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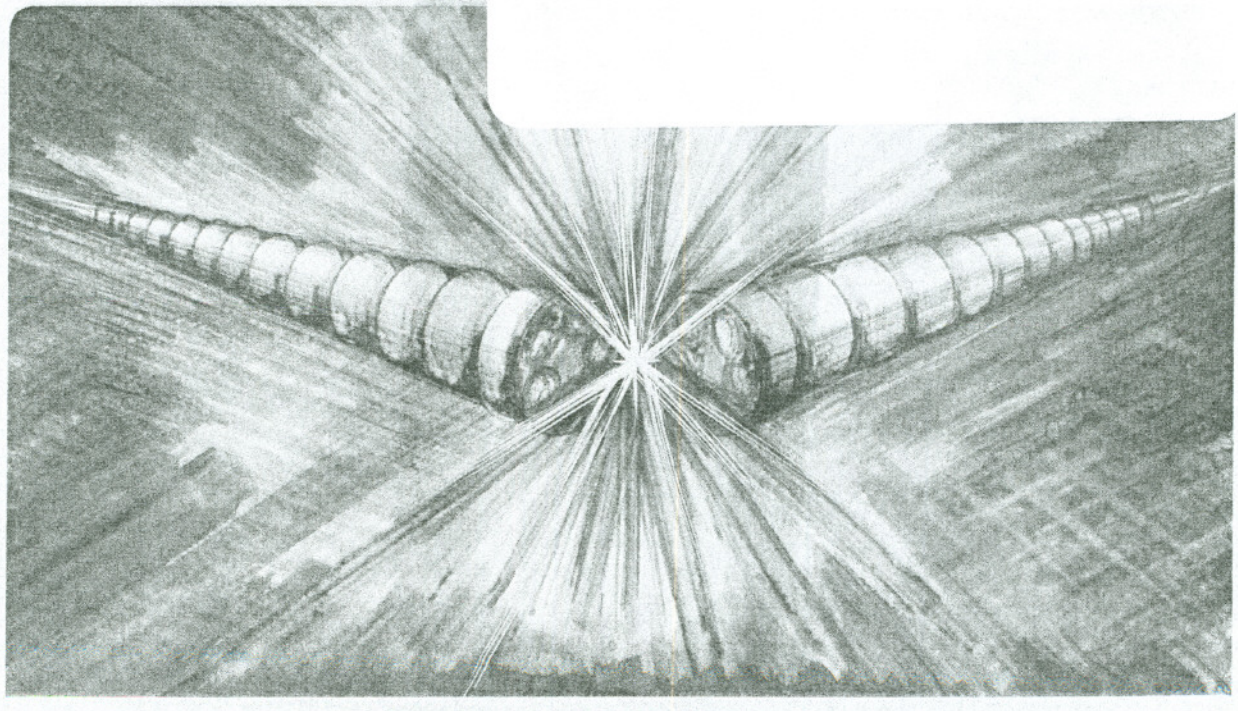

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Volume Production of Negative Hydrogen and Deuterium Ions in a Reflex-Type Ion Source*

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Abstract

The extraction of negative and positive hydrogen and deuterium ions from a reflex-type negative ion source has been investigated. Extracted positive and negative ion currents were measured as functions of the gas flow rate, the axial magnetic field, and the bias potential of the cylindrical wall of the arc-chamber. By biasing the cylindrical wall several volts negative relative to the anode, a maximum H^- current of 9.7 mA ($J^- \simeq 100$ mA/cm^2) and D^- current of 4.1 mA ($J^- \simeq 42$ mA/cm^2) were obtained in steady state operation. This result shows a factor of two improvement over previous data. The total impurity negative ion content was less than 1%. When the source was arranged for positive ion extraction, a high proton ratio (90%) was observed. The extracted negative ion current was approximately as large as the positive ion current.

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I. Introduction

The production of negative ions has found important applications in nuclear physics and accelerators. Recently, the concept of using positive hydrogen ions has been found useful to heat fusion plasmas via energetic neutral beams. In the near-future, the injection of very fast neutral atoms appears to be an attractive method for heating fusion reactor plasmas to ignition temperatures. For these applications, neutral beams of much higher energy may be required in order to penetrate to the center of large fusion plasmas as well as to drive the current needed for D.C. tokamak operation, and to control end plug potentials to increase the plasma confinement time in tandem mirrors. Because of the high neutralization efficiency available for energy exceeding 80 keV for H^- (160 keV for D^-), the use of negative ions may be the only effective method for efficient production of such neutral beams.[1]

In this experiment, negative ions of hydrogen or deuterium gas were generated by volume processes[2] using a reflex-type discharge.[3] Negative ions were extracted directly from the source plasma. Because the discharge volume was small and the plasma density high ($10^{12}/cm^3$), diagnostics inside the source was difficult and was therefore limited to external measurements of voltages, currents, and electrical signals. Efforts were concentrated on modifying the arc-chamber of the ion source in order to improve the negative ion yield. Extracted negative ion current as a function of the gas flow rate, the axial magnetic field, and the bias potential of the cylindrical wall of the arc-chamber was investigated.

The experimental arrangement is described in Sec. II and the experimental results with different gas flow rates and magnetic fields are presented in Sec. III. The effect on the negative ion yield of varying the bias potential

of the cylindrical boundary of the arc chamber is presented in Sec. IV. A discussion of experimental observation is given in the last section.

II. Experimental Arrangement

This investigation employed a DC operated reflex-type negative ion source as illustrated in Fig. 1. The ion source is installed inside a vacuum chamber located in the gap of a large electromagnet. Ions are extracted radially (i.e. normal to the magnetic field). The ion source consists of a heated filament at the top of the cylindrically-shaped anode. The gas feed line is connected to the anode, which has the ion exit slit. An electrically insulated cold reflector cathode is located at the bottom of the cylindrically-shaped anode. The reflector cathode is maintained at the same potential as the heated filament. Both the hot and cold cathodes are made of tantalum and are water cooled. The ion source is operated in a mass spectrometer arrangement with the extracting electrode at ground potential and the source structure biased negatively in order to extract negative ions, or biased positively to extract positive ions. The ion exit slit size is 7.26×10^{-2} cm^2. The radius of the arc defining hole is 0.24 cm, the radius of the relieved cylindrical column is 0.48 cm, and the length of the cylindrical column is 6.03 cm.

Two Faraday cups are installed to monitor the extracted ion currents. One is a traveling Faraday cup, located at the focal plane of the 180° mass spectrometer arrangement, and the other cup, which is located closer to the extracting electrode, is large enough to collect all particles exiting through the extracting electrode. When the negative ions are extracted, a sizable electron current is also removed from the plasma. The drain current of the high voltage extraction supply is equal to the sum of the electron and

negative ion currents extracted from the source. The extracted electrons migrate along equipotential lines normal to the magnetic field by the E x B drift. Unless these electrons are intercepted, they will make their way to the high voltage insulator on which the source structure is supported, and cause breakdown. They are removed by providing a component of electric field in line with the magnetic field. This electric component, provided by a triangular-shape carbon block (not shown), causes these electrons to be dumped in a water-cooled copper cup, which is located just below the ion source.

The source was generally operated at an arc current of 3 A, an arc voltage of 300 V, and an extracting potential of 6 kV. The diffusion pump of the test system has a pumping speed for hydrogen of about 5000 ℓ/sec (untrapped), and the ions are extracted from the ion source into a vacuum of 10^{-5} to 10^{-4} torr. The hydrogen gas feed is variable to 50 sccm, the magnetic field from 1500 to 5000 gauss, and the filament heater current to 500 A.

For the reflex-type negative ion source, the temperature of plasma electrons is expected to be less than the threshold energy for the ionization; 13.6 eV (15.4 eV for molecules). The injected hot primary electrons mostly ionize the hydrogen gas. Ionization occurs in the central region where the primary electrons are confined. Considering the relatively high gas pressure inside the ion source (10^{-1} to 10^{-2} torr, 10^{15} cm^{-3}), the plasma is weakly ionized. Surrounding the central region is a relatively cold plasma region where there are few primary electrons since the arc defining hole has a smaller diameter than the cylindrical anode (Fig. 2a). This "relieved" arc-column geometry is identical to that employed by Ehlers in 1965.[3] We have since realized that this geometry is quite similar to the "Magnetic Filter" arrangement described by Leung et al.[4]

Because a positive bias on the exit electrode of the multicusp magnetic filter geometry is effective in increasing the H^- output and reducing the extracted electron current, it seems logical to employ the bias technique with the PIG-geometry.

For this reason, the reflex-type ion source was modified. The cylindrically-shaped anode is separated into two parts so that a bias potential between the wall anode and the anode which defines the arc column (Fig. 2b) can be varied. Both parts are electrically insulated by two boron nitride insulators. The ion exit slit size of the modified ion source is 35% more than in the unmodified one[3] (9.7×10^{-2} cm^2). Therefore the pressure inside the ion source is less than that of the unmodified one for the same gas feed. Except for this, all of the other parameters of the modified ion source are the same as those of the unmodified one. The potential between the two anodes is variable from - 75 V to + 75 V without plasma (maximum 5 A). For zero potential, one has the unmodified geometry of Fig. 2-a. When the cylindrically-shaped anode is floated, it has a potential 1 to 5 V higher than the primary anode indicating the collection of positive ions.

III. Experimental Result before Source Modification

When the hydrogen gas feed increases, the extracted positive ion current and electron drain current decrease as the gas flow rate is increased above 10 sccm. The extracted negative ion current, however, first increases and then, after reaching a maximum, starts to decrease again. The variation of the extracted H^- current as a function of the gas flow rate under several constant magnetic fields is shown in Fig. 3. A maximum current of 3.6 mA ($J^- \simeq 49.6$ mA/cm^2) was achieved for this operation.

The positive and negative ions extracted from the ion source can be mass-analyzed by the traveling Faraday cup. The dominant species of the positive ion current are H^+ (90%), H_2^+ (4%) and H_3^+ (6%). The dominant species of the negative ion current is H^-. The impurity negative ion content is less than 1%. If the source is operated at the optimum gas flow and the magnetic field is varied, the extracted H^- current first increases, and then, after reaching the maximum at B=4000 gauss, it decreases again.

Figure 4 shows the relations between the extracted D^- current and the gas flow rate for D_2 gas. The maximum D^- current is generally less than half of the maximum H^- current. The maximum positive ion current is slightly higher than that of hydrogen. The gas flow rate which gives the maximum negative current is the same for both H_2 and D_2 gas. However, the magnetic field which produces the maximum negative current is higher for D_2 than H_2.

IV. Experimental Result after Source Modification

In order to investigate the effect of the radial electric field on the extracted negative ion current, the top portion and the cylindrical wall of the anode chamber are electrically separated in the modified reflex-type ion source (Fig. 2-b). Using a separate power supply, the potential of the cylindrical wall anode can be biased either positive or negative in respect to the top portion of the anode, which acts as the main anode.

Figure 5 shows the extracted negative and positive ion currents, and the electron drain current as a function of the bias potential for a fixed optimum magnetic field of 3000 gauss. It can be seen that the extracted negative ion

current increases with decreasing bias potential on the cylinder. The maximum H^- current of 9.7 mA ($J^- \simeq 100$ mA/cm^2) was obtained at a bias potential of -6 V. This H^- current is a factor of 2 larger than the current obtained when the bias potential is zero. Positive bias potentials, on the other hand, only reduce the extracted H^- current. The electron drain current varies in approximately the same manner as the H^- current when the bias potential is changed from -6 to +6 V. However, the extracted positive ion current has a maximum at zero bias and it goes through a minimum as the bias is changed from 0 to -6 V.

We have observed similar relations between the negative ion current and the magnetic field when the source is operated with D_2 gas. A maximum D^- current of 4.1 mA ($J^- \simeq 42$ mA/cm^2) was obtained with about the same arc power.

V. Discussion

The main experimental results were as follows: 1) The extracted negative ion current is approximately as large as the positive ion current under the same operation parameters. However, the negative ion current of deuterium is about half of that of hydrogen. 2) When the amount of hydrogen gas feed is increased, the extracted negative ion current increases initially. Then, after reaching the maximum value, the current decreases again. This phenomenon is not observed for the extracted positive ion current. 3) When the magnetic field is increased, the extracted positive and negative ion current first increase. After reaching the maximum value, the currents begin to decrease again. The optimum magnetic field for D^- is different from that of H^-. 4) The anode was divided into two parts to change the electric

potential. Twice more negative ion current was obtained when the wall anode was negatively biased (-6 V) with respect to the top anode. This large improvement is not observed for the positive ion current.

In this reflex-type negative ion source, the plasma is divided into two regions; the central (hot) region, and the surrounding (cold) region. The plasma together with vibrationally excited molecules are generated in the central region. H^- or D^- ions may be formed by dissociative attachment to the vibrationally excited molecules in the relative cold surrounding region. We are attempting to find models that explain the experimental data.[5] In the multicusp ion source with a magnetic filter, the plasma electrode is biased positively to optimize the extracted negative ion current. The plasma potential of both the reflex-type[6] and sheet plasma sources[7] are negative. On the other hand the potential of the multicusp plasma is positive. The different sign of the optimum bias potential between the reflex-type ion source and the multicusp ion source may be attributed to the sign of the plasma potential in the source.

In conclusion, a maximum steady negative ion current of 9.7 mA for H^- and of 4.1 mA for D^- were obtained, equivalent to a negative ion current density of 100 mA/cm^2 for H^- and of 42 mA/cm^2 for D^-. To the authors' knowledge, this is the largest negative hydrogen and deuterium current density obtained continuously from a volume-production source . Although larger currents could be likely obtained by increasing the size of the ion extraction slit and the vacuum pumps, it will be necessary to learn how to operate this type of sources at lower pressures if large area sources for fusion experiments are to be practical.

Acknowledgments

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Figure Captions

Fig. 1 Experimental geometry of the reflex-type negative ion source.

Fig. 2 (a) Experimental arrangement for the reflex-type negative ion source before it is modified. (b) Experimental arrangement for the modified reflex-type negative ion source.

Fig. 3 Relations between the extracted H^- current and the gas flow rate for several constant magnetic fields at a discharge power of 300 V, 3 A.

Fig. 4 Relations between the extracted D^- current and the gas flow rate for several constant magnetic fields at a discharge power of 300 V, 3 A.

Fig. 5 Relations between the extracted negative ion, positive ion, and electron drain currents and the bias potential for H_2 gas when the magnetic field is 3000 gauss.

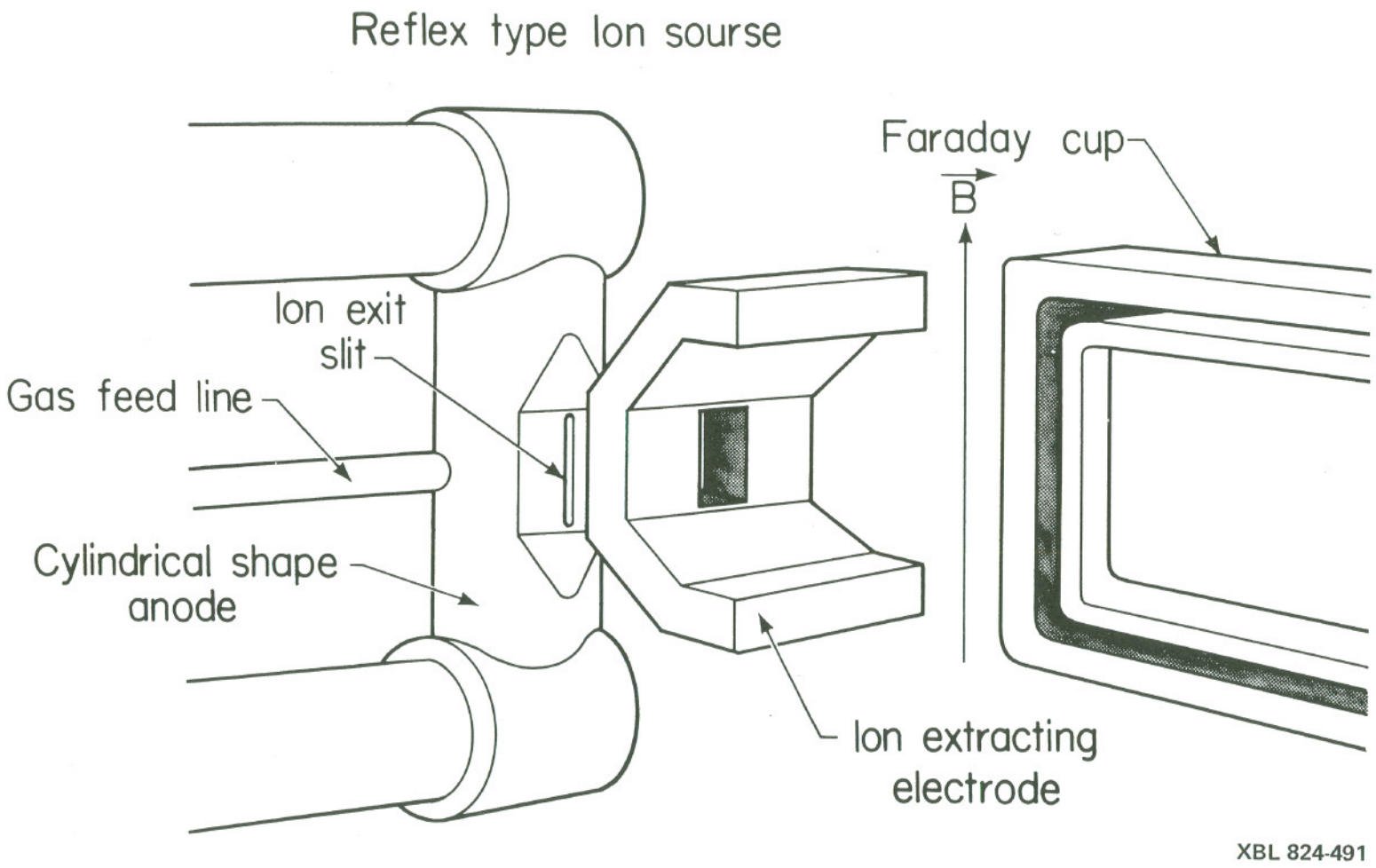
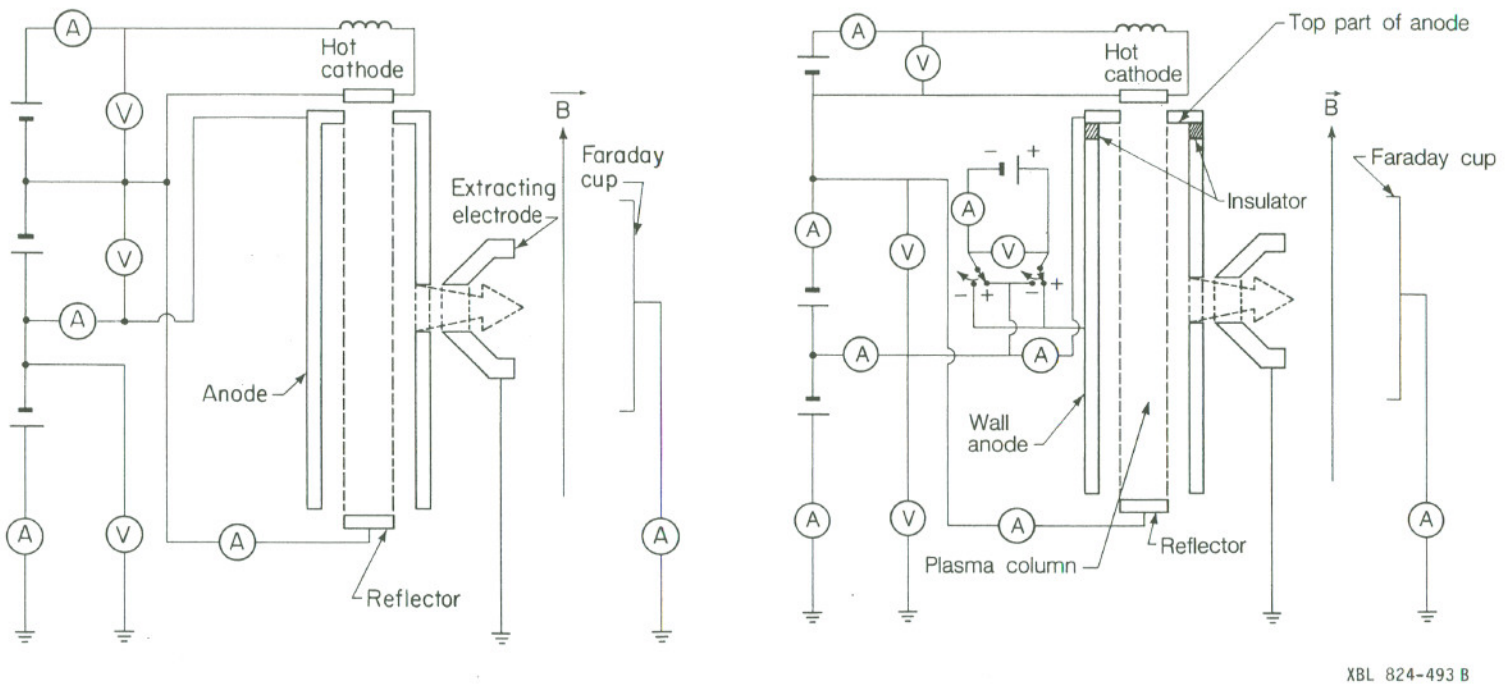

Reflex type Ion sourse
Faraday cup
B
Ion exit slit
Gas feed line
Cylindrical shape anode
Ion extracting electrode
XBL 824-491

Fig. 1


Hot cathode
Extracting electrode
Faraday cup
B
Anode
Reflector
Top part of anode
Insulator
Wall anode
Plasma column
XBL 824-493 B

(a) (b)

Fig. 2

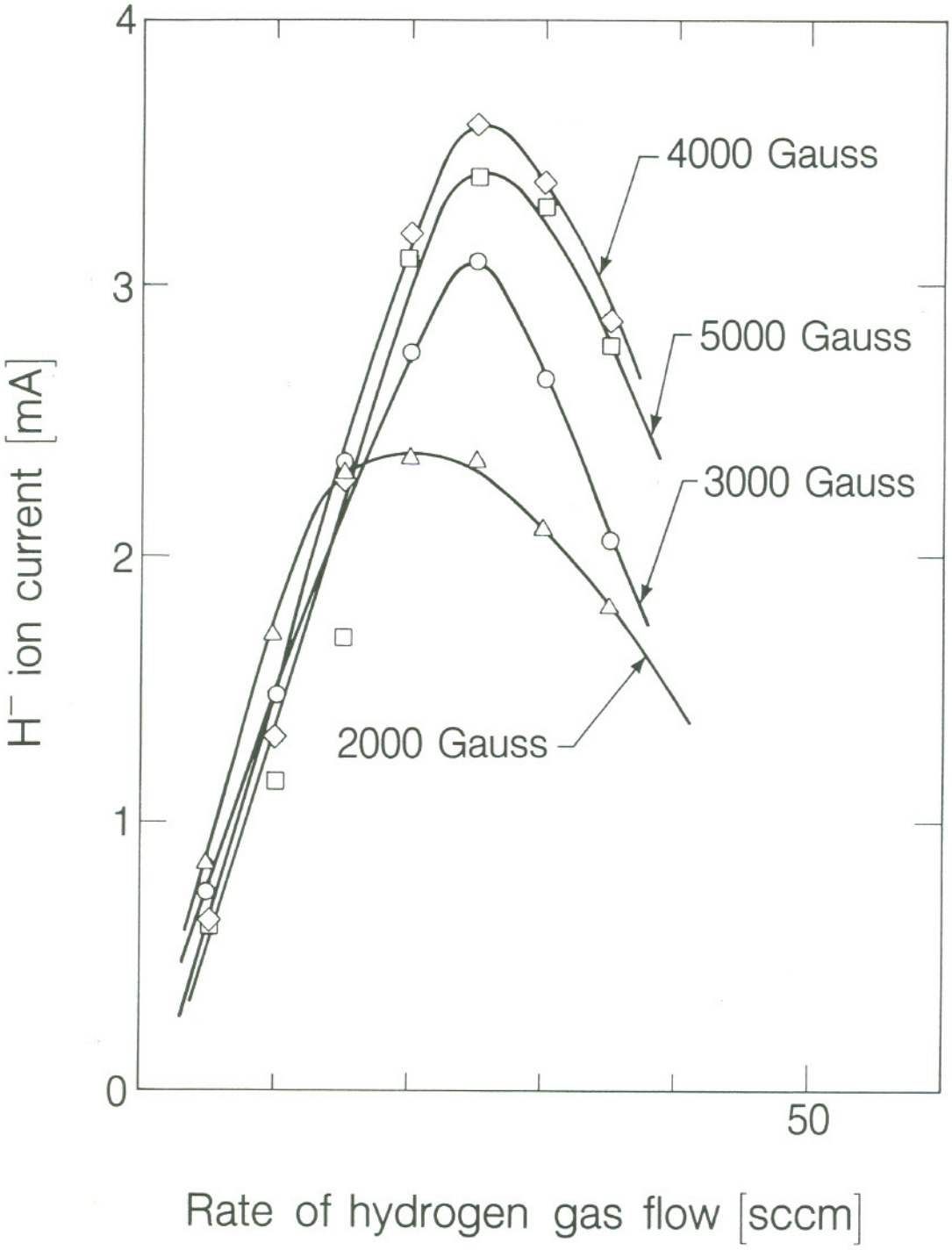


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Fig. 3

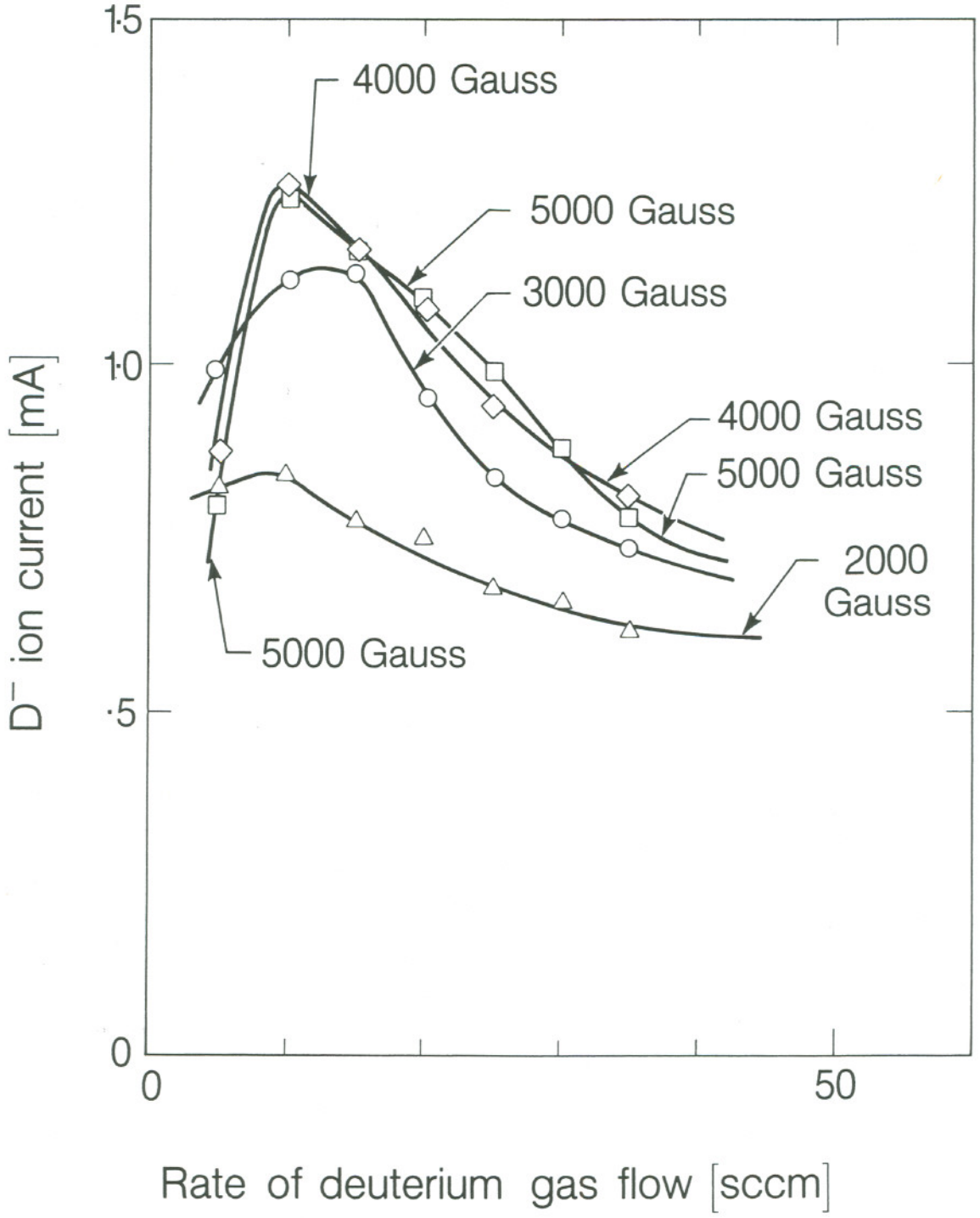

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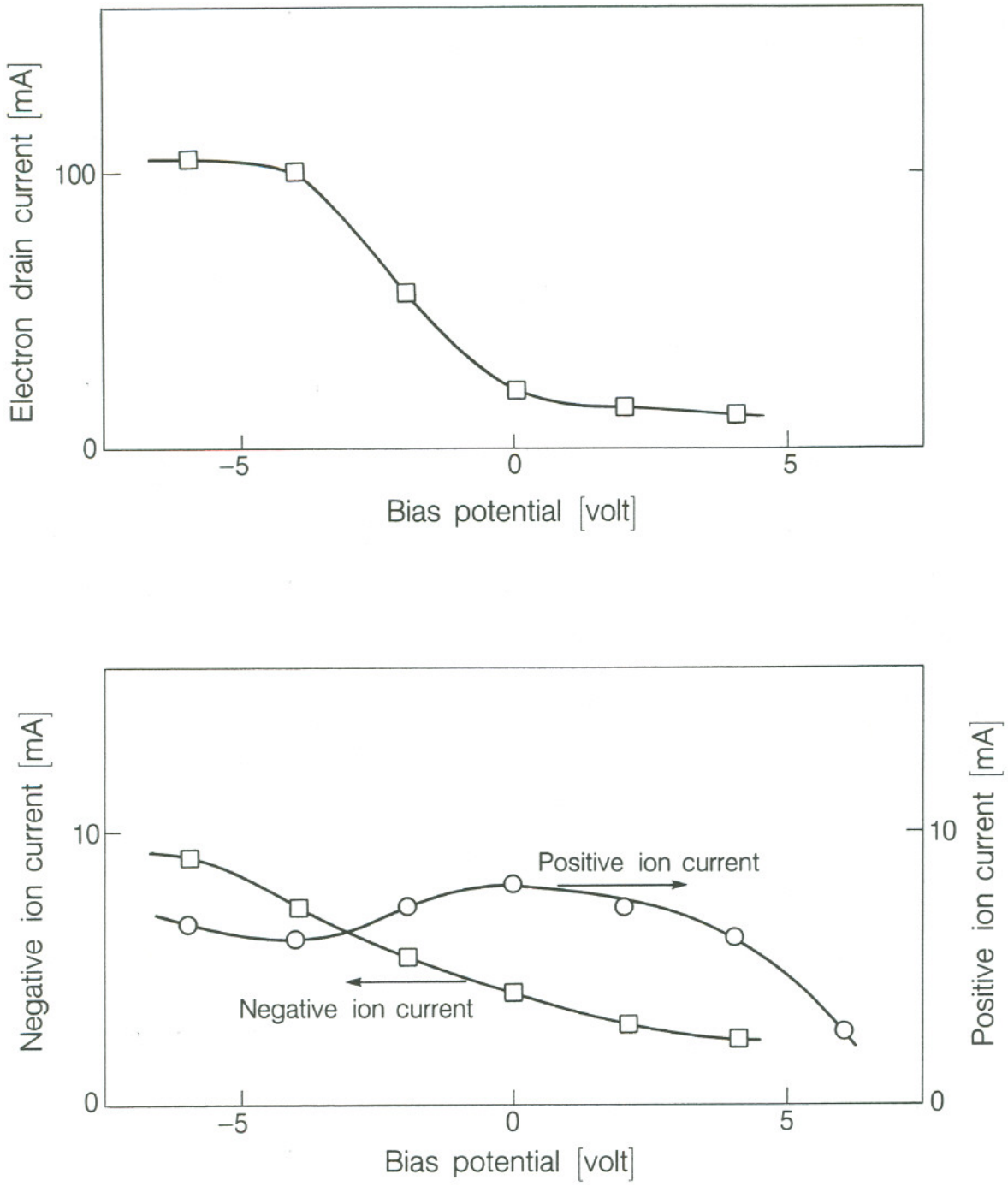
Fig. 4



XBL 8512-9396

Fig. 5

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