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K. Jimbo

November 1985

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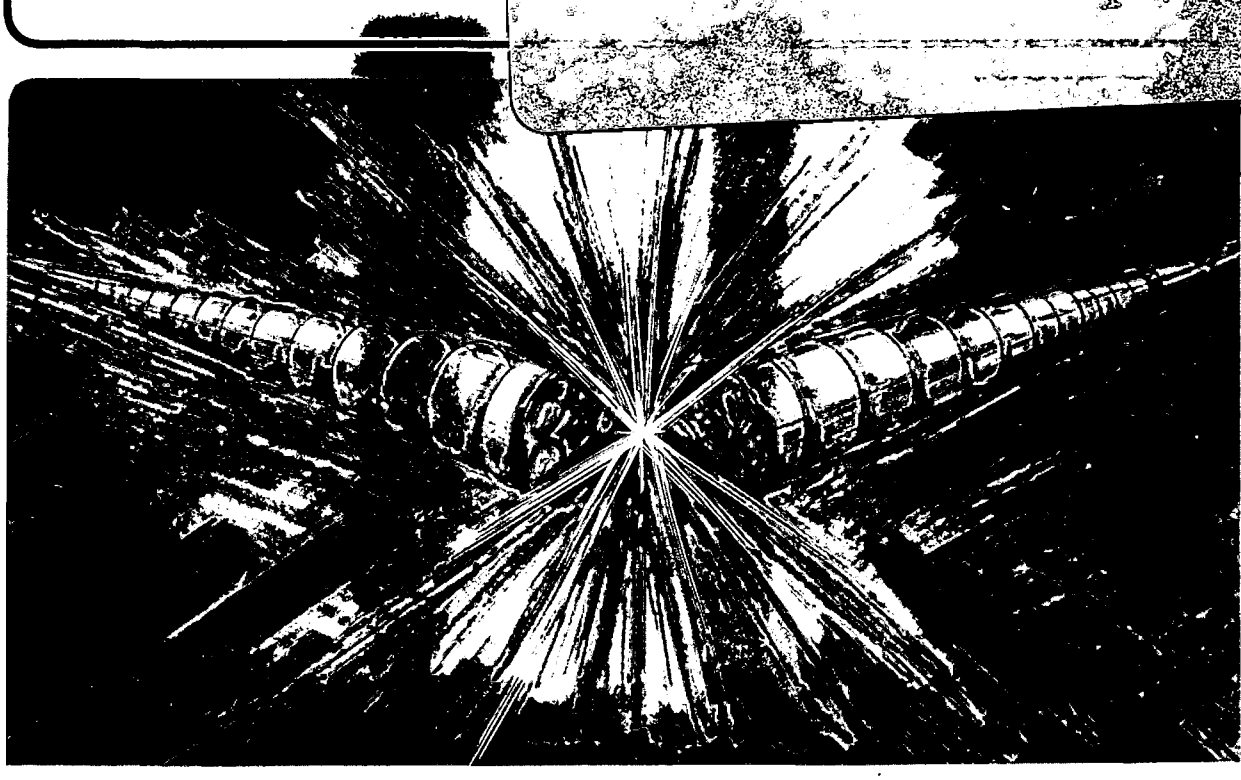

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Physics of the Volume Produced Negative Ions*

Kouichi Jimbo+

Institute of Atomic Energy
Kyoto University
Uji, Kyoto-fu 611

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Abstracts

The physical aspects of volume production of negative ions are discussed with particular emphasis on the extraction of negative ions from a plasma. The dominant negative ion production mechanism recently discovered is the dissociative electron attachment to highly vibrationally excited molecules. The negative ion production and extraction experiments of the multicusp, the reflex-type and the sheet plasma sources are introduced. It seems that the existence of a weak magnetic field is essential to extract the negative ions effectively as well as suppressing electrons.

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I. Introduction

In the late 1970's, the scientists at Ecole Polytechnique found that the calculated density of H^- (negative hydrogen ions) in a hydrogen plasma, using the known formation and destruction processes, led to the conclusion that already known processes could not explain the high current densities observed in various negative ion sources; the equilibrium negative ion density calculated by Nicolopoulou, Bacal and Doucet[1] (1977) for a hydrogen plasma was about 100 times lower than the density measured in their low pressure hydrogen plasma experiment. This discrepancy showed that the known H^- formation processes were not sufficient to explain the actual density of H^-. However, these results were questioned because of the method of measuring the H^- density with a Langmuir probe. The anomalously high H^- density was confirmed by Bacal and Hamilton[2] (1979). They observed the rise in the electron density following the photodetachment of H^-. Demkov[3] (1965) suggested that the cross section of dissociative attachment would be enhanced when the hydrogen molecule is vibrationally excited. This effect has been studied both theoretically, by Wadehra and Bardsley[4] (1978), and experimentally by Allan and Wong[5] (1978); this renewed the interest in negative ion production in hydrogen plasmas. It has been suggested by Bacal et al.[6] that the dissociative attachment of electrons to excited molecules might be responsible for the high negative ion production.

The research of the negative ion sources is active these days. There are mainly three methods to produce negative ions: these are the double charge exchange method for converting a positive ion beam into a negative ion beam, the surface conversion method to generate negative ions in surface interactions principally via desorption or backscattering, and the volume

processes, in which low energy electrons interacting with molecular species lead to negative ion products via dissociative attachment or recombination. There is also a method to produce negative ions by chemical reactions.[7] Hiskes[8] (1979) reviewed the formation of hydrogen negative ions. Bacal[9] (1982) reviewed the volume production. Ehlers[10] (1983) reviewed the negative ion sources (1983).

When negative ions are extracted from a plasma into a vacuum through grids, the electrostatic field in the plasma boundary sheath hinders negative ions more than electrons; the space plasma potential against the vacuum is on the order of the electron thermal energy, and the negative ion temperature is usually much smaller than the electron temperature.[11] This phenomenon is very important. This kind of problem does not arise in positive ion extraction. We just want negative ions but not electrons. Therefore, the effective extraction mechanism of negative ions has to be developed for the neutral beam injection (NBI) systems that use such ions. In this paper we shall consider the physics of volume produced negative ions based on the experiments at Laboratoire de Physique des Milieux Ionises of Ecole Polytechnique, at Lawrence Berkeley Laboratory of the University of California, Berkeley, and at Institute of Plasma Physics of Nagoya University. Many experiments related to negative ions have been done in many places. The reason we cannot introduce the other interesting researches is mostly due to the author's inability to get complete information and lack of space.

The plan of this paper is as follows: In Sec. 2, we briefly explain the concept of NBI. In Sec. 3, we discuss the proposed production mechanism of negative ions through the volume process. In Sec. 4, we introduce several typical volume produced negative ion sources. In Sec. 5, we discuss the

negative ion sources introduced in Sec. 4 from the standpoint of extraction of negative ions. Summary and physical considerations are discussed in the last section.

II. Concept of Neutral Beam Injection

The most common method of heating toroidal plasmas, using Ohmic heating, cannot produce a sufficient plasma temperature to achieve "break even": as much energy is lost as is available to heat the plasma since the latter is limited by the $T^{-3/2}$ dependence of plasma resistivity. Presently the injection of fast neutral atoms appears to be a highly attractive method for heating toroidal plasmas and for bringing a fusion reactor to ignition. The conversion of the fast-ion beam into a beam of fast neutrals to enter the plasma in the strong magnetic field, and the neutrals reconversion to the ionic states in the plasma seem to be quite efficient. In near-future experiments, neutral beams of higher energy and a single atomic component will be necessary to penetrate into the center of large fusion plasmas so as to drive a seed current for D.C. tokamak operation or to control the end plug potential to increase the plasma confinement time in tandem mirrors. Negative ions seem to be the only effective intermediary for efficient development of such high energy neutral beam injection (NBI) system.

The neutral sources currently used in the controlled fusion research convert the extracted positive ions into neutral atoms by electron capture in hydrogen gas. For high energy beams, however, the efficiency of neutralization falls off rapidly. In a thick gas neutralizer, the efficiency of conversion to neutrals is a function of the ratio of the electron capture cross section of the ion to the stripping cross section of the neutral atom. Since the stripping cross section falls above 50 keV asymptotically as

ln(E)/E, while the capture cross section falls off much more rapidly, the efficiency of neutralization falls off faster than linearly in the beam energy.[12] For a negative ion beam the neutralizer efficiency does not suffer from the same unfortunate energy dependence as for a positive ion beam (Fig. 1). This is essentially because the excess electron in the negative ion, which is much less tightly bound (0.754 eV) than the first electron (13.6 eV) of the positive ion, resulting in a much larger collisional detachment cross section for forming a neutral atom in the region of higher energy. This makes the high efficiency production of neutral atom beams at high energy possible. In the positive NBI systems, H_2^+ and H_3^+ are also generated with simultaneously H^+. They give rise to neutral beam constituents at one-half and one-third of the full energy. Since these undesirable fractional energy components are more easily neutralized than the full energy component, they consume a large share of the power in the neutral beam as the energy is increased. Therefore, the higher energy one-component beams (> 200 keV) can be produced most efficiently by stripping an accelerated negative ion beam.

At very high energies, the use of a high density plasma rather than a gas cell has been shown to convert the H^- beam into neutrals effectively.[13] These processes, however, suffer from the fact that an entering negative ion can have two electrons removed, and this results in the production of unwanted positive hydrogen ions. Recently, a new process, namely the photon or laser neutralizer, has received attention.[14] In this case, a large flux of photons with an energy at or near the peak of the photodetachment cross section is required. In principle, the laser neutralizer would permit neutralization efficiency close to 100%. In addition, the use of a laser neutralizer would also eliminate the need to introduce gas near the entrance to the fusion plasma. This eliminates the pumping requirements which a gas

cell would require. Substantial development is required, however, to produce suitable, efficient, dc laser systems. The leading candidate laser for this application is the oxygen-iodine chemical laser,[15] which operates at a wavelength of 1.315μ. The photon energy is ~ 1.06 eV. At this wave length, the photons have enough energy to detach the electron from D^- ions, but not from impurity ions C^-, OH^-, and O^-; this choice of wave length therefore provides substantial discrimination against impurities in the beam.

Recent advances in ion-source technology, new concepts in beam transport and acceleration systems (for example the Transverse Field Focusing principle at Berkeley),[16] and the impending application of efficient laser photoneutralizers have enhanced the prospects of using the negative ion NBI systems on reactors.[17] The application of these advances should lead to NBI systems that are both highly efficient (60 ~ 80%) and radiation-hardened (Fig. 2). What is lacking is just the experimental verification that the concepts will work as anticipated.

III. Production Mechanism

Until recently, it has been generally considered that the main H^- production processes in hydrogen plasmas are the electron collision processes with neutral molecules in the ground state; such as dissociative electron attachment and polar dissociation:

$$e + H_2 \rightarrow H^- + H$$

$$e + H_2 \rightarrow H^- + H^*$$

$$e + H_2 \longrightarrow H^+ + H^- + e.$$

The cross sections for reactions of these kinds have been measured by Schulz[18] (1959); a sharp peak of the cross section with a maximum at an electron energy E_e = 14.2 eV is attributed to the second reaction. Rapp et al.[19] (1965) also observed a similar peak of the cross section. An understanding of hydrogen discharges seemed to be established. However, from the cross-section measurements[20] and the theoretical calculations,[21] it appears that the dissociative attachment of electrons to vibrationally excited molecules H_2^* might be the one responsible for the large fraction of H^- found in the plasma by Bacal and Hamilton.[2] It is, therefore, important to find an explanation for the presence of large densities of H_2^* in the plasma.

This process is interpreted in terms of the formation and dissociation of unstable states of H_2^-. The competition, between electron emission and dissociation of the molecular negative ion, could lead to a strong dependence of the dissociative attachment cross section on the mass of the hydrogen nuclei, and the initial vibrational and rotational state of the neutral molecule:

$$e + H_2^* \longrightarrow H_2^- \begin{cases} \longrightarrow e + H_2^* \\ \longrightarrow H + H^-. \end{cases}$$

Calculations by Wadehra and Bardsley[4] (1978) based on the above mechanism shows a significant enhancement of the dissociative attachment cross section by the vibrational or rotational excitation of the initial molecule. They considered that the probability of dissociation increases since the electron capture produces a larger internuclear separation. Calculations of dissociative attachment rates are also reported by Wadehra[22] (1979). The

attachment rate coefficient at the electron temperature of 1.5 eV was taken to be in the order of 10^{-15} cm^3 sec^{-1} in a previous analysis of negative ion densities in a hydrogen plasma. Wadehra's result, however, indicates that this coefficient could be as high as 10^{-8} cm^3 sec^{-1} if there exist vibrationally excited hydrogen molecules, especially those excited in higher vibrational levels. The dissociative attachment cross sections are greater than 2×10^{-16} cm^{-2} for vibrational levels with $v \geq 6$, for which the threshold is below 1 eV.

On the other hand, it has been suggested by Kunkel[23] (1979) that these highly vibrationally excited molecules are formed in the following reaction;

$$e + H_2\ (v=0) \rightarrow e + H_2^*\ (B\,^1\Sigma_u^+)$$

$$e + H_2\ (v=0) \rightarrow e + H_2^*\ (v>0) + h\nu.$$

The cross sections for this electron excitation process by radiative transfer from singlet electron states of H_2 are calculated by Hiskes[24] (1980). The main H_2^* loss process is de-excitation in wall collisions and in collisions with atomic hydrogen. It is concluded that, to account for the H^- densities which had been measured experimentally in a medium density weakly ionized plasma, H_2^* would be required to survive a large number of collisions with the wall of the containing vessel.[25] Measurements of the densities of vibrational states up to $v=3$ have been made by Pealat et al.[26] (1985) using coherent anti-Stokes Raman scattering. However, it has proved difficult to extend these measurements to higher vibrational states. Graham[27] (1984) used the vacuum ultraviolet emission to study the production mechanism for vibrationally excited molecules. The production rate of vibrationally excited molecules was sufficiently high to allow the H^- production through these molecules.

Pealat et al.[26] found that the choice of copper as a wall material, compared to stainless steel, was unfavorable for H^- production. Leung et al.[28] (1985) reported on the other hand that the wall material Al and Cu generally produce larger H^- current since the second electrons emitted from wall surfaces contribute to production. Uramoto[29] (1985) reported, however, that the H^- production did not depend on the material of vacuum chambers; his experimental results for the stainless steel vacuum chamber was similar to that of the glass chamber. Recently Gorse et al.[30] (1985) indicated that the wall de-excitation was the main destruction mechanism when $v<4$, while the collision with atomic hydrogen was the main destruction mechanism for the highly vibrationally excited molecules ($v\geq5$). Wadehra's calculation[31] (1984) demonstrated that H^- were formed with an average energy of 0.1 to 0.4 eV if they were produced by the dissociative attachment.

According to the production mechanism proposed by Bacal et al.[6] to explain the high negative ion density observed by Bacal and Hamilton,[1] high-energy electrons to produce the vibrationally excited molecules and low-energy electrons to produce the negative ions by dissociative attachment to the vibrationally excited molecules are necessary. The first process[24] has the maximum cross section at an electron energy of about 40 eV, and the latter reaction[22] has the maximum cross section at an electron energy of order of 1 eV. In ordinary discharge plasmas, most electrons are produced by the ionization and the electron energy is low. To obtain many negative ions, we also need high-energy electrons to produce the vibrationally excited molecules; we need something to "heat" the plasma. Jimbo's results[32] (1984) obtained from the phenomenological analysis indirectly support this model. This proposed production mechanism is widely accepted although it is not proved, yet.

The mutual neutralization of H^- with positive hydrogen ions is considered to be the main H^- destruction process since they have a cross section in the order of 10^{-14} cm^2. In the experiment of a multicusp source with the photodetachment technique, a reduction of the relative negative ion density was observed at pressures over 3 mtorr.[33] This effect was attributed to the decrease of positive ion velocities and to the associated increase of the rate coefficient of mutual neutralization when the pressure is increased. Recently, Hiskes et al. reported[34] (1985) that H^- might be mainly destroyed by collisions with hydrogen atoms if their density is not small compared to the hydrogen molecules.

IV. Negative Ion Sources

Hydrogen ion species and discharge characteristics have been compared for different magnet geometries in a multicusp ion source at Berkeley. One magnet configuration indicated that the H_2^+ percentage in the extracted beam could be reduced by eliminating the high energy ionizing electrons near the ion extraction region. To accomplish this and maintain the desired features of magnet geometries, a magnetic filter was installed near the source exit. With this combined arrangement, the H^+ percentage and discharge condition were much improved and a more uniform density profile across the extraction plane was achieved.[35] When Leung et al.[36] (1983) extracted H^- from this source, they observed an increased H^- yield; it was shown that the addition of a permanent magnet filter together with a small <u>positive</u> bias voltage V_b on the plasma electrode (an electrode of the extraction system in contact with the plasma) would not only enhance the H^- yield but also sizably reduce the extracted electron component. With the filter in position, the source is

essentially divided into two chambers. One chamber, which is a complete multicusp plasma source with one leaky side, contains the energetic electrons and it is therefore the main source chamber where all the ionization occurs (the driver chamber). The other chamber, which is the ion extraction region, contains a plasma with only low-energy electrons (the target chamber). This result suggests that an electron temperature gradient is produced by the magnetic filter between the two chambers. The space potential of the plasma in the target chamber is approximately 2 volt more negative than that of the driver chamber for all bias voltages. In the multicusp ion source with the magnetic filter, the electron temperature T_e is lower in the target chamber ($T_e \approx 0.4$ eV) than the driver chamber. Therefore, it is expected that H_2 is produced in the driver chamber and, on the other hand, H^- was produced in the target chamber.[37]

In the original multicusp negative ion source at Berkeley, the filter position had been chosen when this source was designed to produce high atomic positive hydrogen ion beams. The plasma and extractor electrodes were located outside the magnetic field of the filter in order to eliminate the magnetic field effects on the plasma density profile. To study the dependence of H^- yield on the position of the filter, a moveable plasma-extraction electrode and spectrometer system (Fig. 3) was fabricated.[38] A substantial increase in H^- yield occurs when the extractor system is moved from the edge of the source to a position near the filter. Compared to the case when the extractor system located at the edge (d =0), the H^- current density for the same discharge current was increased five times when the extractor system is moved very close to the filter (d = 6 cm).

A high density negative ion current was extracted across the magnetic field in the reflex-type negative ion source at Berkeley. The ion source was

fabricated (Fig. 4) so that the radial electrostatic field was controlled by an outside power supply; the anode was divided into two parts (the top part of the anode and the wall anode) and they were electrically separated. The potential of the wall anode is biased either positively or negatively with respect to the top part of the anode, which acts as a main anode. Jimbo[32] (1984) obtained the largest negative ion current in the reflex-type source when the wall anode was biased negatively with respect to the top part of anode.

Uramoto[39] (1984) suceeded to extract the H^- current in a large area (4 cm^2: with 9 holes on the plasma electrode) across the weak magnetic field in the sheet plasma negative ion source at Nagoya. The sheet plasma consists of an electron beam component (E_e = 50 eV) at the center of the source and large volume low electron temperature plasma (T_e = 2 to 3 eV) outside it (Fig. 5). The H^- current was extracted effectively from the plasma in a weak magnetic field (50 gauss) under the pressure of 7.7×10^{-4} torr. Dependences of I^- on the bias voltage V_b were investigated in the larger chamber. Then Uramoto found that the largest H^- current was obtained when the plasma electrode potential was -4 volt more negative than the anode potential, which was about the floating potential of the plasma electrode against the anode. Bacal et al.[40] investigated a multicusp ion source at Ecole Polytechnique (Fig. 6). Japan Atomic Energy Research Institute[41] and Culham Laboratory[42] are also developing their multicusp negative ion sources. In these sources, both hot and cold plasma regions are created in the source by mounting filaments and permanent magnets properly.

V. Extraction Mechanism

The plasma space potential in an ordinary multicusp source for positive ions is several volt positive with respect to the anode chamber wall, and the plasma electrode floats negative to the anode chamber. Thus, while positive ions can drift freely to this plasma electrode, negative ions are electrostatically trapped within the plasma volume. If the extracting electrode is just biased positively against the plasma electrode, negative ions are accompanied by a large number of electrons. If the plasma electrode were connected to the anode chamber, a small H^- current could be extracted, but it would be accompanied by a large electron current; 10000 times the negative ion current and about 100 times the positive ion current could be extracted.

In the experiment of the surface conversion-type negative ion source at Berkeley,[43] it was observed that the electron density at the exit region (where a weak magnetic field exists) started to decrease when the plasma electrode was biased positively with respect to the anode. The bias produces very little perturbation on the local electron density under the normal operating conditions without a magnetic field across the source exit. Leung et al.[36] tried to extract H^- from the conventional multicusp source for positive ions. They have shown that the addition of a magnetic filter to the source reduces the extracted electron component as well as enhances the H^- current output. In the presence of the filter the ratio of the H^- current to the power supply electron drain current (I^-/I_e) appears to be very sensitive to the bias V_b applied to the plasma electrode. An optimum value of 1/120 was obtained for I^-/I_e when the potential of the plasma electrode with respect to the anode was around + 2.5 volt. When the extractor system was improved to move very close to the filter,[38] I^-/I_e was increased to 1/2.

Leung and Bacal[44] reported that the variation of the extracted H^- current versus V_b in the multicusp source was an electrostatic effect; a significant variation of the plasma space potential V_p, the electron density n_e and the electron temperature T_e were only observed in the neighborhood of the plasma electrode, while in the plasma center the negative ion density n_- and n_e were unaffected. Leung et al.[45] (1985) found that the addition of xenon or argon gas to a hydrogen discharge can enhance the H^- yield since the low temperature electron density increased.

It has been demonstrated that the extracted H^- current from a magnetically filtered multicusp source can provide high-quality H^- beams with sufficient current densities 38 mA/cm^2 (2.7 mA)[46] to be useful for both neutral beam and accelerator applications. Recently Okumura el al.[41] (1985) succeeded to obtain a high H^- current up to 0.1 A (25 keV, 0.2 sec) at a current density of 10 mA/cm^2 by a multi-aperture electrode (grid) system. In their best condition, the electron drain current through the extraction (electron suppression) power supply was about 1.5 A, and the electron drain current through the acceleration power supply was about 0.2 A. The high magnetic field was applied outside the plasma electrode to suppress electrons. The beamlet divergence was as low as 0.8 ~ 0.9 deg. In order to produce such a high H^- current density, however, it was necessary to operate the prototype source system (Fig. 7) with a discharge current as high as 800 A, and the heat load on the extraction (electron suppression) electrode was as much as 1 kW/cm^2.

A high density steady-state H^- current has been also extracted from the reflex-type ion source <u>across</u> a uniform magnetic field.[32] The relations between the extracted negative ion current and the magnetic field with

changing the potential between the top part of anode and wall anode are shown in Fig. 8. The encouragement of anomalous diffusion with increasing negative bias potential is clear since the cross field H^- current increases and then decreases with the magnetic field. In the high pressure region (10^{-1} torr), the sharp increase of H^- current was explained by the anomalous diffusion mechanism. A maximum H^- current of 9,7 mA (100 mA/cm^2) were obtained. An increase of H^- current in the low pressure region (10^{-3} torr), however, was also observed. In that pressure region, the effect of anomalous diffusion could be neglected. A similar phenomenon was also observed later by Uramoto[47] when H^- were extracted from the low pressure sheet plasma (10^{-4} torr) across the magnetic field. In the multicusp source, the plasma electrode was kept positive with respect to the anode. On the other hand, the optimum conditions of the sheet plasma source as well as the reflex-type source were obtained when the plasma electrode was kept negative with respect to the anode. In order to extract H^- effectively, the space dependence of extracted H^- and hydrogen positive ion H_3^+ currents I^- and I^+ were investigated.[48] I^- increases with the distance from the sheet plasma to the plasma electrode in the y direction (Fig. 5), while I^+ decreases.

In the sheet plasma source a plasma space potential distribution in they y direction, which is created by the ambipolar field across the magnetic field, does not hinder the negative ion flow toward the plasma electrode. However, it is expected that a large number of electrons, which are trapped by the magnetic field, exist in the space near the plasma electrode. Therefore, it is necessary to adjust the potential gradient externally so that the number of electrons, which come into the acceleration region, are reduced. A negative potential V_L with respect to the anode is applied to the first extraction

electrode L in order to create a potential barrier in front of the electrode L (Fig. 9). Since H^- are already accelerated by the ambipolar field (the Larmor radius of H^- is large compared to the dimensional length), a slightly negative potential gradient created in front of the electrode L does not hinder H^- coming out but suppresses electrons.[48] In the typical case, when the maximum value of H^- current is obtained, the space potential gradient is about - 0.25 volt/cm. Since H^- ions have an initial energy around 1.0 eV, they can pass through the potential barrier and come into the apertures of the electrode L. On the other hand, the potential barrier is strong enough to repel most of electrons, which drift in front of the electrode like an electron cloud and create a strong negative space charge. Then, H^- are not repelled anymore by the large negative space charge of the electrons and come out of the plasma. In the extraction experiment with a two-electrode system, in which the second electrode is used for acceleration, however, many thermal electrons still stray into the acceleration region. The extracted electron current is not negligibly small compared to the H^- current. An effective development of a large area negative ion source seems to be very difficult with a two-electrode system. Uramoto[39] (1984) developed an extraction method with a three-electrode system to increase the ratio of the extracted H^- current density against the extracted electron current density through the multi-aperture electrodes (4 cm^2: 9 holes). An intermediate electrode M was introduced between the two extraction electrodes L and E. The electrodes L and M have multi-apertures and the electrode E has one aperture (Fig. 9). Under the proper extraction voltage of the electrode E and the bias voltage V_M of the electrode M, the H^- current was extracted effectively if the electrode L was biased slightly below the floating potential. In the weak magnetic field (about 50 gauss), the accelerated

electron Larmor radius was comparable with the distance between the electrodes L and M and is also comparable with the aperture diameter. It was found that stray electrons were effectively absorbed into the electrode M by the magnetron cut-off mechanism: Uramoto[39] called it "Magnetron absorption of electrons." Uramoto proposed to introduce this three electrode system (in the order of 1 keV) to shut out electrons in front of the pre-accelerator (in the order of 10 keV) so that the load on the acceleration power supply is reduced. H^- current of 75 mA was extracted[49] through the 9 apertures in 4 cm^2 at V_E = 3 keV for a discharge current of 150 A. In his most recent experiment, he has obtained up to 210 mA through 25 apertures (7 cm^2 total area of apertures; 13 cm^2 the occupied area of apertures).

VI. Consideration

In the sheet plasma source experiment, the extracted H^- current increased as the electrodes and mass spectrometer system was moved toward the outside across the magnetic field but the extracted positive ion and electron current decreased.[48] This fact suggests that only H^- is produced in the outside region but not positive ions: they are produced in the different regions. In this outside region, the electron temperature is low, H^- and electrons are well-confined by the electrostatic field along the weak magnetic field but positive ions are lost rapidly; this circumstance is favorable for the formation of H^- and the produced H^- are not lost by the recombination with the positive ions. Since the ambipolar electric field forces negative charges toward the outside region, H^- diffuse in that direction and are easily extracted. The reflex-type negative ion source has similar characteristics. Since the magnetic field is strong (3000 gauss) and the

source itself is small, both the ion and electron Larmor radii are small compared to the experimental scale length.[32] In the sheet plasma source, the ion Larmor radius is not small, it is much longer than the distance between the slits. Therefore, H^- are effectively separated from electrons with the three slits system.[39]

The permanent magnet-generated multicusp source is capable to produce a large volume of uniform and quiescent high density plasma. The large increase in density in this type of source is mainly due to the good confinement of the primary ionizing electrons, as well as the positive and negative ions, by the dipole fields of the magnet. However, the negative ions are expected to be concentrated near the center by the positive plasma space potential. Then, the plasma electrode was biased positively to extract negative ions effectively from the plasma; the electrons were absorbed electrostatically. However, I^-/I_e was still small. When the multicusp source was improved by introducing the magnetic field in the extraction region, however, much more negative ion current was observed and I^-/I_e is increased.[38] In the conventional multicusp sources, the magnetic field exists outside the extraction (exit) region to separate electrons from the negative ions while they are accelerated. No magnetic field exist in the extraction region of the conventional multicusp ion source. It seems that the existence of <u>a weak magnetic field</u> in both the plasma and extraction regions is essential to optimize the negative ion extraction as well as suppress electrons.[50] In the multicusp source, the extracted H^- current will be increased if the volume of the source is enlarged (3 dimensional), but the H^- current might be increased by enlarging just the area of the sheet plasma (2 dimensional) in the sheet plasma source. The multicusp ion sources have been investigated

eloborately while they have been developed for the large area positive ion NBI systems. Development of the sheet plasma source is still in the preliminary stage. Further investigation is necessary to decide the ideal configuration of negative ion sources for the future NBI systems.

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Figure Captions

Fig. 1 Neutralization efficiency for hydrogen and deuterium ions versus energy.

Fig. 2 A conceptual design for a 400 keV negative ion NBI system utilizing TFF beam transporters proposed by Lawrence Berkeley Laboratory. (The ion source in the figure is the surface-type negative ion source.)

Fig. 3 Schematic diagram of the multicusp ion source equipped with a magnetic filter and a moveable extraction-spectrometer system.

Fig. 4 Schematic diagram of the reflex-type negative ion source.

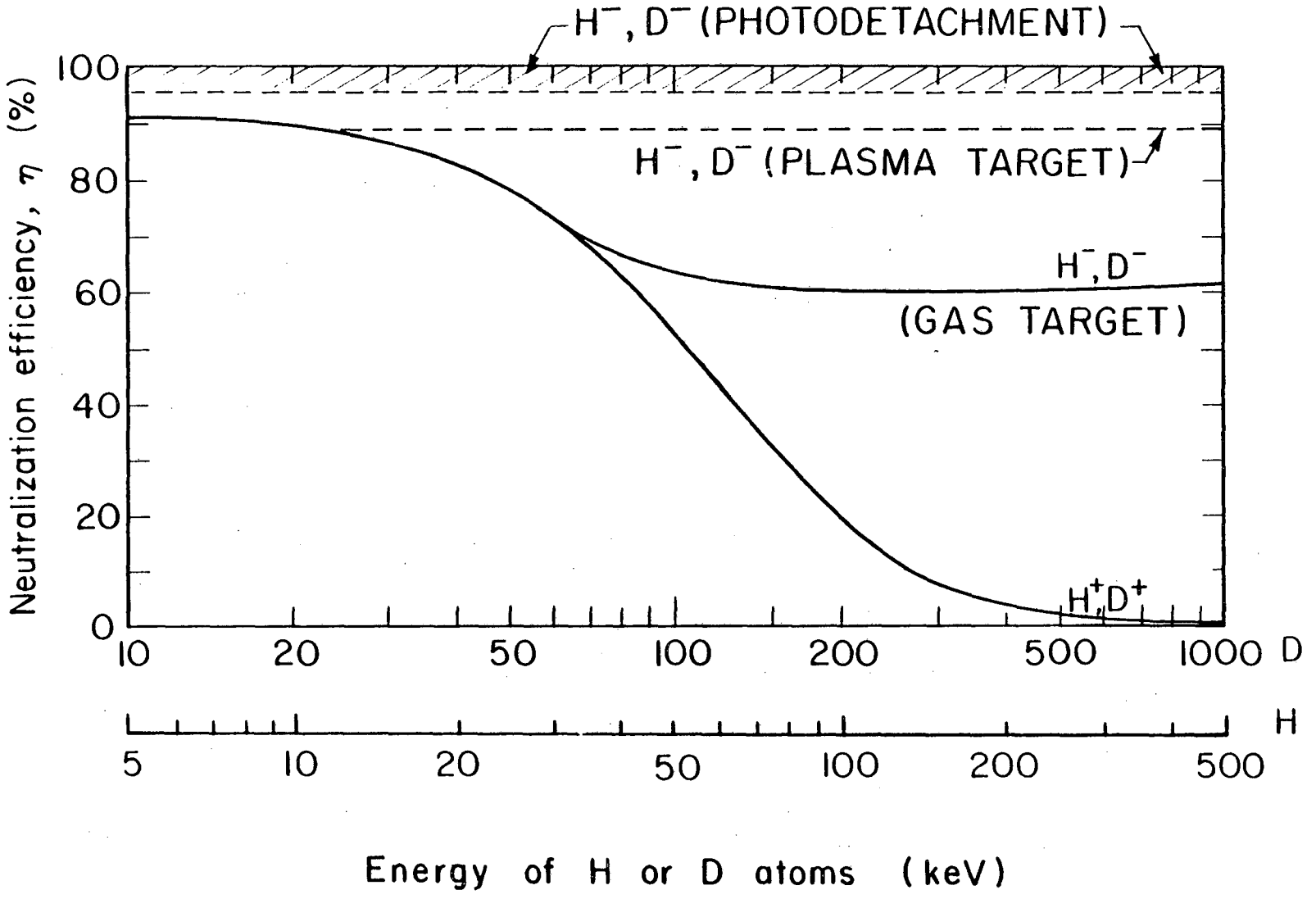
Fig. 5 Schematic diagram of the sheet plasma source with the plasma electrode and mass spectrometer.

Fig. 6 Schematic diagram of the multicusp ion source in which the filaments are located so that the primary electrons are trapped in the multicusp magnetic field.

Fig. 7 Cross sectional view of the multicusp ion source and extraction system with the electrical connection of the power supplies.

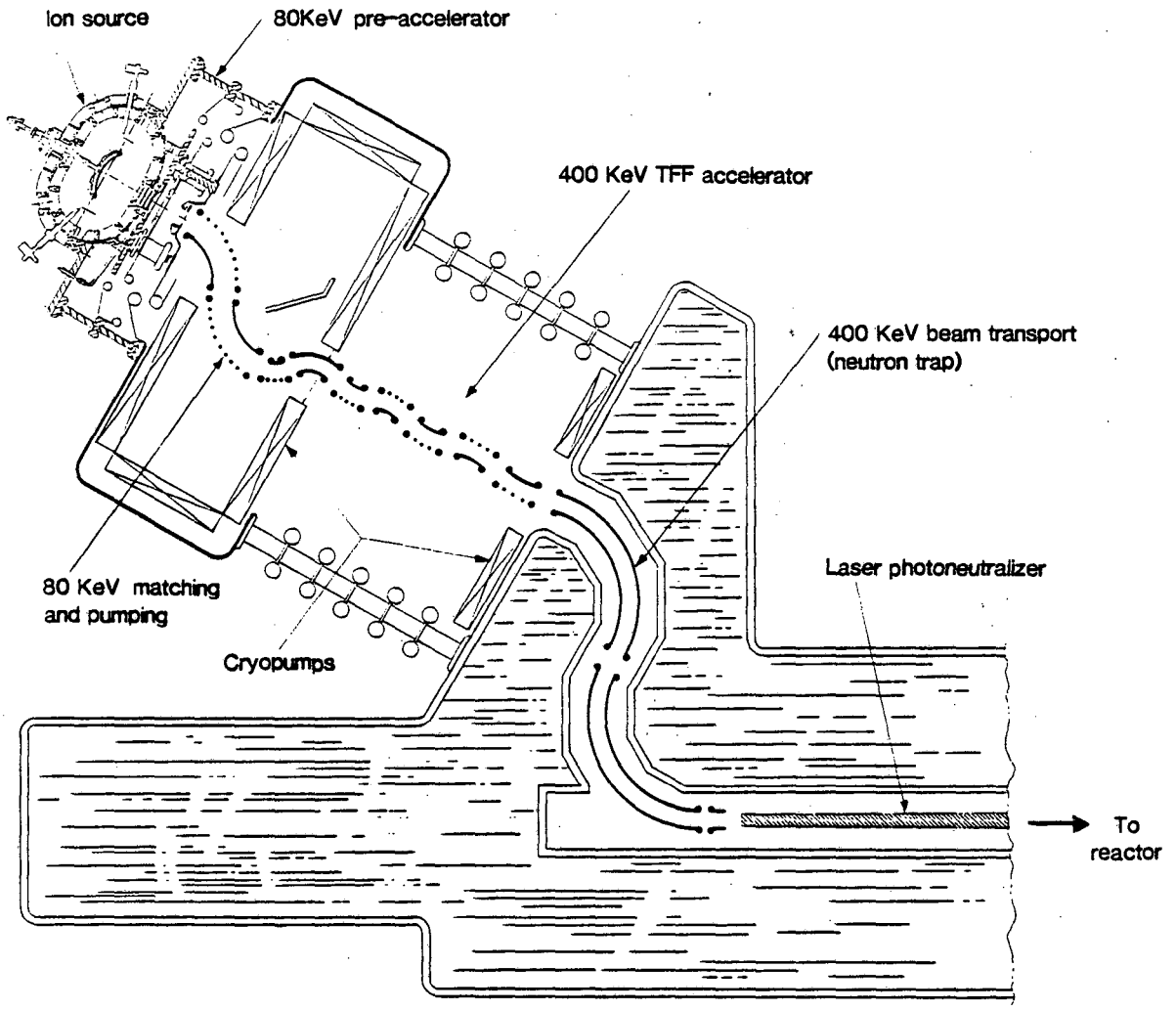
Fig. 8 Relations between the extracted negative ion current and the magnetic field with changing bias potential.

Fig. 9 Schematic diagram of the sheet plasma with the three electrodes, extraction electrodes L, M (with multi-apertures) and E (with single-aperture), and mass spectrometer system.



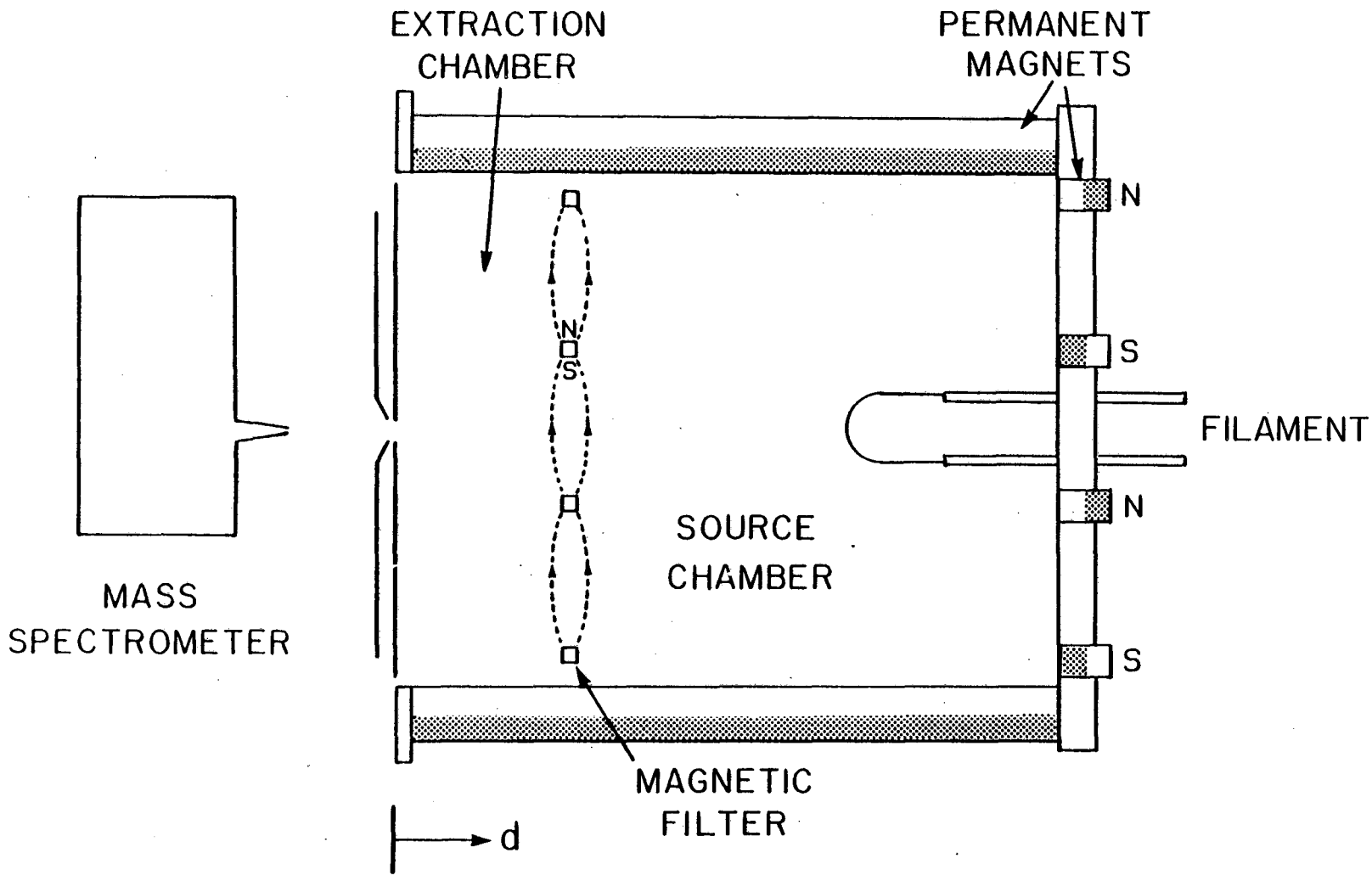
XBL 827 – 933

Fig. 1



XBL 8310-12264

Fig. 2



XBL 847-2898

Fig. 3

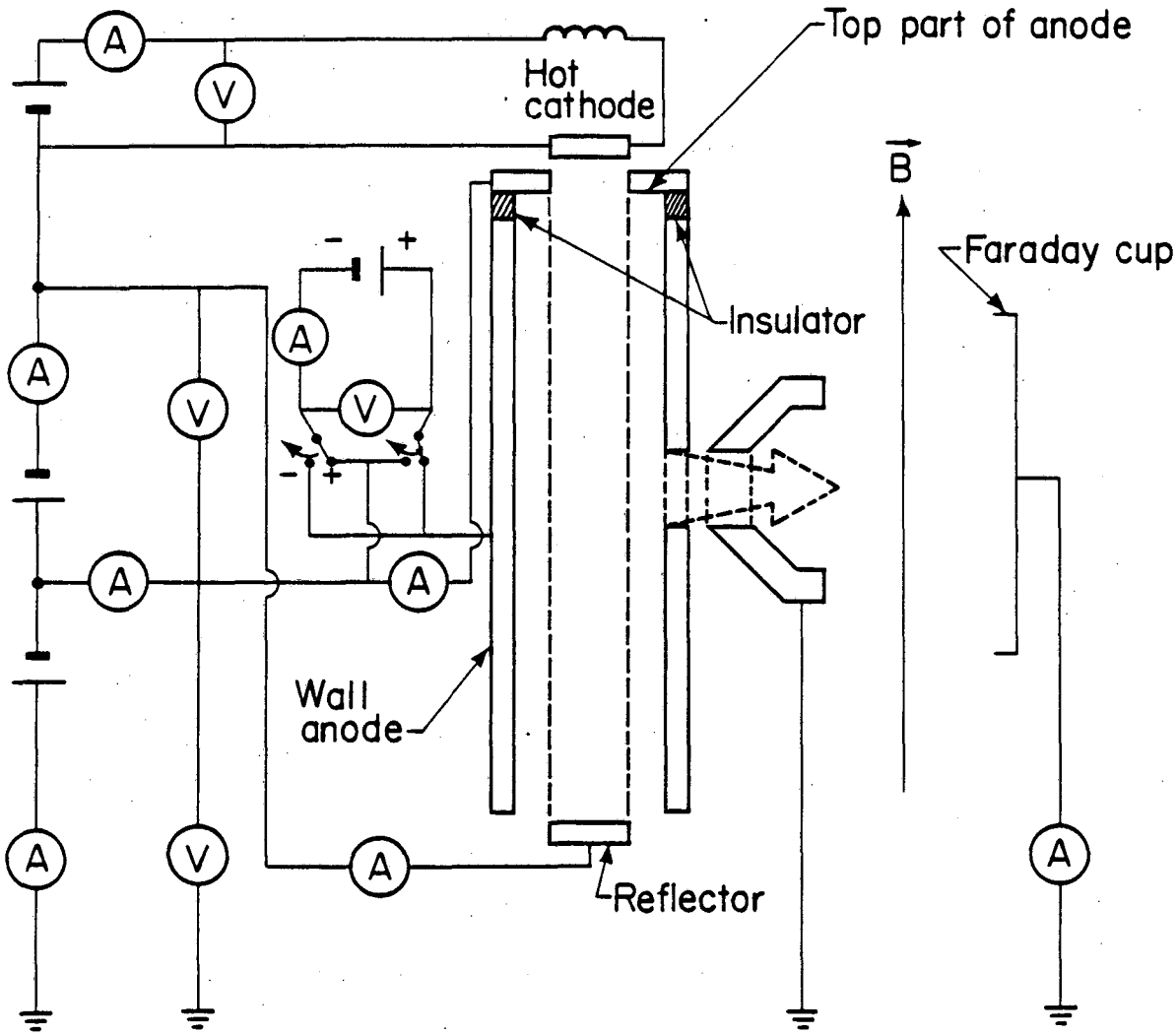
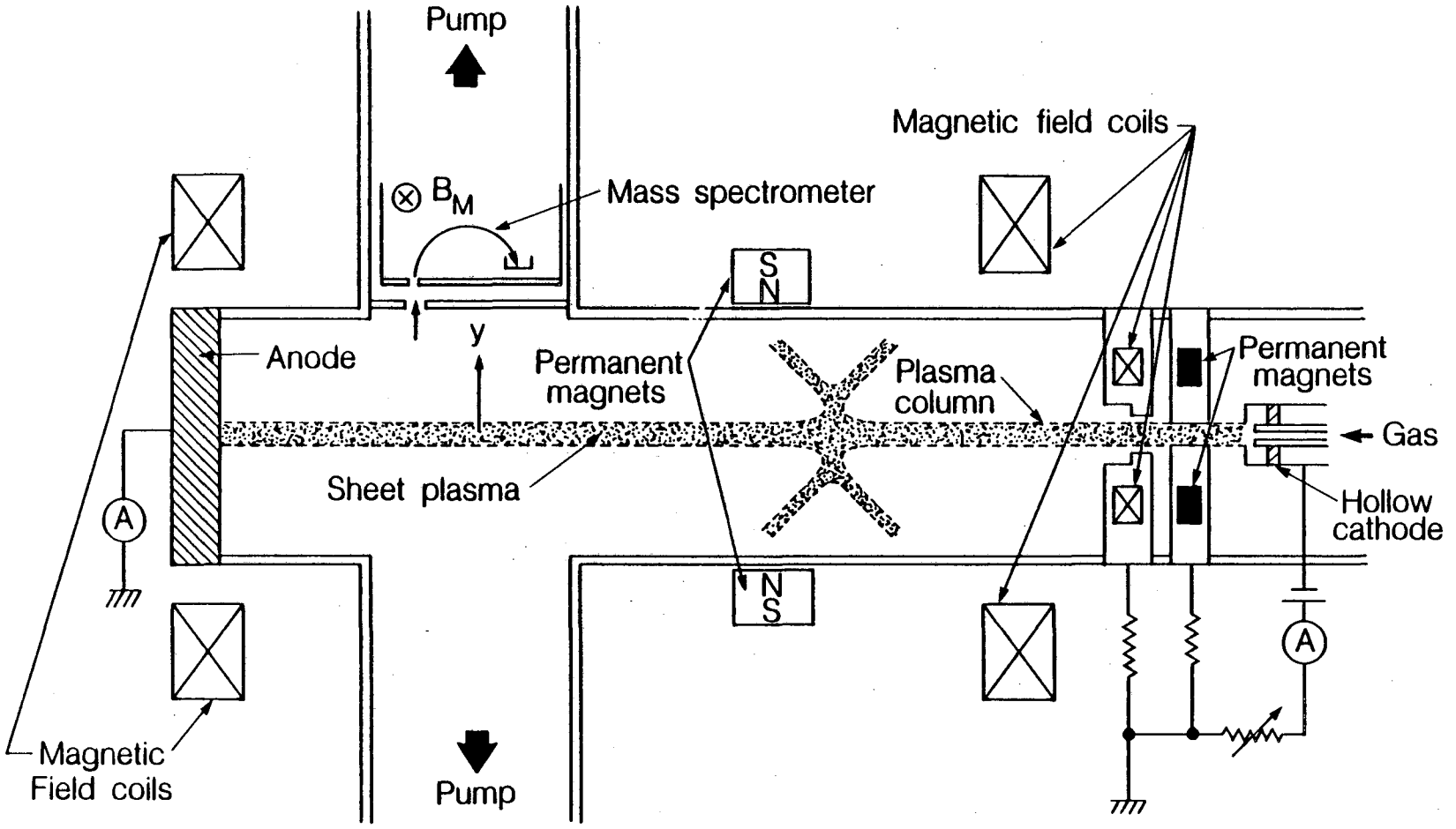
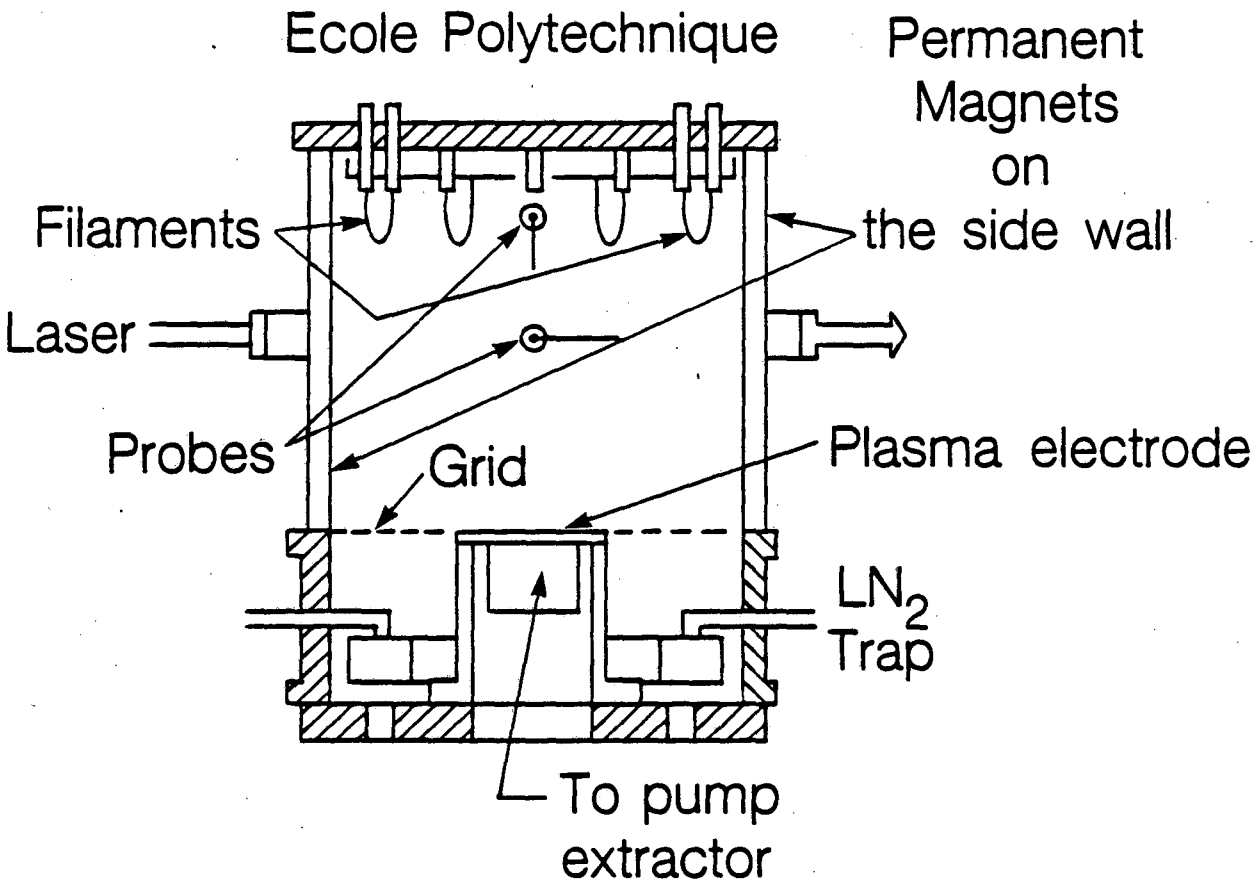

Top part of anode
Hot cathode
B
Faraday cup
Insulator
Wall anode
Reflector
A
V
XBL 824-493

Fig. 4



XBL 8511-4550

Fig. 5



XBL 8511-4552

Fig. 6

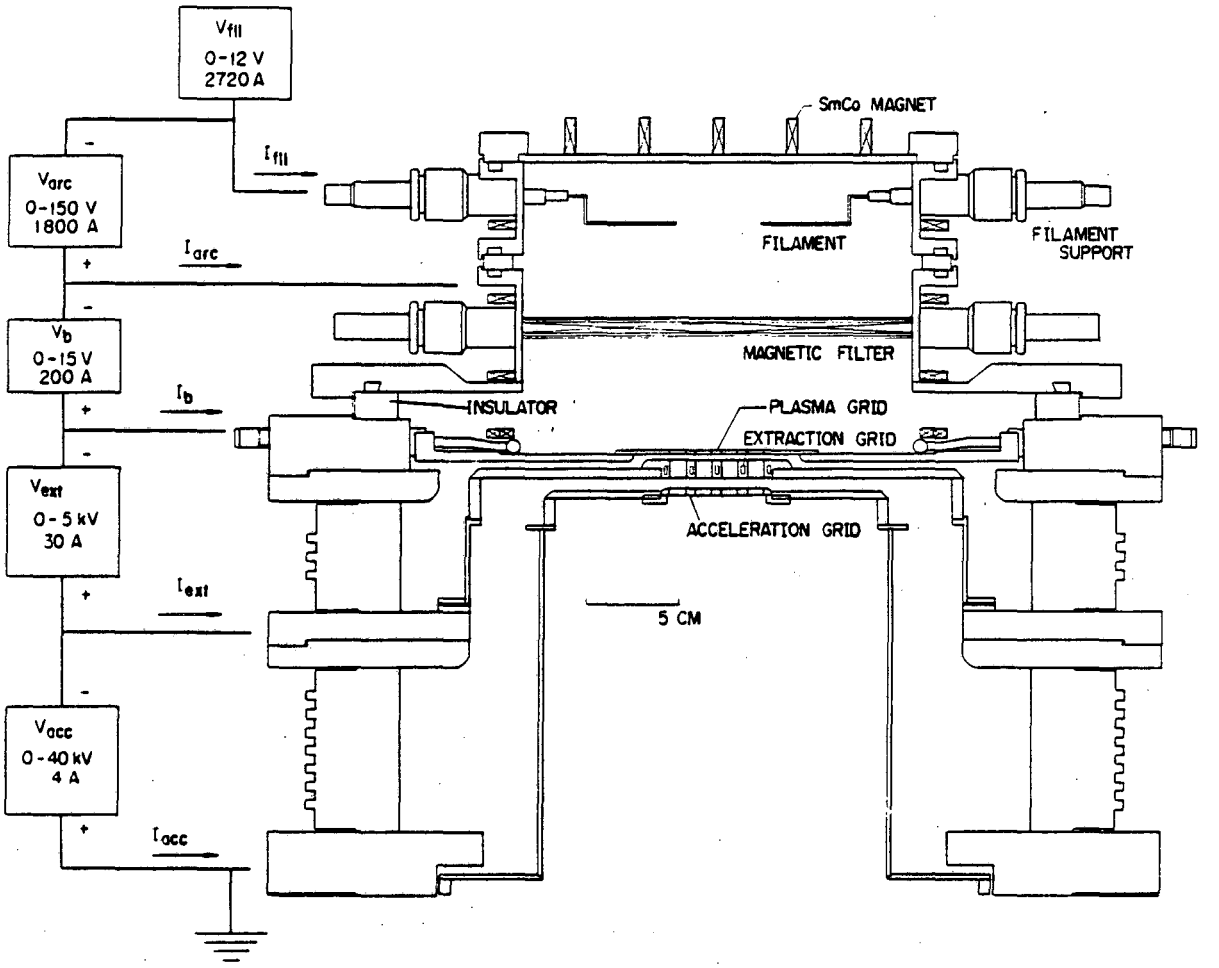


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Fig. 7

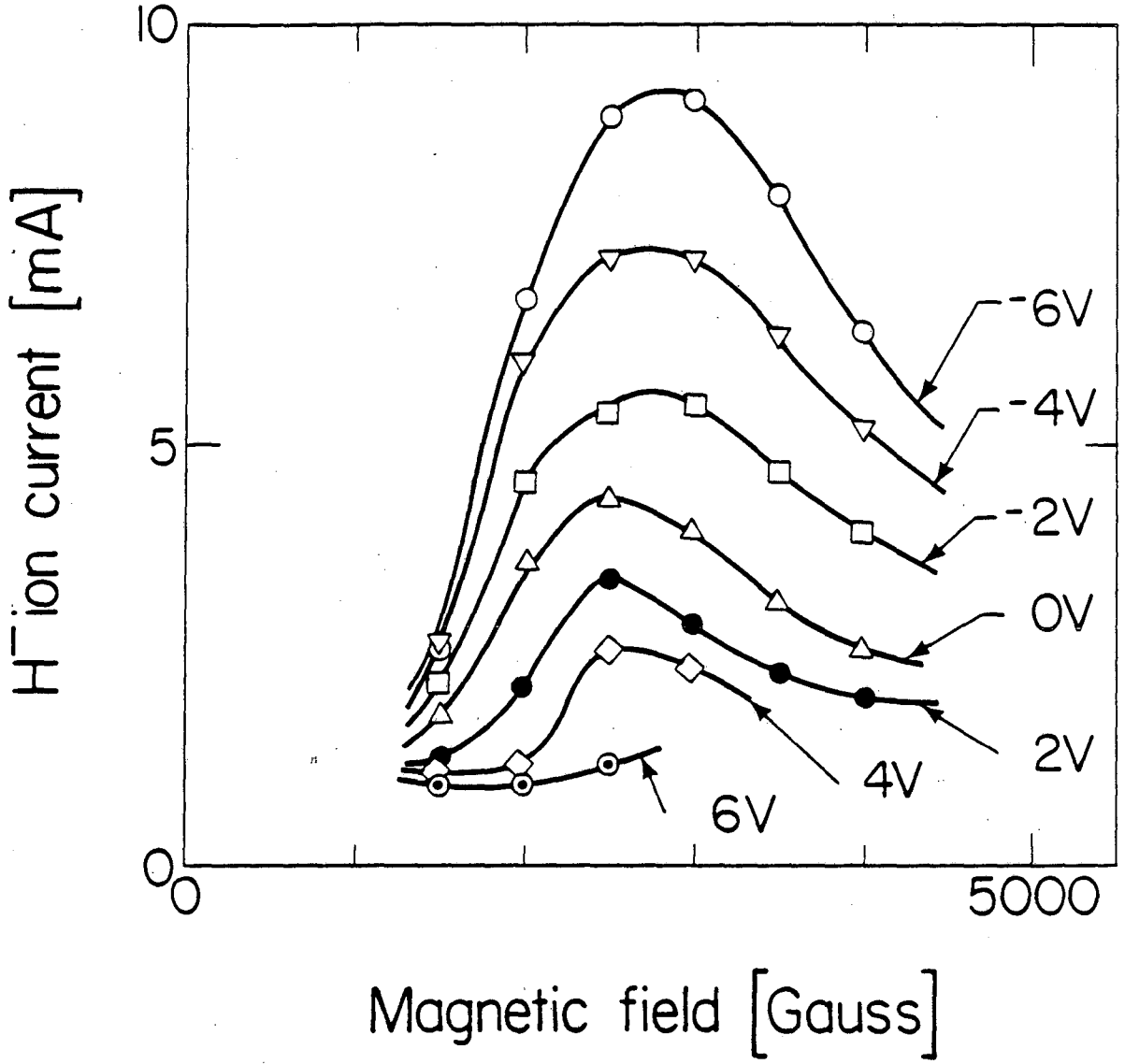

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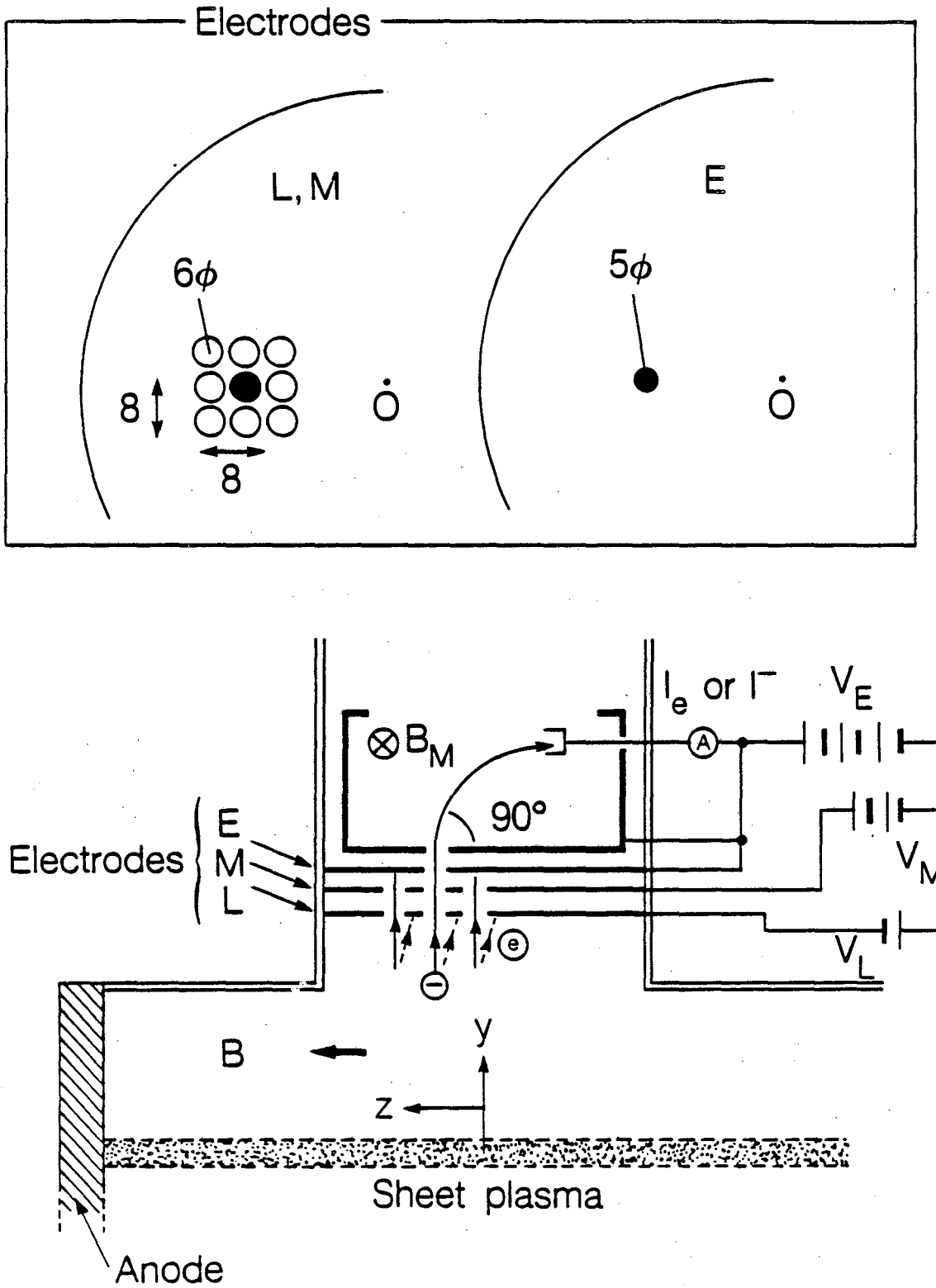
Fig. 8



XBL 8511-4551

Fig. 9

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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