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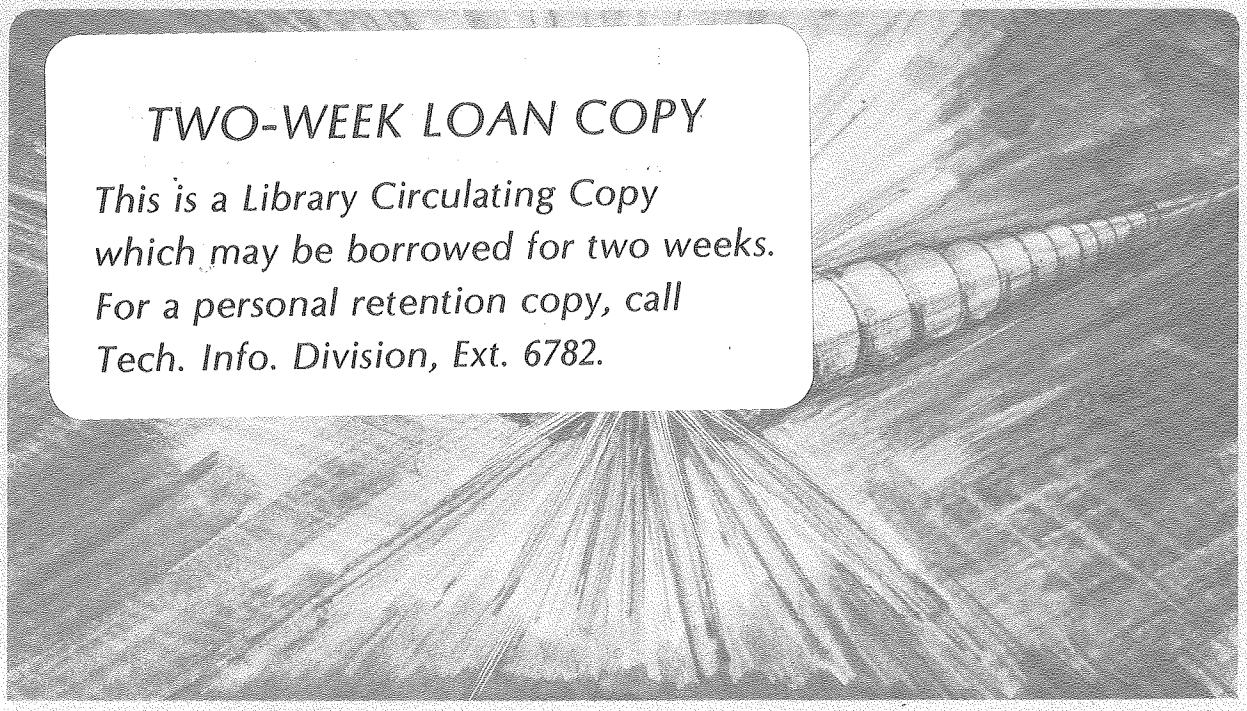

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A Multicusp Negative Ion Source

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Abstract

The characteristics of a steady state, surface conversion, multi-line-cusp negative ion source have been investigated for the production of high-energy neutral beams. With the presence of cesium, this source has been operated at a neutral pressure of 1×10^{-3} Torr to generate a H^- ion current greater than 400 mA. The percentage of impurities in the self-extracted negative ion beam has been analyzed by a mass spectrometer. A technique for reducing the background electron density at the source exit is also presented.

INTRODUCTION

In order to heat plasmas in the next generation of fusion devices to thermonuclear temperatures, high-energy neutral beams are required. The neutralization efficiency for positive hydrogen or deuterium ion beams at energies greater than 150 keV is low.[1] On the other hand, H^- or D^- ions have high stripping efficiencies (>60%) for beam energies greater than 150 keV. Thus at energies in excess of 150 keV, an alternate procedure is to produce neutral beams from H^- or D^- ion beams.

There are different approaches for the production of negative ions.[2-4] H^- ions can be extracted directly from a hydrogen discharge plasma. Low-energy positive hydrogen or deuterium ions can be converted into negative ions by double charge exchange in a sodium or cesium cell. There are also H^- ion production systems that are based on surface conversion of positive hydrogen ions. The device described in this paper is a surface conversion multiline-cusp negative ion source. This system has been operated in a dc mode, and the H^- or D^- ions generated are self-extracted from the source. A total negative ion current of approximately 0.5 A has been obtained through an exit aperture of 4 x 10 cm^2 with the source pressure maintained at 1 x 10^{-3} Torr. The impurities present in the negative ion beam have been studied by using a mass spectrometer. It is also shown that the background electron density at the source exit can be greatly reduced by creating a negative plasma potential in the source.

I. APPARATUS

Figure 1 is a schematic diagram of the negative ion source. The device is a cylindrical multiline-cusp plasma source[5,6] (20-cm diam. and 23 cm long) with 10 columns of samarium-cobalt magnets ($B_{max} \simeq 4$ kG) mounted externally around the chamber wall. The resulting cusp-field pattern, mapped by iron filings, is illustrated in Fig. 2(a). The source pressure is normally maintained at 1×10^{-3} Torr. A steady state hydrogen or deuterium plasma is generated by 60 eV primary electrons emitted from two 0.15 cm diameter tungsten filaments mounted on the end flanges. The entire chamber wall serves as the anode for the discharge.

To produce negative ions, a movable, water-cooled, concave copper converter (6 cm high by 10 cm long, focal length $\simeq$ 8 cm) is inserted into the plasma through a high-voltage insulator mounted on the side-wall. By biasing the converter negatively ($\sim$300 V) with respect to the plasma, positive hydrogen or deuterium ions from the plasma are accelerated across the sheath and strike the converter surface. Any negative ions formed at the converter surface will then be accelerated back across the sheath by the same potential. They pass through the plasma and will be self-focused at the exit aperture of the source which is located between two magnet columns. Thus no additional electric field is required to extract the negative ions from the source in this system. By spacing the two magnet columns farther apart, the B-field in the region of the negative ion exit aperture is reduced to approximately 100 G. This field is strong enough to reflect electrons which may have energies as high as 300 eV,[7] but it produces only a small perturbation on the trajectories of the energetic H^- or D^- ions. The magnet columns which form the line cusps

in the remainder of the geometry are closer spaced and the dipole fields have a maximum value of approximately 400 G. A plot of the B-field in the radial direction through the exit aperture of the source is shown in Fig. 2(b).

To avoid contamination of the converter surface by pump oil, a closed-loop cryopumping system has been used for this experiment. In normal operation, a base pressure of about 1×10^{-7} Torr is achieved.

It has been shown that cesium or other alkali-metal coverage can reduce the work-function of a copper surface and consequently enhance the yield of negative ions.[8,9] In this source, alkali metals were deposited on the converter surface by evaporating the metal directly into the plasma from two 10 cm long SAES dispenser strips. However, for dc operation with alkali metals, a jet connected to an external oven is employed.

II. EXPERIMENTAL RESULTS

To study the characteristics of this negative ion source, three diagnostic techniques have been used. (1) Plasma parameters such as electron density, electron temperature, and plasma potential inside and outside the source are obtained by Langmuir probes. (2) The H^- or D^- ions as well as higher mass negative ion impurities are detected by a magnetic deflection mass spectrometer whose design has been previously described in detail by Ehlers *et al.*[10] (3) The total negative ion current output is measured by a large (4.5 cm by 12 cm) gridded Faraday cup. A magnetic mass separator installed behind the cup is used to measure the percentage of impurities in the negative ion beam.

Figure 3 is a Langmuir probe trace obtained outside the discharge near the source exit with the converter removed. For this measurement, the source was operated with a discharge voltage of 250 V and at a neutral pressure of 8×10^{-4} Torr. The probe trace shows the background electron temperature in that region to be 0.3 eV (approximately an order of magnitude lower than that at the center of the source). However, no high energy electrons are observed, which confirms the prediction from single-particle calculations that the B-field at the exit aperture can contain 250 eV electrons.

(a) Copper Converter Without Cesium:

In the preliminary study, the source was operated with a clean copper converter in order to check the diagnostics. The negative ions coming from the source were monitored by a compact mass spectrometer located at the source exit. Figure 4 shows the typical spectrometer output signals of the

D^- and H^- ions obtained from the copper converter biased at -320 V relative to the anode. The broad energy spectrum shows that the negative ions are not monoenergetic. In fact, the output signal of the H^- or D^- ions contains three distinctive groups, as illustrated by Fig. 5.

H^- ions can be produced on the converter surface either by desorption[8,11-13] or by reflection.[14,15] The H^- ions can be desorbed from the converter surface when positive ions enter the surface layer provided the energy transferred in the collision is equal to or greater than the adsorption energy of hydrogen. In this case, the average energy gained by the H^- ions is usually small, and their final energy should be approximately equal to the sheath potential. H^- ions can also be desorbed from the converter surface when the impinging positive ions are backscattered from the interior of the converter to the surface. An incoming H^+ ion strikes the surface with energy E after falling through the sheath. The molecular components (H_2^+ and H_3^+) are fragmented to form atomic hydrogen particles with energy E/2 and E/3 respectively. If any H^- ion residing on the converter surface is desorbed by a backscattered atomic hydrogen particle belonging to one of the above three groups, the peak energy of the H^- ions determined by the "jellium model" is less than 15% of the backscattered particle energy.[4] If a simple "billard-ball model" for elastic collision[16] is employed, the mean energy transferred will be E/2, E/4 or E/6. Then the H^- ions will have an average energy of E + E/2, E + E/4, or E + E/6 when they arrive at the plasma region.

On the other hand, if the H^- ions are converted from the three groups of backscattered atomic hydrogen particles by capturing the additional electrons, then their average energy should be close to the limiting values 2E, E + E/2, or E + E/3.[4,17] The two sets of energy values are displayed in

Fig. 5 along with the energy spectrum of the H^- ion beam. The positions of the three peaks suggest that the H^- ions are formed mainly by the reflection process. The H^- ions of peak I_1 are formed from the atomic species H^+, while those of I_2 and I_3 are converted from the molecular H_2^+ and H_3^+ ions respectively. A detailed discussion on the principal mechanism leading to the surface production of H^- ions can be found in Ref. 4.

Figure 6 shows the shape of the energy spectrum of the H^- ion beam as the neutral pressure is varied from 5×10^{-4} Torr to 1.5×10^{-3} Torr. It can be seen that the percentage of I_3 increases from 28% to 40% while I_2 decreases from 53% to 40%. The percentage of I_1 remains at approximately 19%. This result is consistent with the fact that an increase in neutral pressure is generally accompanied by an increase in H_3^+ percentage, but with a decrease in H_2^+ percentage for constant discharge power.[18]

Figure 7 shows the H^- ion beam spectrum as a function of discharge power. In this measurement, the copper converter is biased at -320 V relative to the anode. The discharge voltage is varied from 1.6 A to 4.7 A. The total H^- ion yield is found to be proportion to the discharge current. If the discharge power is kept constant and the bias voltage of the converter is changed from 320 V to 100 V, it can be seen from Fig. 8 that the H^- ion peaks shift towards the lower B-field (or energy) region. This indicates that the H^- ions originated at the converter surface. The peaks of the H^- ion beam spectrum diminish in size as the converter bias voltage drops. This decrease is due mainly to the decrease in H^- production as the converter potential is reduced, and to a possible increase in H^- production as the converter velocity of the outgoing negative ions decreases.[9]

Figure 9 shows the H^- ion spectrometer signal as the position of the uncesiated converter is changed. In this measurement, the spectrometer is located near the exit aperture. The H^- ion signal is highest when the

separation between the converter and the spectrometer is 8.5 cm. This distance is approximately equal to the focal length of the converter's concave surface. The H^- ion signal decreases as the converter is moved both closer and farther away from the spectrometer. At 20.5 cm from the spectrometer, the converter is in contact with the chamber wall. Hence the bias voltage is removed and the converter becomes part of the anode. As expected, no H^- ions are detected. In general, the converter should not be placed too far away from the exit aperture because destruction of the H^- ions by the plasma and neutral particles will become significant. On the other hand, if the converter is located too close to the exit, the plasma density in front of the converter will be low (due to penetration of the dipole fields), thus resulting in a lower H^- ion yield.

(b) Copper Converter with Cesium:

Experiments have shown that it is possible to increase dramatically the H^- ion production from surface conversion negative ion sources by adding an alkali metal to the discharge.[11,19] For this measurement, two 10-cm long SAES alkali metal dispensers were installed about 10 cm from the front surface of the converter. The alkali metal comes from a slit when the dispenser is heated by either a dc or an ac current. The amount of alkali metal introduced to the discharge can be controlled by adjusting the heater current. The mass spectrometer was used to measure the H^- ion yield for several alkali metals. It was found that lithium increased the maximum H^- yield by a factor of 10 above the yield produced by a clean copper surface. Sodium increased the yield by a factor of approximately 50, and for cesium the increase was approximately a factor of 100.

In Fig. 10, the spectrometer output signal for the plain copper converter

is compared with the signal obtained when cesium is added. For the latter, it can be seen that the H^- ions are generated with a narrower energy spread. This suggests that the production mechanism may have changed or else the percentages of H_2^+ and H_3^+ in the discharge have been radically increased by the addition of cesium. In a side experiment, it was found that by adding cesium to a discharge, the H_3^+ percentage did increase while the H^+ percentage dropped. However, the magnitude of the change is not sufficient to explain the result observed in Fig. 10. A detailed study of this change in ion species distribution is in progress and the results will be reported.

Langmuir probe characteristics obtained at the source exit (Figs. 3 and 11) have shown that the local electron temperature is very low (T_e <1 eV). Therefore by biasing the tungsten screen (79 lines/cm and 70% transparency) in front of a Faraday cup (4.5 x 10 cm^2) several volts negative with respect to the anode, all background electrons are repelled. Low energy positive ions and energetic negative ions can still strike the cup. If the Faraday cup is now biased several volts positive with respect to the anode, the positive ions will be repelled and only the energetic negative ions are collected. The fact that the current of the Faraday cup drops to zero when the voltage on the converter is made equal to anode potential demonstrates that only the energetic negative ions can reach the cup. This gridded Faraday cup has been used successfully to monitor the total negative ion current extracted from the source. Without using cesium, a steady state hydrogen plasma of density 1.2×10^{12} ions/c.c. was generated with 60 V of discharge voltage and 70 A of discharge current at a neutral pressure of 1×10^{-3} Torr. Operating the copper converter at -300 V and 30 A at this level produced approximately 20 mA of negative ion current through an exit opening of 4 x 10 cm^2. When cesium

was added, approximately 0.5 A of negative ion current was generated for several seconds before the cesium dispensers were depleted. This corresponds to a gas efficiency of approximately 4%. The gas efficiency can be further improved by decreasing the height of the exit aperture.

Figure 11 shows a similar but much smaller-sized gridded Faraday cup with an entrance aperture of 0.6 cm in diameter. This cup was mounted at the end of a metal rod which could rotate in a plane parallel to the converter surface at the source exit. When the rod is rotated through an angle greater than 180°, the negative ion current collected by the cup shows two peaks (Fig. 11). Each maximum occurs at the moment when the entrance aperture of the cup crosses the midplane of the converter. This result therefore shows that the concave shape of the converter surface does produce a geometric focusing effect.

III. IMPURITY STUDY

Negative ions other than H^- can be generated at the surface of the copper converter and will therefore form a part of the extracted beam. The impurities have been detected by using the mass spectrometer. It has been found that mass 17 (OH^-) and mass 25 (believed to be C_2H^-) are the principal impurities in the negative ion beam. A small mass separator, utilizing permanent magnets and capable of separating H^- and D^- from the heavy-mass impurities, was mounted behind the gridded Faraday cup so as to sample a small portion of the beam. Thus the total negative ion current as well as the percentage of impurity in the beam can be measured simultaneously. With the use of this separator, it was observed that the level of impurity can be very high (typically 75%) when a new uncesiated copper converter is first employed. Similar impurity levels are observed when the source has not been operated for a long period of time. The impurity level gradually decreases as a function of operating time while the H^- current remains essentially constant for a fixed discharge power. The percentage of impurity normally decreases asymptotically to approximately 40% of the negative ion beam in about twenty minutes of operation. When cesium is introduced into the discharge by means of a cesium jet connected to an external oven, the H^- current increases rapidly, but no big increase in the impurity level is observed. The electron binding energies of OH^- and C_2H^- ($E_{OH^-} \simeq 1.8$ eV, $E_{C_2H^-} \simeq 3$ eV) are much higher than that of H^- ($E_{H^-} \simeq 0.75$ eV). Therefore the introduction of cesium should not necessarily enhance the impurity yield as much as it does the H^- yield. With cesium, the percentage of impurity in the extracted beam has been reduced to about 14%. This result is expected to improve as the source and the oven become better conditioned.

IV. BACKGROUND ELECTRON SUPPRESSION

In most experiments, electrons as well as H^- ions are extracted from a negative ion source. These electrons are not desirable because they contribute to a large power dissipation when accelerated to a high voltage. They are normally separated from the H^- ion beam by applying an external B-field.[11] In this negative ion source, energetic electrons from the plasma are excluded, yet Langmuir probe measurements show that there can be a considerable density of very low energy electrons just outside the source exit (Fig. 3). The B-field in the exit region cannot confine the positive ions efficiently. Electrons found in this region could either diffuse across the magnetic field with the positive ions (because the plasma potential is generally several volts positive relative to the chamber wall), or they can be produced by photons illuminating surfaces near the exit region.

In a multiline-cusp plasma source, the plasma potential can be made negative by the low-energy electron injection technique.[20-22] A background hydrogen plasma was produced initially by injecting 1 A of 60 eV electron from a 0.15 cm diameter tungsten filament. The Langmuir probe traces obtained at the center and the exit of the source are shown in Fig. 12 (labeled A). An additional 2 A of primary electrons with energy approximately equal to 5 eV were then emitted from a second filament. These primaries cannot cause ionization but are confined very efficiently by the cusp-fields. The presence of a large quantity of these low-energy electrons can produce a negative plasma-potential well that will contain the positive ions. The Langmuir probe trace in Fig. 12(a) (labeled B) indicates that the plasma potential at the center of the source becomes negative. Meanwhile the probe trace shown in Fig. 12(b) (labeled B) shows that the plasma density at the source exit has been reduced

by two orders of magnitude. Thus the extracted electron current is suppressed by a potential which would be expected to extract them from the source.

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REFERENCES

1. K. H. Berkner, R. V. Pyle, and J. W. Stearns, Nucl. Fus. *15*, 249 (1975).
2. K. Prelec and Th. Sluyters, Rev. Sci. Instrum. *44*, 1451 (1973).
3. E. B. Hooper, Jr., Lawrence Livermore Lab. Report UCID-18067 (Feb. 1979).
4. John R. Hiskes, invited paper presented at the XIVth International Conference on Phenomena in Ionized Gases, Grenoble, France (July, 1979); Lawrence Livermore Lab. Report UCRL-82889 (June, 1979).
5. R. Limpaecher and K. R. MacKenzie, Rev. Sci. Instrum. *44*, 726 (1973).
6. K. N. Leung, T. K. Samec, and A. Lamm, Phys. Lett. *A 51*, 490 (1975).
7. T. K. Samec, K. N. Leung, K. R. MacKenzie, and B. D. Fried (unpublished); T. K. Samec, Ph.D. Thesis, University of California, Los Angeles, CA, UCLA Report PPG-281 (1976).
8. M. L. Yu, Phys. Rev. Lett., *40*, 574 (1978).
9. P. Schneider, Ph.D. Thesis, University of California, Berkeley, CA (1979).
10. K. W. Ehlers, K. N. Leung, and M. D. Williams, Rev. Sci. Instrum. *50*, 1031 (1979).
11. Yu I. Bel'chenko, G. I. Dimov, and V. G. Dudnikov, Nucl. Fus. *14*, 113 (1974).
12. M. Seidl and A. N. Pargellis, Bull. Am. Phys. Soc., *23*, 804 (1978).
13. K. Wiesemann, Proceedings of the Symposium on Production and Neutralization of Negative Hydrogen Ions and Beams (Brookhaven Nat. Lab., Sept. 1977).
14. J. R. Hiskes, A. Karo, and M. Gardner, J. Appl. Phys. *47*, 3888 (1976).
15. P. J. Schneider, K. H. Berkner, W. G. Graham, R. V. Pyle, and J. W. Stearns, Proceedings of the Symposium on Production and Neutralization of Negative Hydrogen Ions and Beams (Brookhaven Nat. Lab., Sept. 1977).
16. F. Llewellyn-Jones, Ionization and Breakdown in Gases (Methuen & Co., London, 1957).
17. O. S. Oen and M. T. Robinson, Nucl. Instrum. Methods, 132, 647 (1976).
18. K. N. Leung et al., Rev. Sci. Instrum. 49, 321 (1978).

19. Th. Sluyter, Proceedings of the Second Symposium on Sources and Formation of Ion Beams, Berkeley (1974).

20. N. Hershkowitz and K. N. Leung, Appl. Phys. Lett. *26*, 607 (1975).

21. Y. Nakamura, B. H. Quon, and A. Y. Wong, Phys. Lett. *A 53*, 85 (1975).

22. K. N. Leung, R. D. Collier, G. R. Taylor, and R. E. Kribel, Appl. Phys. Lett. *31*, 154 (1977).

Figure Captions

Fig. 1 Schematic diagram of the multicusp negative ion source.

Fig. 2 (a) The magnetic field pattern generated by the samarium-cobalt magnets. (b) A plot of the magnetic field as a function of radial position through the exit aperture of the source.

Fig. 3 A Langmuir probe trace obtained at the source exit with a discharge voltage of 250 V and a discharge current of 4 A.

Fig. 4 Typical spectrometer output signals of the D^- and H^- ions produced by an uncesiated copper converter.

Fig. 5 The three distinctive groups of H^- ions that can be identified from the energy spectrum.

Fig. 6 The energy spectrum of the H^- ions as a function of neutral pressure.

Fig. 7 The H^- ion beam spectrum as a function of discharge power.

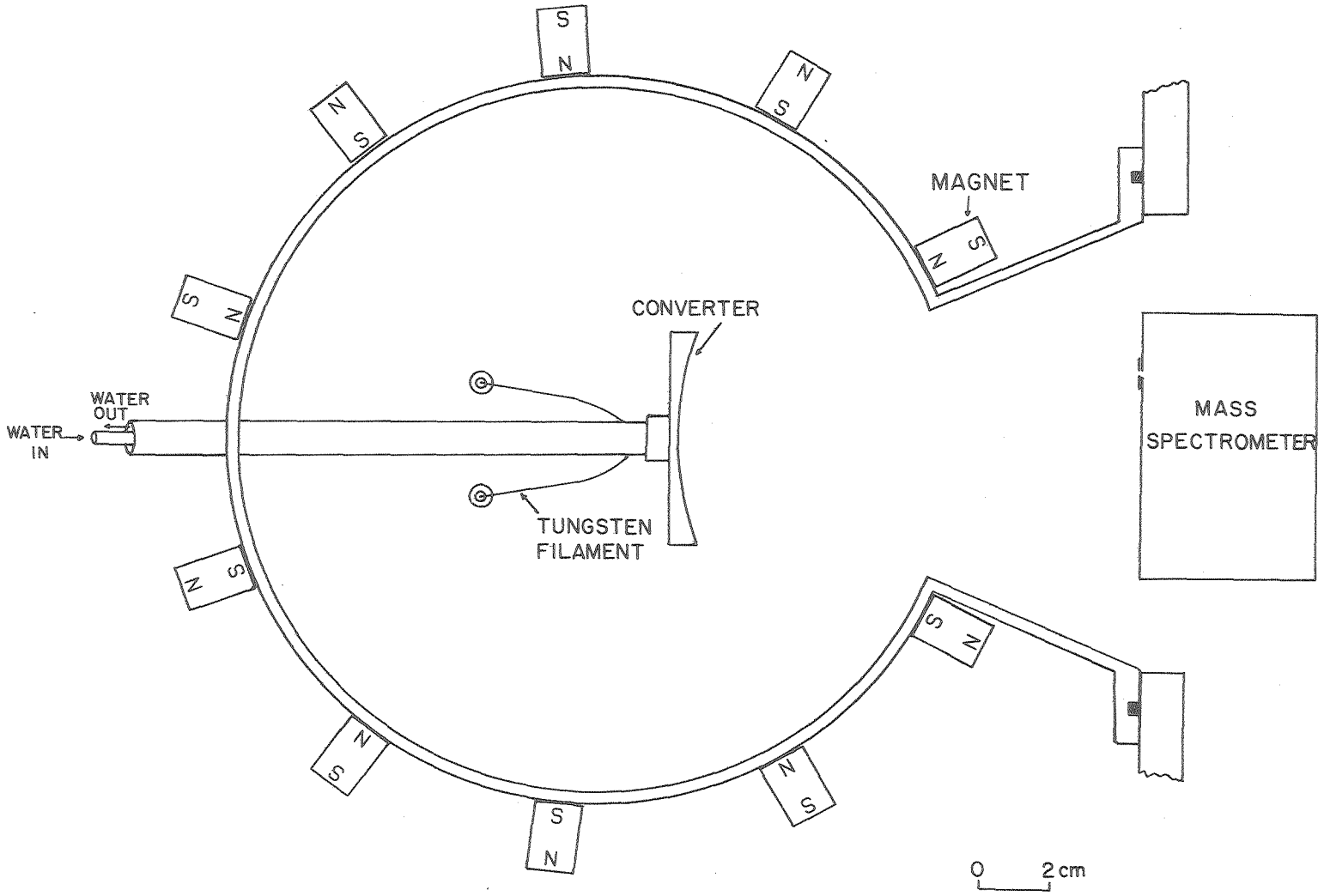
Fig. 8 The H^- ion beam spectrum as a function of converter bias voltage at constant discharge power.

Fig. 9 The H^- ion spectrometer signal as a function of converter position at constant discharge power.

Fig. 10 The H^- ion spectrometer signal obtained when the source is operated with and without cesium in the discharge.

Fig. 11 The negative ion current obtained by a small gridded Faraday cup as it rotates through an angle greater than 180°.

Fig. 12 Langmuir probe traces obtained at (a) the center and, (b) the exit of the source with and without low-energy electron injection.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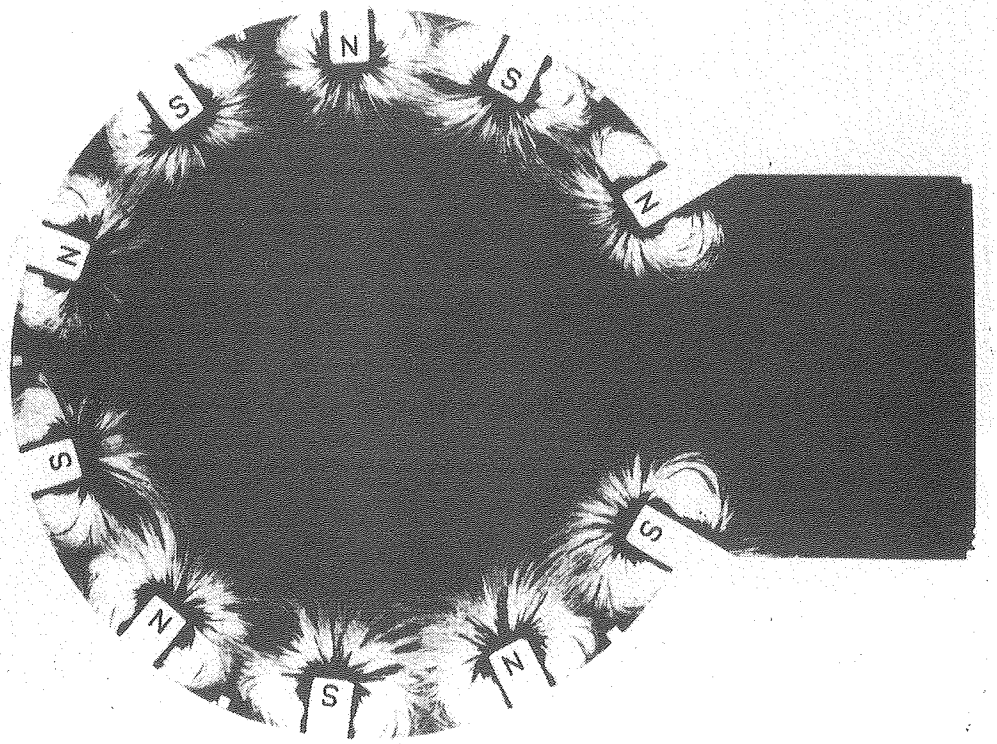
WATER IN
TUNGSTEN FILAMENT
MASS SPECTROMETER
0 2 cm
XBL 792-8379

Fig. 1



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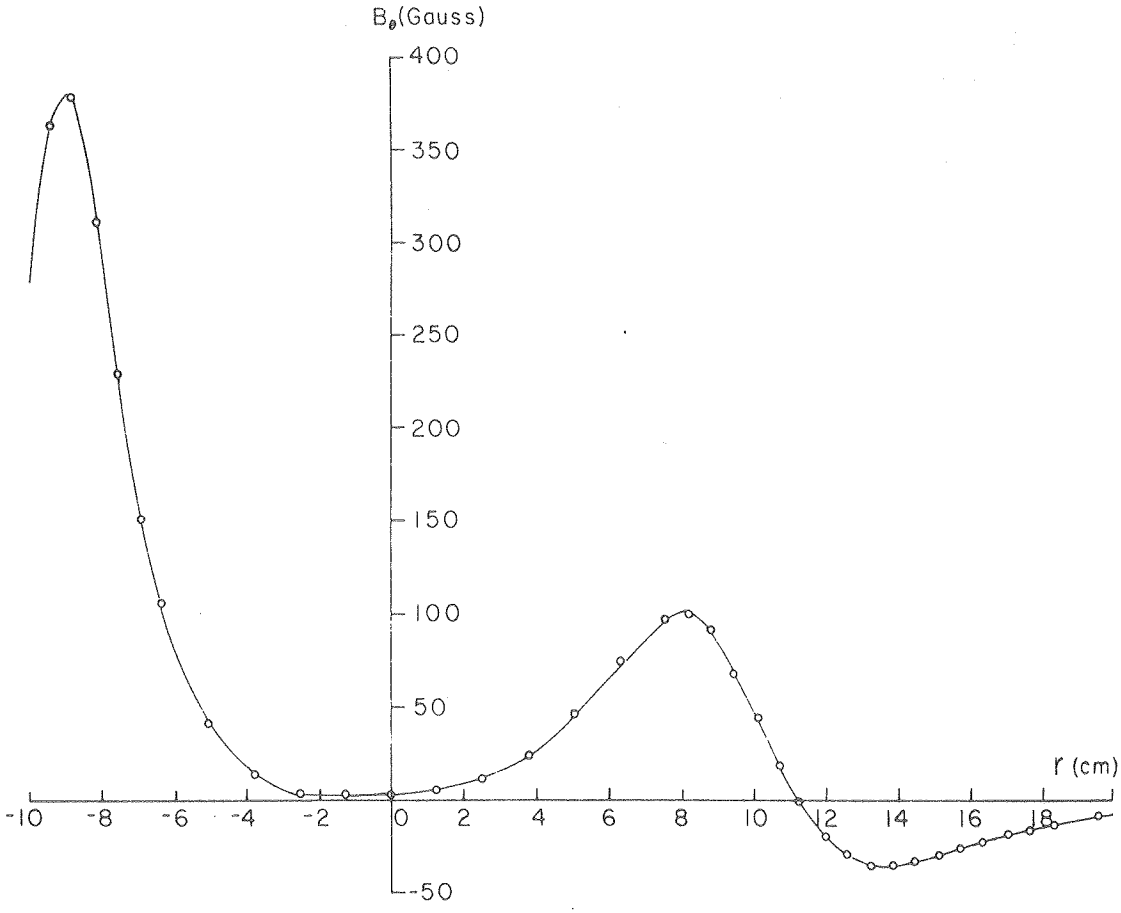

(B)

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Fig. 2

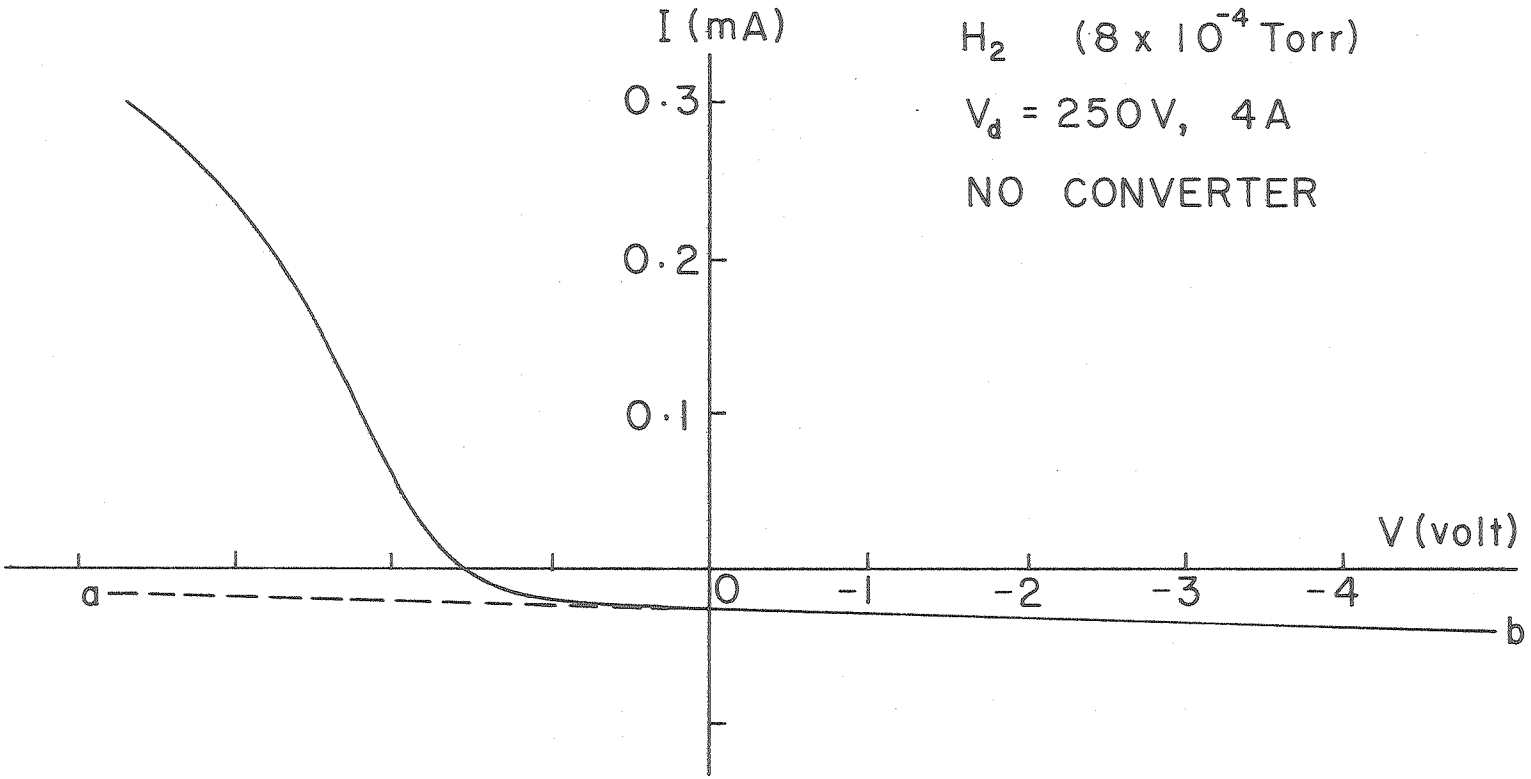

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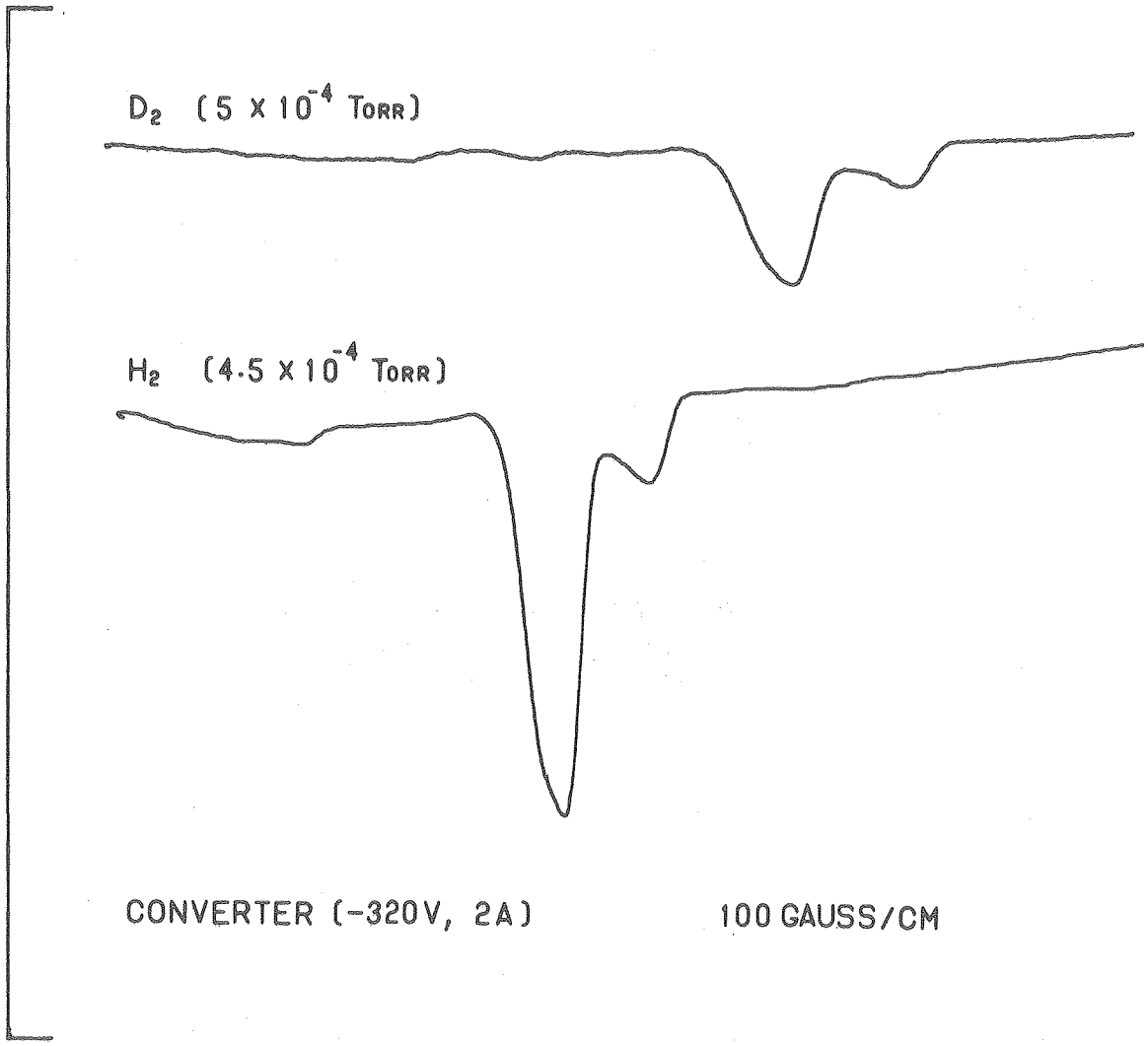
Fig. 3



XBL 791-8180

Fig. 4

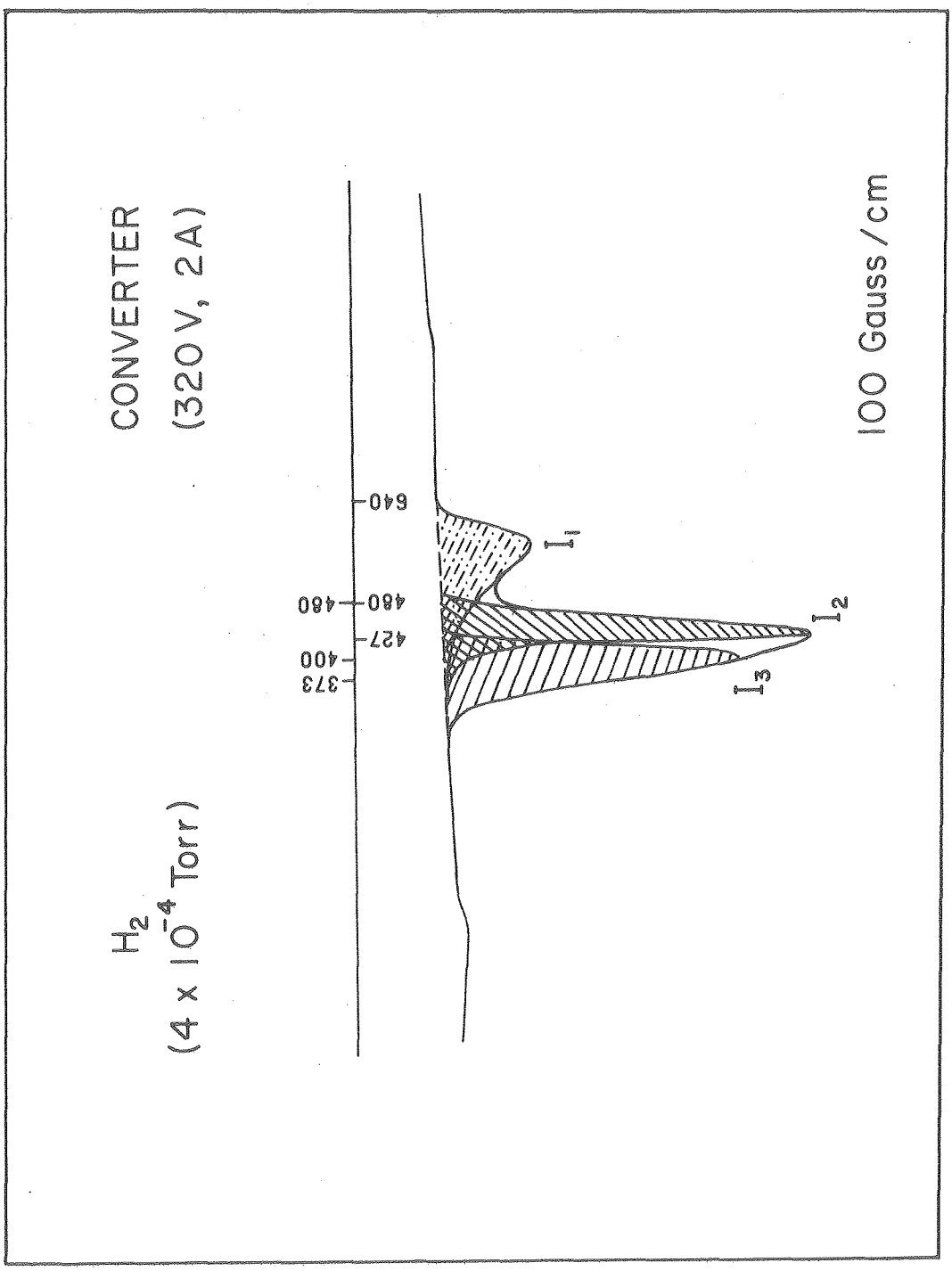


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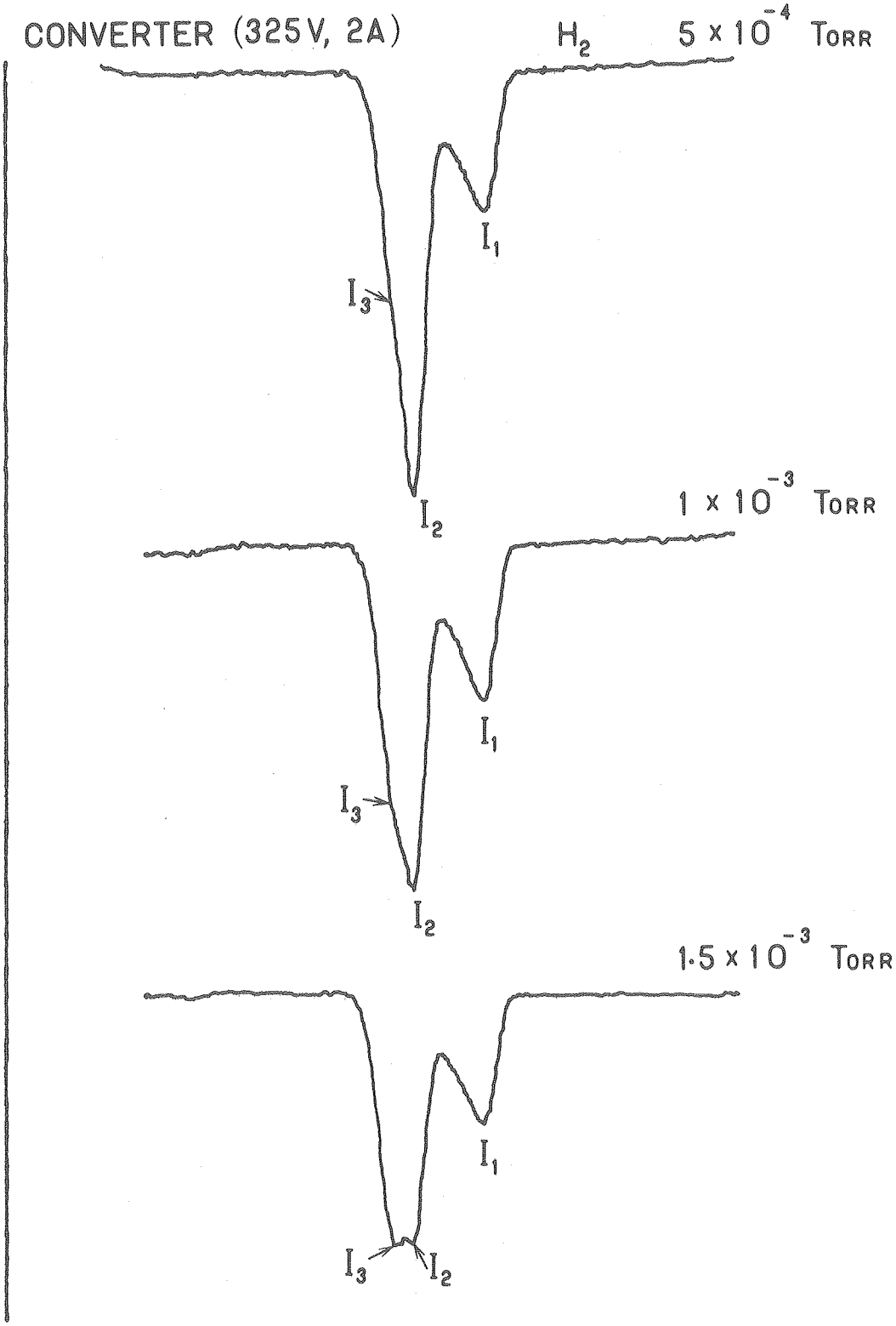
Fig. 5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H2
5 x 10-4 TORR
I1
I3
I2
1 x 10-3 TORR
I1
I3
I2
1.5 x 10-3 TORR
I1
I3
I2

Fig. 6

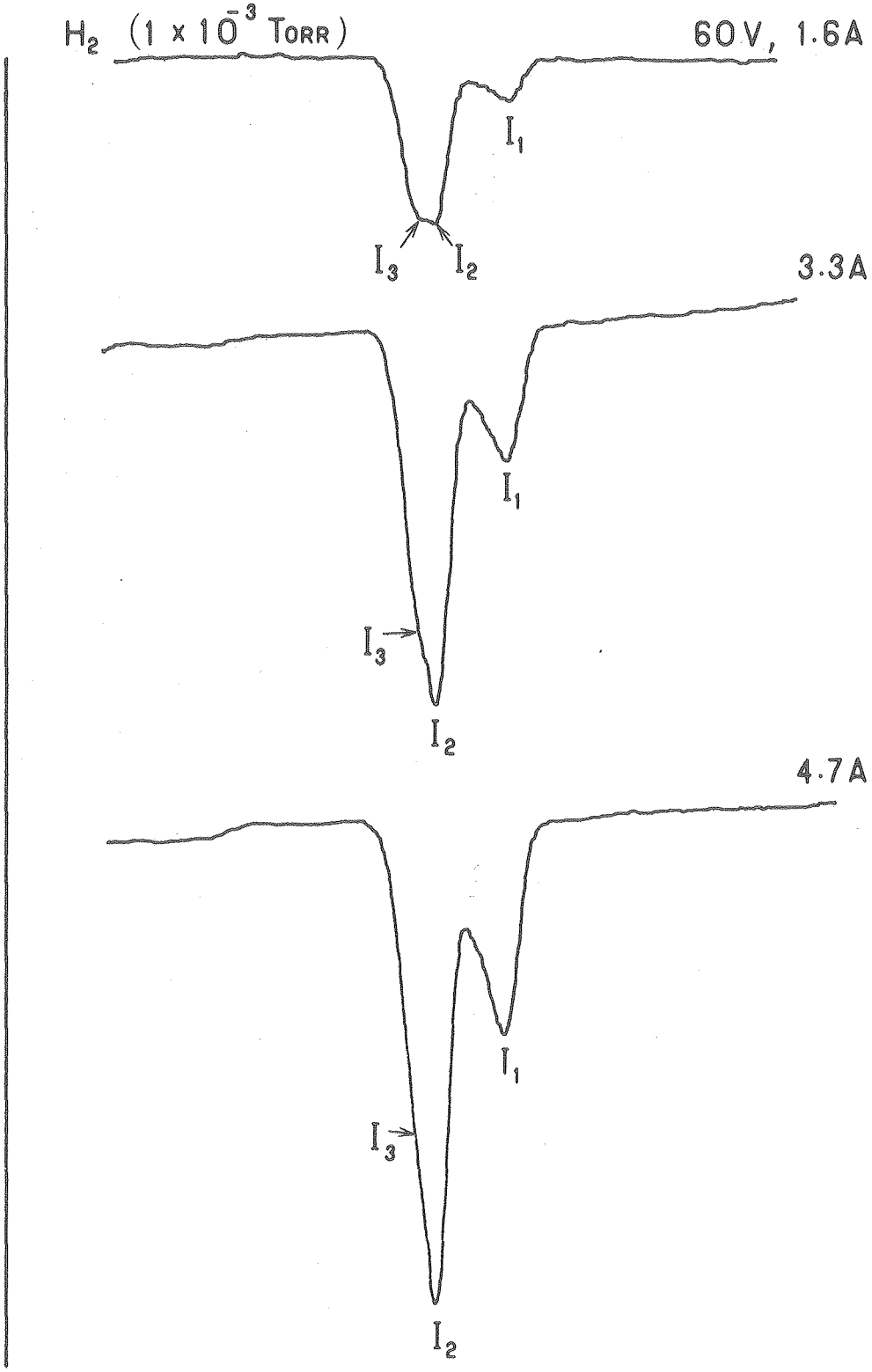
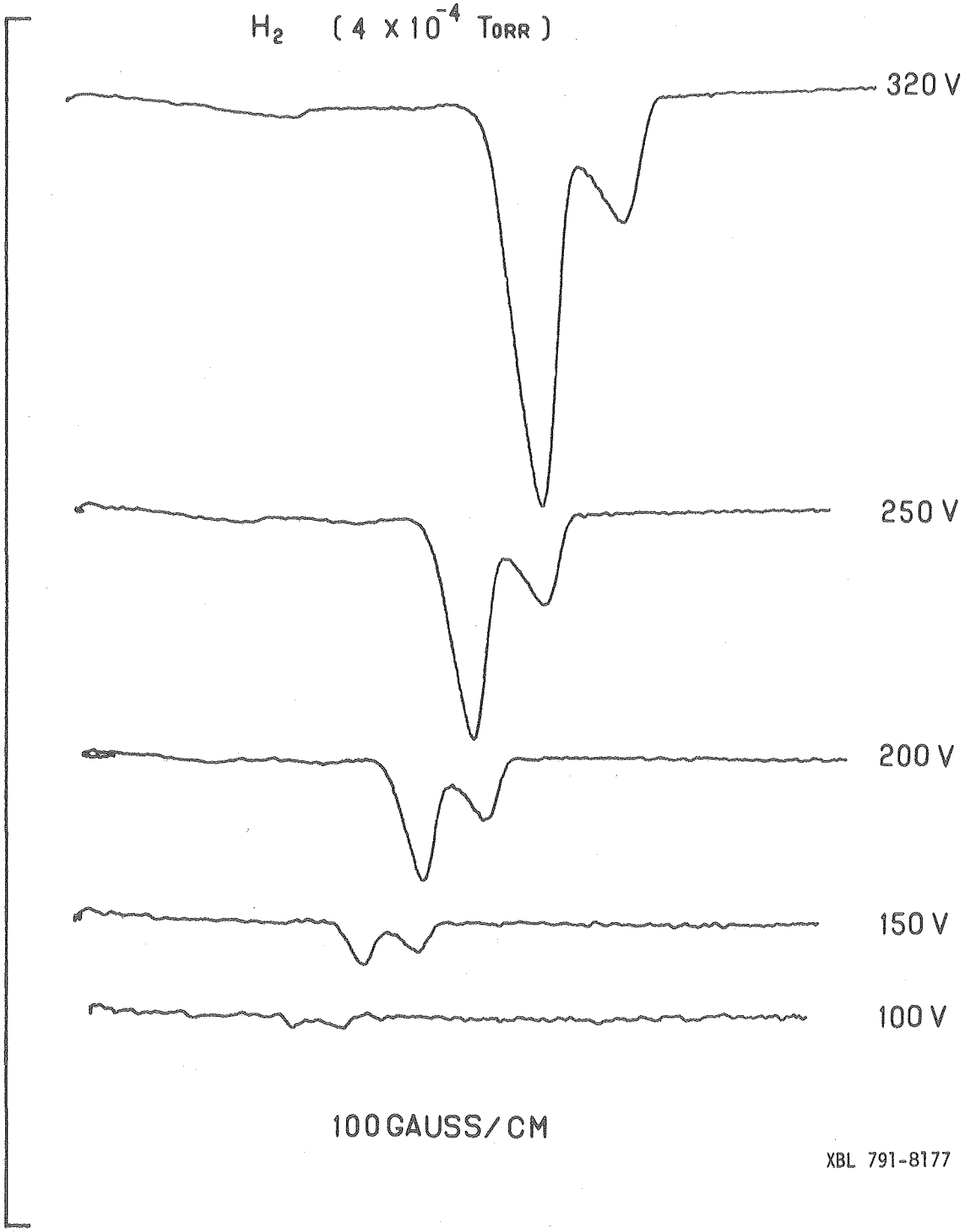


Fig. 7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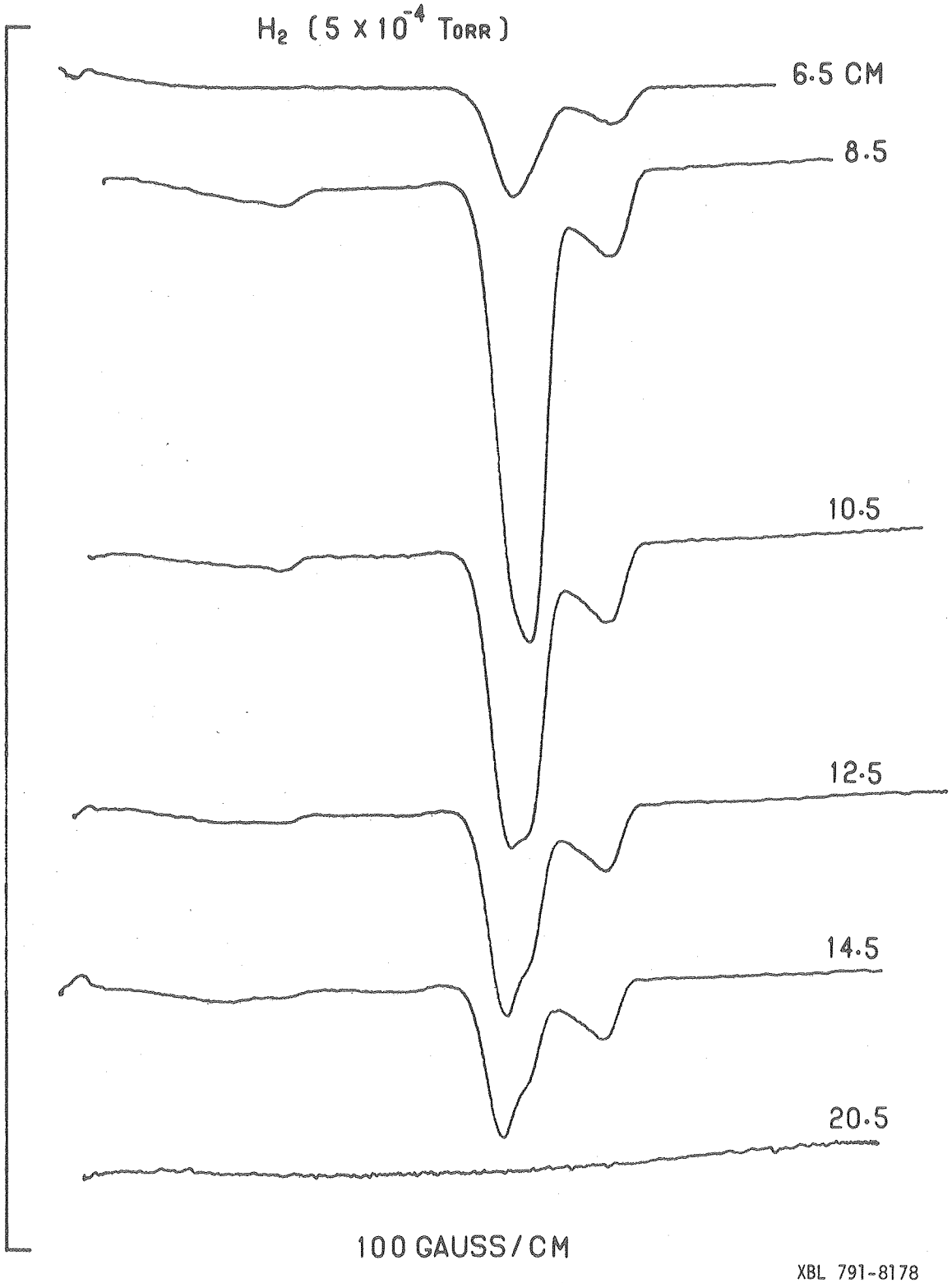
250 V
200 V
150 V
100 V
100 GAUSS/CM
XBL 791-8177

Fig. 8


H_2 (5×10^{-4} TORR)
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8.5
10.5
12.5
14.5
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XBL 791-8178

Fig. 9

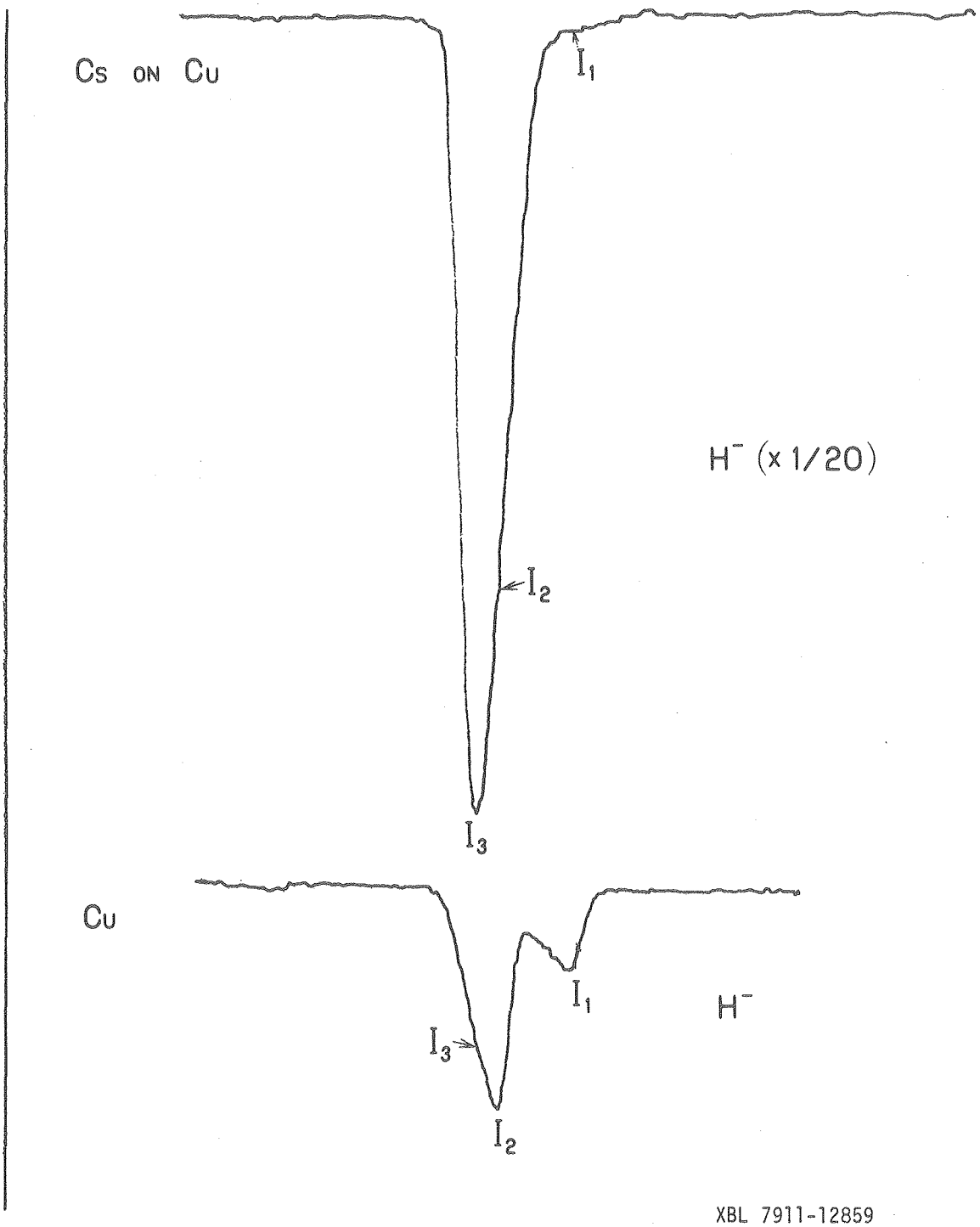
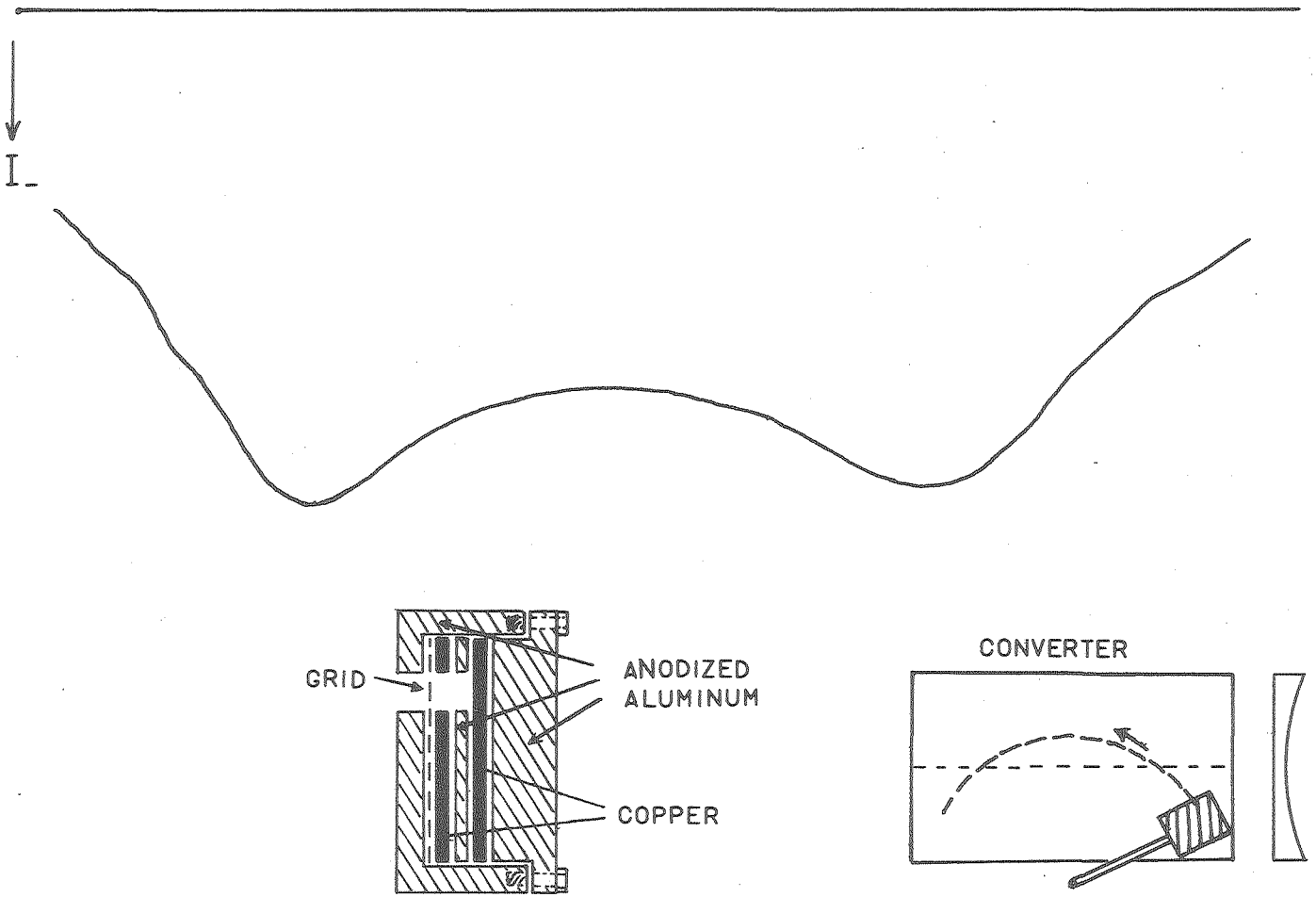


Fig. 10



A GRIDDED FARADAY CUP

XBL 7910-12117

Fig. 11

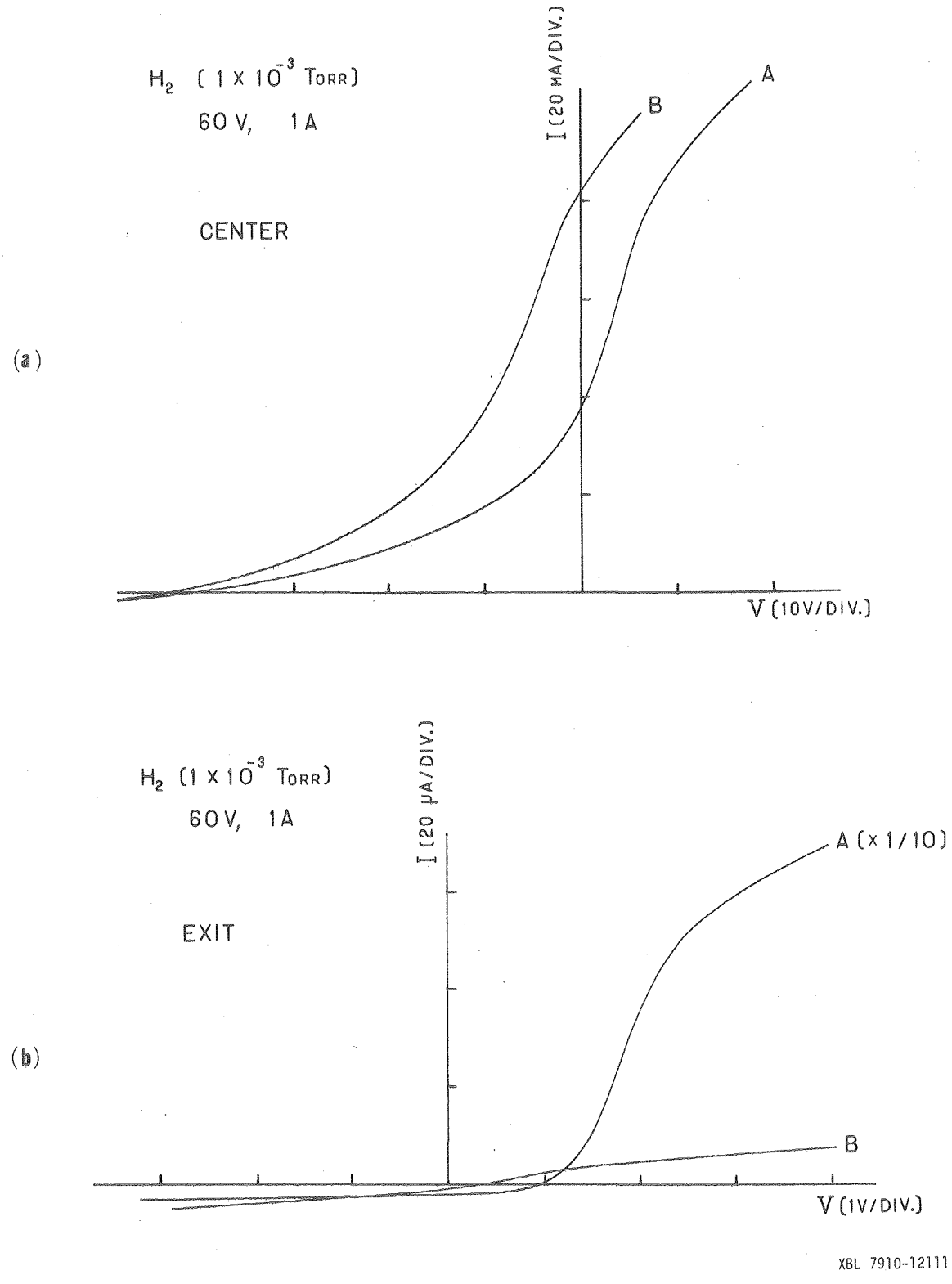

H2 (1 X 10-3 TORR)
60 V, 1 A
CENTER
I (20 MA/DIV.)
A
B
V (10V/DIV.)
(a)
H2 (1 X 10-3 TORR)
60 V, 1 A
EXIT
I (20 μA/DIV.)
A (x 1/10)
B
V (1V/DIV.)
(b)
XBL 7910-12111

Fig. 12