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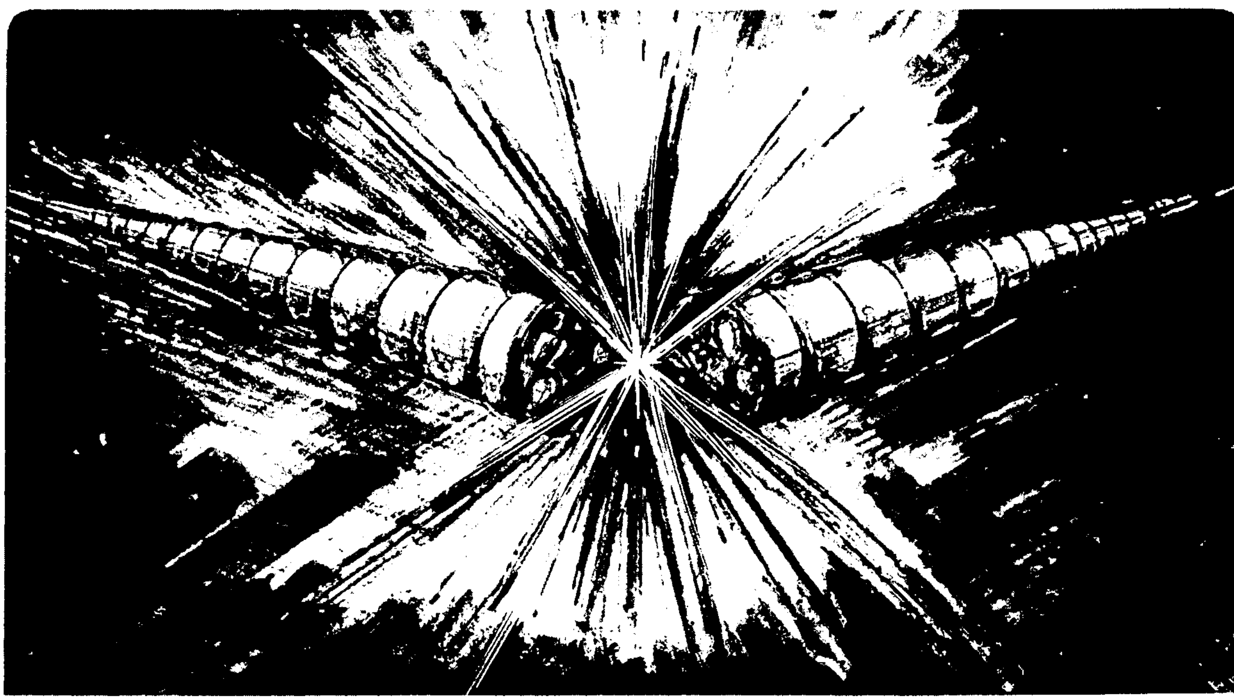

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ABSTRACT

A JAERI negative ion source was tested at LBL as part of the U.S.-Japan Fusion Cooperation Program. By varying the strength of magnetic filter from 450 to 930 Gauss-cm, we compared production, transport, and extraction of the negative ions. The maximum current densities, which obtained at the corresponding optimum filter strength for each gas species, were 10.4 mA/cm^2 for H^- and 8.4 mA/cm^2 for D^- at arc discharges of 40 kW. The ratio of the ion current densities (J_{D^-}/J_{H^-}) is about 0.8, which is higher than $1/\sqrt{2}$. The electron to negative ion ratio was 13 for hydrogen and 38 for deuterium at the corresponding optimum filter strength. The higher ratio in deuterium is probably due to higher space potential of deuterium plasma by a few volts.

1. INTRODUCTION

In an effort to realize a high power neutral beam injector (NBI) system for the next generation of thermonuclear fusion machines[1-3], R&D work on high current negative ion sources has made progress in many laboratories[4-7]. At JAERI, an H^- beam of 75 keV / 3.4 A was produced from a volume production source with a multi-aperture extractor[5]. Leung et al. succeeded in producing a H^- current density up to 240 mA/cm^2 from a single aperture of 1 mm diameter[6].

Although most of these experiments were performed with hydrogen, it is indispensable to use deuterium for the fusion application. Experimental results of deuterium operation are important for design work of a negative-ion-based NBI. It is essential to make clear how the negative ion current densities, the electron currents, the beam emittance, etc., change in hydrogen and deuterium operation.

As part of the U.S.-Japan Fusion Cooperation Program, we tested a JAERI negative ion source at LBL with both hydrogen and deuterium gases. By varying the strength of magnetic filter over a wide range of Gauss-cm, we compared H^- and D^- production, transport, and extraction characteristics. The results of these experiments are discussed in the present paper.

2. EXPERIMENTAL SETUP

A schematic diagram of the JAERI "one-ampere negative ion source" is shown in Fig.1. The discharge chamber of the source is 36 cm long x 21 cm wide x 15 cm deep. The arc discharge is maintained by eight tungsten filaments as cathodes while the entire wall acts as an anode. For better plasma confinement, permanent magnets are used to form magnetic line cusps. In addition, a pair of large permanent magnets is installed outside of the extraction area to form an "external magnetic filter"[8]. The strength of the filter field can be varied from 450 to 910 Gauss-cm by adding or subtracting magnets of various sizes. The end of the discharge chamber and the extractor are connected with an insulating spacer in order to apply bias voltage to the plasma grid. The extractor consist of four grids. The volume produced negative ions are extracted at 4~5 keV through an array of 9 apertures (each one 9 mm in diameter) and subsequently accelerated up to 50 keV. The electrons, which are extracted together with the negative ions, are deflected by permanent magnets embedded in the second grid.

The source was typically operated with a 400 ms beam pulses, which were long enough to produce steady state beam conditions. In order to keep a constant discharge condition during the pulse, the filament heater current was stepped down to avoid overheating by the plasma. A current transformer located at 19 cm down stream from the exit of the source was used to measure the negative ion current. Using a bending magnet, we confirmed that the electron current contained in the measurement was negligible. A calorimeter was utilized to evaluate the stripping loss of negative ions between the exit of the extractor and the current transformer. The projectional emittance of the negative ion beam was measured by two electric-sweep type[9] emittance scanners in both transverse directions.

3. RESULTS AND DISCUSSION

3.1 Extraction voltage dependency

By varying the extraction voltage, negative ions were extracted from both hydrogen and deuterium plasmas. In each case the gas flow rates were optimized. The operational conditions were set to be the same in both gas operations (70 V x 300 A discharge, 35 keV acceleration, and 710 Gauss-cm filter strength). Fig. 2 shows the result of H^- and D^- extractions including the space charge effect of the extracted electrons. D^- and electron currents are normalized to produce the same space charge equivalence as H^- ions. (D^- current is multiplied by $\sqrt{2}$ and electron current is divided by 43.)

When the extraction voltage is low, the H^- equivalent current increases steeply as the voltage increases. For extraction voltages above a threshold, there is a gentle rise in H^- and D^- currents. These results are similar to those found in other experiments[4,7]. In the low voltage extraction, the H^- equivalent currents are proportional to $V^{3/2}$ like positive ion extraction; this shows that the negative ion extraction in this region is dominated by the space charge effect (Child-Langmuir law).

The H^- equivalent current in deuterium operation is about 20 % lower than that in hydrogen. However, the stripping loss in the beam line is estimated to be roughly 18 % higher for D^-, since the loss of fully accelerated ions is larger in deuterium. Hence the ratio of these ion currents produced by the source is approximately $1/\sqrt{2}$ in accordance with the velocity ratio of the ions.

The following results were all obtained with adequate extraction voltage, so that the extraction voltage dependency was relatively small. Thus it enabled us to examine the amount of the negative ions in front of the extraction surface.

3.2 Emittance study

The emittance of the negative ion beam was measured under various source conditions. A typical emittance diagram is shown in Fig. 3. Only arc current, gas species, and filter strength were found to affect the beam emittance.

The rms emittance obtained with filter strength of 710 Gauss-cm at 40 kW discharge was 0.0230±0.0012 π-cm-mrad for H^- and 0.0150±0.0014 π-cm-mrad for D^-. They correspond to effective ion temperatures of 2.46 eV and 2.09 eV for H^- and D^-, respectively (assuming a Gaussian distribution in the beam intensity). The D^- temperature was slightly lower than the H^- one. By decreasing the arc discharge current to 330 A with hydrogen operation, the effective H^- temperature decreased to 1.62 eV. The effective D^- temperature was increased to 3.71 eV with a stronger magnetic filter (750 Gauss-cm).

3.3 Plasma grid biasing

The plasma density in the extraction region is balanced by diffusion through the magnetic filter field and loss to the wall. The diffusion process can be described as follows; the diffusion coefficient of ions is proportional to square root of the mass ($D \sim \sqrt{m}$), and low temperature electrons flow by ambipolar diffusion. The loss rate is defined by the plasma behavior in front of the wall. If the plasma grid is biased with respect to the anode, the loss rate can be varied due to the change of the plasma condition in front of the plasma grid.

Fig. 4 shows extracted electron currents as functions of the bias voltage in both gas operations. The electron current in deuterium operation was more than twice of that in hydrogen. If we assume the electron current is proportional to the electron density in the extraction region plasma, it implys that the electron density was more than twice denser than hydrogen. As the bias voltage increased, the electron currents dropped exponentially. The curve of electron current in deuterium operation appeared as if that of hydrogen was shifted by 2 volts to a higher bias voltage. The variation of negative ion beam currents are shown in Fig. 5. The shift is also observed in the ion currents. H^- current decreased monotonously with increasing bias voltage starting from V_b = 0 V (i.e. anode potential), while the D^- current kept constant up to $V_b \sim 3$ V, though the electron current decreased as the bias voltage increased. Namely, the D^- current is independent of the plasma density in this range of bias voltage. The D^- current began to fall at higher voltage.

Because of the heavier mass of the deuterium ions, it is expected that the ion loss rate is smaller in deuterium plasmas than in hydrogen ones. Hence the deuterium plasma potential may be 2 volts higher than that of hydrogen. By applying 2 volts more positive plasma grid bias, the same extraction condition as hydrogen operation will be achieved in deuterium plasma. This explains the shift of the extracted currents.

3.4 Filter strength variation

The maximum negative ion currents obtained with an arc discharge of 40 kW are presented in Fig. 6 as functions of magnetic filter strength. The source was operated at the optimum pressure, and with enough extraction voltage. Plasma grid was at anode potential. The optimum filter strength for D^- is higher than that for H^-. The maximum current densities, defined as the ion current measured at the exit of the accelerator divided by the net extraction area, were 10.4 mA/cm^2 for H^- and 8.4 mA/cm^2 for D^- at the corresponding optimum filter strengths. The ratio of these current densities (J_{D^-}/J_{H^-}) is about 0.81, which is higher than $1/\sqrt{2}$. Comparing deuterium operation with hydrogen, the extracted electron current was larger by more than a factor of 2. For both H^- and D^-, the electron current decreased rapidly with increasing filter field, but eventually reached an asymptotic limit as the filter field was increased beyond

700 Gauss-cm.

The electron to negative ion ratios are shown in Fig. 7 for each gas. The ratios at each optimum filter strength are 13 for hydrogen and 38 for deuterium. Since the D^- current becomes smaller than H^- by $1/\sqrt{2}$ due to the extraction mechanism, we compare the electron to H^- equivalent ratio for deuterium; i.e. $I_e/(\sqrt{2} \times I_{D^-}) = 27$. It indicates that the electron current in deuterium operation is twice as high as that in hydrogen one. As discussed in section *3.3*, the electron current in deuterium operation is higher because of its higher plasma potential. Although plasma grid was tied to anode in this experiment, the electron to D^- ratio could be made closer to that of hydrogen by applying a few volts of bias voltage.

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Figure Captions

Fig. 1 Schematic diagram of the negative ion source.

Fig. 2 Dependence of H^- and D^- current on extraction voltage. The currents including electron are summarized so that they produce the same space charge effect as H^-.

Fig. 3 A typical emittance diagram obtained in deuterium operation; 40 kW discharge, filter strength = 710 Gauss-cm, vertical scan.

Fig. 4 Electron currents as functions of plasma grid bias voltage.

Fig. 5 Variation of negative ion currents by biasing plasma grid.

Fig. 6 The maximum negative ion currents obtained under several strengths of magnetic filter.

Fig. 7 The electron to ion ratios as functions of filter strength.

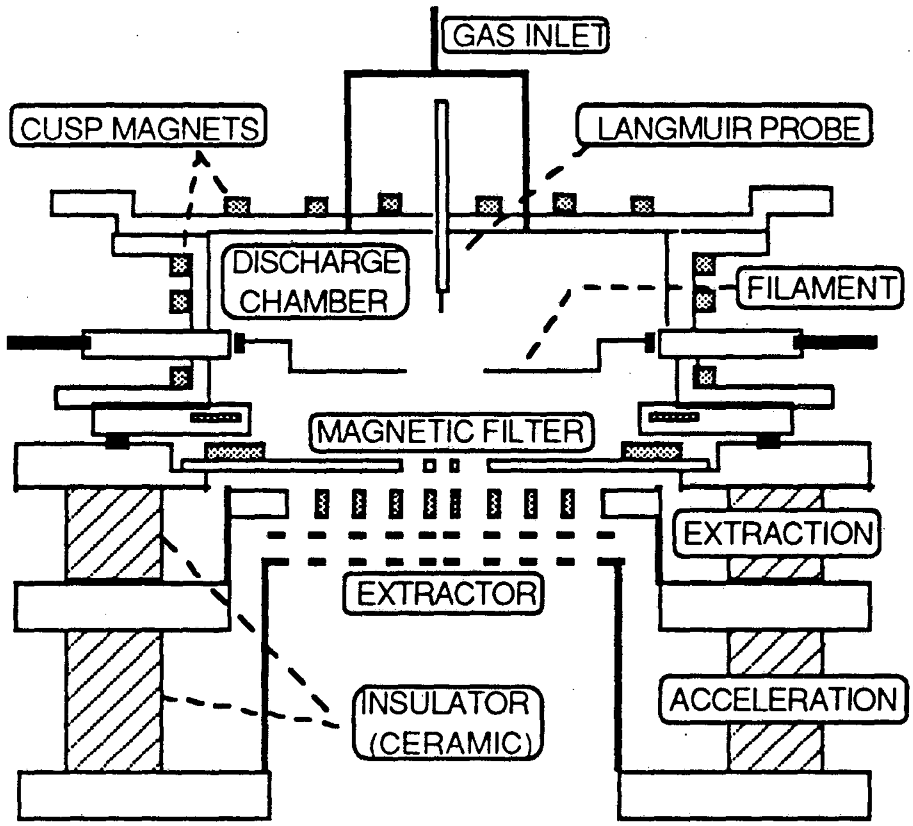

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Figure 1

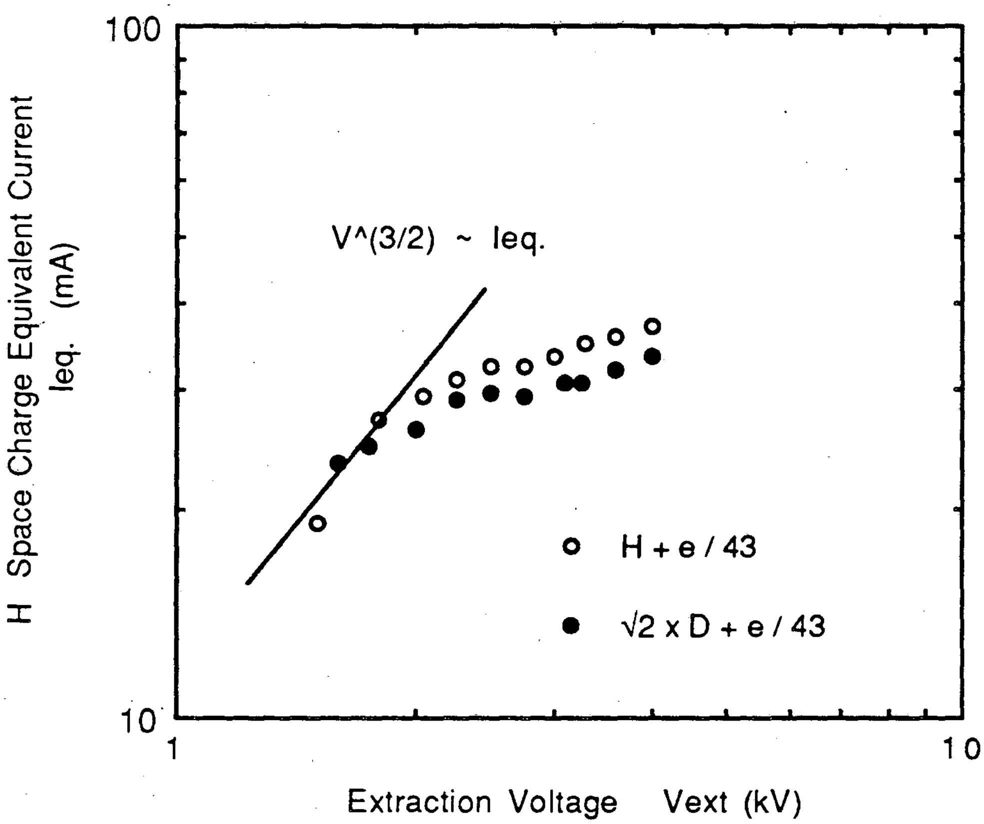

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Figure 2

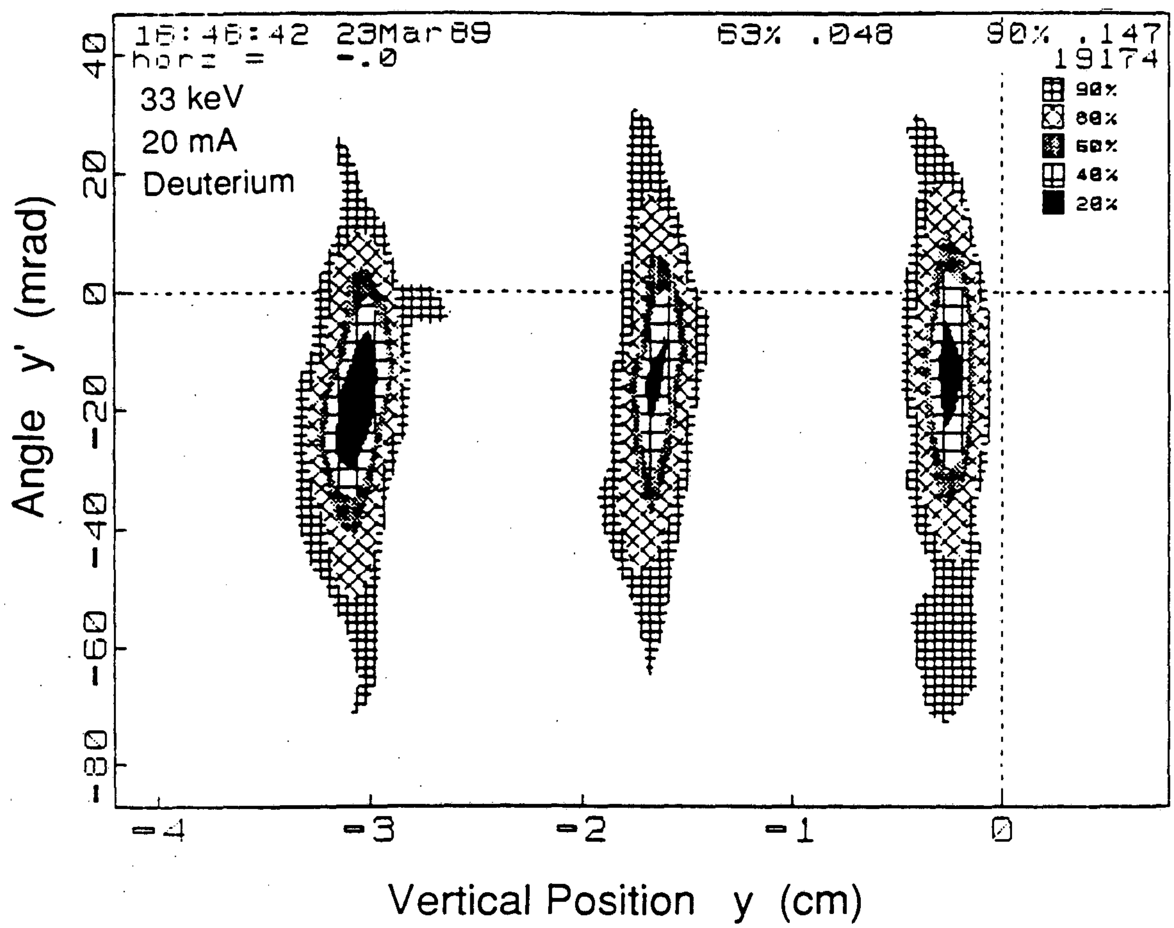

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Figure 3

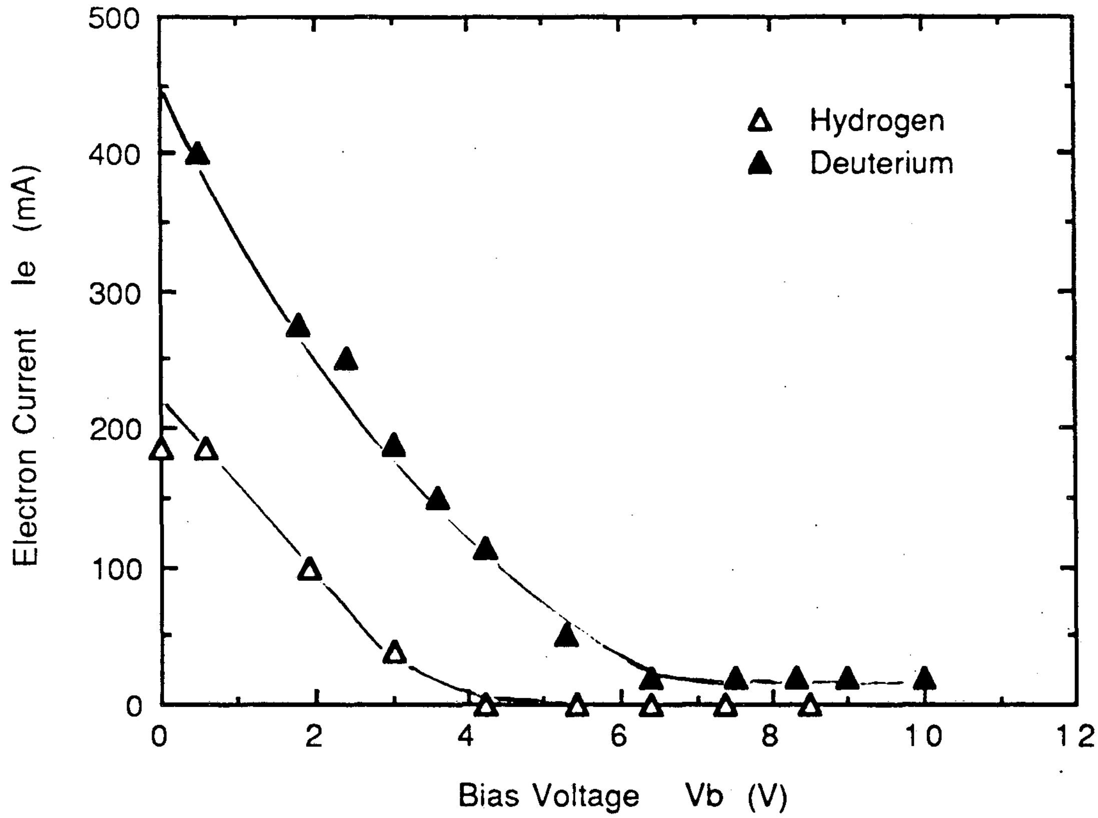

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Figure 4

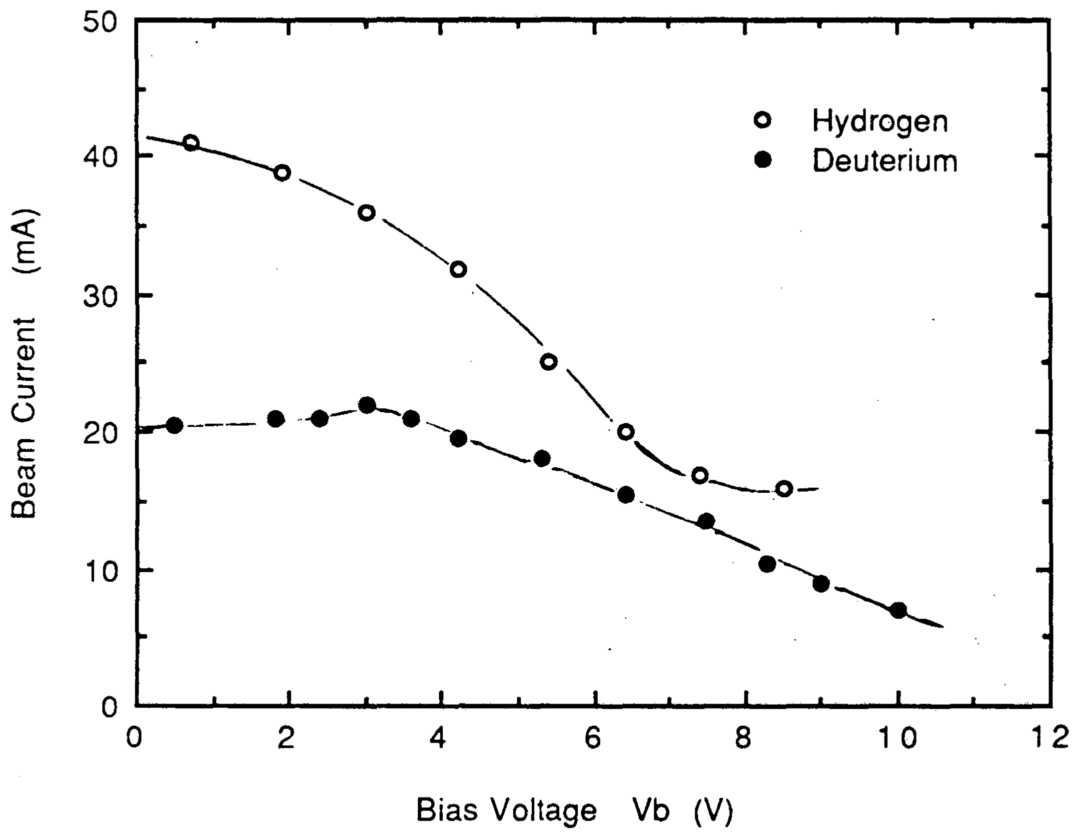

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Figure 5

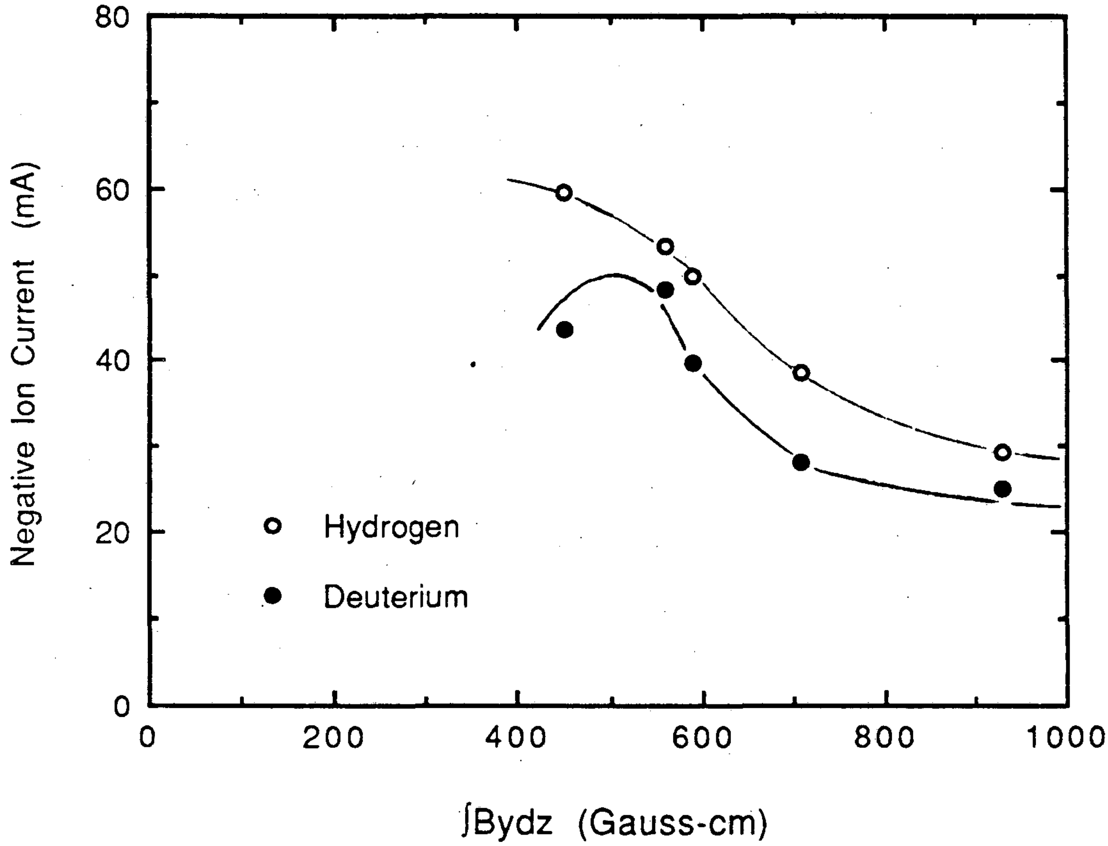

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Figure 6

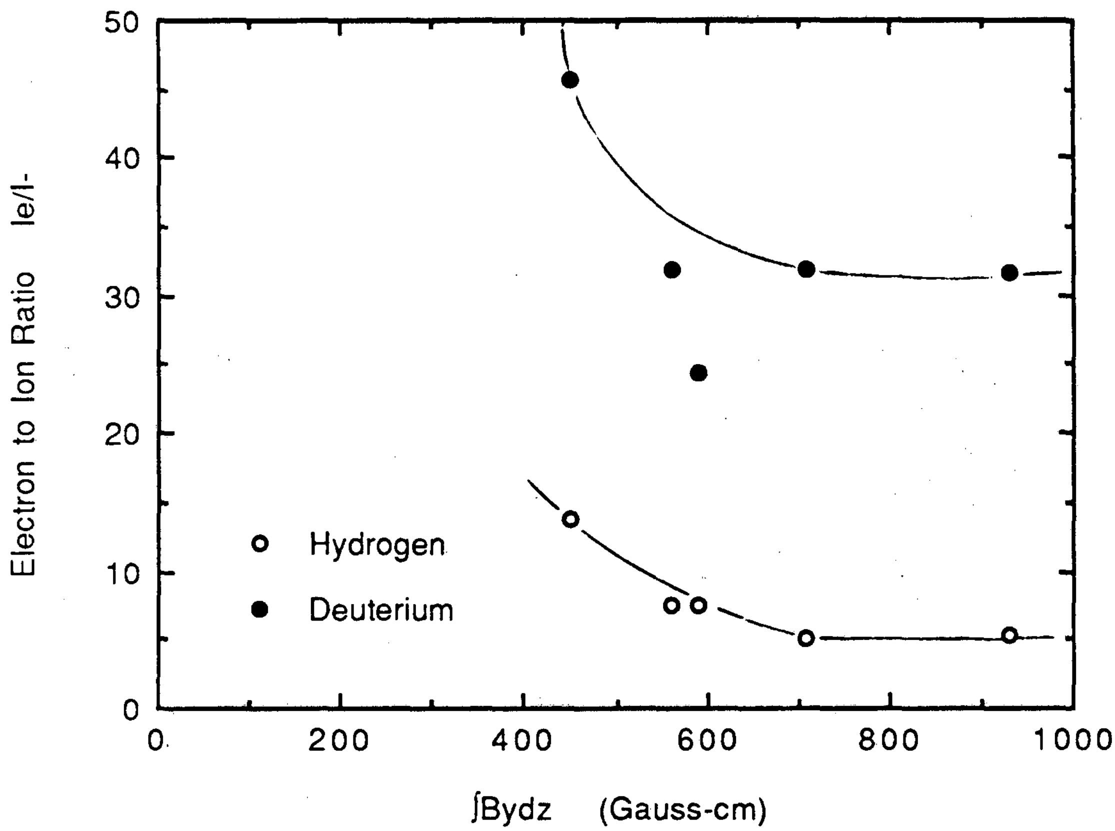

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Figure 7

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