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LBL SELF-EXTRACTION NEGATIVE ION SOURCE

K.N. Leung and K.W. Ehlers

August 1981

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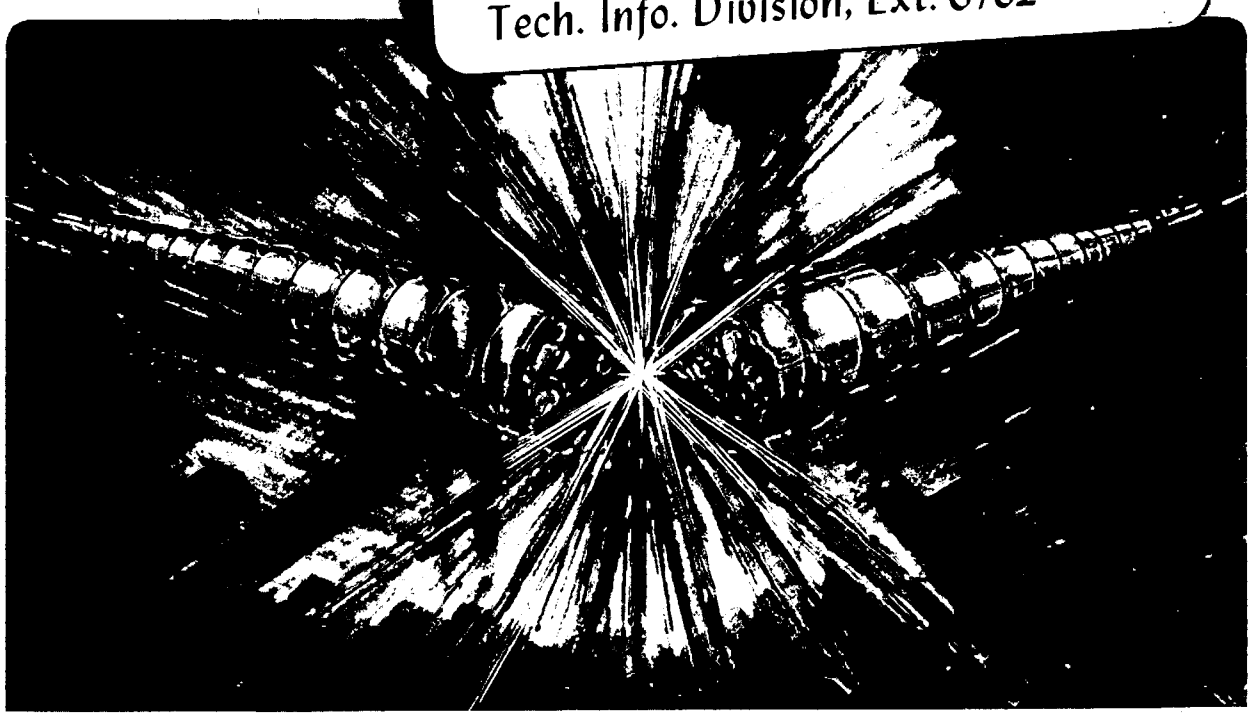

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LBL Self-Extraction Negative Ion Source*

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August 1981

Abstract

A large multicusp negative ion source has been constructed to generate H^- or D^- ions for high energy neutral beam systems. With the presence of cesium, the source has produced a steady-state H^- ion beam current greater than 1 A with an impurity level less than 1%. The vertical and horizontal profiles of the self-extracted beam have been measured with a gridded Faraday cup. The gas efficiency of the source and the electron component in the accelerated beam have been measured for two different pumping conditions.

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Introduction

In order to heat plasmas in future fusion reactors and for current drive in tokamaks, multiamperes of very high energy neutral beams will be required. The high neutralization efficiency (> 60%) of H^- or D^- ions makes them favorable to form neutral atoms with energies in excess of 150 keV.[1] The initial goal of the LBL negative ion program was to accelerate a H^- ion beam of 1 A or greater to an energy of about 40 keV with pulse lengths from 5 seconds to steady state. In order to meet these objectives, a large self-extraction negative ion source, together with an electrostatic accelerator was fabricated. This report provides a summary of the operational characteristics of this negative ion source. The source geometry is described in Section I and the experimental results are given in Section II. Measurement of the source gas efficiency and the percentage of electrons in the accelerated beam are presented in the last section.

I. Experimental Arrangement

Figure 1 is a schematic diagram of the negative ion source geometry. The device is a 37.4 liter stainless-steel chamber with 12 columns of samarium-cobalt magnets ($B_{max} \cong 3.6$ kG) and 2 columns of ceramic magnets ($B_{max} \cong 1.6$ kG) installed on the external wall. These magnets are mounted in water-cooled housings which also serve as mechanical stiffeners to support the vacuum load. 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 or

less as measured by a Barocel attached to the source chamber. A steady-state hydrogen or deuterium plasma is generated by ~ 80 eV primary electrons emitted from eight 0.15 cm diam. tungsten filaments with four located at the top and four at the bottom of the chamber. The entire chamber wall serves as the anode for the discharge.

To produce negative ions, a water-cooled concave, molybdenum converter (8 cm high and 25 cm long) is inserted into the plasma through two feed-through insulators. By biasing the converter negatively (~ 200 V) with respect to the plasma, positive ions from the plasma are accelerated across the sheath and strike the converter surface. Negative ions that are formed at the converter surface are then accelerated back through the sheath by the same potential. The bias voltage on the converter thus becomes the negative ion extraction potential. The converter surface is curved to geomertrically direct the negative ions through the plasma to a position at the exit aperture which is located between the two ceramic magnet columns. The B-field in the region of the exit aperture is adjusted to a maximum value of about 80 G. (Fig. 2(b)). This B-field is strong enough to reflect electrons which may have energies as high as 300 eV, but it produces only a small lateral displacement (~ 1 cm) on the trajectories of the energetic H^- or D^- ions. The samarium-cobalt 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 350 G. A plot of the B-field along the horizontal direction through the exit aperture of the source is shown in Fig. 2(b). It can be seen that the converter is located in the almost field-free region of the source. Molybdenum is

chosen as the converter material because it has a relatively low sputtering rate under hydrogen and cesium ion bombardment. In addition, we have found that molybdenum produces the highest H^- ion yield compared with other materials under the same conditions of gas pressure, cesium environment, discharge current and converter potential.[2] The entrance support, the rear and the side surfaces of the converter are protected from ion bombardment by a boron-nitride housing which floats electrically at about 40 V below the plasma potential. This arrangement reduces the current drawn by the converter bias power supply by about a factor of two as the current read at the converter power supply is that from the active part of the converter only.

The shape of the source is designed to be scalable in both the vertical and horizontal dimensions in order to obtain larger negative ion currents than from just the one converter shown. By increasing the height of the source chamber, and maintaining the magnet spacing shown for the single exit aperture, additional ion exit apertures could be added, along with more converter electrodes which would be placed above and below the single one shown.

The electrode which defines the exit aperture is electrically isolated so that a positive bias potential can be applied for electron suppression[3] as well as for space charge control. The size of the exit opening (25 cm long and max. height = 3 cm), which can be adjusted mechanically, will be made as narrow as possible so as to reduce the gas flow rate, yet not so narrow as to impede the exit of optically-useful negative ions.

Previous study of a smaller self-extraction negative ion source unit indicated that the yield of H^- ions can be greatly enhanced by adding

cesium into the hydrogen plasma.[4] In this source, cesium vapor is introduced into the discharge from an external oven through an ohmic-heated, coaxial pipe located below the exit aperture. Figure 3 is a photograph of the source chamber together with the oven and cesium jet assembly. The cesium is sprayed into the discharge from a 0.3 cm x 1.9 cm slit located at the end of the transfer tube which is maintained at about 300 °C by a dc heater current of ~ 25 A.

After emerging from the source exit aperture, the H^- ion beam is accelerated to higher energies by means of a four-electrode accelerator (Fig. 1). The accelerator geometry design together with the voltage distributions was determined by the WOLF computer code.[5]

The source chamber is attached to a 6.5 cm thick epoxy flange which in turn is bolted onto a large vacuum tank. The whole system is pumped by two turbo-molecular pumps for source operations. Two auxilliary liquid-helium cryo-pumps (~ 12,000 l/sec each) are used when additional pumping speed is required.

II. Experimental Results

To study the characteristics of this negative ion source, three diagnostic techniques have been employed. (1) Plasma parameters such as electron density, electron temperature, and space potential of the source plasma were obtained with Langmuir probes. (2) The total "self-extracted" negative ion current was measured by a large (28 cm by 7.5 cm) gridded Faraday cup which was also equipped with a permanent magnet mass separator to measure the percentage of impurities in the negative ion beam. (3) A small gridded Faraday cup (1.6 mm diam)

mounted at the end of a long stem was used to scan the vertical and horizontal beam profiles outside the source exit.

(a) Source Characteristics

The source was first operated in the pure hydrogen mode without the presence of the molybdenum converter. With a discharge voltage of 70 V and a discharge current of 100 A, a hydrogen plasma with density $n \approx 1.2 \times 10^{12}$ cm^{-3}, $T_e \approx 3.7$ eV and $V_p = +4$ V was obtained at the center of the source. A series of Langmuir probe traces were also taken from the center of the source towards the beam exit aperture without the biased aperture electrode. Figure 4 shows that the electron saturation current at the edge of the source chamber is approximately two orders of magnitude lower than that at the center of the source (source center $\approx$ 10.8 cm). However, when the source was operated with an argon plasma, Fig. 5 shows that the electron saturation current at the edge is reduced by only a factor of 8. Both of these sets of probe traces show that the electrons present near the ion exit region are considerably colder than those in the central discharge region.[3] The B-field in the exit region is strong enough to contain the primary electrons and the majority of the hydrogen ions but is too weak to confine argon or higher mass ions. The cold electrons found in the exit area come from the plasma volume by diffusion across the magnetic field with the positive ions. Thus, a substantial number of electrons could exist at the beam exit region if the source is operated in a hydrogen-cesium mode. With the installation of the positively-biased electrode at the exit aperture, it has been demonstrated that the

background electron density in that region can be suppressed quite effectively.[3] By varying the bias voltage on the aperture electrode, it is possible to adjust the background positive ion density n_+ at the exit region to be approximately equal to the negative ion density n_b of the self-extracted beam so as to provide space charge neutrality. The effect of space charge compensation on the negative ion beam has been observed and will be discussed in Section II(C).

With the molybdenum converter installed at the center of the source chamber and biased at -200 V with respect to the anode, the converter collects ~ 20 A of current at a discharge voltage of 80 V and a discharge current of 145 A in the hydrogen mode. A plot of the ion saturation current as a function of the horizontal direction in front of the converter surface shows that the converter is well within the uniform plasma region (Fig. 6). In fact, the uniformity extends to about 8 cm beyond the edge of the converter. No measurement were made on the vertical density profile, but it is expected that the converter is illuminated by a uniform plasma in that direction.

(b) Beam Current Measurements

The total negative ion current was measured by the Faraday cup (Fig. 7) which was positioned 16 cm from the source exit edge or ~ 27 cm from the converter surface. The exit aperture electrode was adjusted to have an opening of 3 x 25 cm^2 and was biased at +8 V relative to the anode. A 70% transparent fine mesh tungsten screen, mounted in front of the collector cup, was biased approximately -10 V relative to the anode

to collect any low energy positive ions and to repel any background electrons. The cup was biased +17 V with respect to the anode to collect the energetic negative ions and to suppress secondary electrons. In addition, a portion of the beam was sampled by a small mass spectrometer constructed from a pair of iron shielded permanent magnets. The magnet was designed to deflect H^- or D^- ions on to one collector, and all other impurity negative ions with mass $\geq$ 12 are received on a second collector. A schematic diagram of the Faraday cup is shown in Fig. 8.

During the initial operation of the source (without cesium), the total negative ion current I^- recorded was approximately 25 mA with a converter bias voltage of 200 V and a converter current of 15 A (Fig. 9(a)). The mass spectrometer collector signals (Fig. 9(b)) show that the percentage of impurity negative ions in the beam was very high (~ 90%). The impurity level was directly related to the system's cleanliness and it gradually decreased to about 40% of the total negative ion beam after several discharge cleaning operations.

When cesium was introduced into the discharge by means of the cesium jet connected to an external oven, the H^- ion current increased rapidly. However, there was generally no large increase in the impurity level. The electron binding energies of the main impurities observed are considerably higher than that of H^- ions.[4] Thus, impurity negative ions can be formed more easily than the H^- ion with an uncesiated converter, and the introduction of cesium does not necessarily enhance the impurity yield as much as it does the H^-

yield. In addition, it is possible that impurities in the system may be gathered or chemically pumped by the cesium which condenses on the walls of the source.

Figure 10(a) shows that the total negative ion current I^- increases gradually with the discharge current. As can be seen, the source can be operated quite steadily to generate about 1.1 A of total negative ion current for several minutes with a converter voltage -160 V and a converter current ≈ 20 A. The spectrometer signals in Fig. 10(b) indicate that the impurity level has now decreased to approximately 1% of the total beam current. The discharge for this particular operation was terminated by the crowbar protection system due to a power supply failure. Longer durations (~ 30 min.) of operation have been achieved after the electrical problems were resolved.

(c) The Self-extracted Beam Profile

A small gridded Faraday cup (1.6 mm diam) was constructed to measure the horizontal and vertical profiles of the self-extracted beam. The cup was mounted at the end of a long metal rod which could rotate in a plane almost parallel to the converter surface outside the source exit. The cup and the fine screen in front of it were biased at the same potentials as those of the large gridded Faraday cup.

The source was operated in the hydrogen-cesium mode with the exit aperture adjusted to 3 cm wide. Figure 11 shows the vertical beam profile scan at a distance of 11 cm from the source edge (approximately at the position of the entrance to the accelerator) with the exit

aperture electrode biased at either +10 V or +1 V relative to the anode. It can be seen that the profiles are non-uniform, but they are symmetric and peak at the center due largely to vignetting - more uniform profiles should result if a larger converter had been used. When the aperture electrode bias voltage is reduced from +10 to +1 V, the integrated beam current increases by about 15%. This result shows that if the aperture electrode is biased too positive, the beam particle density n_b is larger than the local positive ion density n_+. Thus the beam becomes more divergent due to the lack of positive ions for space charge neutralization. This same increase has been observed on the H^- as well as the impurity negative ion signals from the two mass spectrometers.

The horizontal profile scan which was obtained at the same distance from the source edge and with the aperture electrode biased at +10 V, shows a very uniform beam profile of approximately 23 cm (the width of the exit aperture is 25 cm). Figure 12(b) shows that the center of this profile is shifted to the left by about 1 cm as the beam traversed the B-field at the exit region. From Fig. 12(a), it can be seen that the uniformity of the profile in the +x direction can be improved by increasing the length of the converter in that direction. A similar increase in the cup current was also observed in the horizontal profile scan when the aperture electrode bias voltage is reduced from +10 to +1 V.

III. Gas Efficiency and Electron Concentration

A big concern with the design of a neutral beam system based on negative ions is the gas efficiency of the source. H^- or D^- ions can be so easily stripped when passing through residual gas that it is

essential to maintain a low gas pressure in the high voltage accelerator region. Thus to make the vacuum pumping requirements reasonable, it is necessary to have as good a source gas efficiency as possible.

The gas efficiency of this source was measured during the time the Faraday cup was present and the system vacuum was provided only by the two turbo-pumps. The mass flow rate for hydrogen as determined by a Hastings mass-flowmeter before the source plasma was turned on was 37 sccm, corresponding to approximately 3.3×10^{19} hydrogen atoms/sec. The gas efficiency for a self-extracted H^- ion current of 1.1 A ($\sim 6.87 \times 10^{18}$ ions/sec) was therefore 20%.

After the four electrode electrostatic accelerator was installed at the exit of the ion source, the percentage of electrons in the accelerated beam was investigated by using a permanent magnet mass-separator. This spectrometer is quite similar to the unit described in Section II(b), but designed to deflect 200 V to 15 keV electrons onto one collector and all accelerated negative ions onto a second collector.

Electrons detected in the accelerated beam can either come directly from the plasma source or they can be produced by the stripping of H^- ions in the accelerator region ($H^- + H_2 \rightarrow H + H_2 + e^-$). In the latter case, the number of electrons generated should be proportional to the neutral gas density and the length of the accelerator gap. For a gas pressure of 1×10^{-3} Torr and an average stripping cross-section of 10^{-15} cm^2, the ratio of electrons to H^- ions at the exit of the 5 cm long accelerator gap, shown in Fig. 1, is estimated to be 0.18.

With the source operated without cesium and the vacuum system pumped by two turbo-molecular pumps, the ratio of electrons to negative ions I_e/I^- in a 12 keV beam was 8 when the exit aperture electrode was

biased at the anode potential. However, when the electrode was biased at approximately +15 V relative to the anode potential, the ratio I_e/I^- dropped to 0.12. Thus, these measurements demonstrate the effectiveness of the exit electrode bias in controlling the leakage of electrons from the source plasma.[3]

When cesium vapor was introduced into the discharge and the exit electrode biased at +15 V, it was found that the ratio of electrons to H^- ions in the accelerated beam was about 0.11. This result is consistent with the theoretical estimation presented in the previous paragraph. With additional pumping provided by a liquid-helium cryo-pump, the ratio I_e/I_{H^-} dropped to 0.038. This decrease is due to the reduction of gas density in the accelerator gap. The additional pumping which had provided the reduction of pressure in the accelerator gap region also required the hydrogen gas flow rate to the source to be increased from 37 sccm to 65 sccm in order to maintain the required source pressure. If the accelerated H^- ion current is assumed to be equal to the high voltage power supply current which was measured to be 1.25 A, then the gas efficiency of the source decreases to approximately 13%.

Thus far, we have succeeded in accelerating a dc self-extracted negative ion beam current of 1 A to approximately 34 keV for a pulse length of 7 seconds. The pulse length was limited by the thermal capacity of the inertial beam stop. Beam quality measurement together with higher energy and longer pulse operation will be performed after the power supplies and beam-dump have been upgraded.

Acknowledgments

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2. K. N. Leung and K. W. Ehlers, J. Appl. Phys. 52, 3905 (1981).
3. K. W. Ehlers and K. N. Leung, Appl. Phys. Lett., 38, 287 (1981).
4. K. W. Ehlers and K. N. Leung, Rev. Sci. Instrum., 51, 721 (1980).
5. O. A. Anderson, Proceedings of the Second International Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams, Brookhaven National Lab., 1980.

Figure Captions

Fig. 1. Schematic diagram of the LBL Self-extraction negative ion source.

Fig. 2. (a) The magnetic cusp field pattern generated by the permanent magnets.

(b) A plot of the B-field along the horizontal direction through the exit aperture of the source.

Fig. 3. The source chamber and the cesium oven and jet assembly.

Fig. 4. Langmuir probe traces obtained at various positions between the center and the exit edge of the source without a biased aperture electrode for a hydrogen plasma.

Fig. 5. Langmuir probe traces obtained at various positions between the center and the exit edge of the source without a biased aperture electrode for an argon plasma.

Fig. 6. Horizontal plasma density profile measured near the converter surface.

Fig. 7. A large gridded Faraday cup for measuring the self-extracted negative ion current.

Fig. 8. A schematic diagram of the gridded Faraday cup with mass analyzers for impurity detection.

Fig. 9. (a) Total negative ion cup current without cesium.

(b) Mass analyzer output signal showing H^- and impurity level for the case without cesium.

Fig. 10. (a) Total negative ion cup current in the presence of cesium.

(b) Mass analyzer output signal showing H^- and impurity level when the source is operated with cesium.

Fig. 11. The vertical beam profile scans with the exit aperture electrode biased at +1 V (dotted line) and +10 V (solid line).

Fig. 12. (a) The horizontal beam geometry with the dashed lines showing the beam-forming electrode with was not present during beam scan. The lateral displacement of the beam is calculated for 150 eV H^- ions.

(b) The horizontal beam scan.

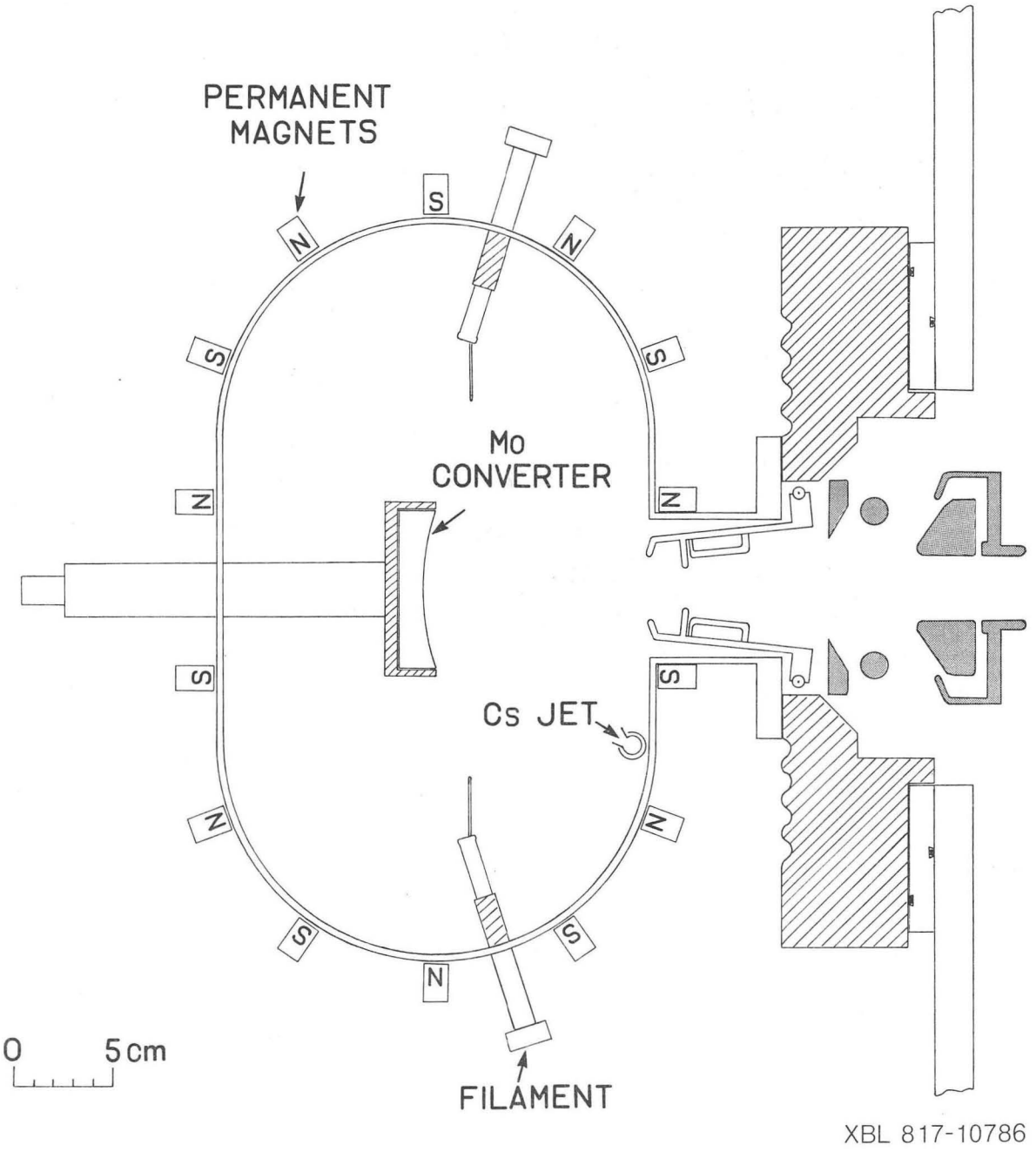
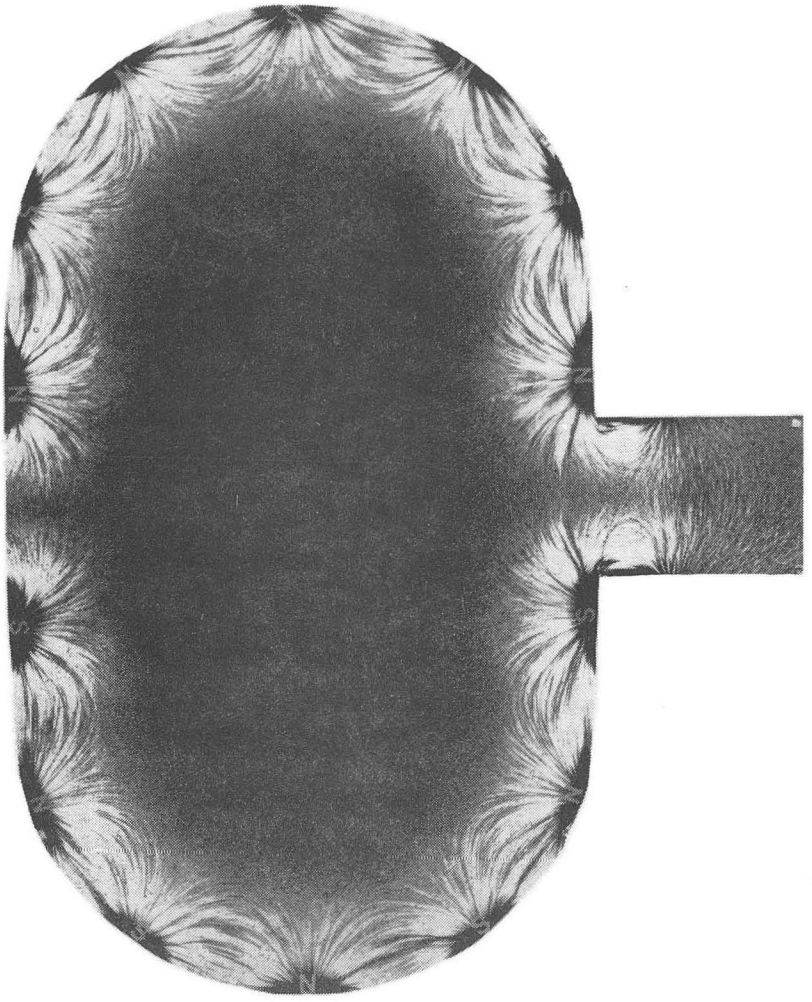

PERMANENT
MAGNETS
S
N
N
S
S
Mo
CONVERTER
N
N
S
S
Cs JET
N
N
S
S
N
0
5 cm
FILAMENT
XBL 817-10786

Figure 1



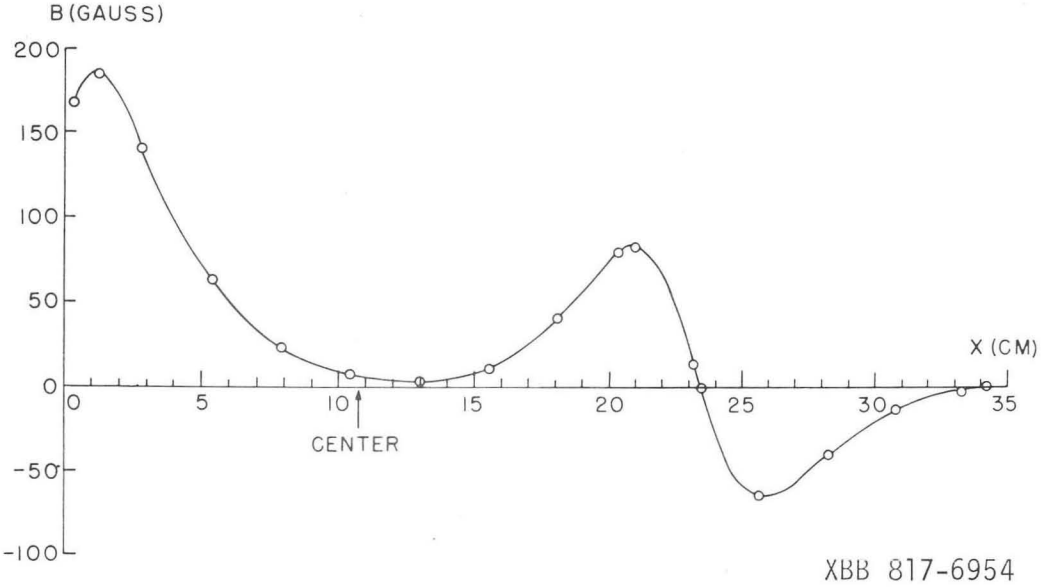

B (GAUSS)
200
150
100
50
0
-50
-100
X (CM)
0
5
10
15
20
25
30
35
CENTER
XBB 817-6954

Figure 2

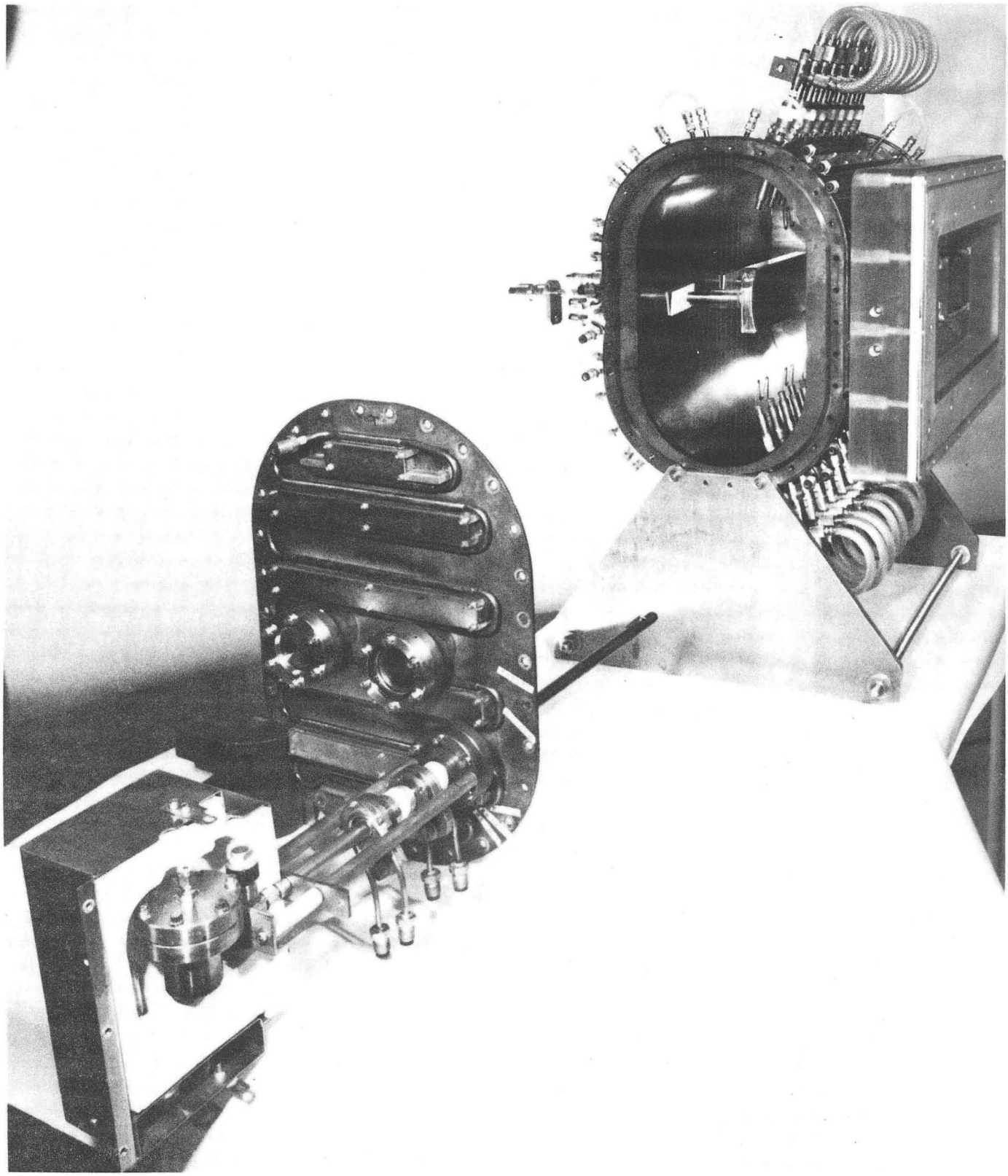


Figure 3 CBB 814-3550

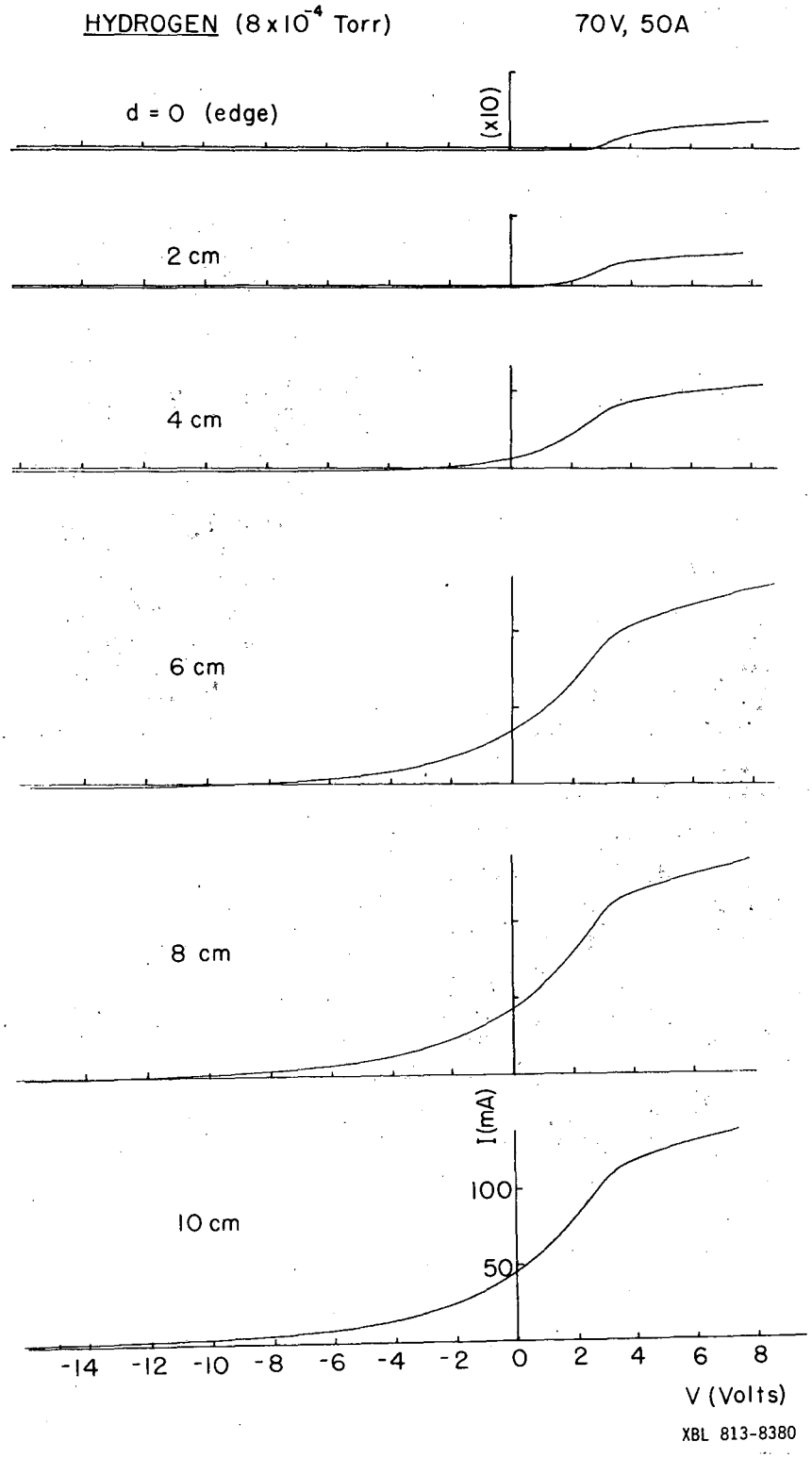

HYDROGEN (8 x 10^-4 Torr)
70V, 50A
d = 0 (edge)
(x10)
2 cm
4 cm
6 cm
8 cm
10 cm
I (mA)
100
50
-14 -12 -10 -8 -6 -4 -2 0 2 4 6 8
V (Volts)
XBL 813-8380

Figure 4

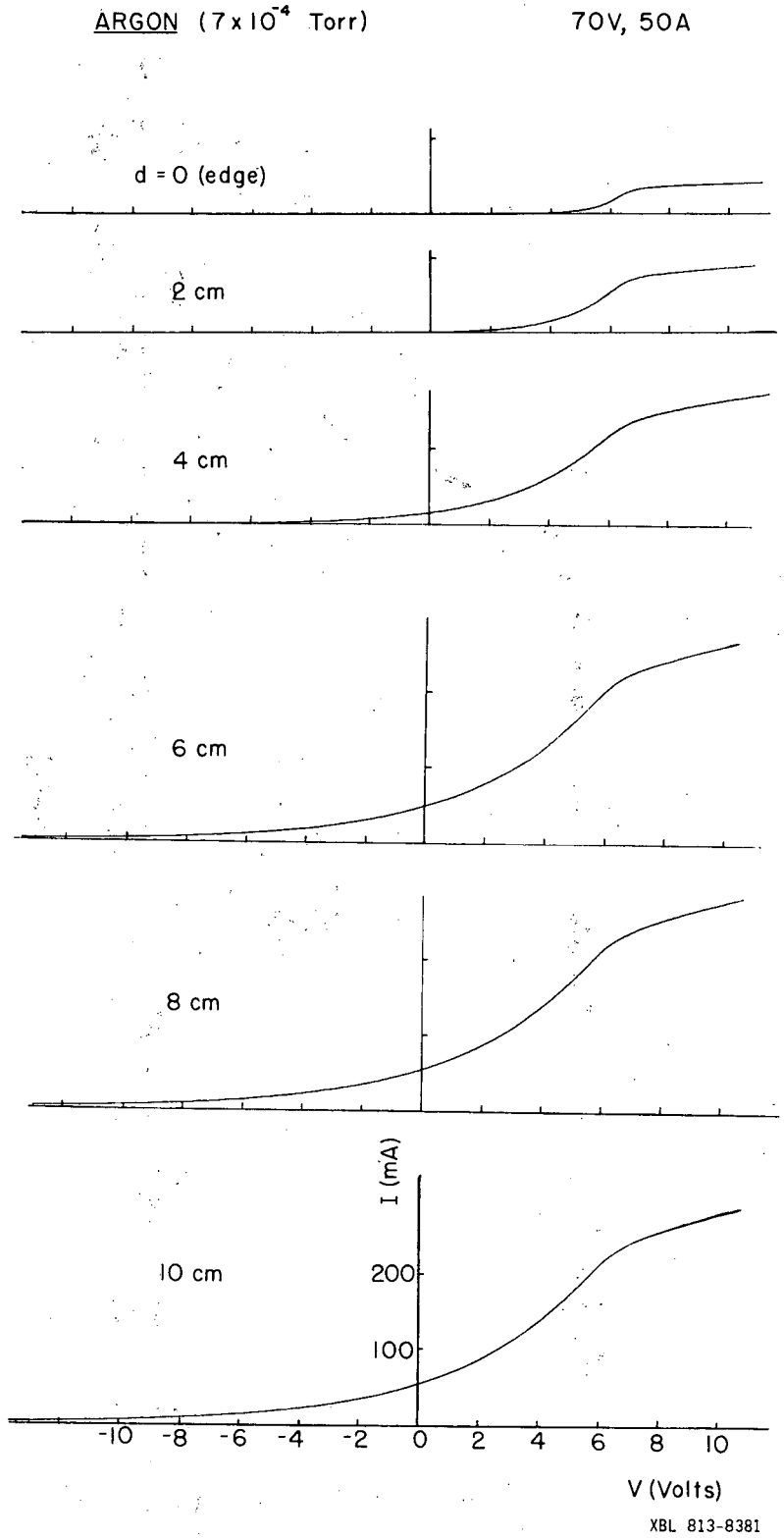

ARGON (7 x 10^-4 Torr)
70V, 50A
d = 0 (edge)
2 cm
4 cm
6 cm
8 cm
10 cm
I (mA)
200
100
-10
-8
-6
-4
-2
0
2
4
6
8
10
V (Volts)
XBL 813-8381

Figure 5

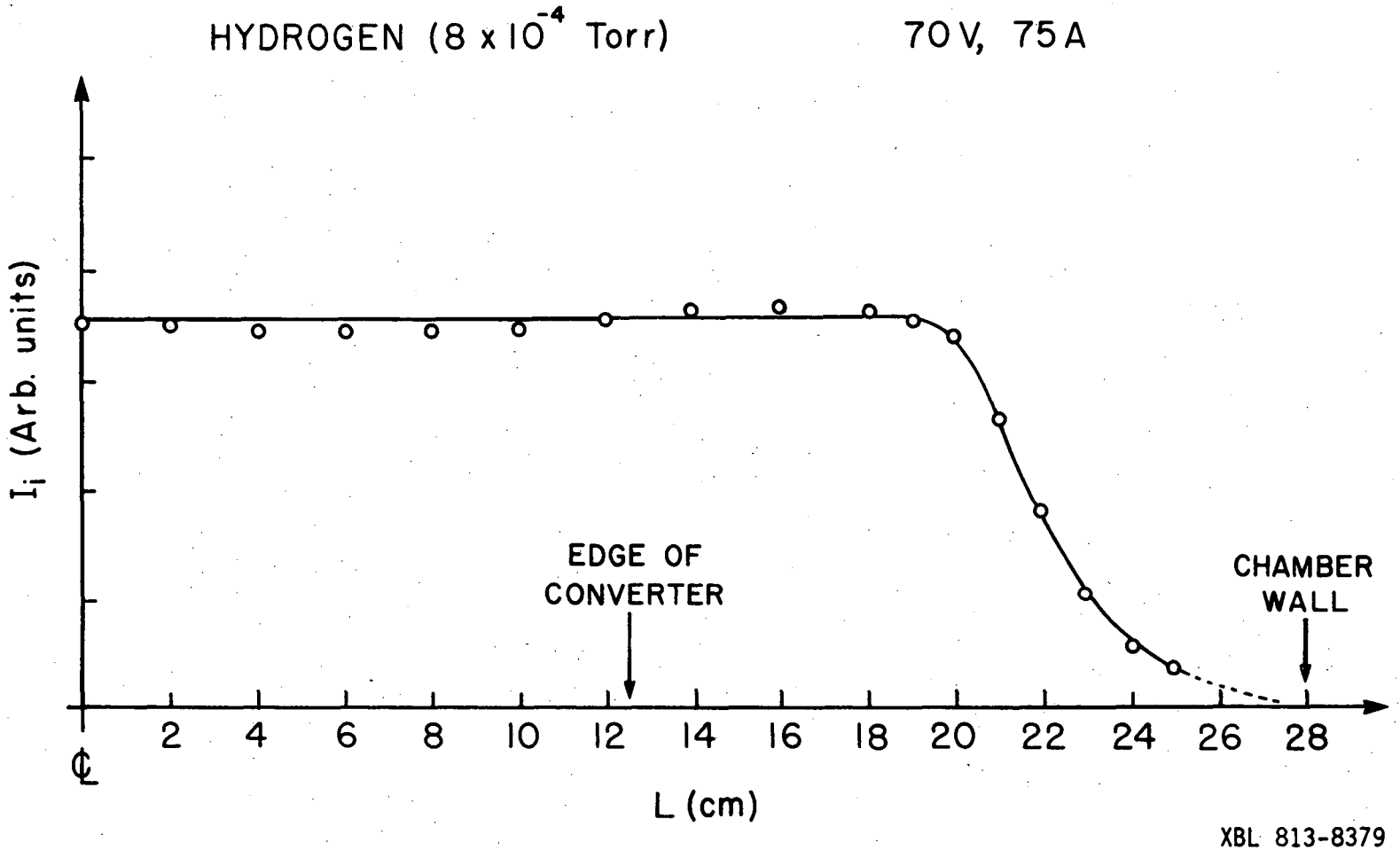
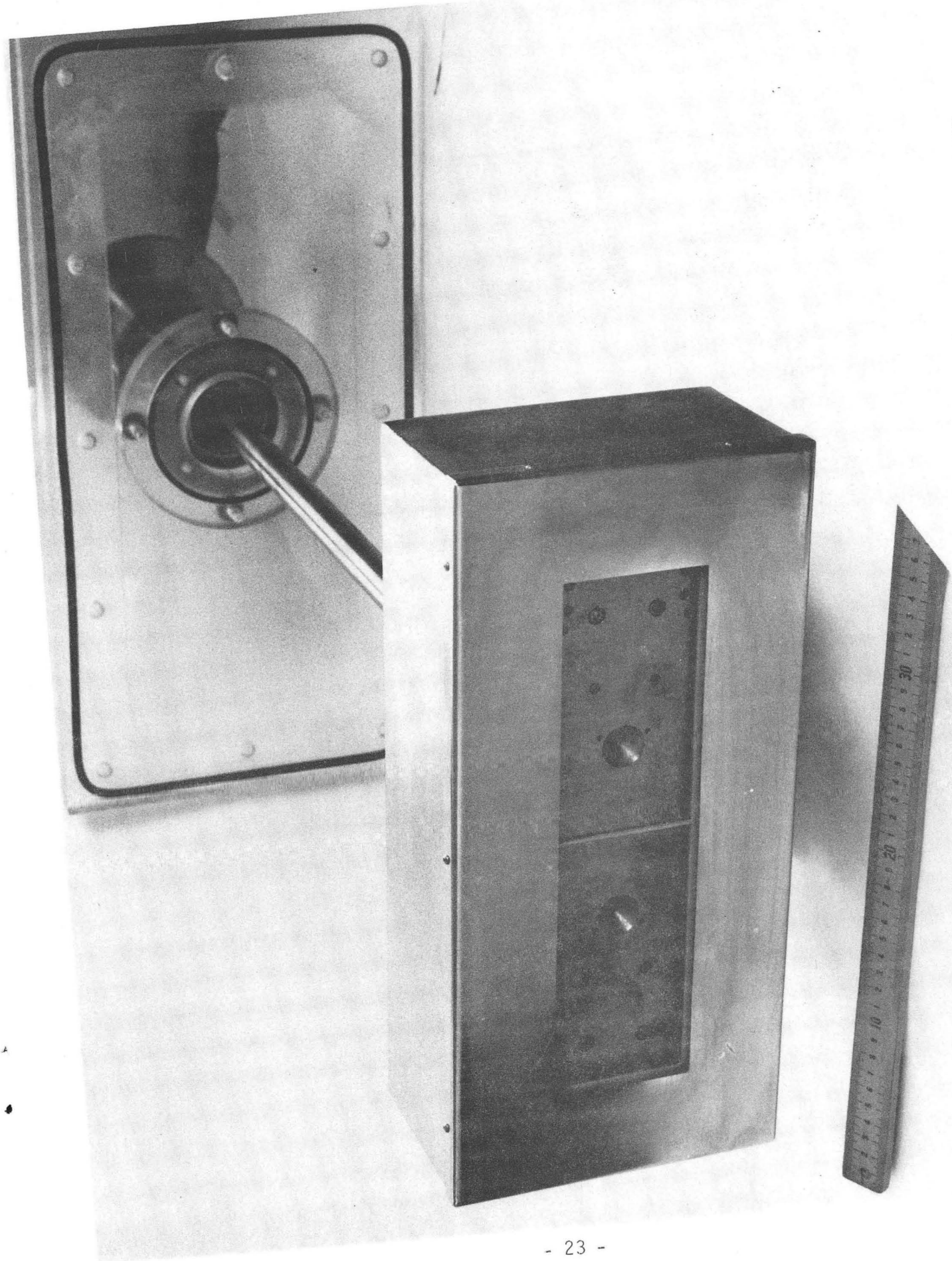

HYDROGEN (8 x 10^-4 Torr)
70 V, 75 A
I_i (Arb. units)
EDGE OF CONVERTER
CHAMBER WALL
2
4
6
8
10
12
14
16
18
20
22
24
26
28
℄
L (cm)
XBL 813-8379

Figure 6



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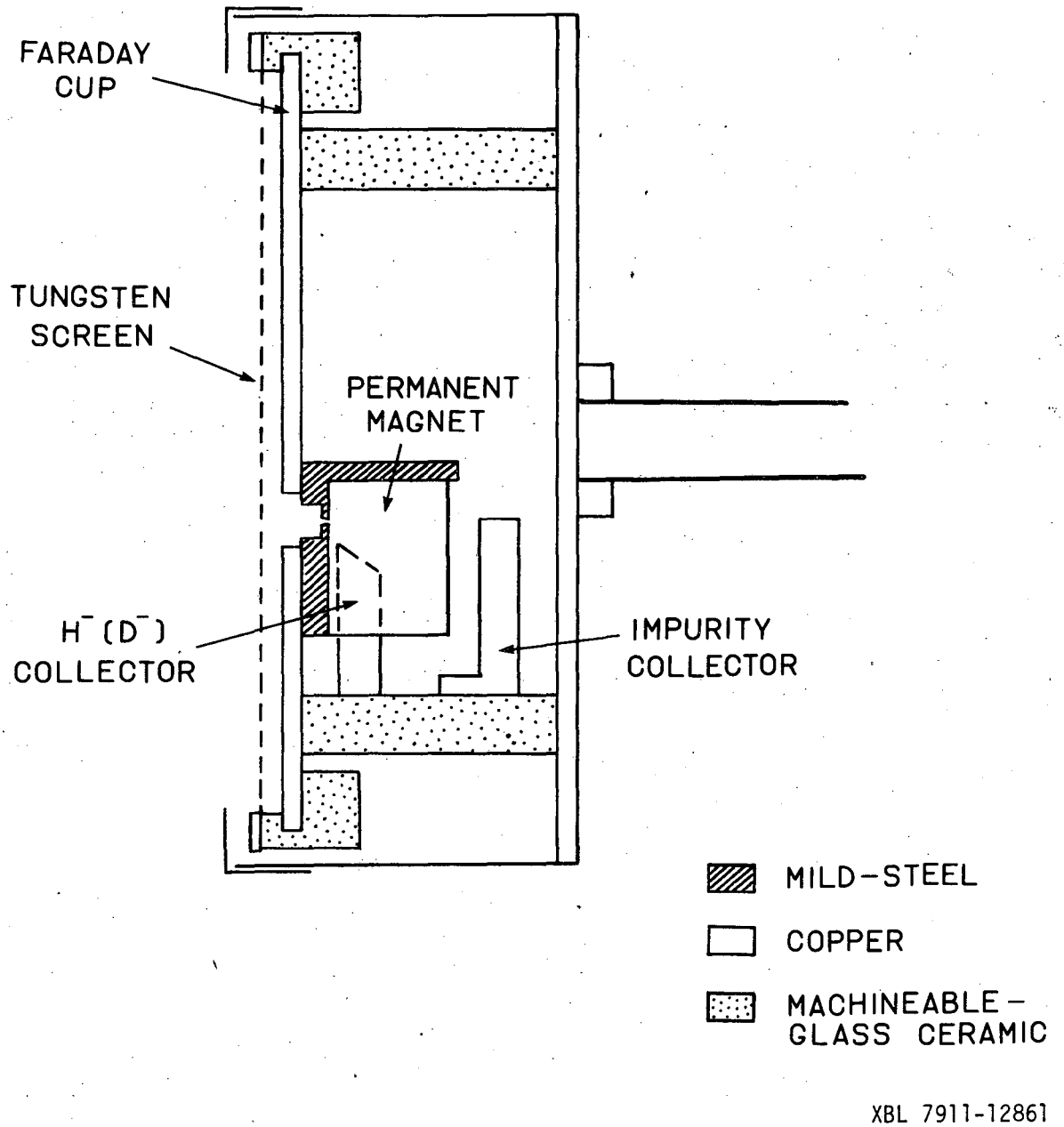
FARADAY CUP
TUNGSTEN SCREEN
PERMANENT MAGNET
H⁻ (D⁻) COLLECTOR
IMPURITY COLLECTOR
MILD-STEEL
COPPER
MACHINEABLE-GLASS CERAMIC
XBL 7911-12861

Figure 8

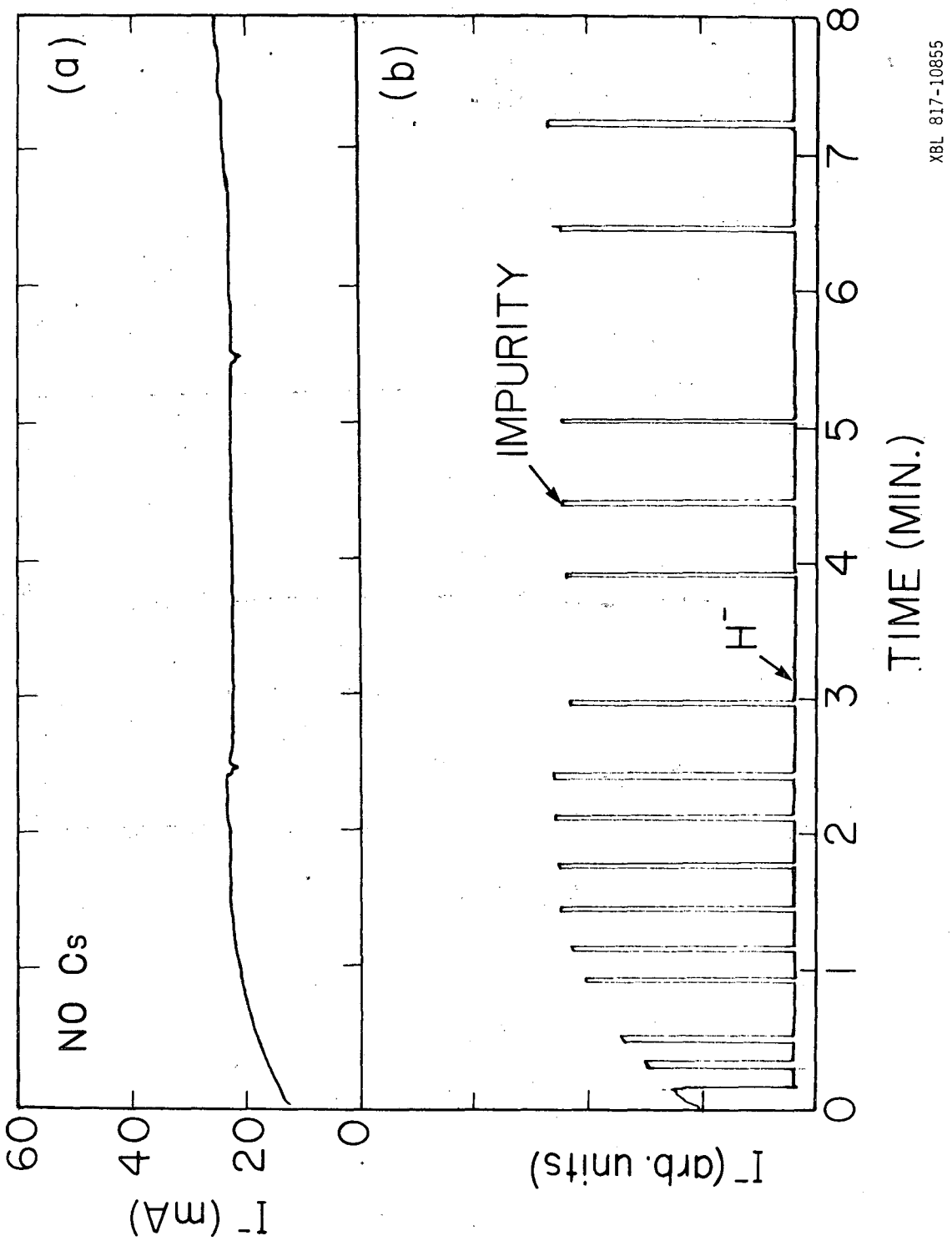
(a)
NO Cs
I⁻ (mA)
60
40
20
0
(b)
IMPURITY
H⁻
I⁻ (arb. units)
0
1
2
3
4
5
6
7
8
TIME (MIN.)
XBL 817-10855

Figure 9

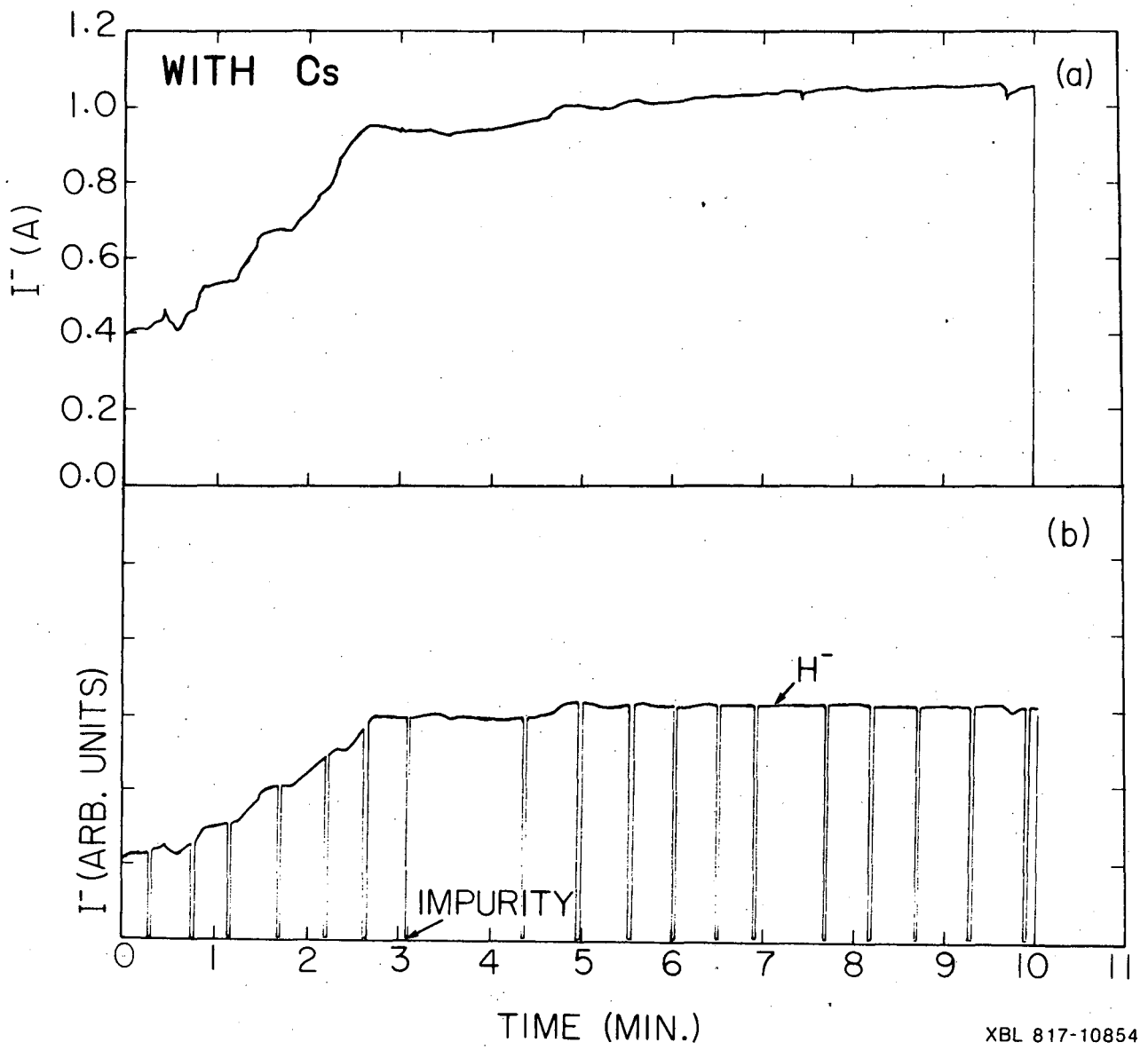

Figure 10

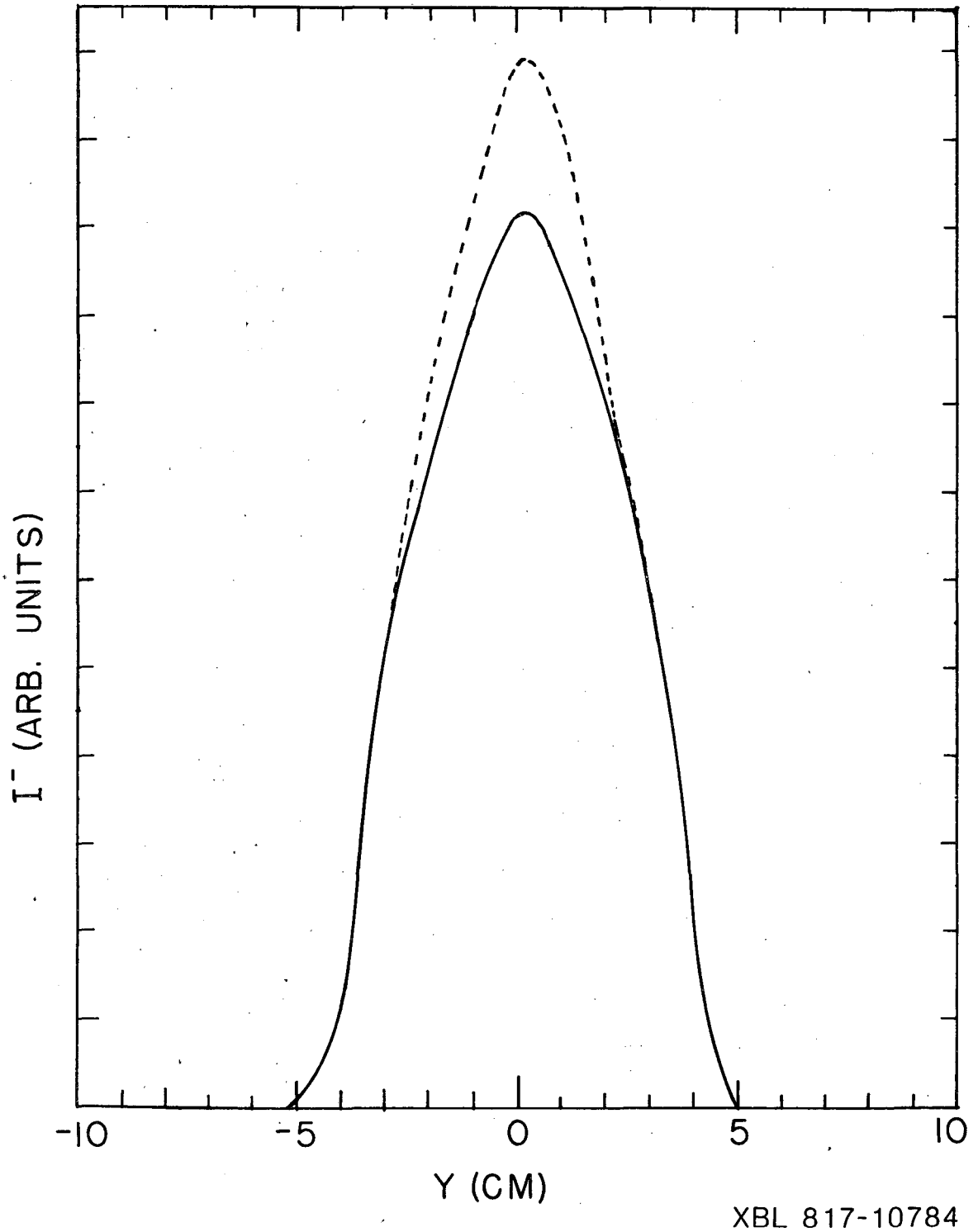

Figure 11

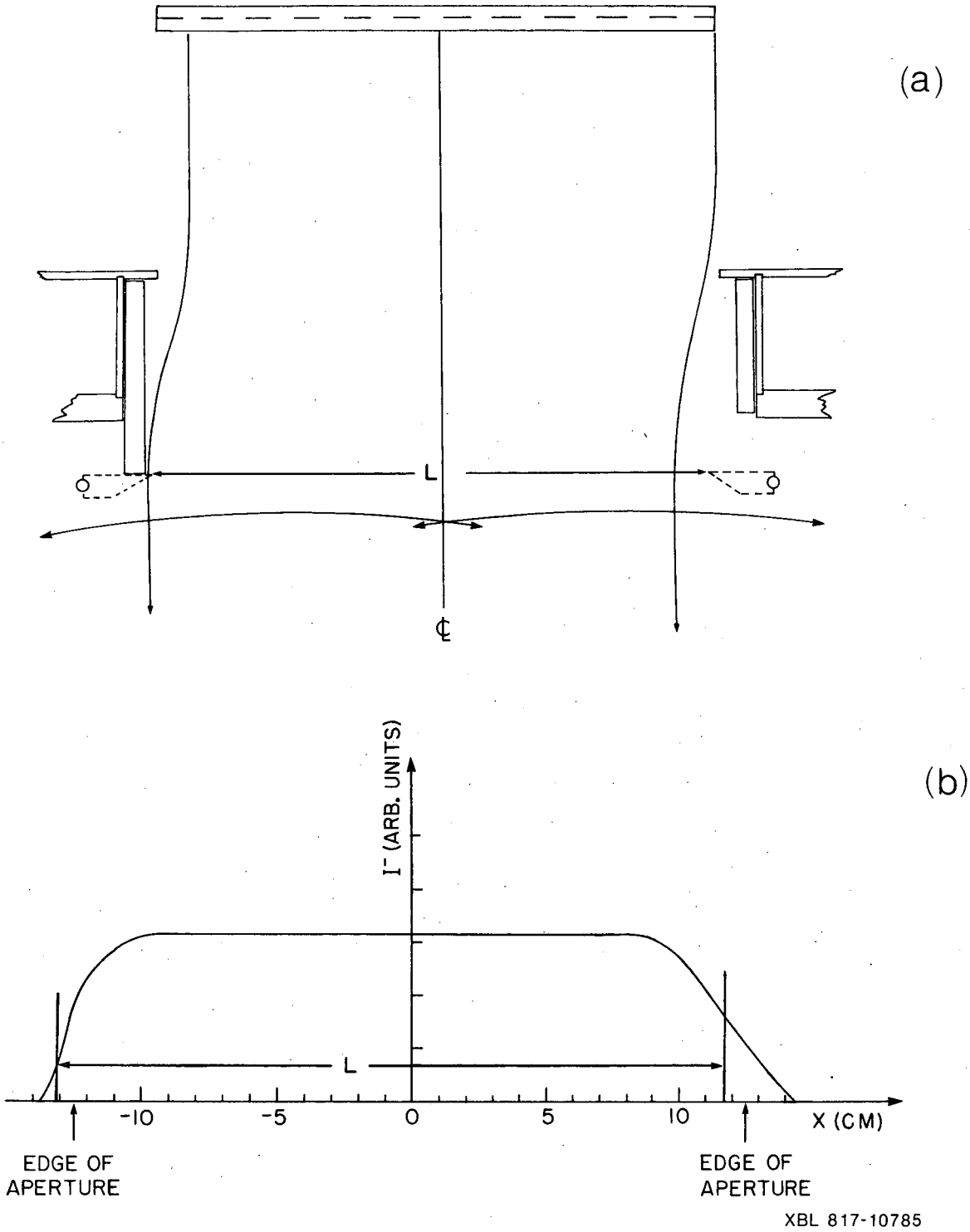
(a)
L
℄
(b)
I⁻ (ARB. UNITS)
L
-10
-5
0
5
10
X (CM)
EDGE OF
APERTURE
EDGE OF
APERTURE
XBL 817-10785

Figure 12

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