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Effective Extraction Mechanism of Volume-Produced Ions in the NIPPER I Device

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ABSTRACT

A mass spectrometer system is developed to extract and analyze hydrogen ions from a volume plasma hydrogen ion source. A 180° magnetic deflection-type mass analyzer is coupled to NIPPER I (National Institute of Physics Plasma Experimental Rig I), a negative ion source. Hydrogen plasma is produced from a low pressure gas (10^{-2} Torr) with a transition of the glow discharge (254 volts, 75 mA) to an arc plasma (78 volts, 14 amperes) in a few seconds. The usually cylindrical plasma is converted into a sheet configuration using a pair of Sm-Co magnets. This optimizes ion current extraction by reducing (a) the ion loss to the discharge anode and (b) the decay of the ion current produced in the plasma. Negative hydrogen ions (H^-) are volume-produced by dissociative attachment of low energy electrons to highly vibrational excited hydrogen molecules.

The extraction of H^- ions from this volume source is optimized by the proper choice of apertures of the limiting electrodes and of the applied bias potential. A proper combination of extraction electrodes gives an optimum H^- current extracted without the electrons. When one of the extraction electrodes is biased negatively near the value of the plasma floating potential, a maximum H^- current is also obtained. The methods of effective extraction of H^- are discussed.

INTRODUCTION

The production and extraction of negative ions has been of considerable interest worldwide from view points of heating and diagnostic beams for nuclear fusion devices and injectors to high energy accelerators. Surface conversion negative ion sources have been known as efficient H^-/D^- sources (1). Alkali metals such as cesium are usually introduced into an ion source so as to reduce the work function of the converter surface. Ions are generated in surface interaction principally via desorption or backscattering. Cesium, however, is difficult to handle and causes impurity problems. It might also cause the breakdown of insulation of the electrostatic beam acceleration system in actual applications.

On the other hand, the H^- sources that produce H^- in plasma volume through dissociative attachment of low-energy electrons to highly vibrationally excited molecules are considered to be most appropriate for nuclear fusion applications because they have better beam quality (2). That is, the volume-produced H^- beam has a characteristic low emittance, high brightness, stable output, and low beam noise. The only disadvantage of volume production H^- sources is the large electron current which is extracted with H^- ions. The extracted negative ions and electron currents appear to be sensitive to the bias potential applied to the electrode of the extraction system in contact with the plasma (3, 4). It has been shown, however, that this problem can be solved by properly arranging the electric and/or the magnetic field in the beam extraction region (5).

These observations suggest that the plasma region next to the so-called plasma electrode (the plasma in contact with the extraction system) is very important for negative ion extraction and deserves a detailed study.

In this article, a systematic study of the extracted charged particle currents is reported. An effective extraction method for H^- ions has been developed in order to optimize extraction of volume-produced ions and reduce considerably the extracted electron component. The method used is a focusing-type of acceleration which suppresses the electron density in the neighborhood of the extraction aperture and allows only negative ions to pass through.

EXPERIMENTAL SETUP

The negative ion source studied in these experiments has been described in detail elsewhere (6, 8). A schematic diagram of the device is shown in Fig. 1. The ion source consists of four main components, vis.: a) the cathode, b) the first and

second plasma limiters, c) the main vacuum discharge chamber, and d) the anode. The cathode is made of the disc-shaped lanthanum hexaboride (LaB_6) as the primary ionizing electron emitter which can be operated at a relatively low temperature with a work function of 2.36 eV. LaB_6 has a characteristic high discharge current density and relatively long operational lifetime, compared to tungsten. The cathode chamber acts as the plasma production area and is separated from the plasma utilization area (the main vacuum chamber) by a couple of plasma limiters. The plasma limiters consist of a circular ferrite permanent magnet and a coreless magnetic coil. The composite magnetic field configuration of these magnets provides the ideal magnetic field for plasma production and keeps the radial magnetic field component near the extraction electrode to a very low value (<1.0 gauss) in order to obtain unambiguous values in the ion currents. These plasma limiters also differentiate the pressures in the cathode chamber and the main vacuum chamber. Thus a neutral hydrogen gas pressure of 0.9 Torr in the cathode chamber has a corresponding neutral hydrogen gas pressure two orders of magnitude less in the main discharge chamber.

Plasma production is done in a sequential process. A pre-discharge plasma is created in the cathode chamber in order to heat up the LaB_6 cathode until it emits ionizing electrons to the main discharge chamber. This occurs when the glow discharge of 254 volts, few mA in the cathode chamber transforms to an arc plasma (78 volts, 14 amperes) in the main chamber. The steady-state cylindrical plasma, 2 cm in diameter and 39 cm long, is sustained by sequential switching from the cathode to the anode.

The formation of a negative hydrogen ion first requires the transformation of the 2 cm diameter cylindrical plasma into a sheet plasma. In the sheet configuration the highest ion current can be collected because of the wider plasma area. The sheet plasma will include the fast energetic electrons accompanied by cold diffused plasma electrons around it. These low energy electrons interact with molecular species leading to the production of negative ions. The transformation is done by arranging two rectangular 1 cm x 3 cm x 5 cm Sm-Co permanent magnets of ~3.0 kGauss on the surface in a SN-NS position on opposite sides of the plasma column and about 7 cm from the second plasma limiter. The sheet plasma that is formed includes the fast energetic electrons accompanied by cold diffused plasma electrons around it. These low energy electrons interact with molecular species leading to the production of negative ions.

Experimental access to the plasma is by a pump port 15.0 cm from the anode (Fig. 1). A 180° deflection mass spectrometer is used (9). The spectrometer is

compact, 7.0 cm wide, 5.53 cm deep, and 5.18 cm high, and fits the vacuum chamber conveniently.

RESULTS AND DISCUSSION

We first consider an extraction by first stage acceleration of H^- from a single aperture, assuming that the initial energy of H^- is comparable to the thermal electron energy. As shown in Fig. 2a, we consider electron magnetron cut-off using the axial magnetic field B_z for the sheet plasma. The H^- ions are accelerated across this field. The acceleration distance d for magnetron cut-off for H^- ions is given by the relation

$$3.4\sqrt{V_E}\ /B_z \leq d << 144\sqrt{V_E}/B_z \qquad (1)$$

where V_E is the extraction voltage in volts, B_z is the axial magnetic field in gauss and d is in cm. Since B_z is about 100 gauss, we have from Eq. (1),

$$0.5d^2 << V_E \leq 10^{-1} d^2 B_z^2 \approx 10^3 d^2. \qquad (2)$$

Equation (2) signifies a sharp cut-off for electrons. The electrons, however, are deviated from the small aperture of the extraction electrode E by a much lower magnetic field so that an upper limit of V_E may be much larger than what is to be expected from Equation (2).

The space charge limited current density j_{H^-} for H^- for the extraction voltage V_E and a given distance d is determined by

$$j_{H^-} = 5.4 \times 10^{-8} V_E^{3/2}/d^2. \qquad (3)$$

Equations (1) to (3) lead to

$$j_{H^-} = \leq 1.7 \times 10^{-9} d B_z^3 \approx 1.7 \times 10^{-3} d. \qquad (4)$$

The simple method just discussed does not consider electron diffusion across B_z. The electrons can diffuse by collisions with neutral particles and with the walls of the vacuum chamber. Thus, the electron magnetron cut-off method is not always effective.

Another method utilizes a limiter for electrons. An electrode L with an aperture is introduced as shown in Fig. 2b. Electrode L can be biased negatively. Since H^- has the same sign of charge with the electron, this electrical limiter action poses some problems. We must exclude the electrons from the ion extraction. The set up of Fig. 2b is improved by considering a focusing acceleration method for H^-. This is shown in Fig. 2c where the aperture of electrode L is much wider than that of electrode E. An added diffusion space *d'* helped in the effective electron suppression. The distance also prevented the breakdown between discharge electrodes and extraction electrodes.

Using the configuration of Figure 2c, the magnetic field B (in gauss) for deflecting an ion of mass m_i and energy E (in eV) to a gyroradius *r* (in cm) is given by

$$B = 144 \sqrt{\mu E / r} \qquad (5)$$

where $\mu = m_i/m_p$, m_p is the proton mass. For H^- the radius of curvature is

$$r = \frac{144\sqrt{V_E}}{B_A} \qquad (6)$$

where V_E and B_A are the extraction voltage and analyzing magnetic field, respectively. A typical mass analyzing pattern is shown in Fig. 3 corresponding to an ion cyclotron radius of about 3.5 cm.

An estimate of the current density of H^- can be obtained by modifying the mass analyzer into a 90° deflection type as shown in Fig. 4. To check the extraction method, the aperture of the extraction electrode E is held fixed at 3 mm diameter and that of the plasma flux limiting electrode L varied. Electrodes E and L are separated by about 1.0 cm. Electrode E is biased at 250 V and electrode L is at floating potential. This result is shown in Fig. 5, which shows an optimum H^- ion current at 1.6 cm for the aperture of electrode L. It should be noted also that the electron current decreases as the aperture diameter of the electrode L becomes larger. The focusing nature as indicated in Fig. 5 gives a limiting aperture for

optimum H^- current. Beyond 1.6 cm, the H^- current is observed to decrease. This could be attributed to the number of constituent ions or nuclei which are able to react with H^- contributing to a loss mechanism for H^-, hence the decay of the H^- ion current as the aperture is further enlarged.

A similar focusing condition is observed on the dependence of H^- current on the potential of the limiting electrode L, with the potential of electrode E fixed. The result, as shown in Fig. 6, indicates that a maximum current of H^- is obtained if the limiting electrode is biased negatively near the value of the plasma floating potential.

What these results indicate is that the extracted H^- current is conditioned by the apertures of the limiting electrodes and of the applied bias potential. Exploiting these effects fully could eliminate the electron extraction from volume H^- sources.

CONCLUSIONS AND RECOMMENDATIONS

A mass spectrometer system for measuring the species composition of the plasma has been developed. It has been shown that with proper choice of apertures and proper biasing of extraction electrodes, the optimum H^- current is extracted with an insignificant accompanying electron current. Other gas operating conditions could be tried, but we are currently limited by the present capability of existing power supplies.

ACKNOWLEDGMENTS

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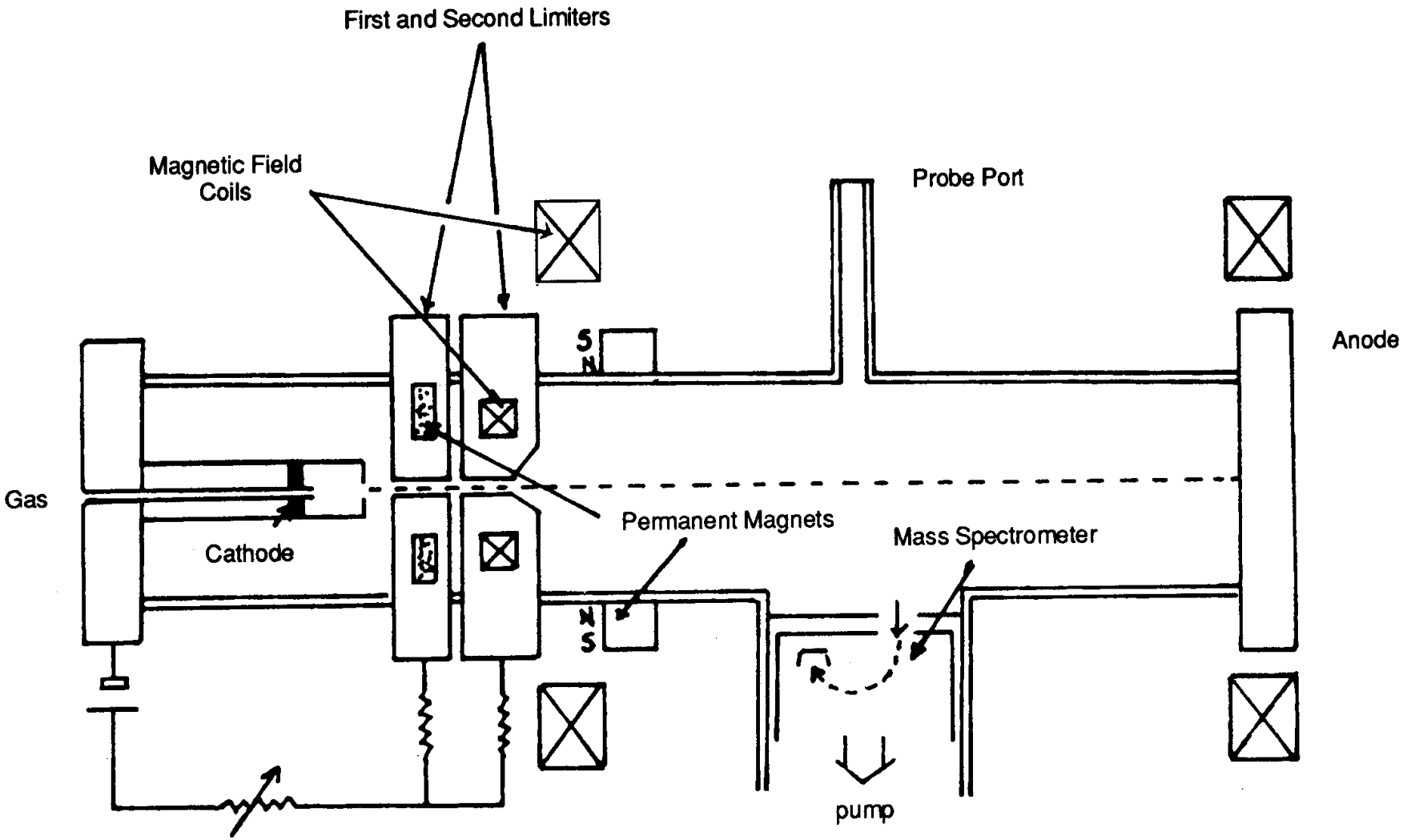

Figure 1. Schematic diagram of the NIPPER I device.

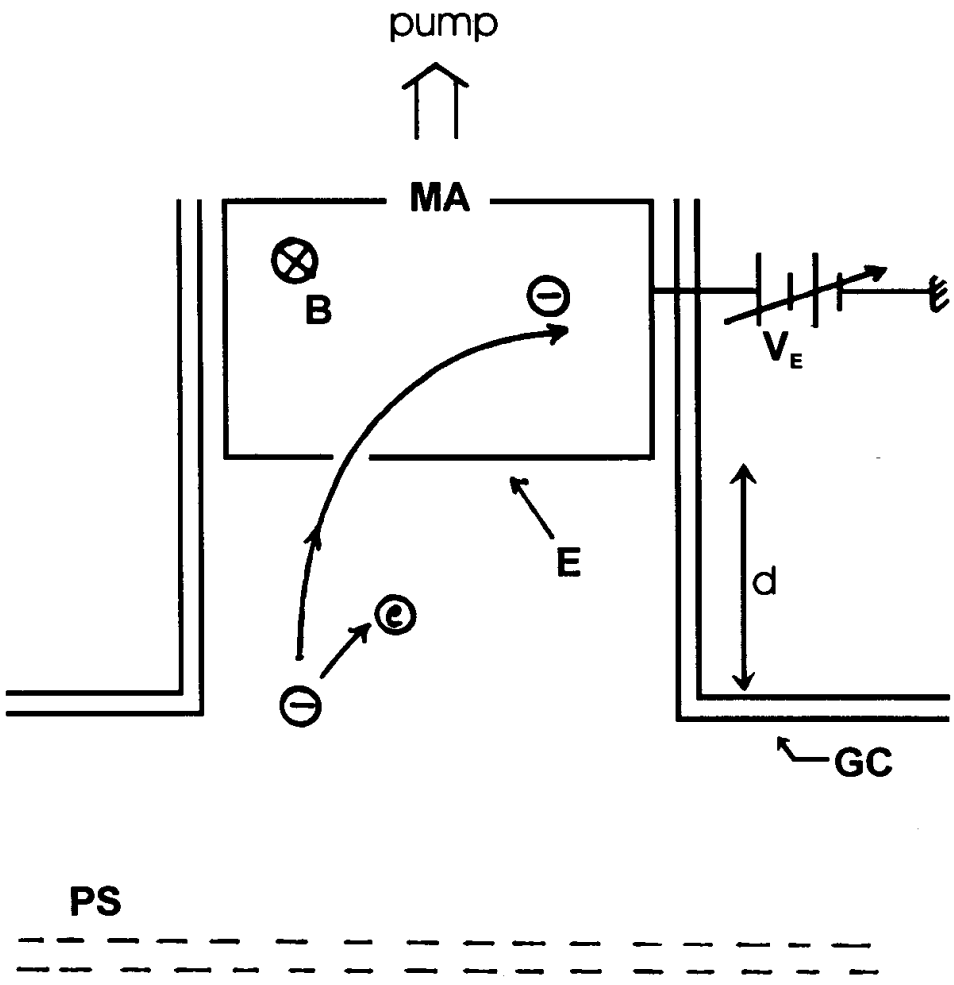

Figure 2a. H^- ion extraction method. GC: Glass chamber. MA: mass analyzer. B: Analyzing magnetic field. V_L extraction voltage. E: extraction electrode. V_L: bias voltage. L: limiting electrode. d: distance between electrodes E and L. d': distance between glass chamber and electrode L. PS: plasma sheet.

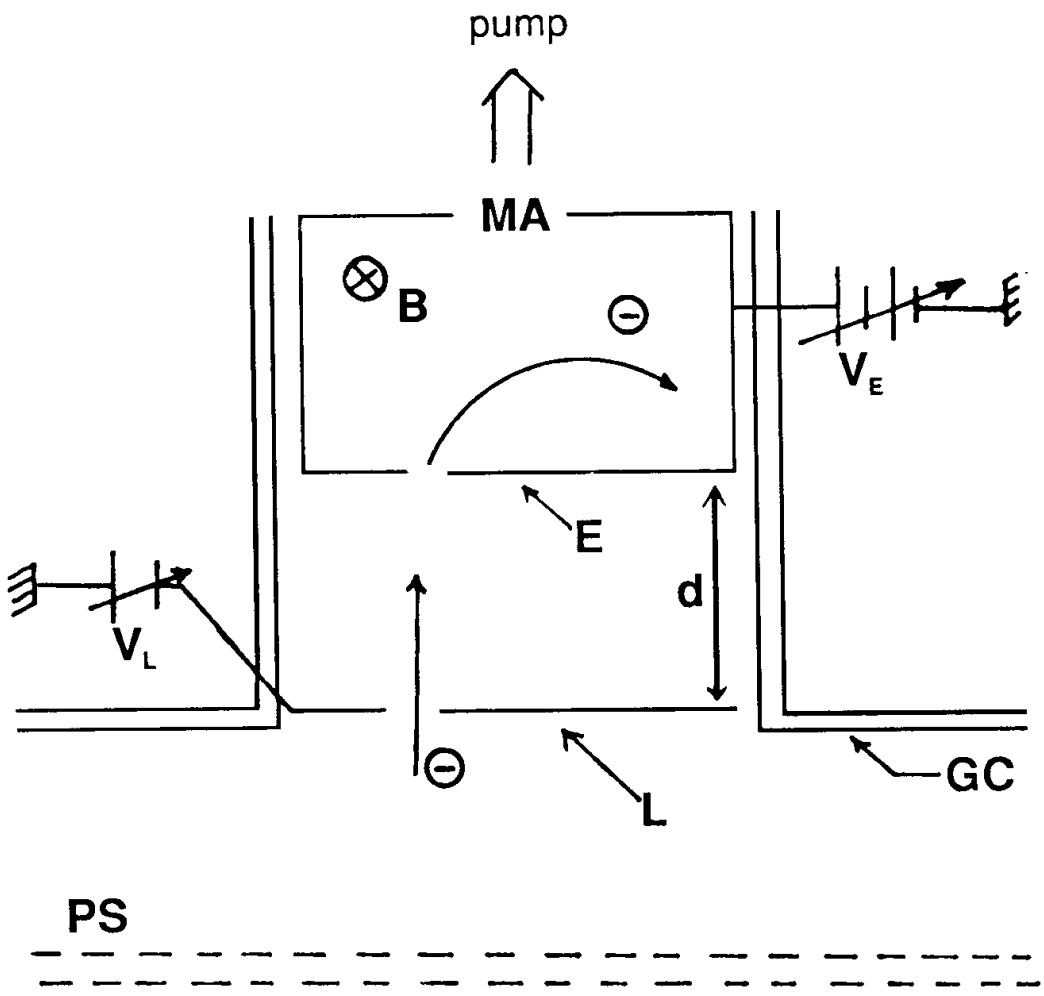

Figure 2b

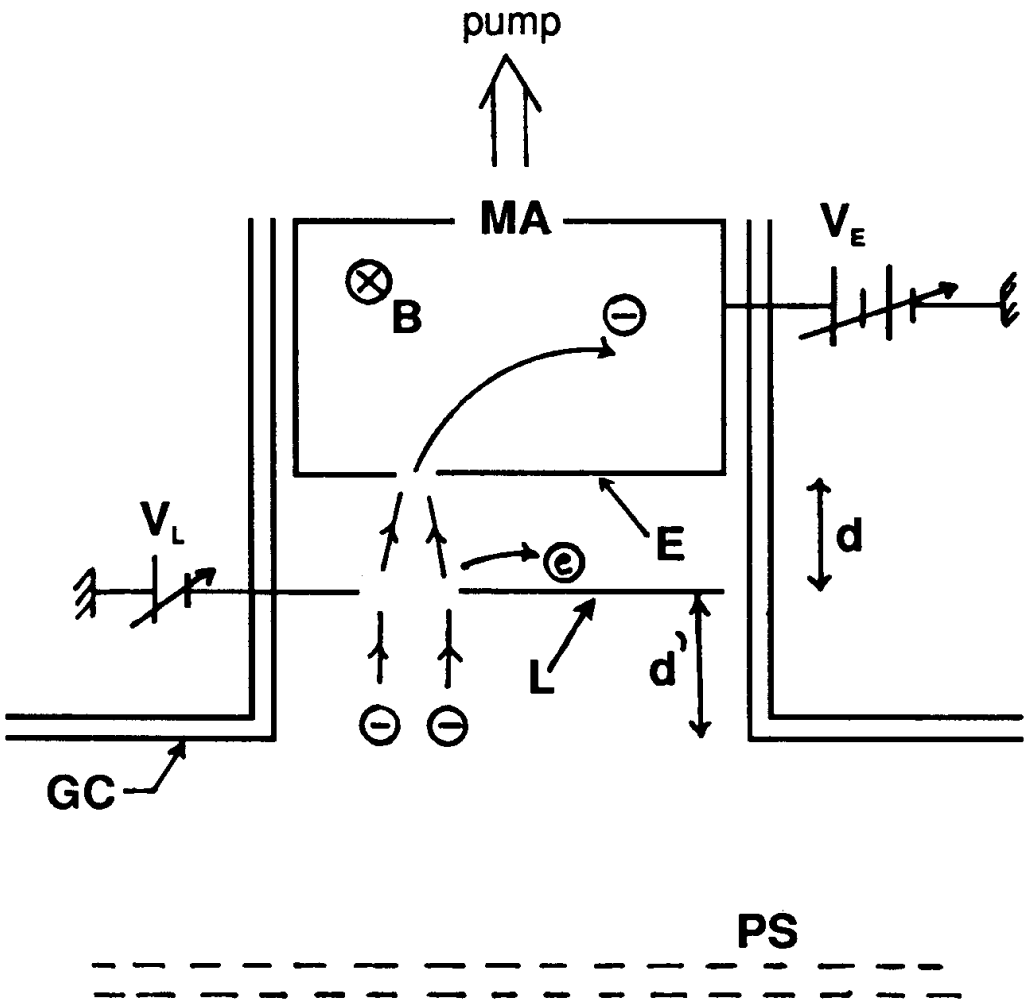

Figure 2c

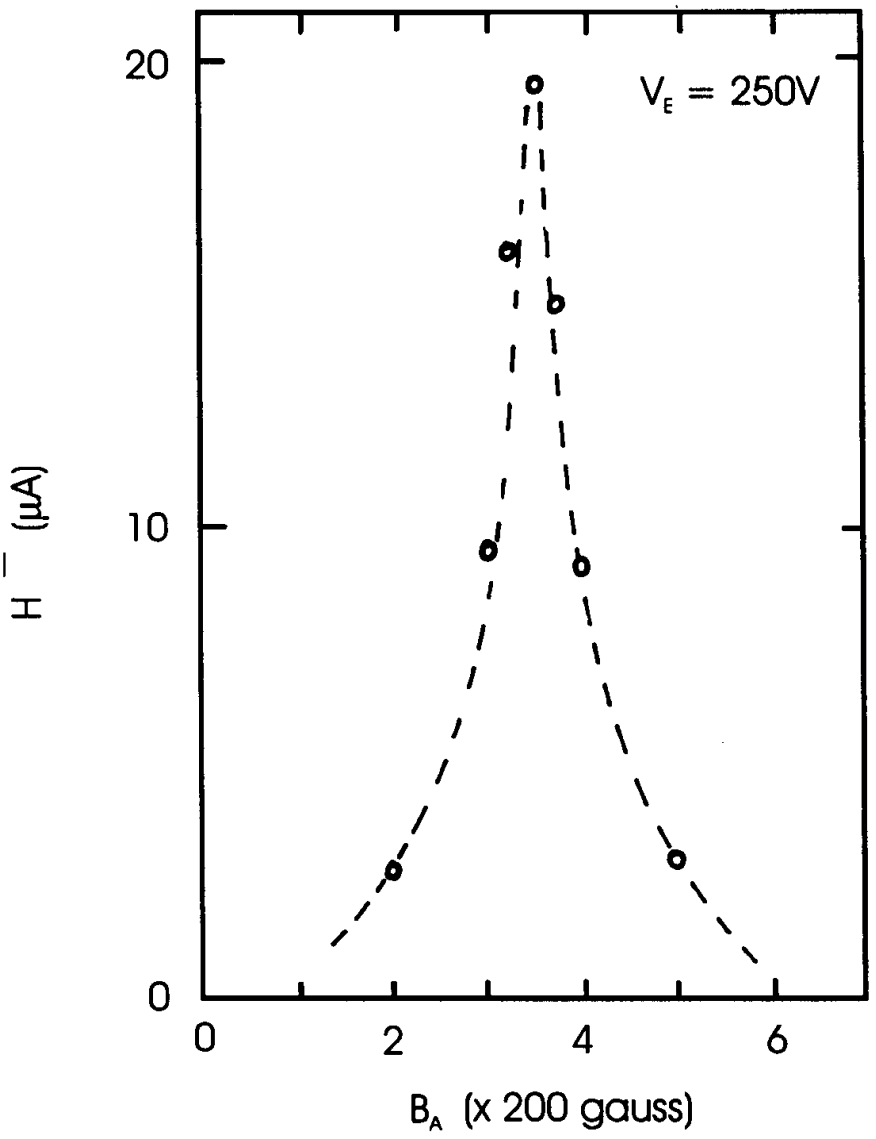

Figure 3. Typical mass analyzing pattern.
B_A: analyzing magnetic field. V_E: extraction voltage.
H^-: negative ion current

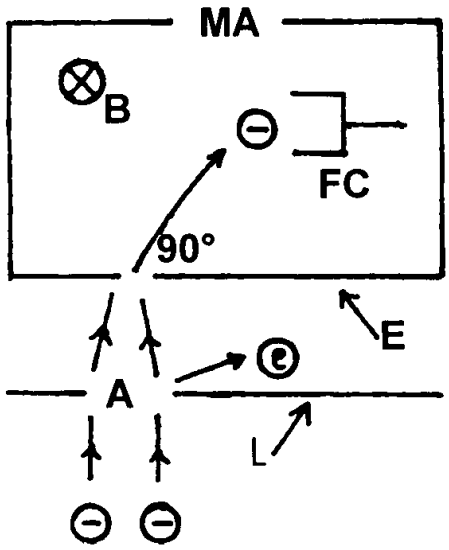

Figure 4. 90°-deflection type mass analyzer (M.A.). E and L are extraction electrodes. B_A: analzying magnetic field. A: aperture. FC: Faraday cup.

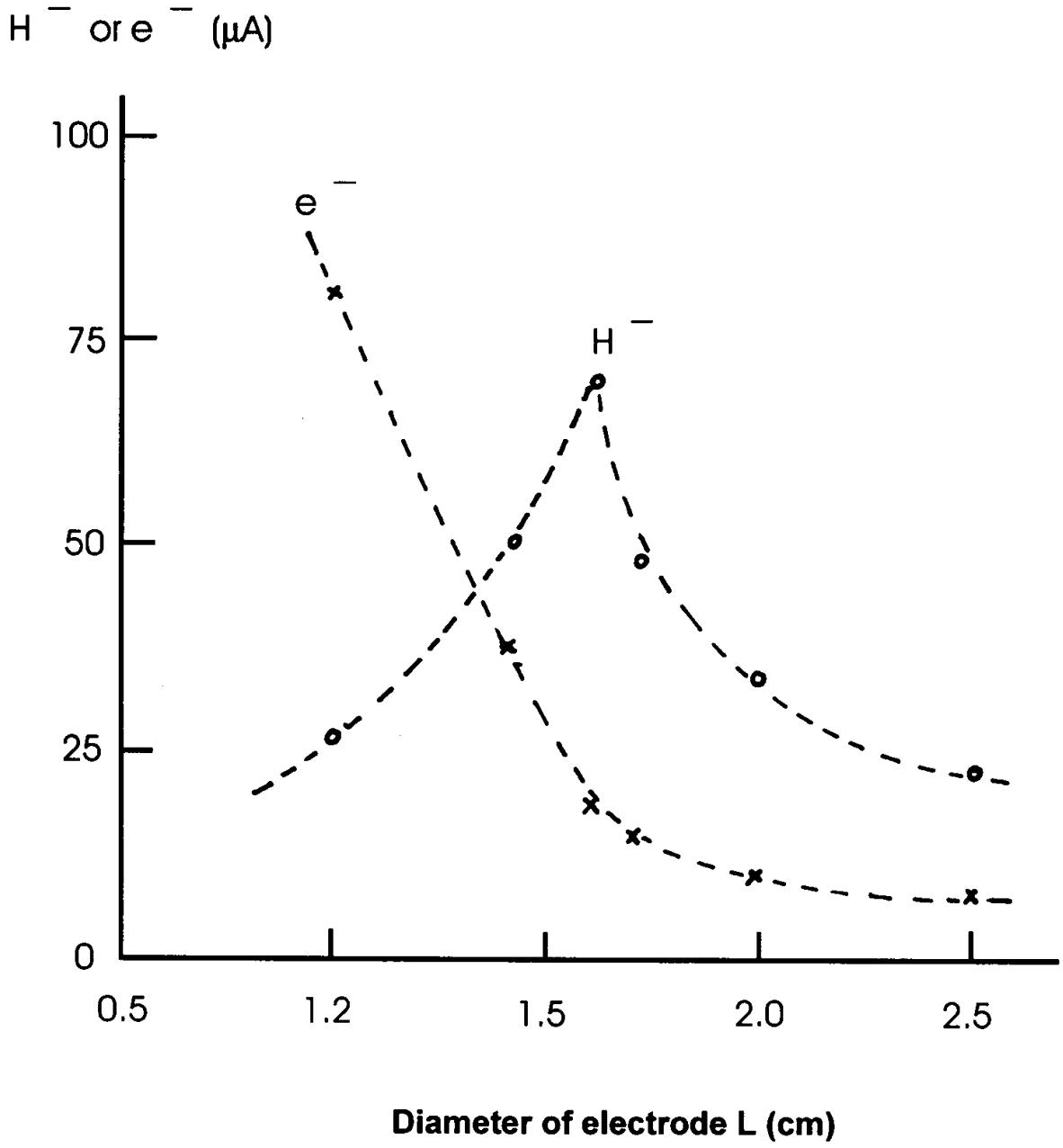

Figure 5. Dependence of H– and electon current on aperture diameter A f limiting electrode L using a 90°-deflection type mass analyzer.

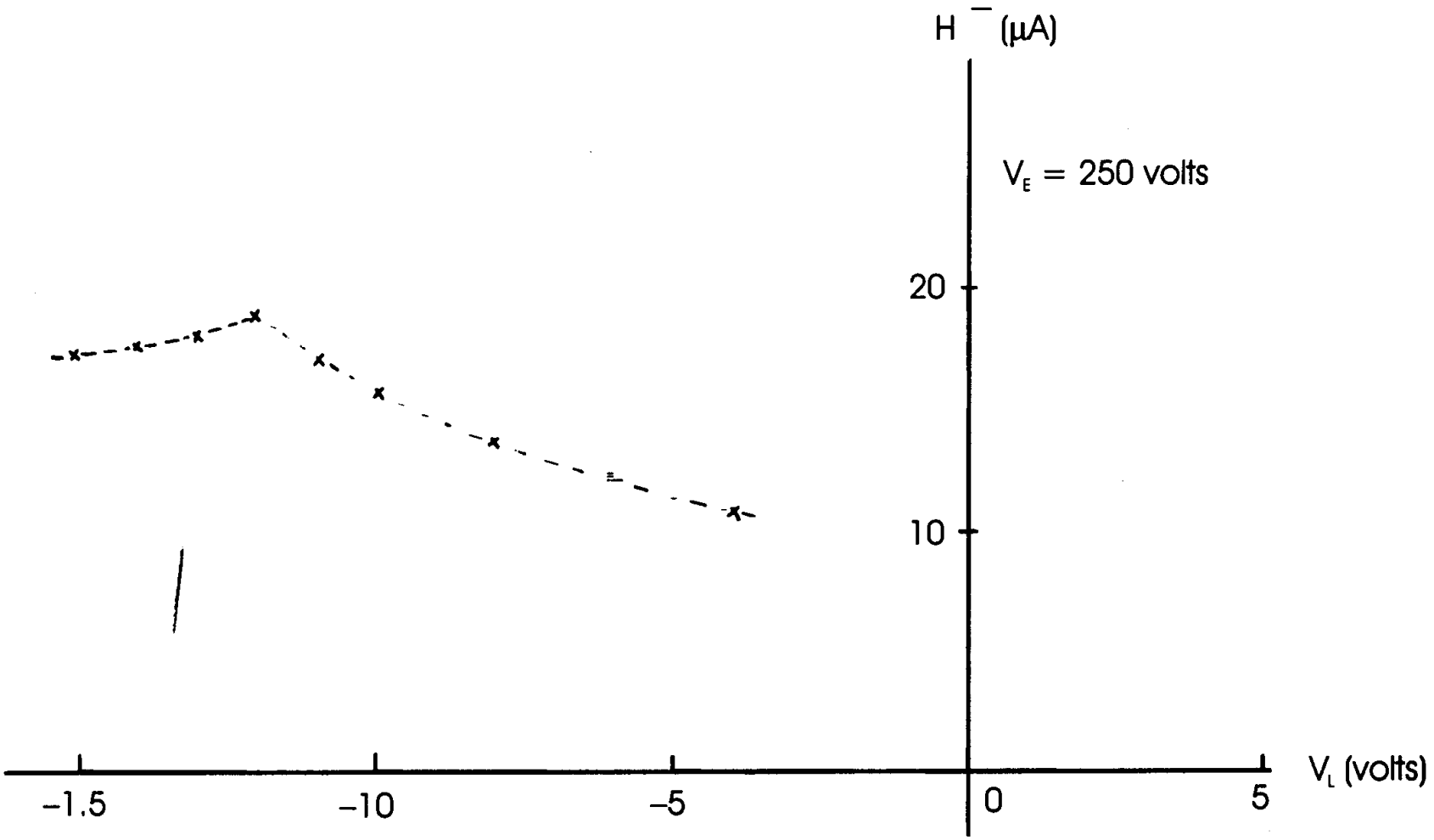

Figure 6. Variation of H^- current with the bias potential of limiting electrode L.