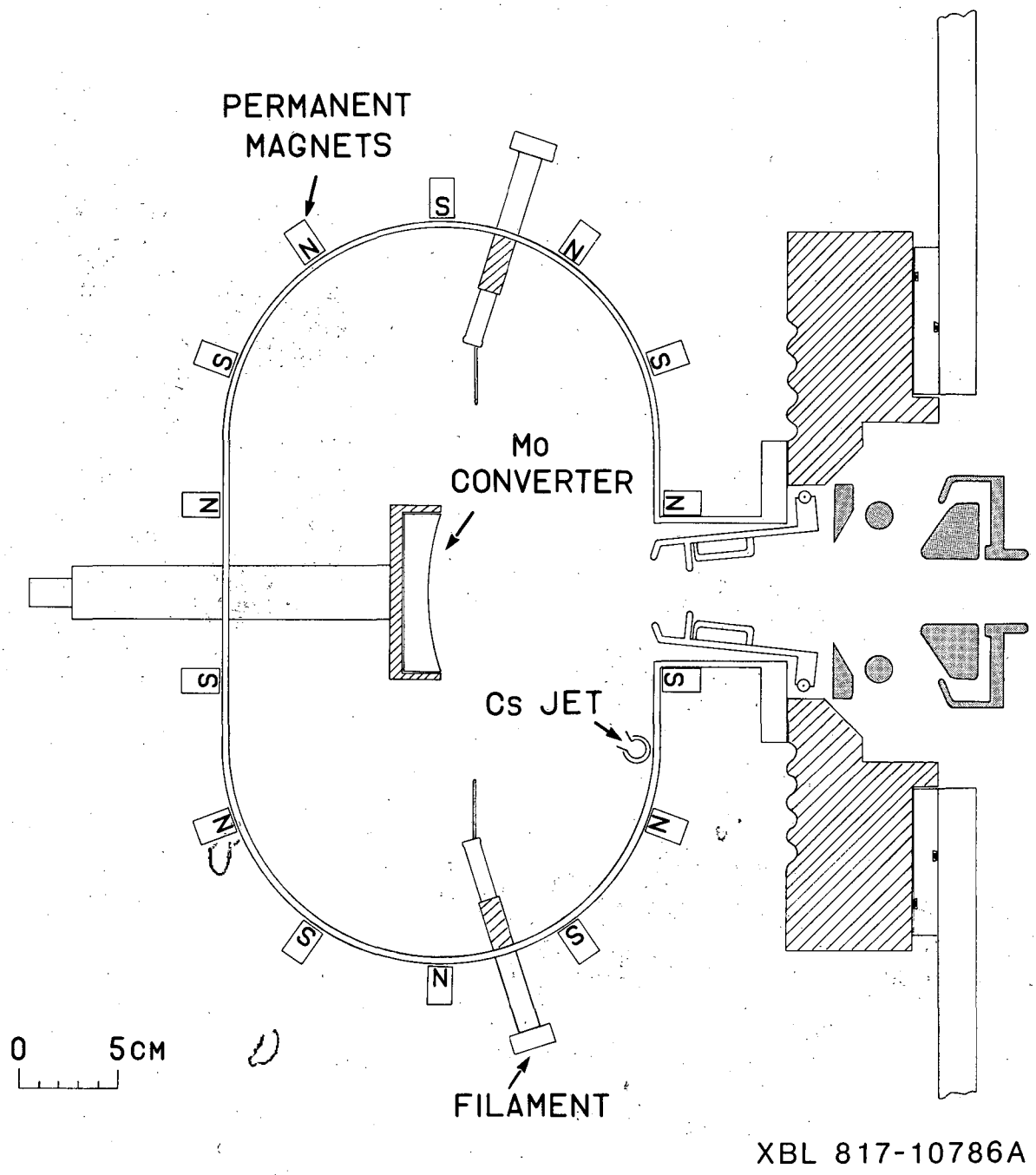

strong filter
weak filter
no filter
$I^-$ (μA)
(a)
$V_b$(volt)
no filter
strong filter
weak filter
$I_e$ (mA)
(b)
$V_b$(volt)
no filter
strong filter
weak filter
$I^+$ (μA)
(c)
$V_b$(volt)
XBL 824-9253B

Fig. 10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Cs JET
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0
5cm
FILAMENT
XBL 817-10786A

Fig. 11

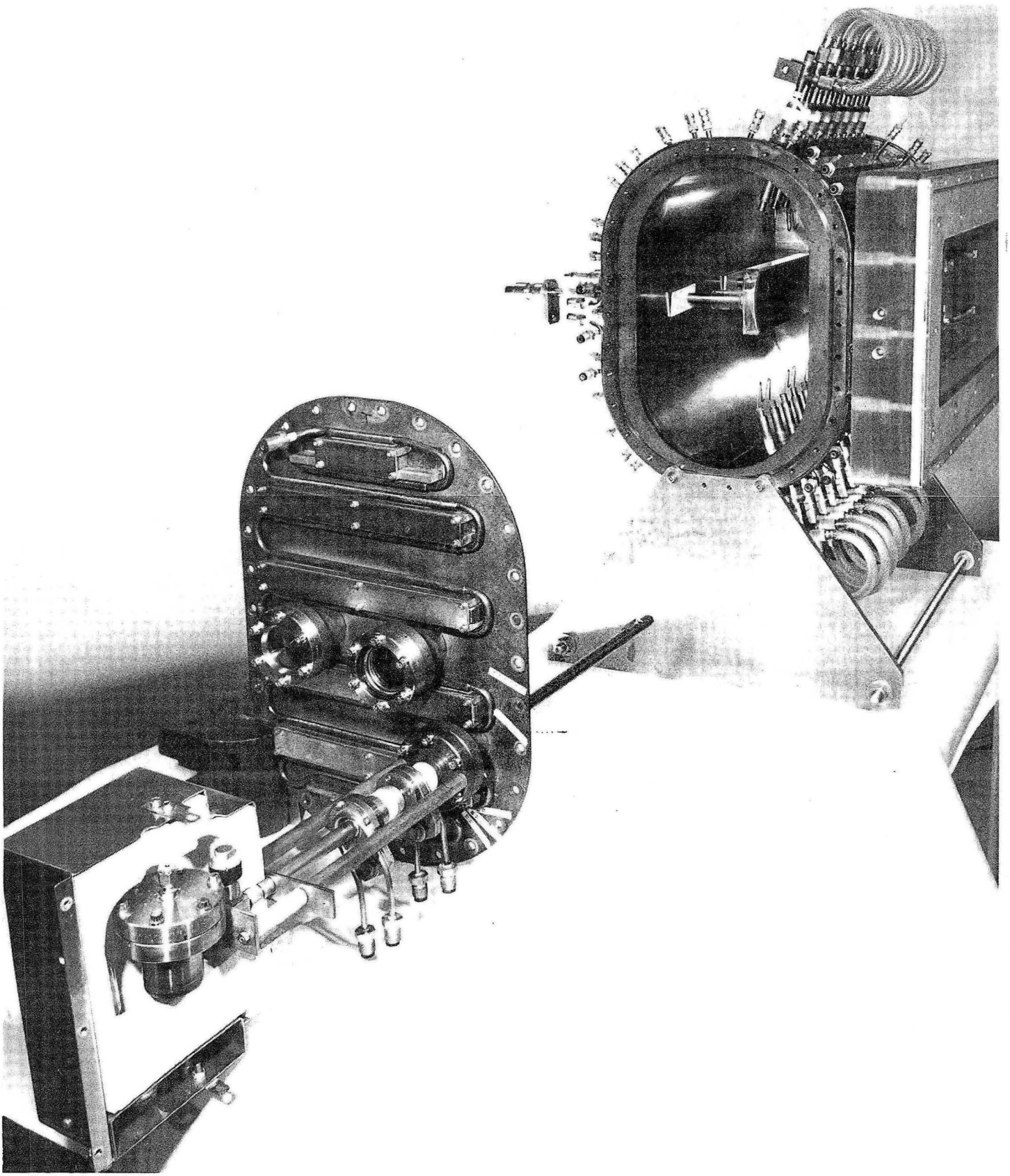
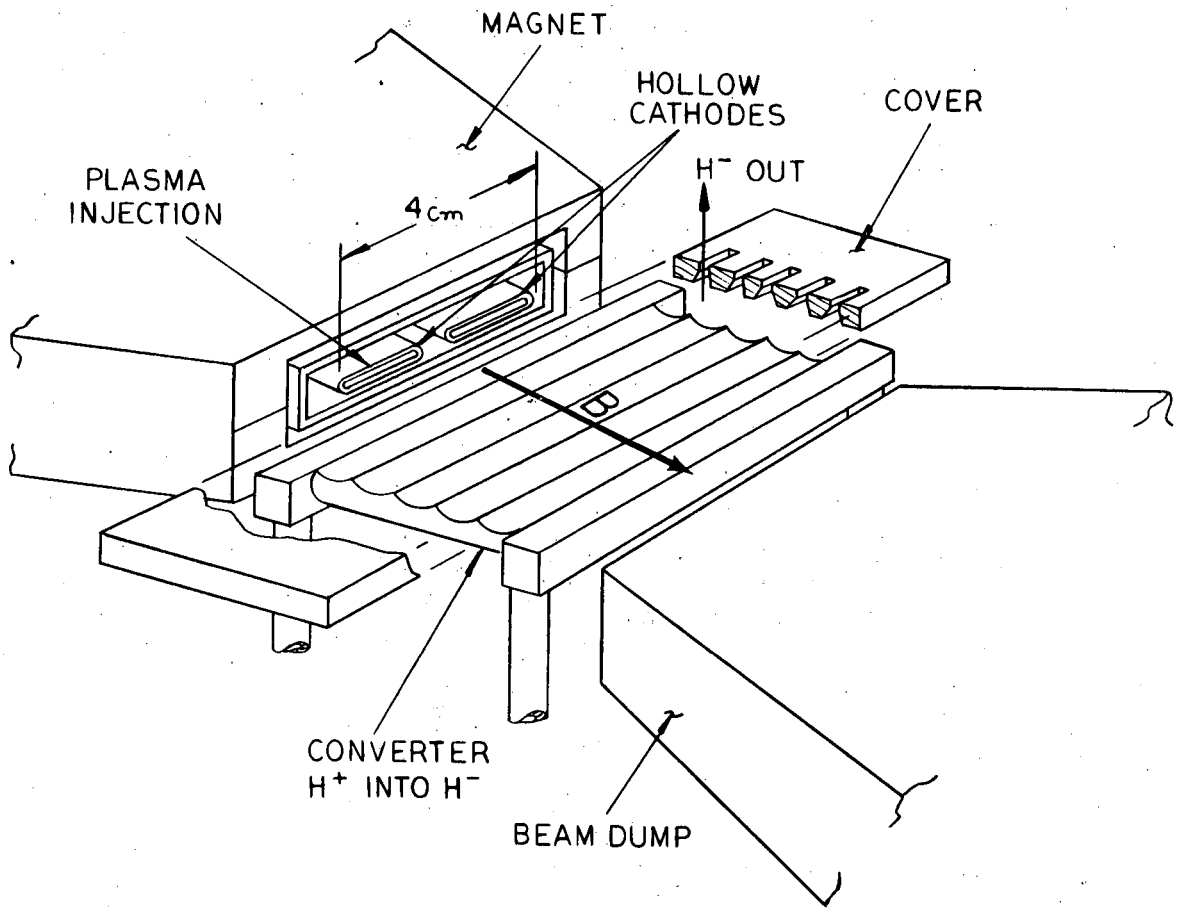


Fig. 12

CBB 814-3550




XBL 827 – 935

Fig. 13

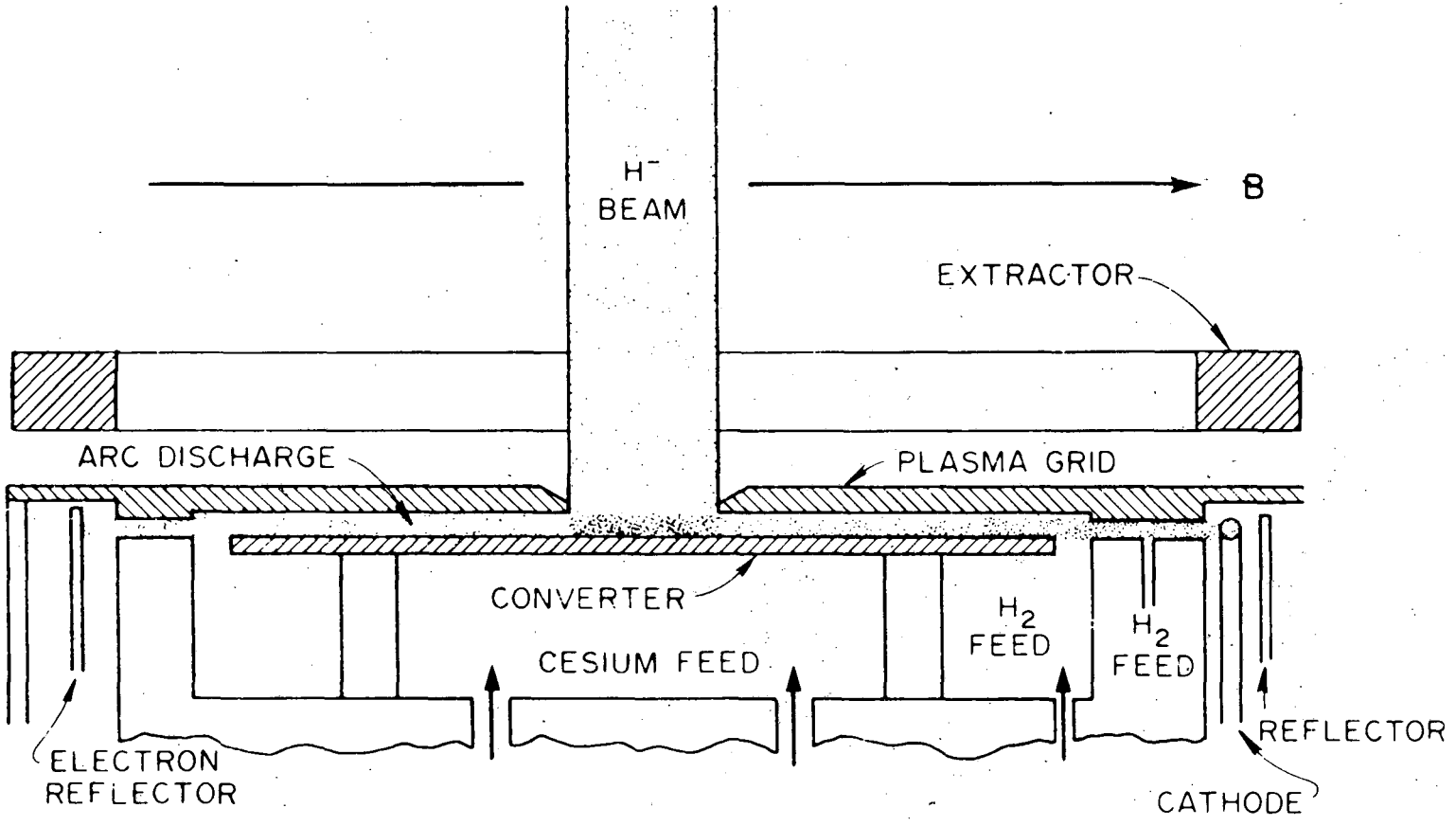



Fig. 14

XBL 828-11165

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