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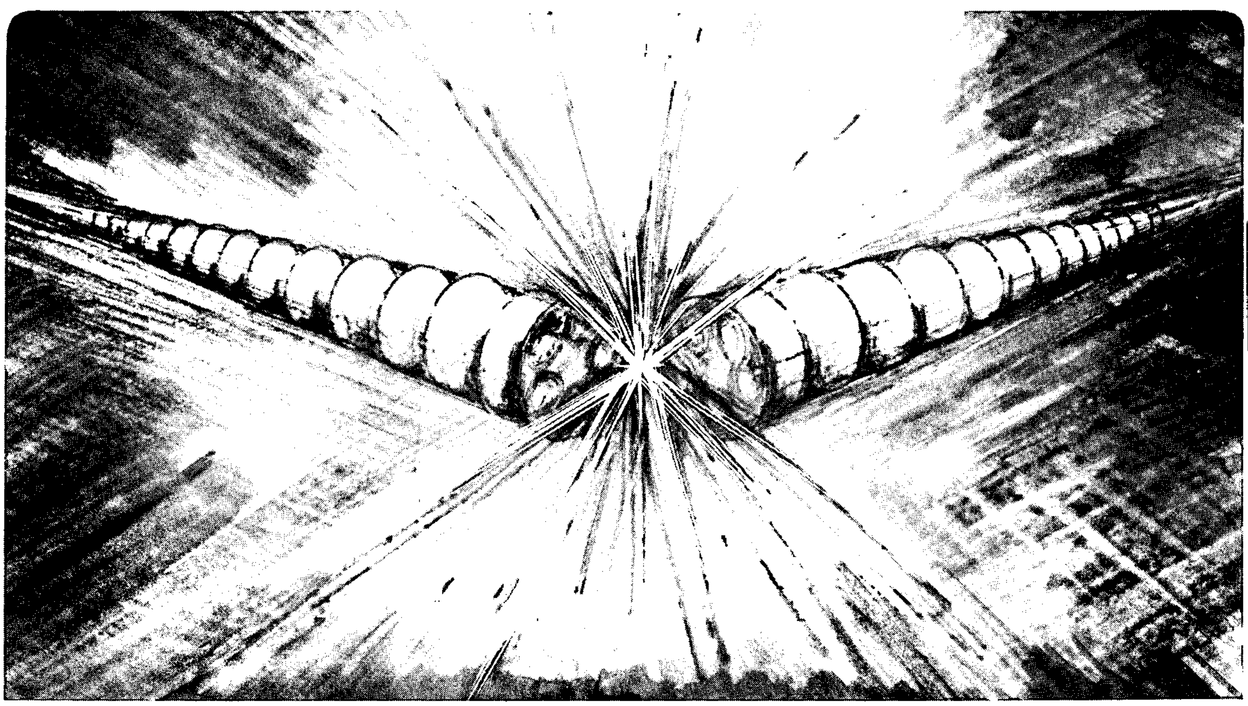

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Electron Suppression Experiments in a Small Multicusp H^- Source*

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Abstract

Several techniques for suppressing the electrons before they form part of the extracted beam have been studied in a small multicusp H^- source. It is found that some schemes reduce both the electron and the H^- output currents. Other approaches, such as the installation of a collar at the extraction aperture, the addition of xenon or cesium to the hydrogen discharge, or the reduction of the source plasma potential, not only can reduce the electron current substantially, but bring about an enhancement in the extracted H^- current.

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Introduction

A small 7.5-cm-diam multicusp source has been developed to generate volume-produced H^- beams.[1,2] At high discharge power, this source is capable of producing H^- current densities higher than 250 mA/cm^2. However, the ratio of electron to H^- ions in the extracted beam is large and is usually greater than 100. The extracted electrons are normally deflected by a magnetic field and are captured on one of the accelerator electrodes at relatively low energy before they arrive at ground potential. If the e/H^- ratio is large, the power dissipated by these electrons on the electrode will become too high for long pulse or steady-state beam operations.

In this article, we discuss various methods of reducing the electron content in the accelerated beam of the small multicusp source. It is found that a positive bias on the plasma electrode or the use of a multi-aperture insert at the exit hole can reduce both the electron and the H^- currents. Other approaches, such as the installation of a collar structure at the extraction aperture, the addition of xenon or cesium to the hydrogen discharge, or the reduction of the source plasma potential, not only can reduce the electron current substantially, but bring about a significant enhancement in the extracted H^- current.

I. Experimental Setup

The experimental investigation was performed in a small (7.5-cm-diam by 8-cm-long) multicusp source shown schematiclly in

Fig. 1. A detailed design of this source has already been described in previous articles (Ref. 1 and 2). The hydrogen plasma was generated by primary electrons emitted from a tungsten cathode located at the center of the source chamber. The entire chamber wall, together with the filter rods, served as the anode for the discharge. Depending on the discharge power, the source could be operated either in steady-state or in pulsed modes.

When cesium was used in the hydrogen discharge, a thin molybdenum liner was installed against the inner walls of the source chamber and around the filter rods. The liner maintained a high temperature due to radiation from the filament and discharge heating by the plasma. As a result, cesium could recycle inside the source chamber and continuous addition of cesium vapor could be minimized.

In this experiment, the maximum extraction voltage used was ~18 kV. Electrons in the accelerated beam were separated from the H^- ions by a permanent-magnet mass analyzer. The magnetic field of the analyzer was strong enough to deflect the electrons, which were then collected on the grooved graphite plates. The accelerated H^- ions were slightly deflected and were then detected by a graphite Faraday cup which was biased slightly positive relative to ground potential for suppression of secondary electron emission. At low discharge power, plasma parameters (such as plasma density and potential and electron temperature) were obtained by a small planar Langmuir probe located near the center of the source.

II. Experimental Results

A. Effect of a Positive Bias Potential on the Plasma Electrode

When H^- ions were extracted from a large 24-cm-diam multicusp source[3], it was found that the electron output current could be reduced substantially if the first accelerator or plasma electrode was biased at a potential more positive than the anode walls. If this bias potential was properly optimized, the H^- current could be enhanced or remained unchanged. Thus, the ratio of e/H^- in the extracted beam was reduced.

The ratio of the extracted electron to H^- current is much higher in this small source than the large multicusp source. For high discharge power, this ratio typically exceeds 100. Attempts have been made to reduce the e/H^- ratio by biasing the plasma electrode positive with respect to the source anode. This technique is found to be effective only at low discharge currents. At high discharge currents (> 100 A), however, a positive bias voltage applied on the plasma electrode always results in a reduction in <u>both</u> the extracted electron and H^- currents.

Figure 2 shows a plot of the extracted H^- and electron currents as a function of the plasma electrode bias voltage V_b when the source is operated at 150 V, 220 A discharge. In this measurement, a single 1-mm-diam aperture is used for extraction. With $V_b = 0$, the e/H^- ratio is approximately 160. As V_b increases, both H^- and electron currents drop. In the range $0 < V_b < 10$ V, the electron current decreases faster than the H^- current. As a result, the e/H^- ratio is reduced to 90 at $V_b = 10$ V. However, the H^- output current at this bias voltage is now only about half of its value at $V_b = 0$.

B. Effect of a Multi-Small-Aperture Extraction Geometry

The scaling of H^- ion current as a function of extraction area is of great interest. In the small multicusp source, it has been observed that as the extraction aperture size increases, the noise level of the accelerated H^- beam becomes very large. The cause of this beam fluctuation is not understood. Presumably, it is related to the stability of the plasma sheath at the extraction surface.

Large beam oscillations should be avoided because they can generate emittance growth[4]. Experimental investigation shows that the use of a multi-small-aperture geometry at the extraction hole can greatly improve the quiescence of the H^- beam. This multi-aperture arrangement can be easily applied to the plasma electrode by the use of removable inserts[2].

Several multi-aperture configurations have been tested. In addition to beam fluctuation, it is found that the H^- and electron output currents are also affected by the multi-aperture geometry. The dependence of the extractable H^- and electron current on the discharge current for three different aperture geometries is illustrated in Figs. 3 and 4. In this study, three plasma electrode inserts were employed; one contained a single 3.2-mm-diam aperture, the other two contained respectively 7 apertures (each of 1.02-mm-diam) and 19 apertures (each of 0.57-mm-diam) inside a 3.2-mm-diam circle. Since the thickness of these three inserts are the same, the over-all transparency as well as the aspect ratio of the aperture are different for these three geometries.

The data in Figs. 3 and 4 shows that both the H^- and electron current decreases as the number of apertures within a 3.2-mm-diam circle increases. However, in the case of 19-aperture insert, the electron current decreases faster than the H^- current. For a discharge current of 300 A, the reduction of electron current from a single to 19-apertures is 60% while the corresponding H^- current decreases by only 30%. As a result, the e/H^- ratio of the extracted beam is reduced.

Since a weak magnetic field (~ 50 G) exists in the extraction aperture, electrons will be deflected as they are accelerated out of the ion source. Some of the electrons will be captured by the aperture wall before they leave the plasma electrode. The deeper the aperture channel, the more electrons will be captured before they escape and form part of the extracted beam. The reduction in H^- current from a single to 19 apertures, is primarily due to the decrease in the overall transparency of the exit aperture.

C. Effect of a Collar Electrode at the extraction Aperture

It has been demonstrated that H^- ions in a pure hydrogen discharge are produced in the plasma volume via collisional processes between electrons and hydrogen molecules or between electrons and molecular ions.[5,6] All these processes require the presence of relatively low energy electrons. In order to enhance H^- ion production, a large quantity of these electrons are needed in the regions where the H^- ions are formed. Previous investigations have shown that the extracted H^- ions are mainly generated in the filter region and the extraction chamber[7]. The fact that the e/H^- ratio is larger than 100 indicates that there is an excess of electrons in the extraction region for the small multicusp source.

Low energy electrons can reach the extraction region by crossing the magnetic field with positive ions. These electrons can be suppressed by applying a positive bias on the plasma electrode. This will inhibit the flow of positive ions to the extraction area which in turn will reduce the electrons. (This technique has been described in Sec. A). There are also electrons trapped on the field lines between the filter rods. An effective way of reducing the trapped electrons is by installing a collar electrode around the extraction aperture. A similar arrangement has been found successful by others in suppressing electrons in a large H^- source.[8]

Figure 1 is a schematic diagram showing the collar arrangement in the small source. The cylindrical collar is fabricated from stainless-steel. Collars with different lengths and diameter have been tested for an extraction aperture of 5-mm-diam. Figure 5 is a plot of H^- output as a function of discharge current for different collar lengths but with a constant diameter of 11.6 mm. For comparison, the H^- current obtained with no collar is also presented. For the range of discharge current considered, collars with lengths of 3, 6 and 9 mm produce about the same H^- output as in the case of no collar. When the collar length exceeds 12 mm, the H^- output current drops. On the other hand, the extracted electron current decreases linearly with collar length as illustrated in Fig. 6. In order to optimize the H^- output and the e/H^- ratio, the results shown in Figs. 5 and 6 suggest that the source should be operated with a 9-mm-long collar. In this collar configuration, the electron current is reduced by a factor of two compared with the case of no collar and with no degradation in H^- current.

The dependence of extracted H^- and electron current as a function of discharge current for three collar diameters are shown in Figs. 7 and 8. In this study, the length of the collar was maintained at 9 mm. The results indicate that the H^- output is about the same for collars of 11.6 and 15.1 mm in diameter. However, the H^- current drops when the collar diameter is reduced to 8.5 mm. The extracted electron current, on the other hand, decreases with the diameter of the collar. Thus, for a 5.4-mm-diam extraction aperture and a 9-mm-long collar, the optimum diameter of the collar is about 11.6 mm.

D. <u>Effect of Mixing Xenon with Hydrogen in the Discharge</u>

The effect on H^- production when the small multicusp source was operated with a mixture of hydrogen and xenon had previously been studied in pulsed high power discharges[2]. The result can be summarized as follows. When the source was operated below the optimum hydrogen pressure and, therefore, with lower H^- output, two effects were observed when a small amount of xenon (14% of total pressure) was added to the hydrogen discharge. First, the H^- output could be optimized by applying a positive bias voltage of several volts on the plasma electrode, resulting in a 36% increase of H^- current than the case of pure hydrogen operation. Second, the electron current was reduced by a factor of 6 at the optimum plasma electrode bias. Consequently, the e/H^- ratio was reduced by a factor of 8.

When the source was operated near optimum pressure, adding xenon did not improve the H^- output current. At the optimum bias voltage, Fig. 11 in Ref. 2 shows that the H^- output is about the same as before xenon was added to the discharge. However, the extracted electron current, and therefore the e/H^- ratio, is suppressed by more than a factor of 4.

Adding xenon to the hydrogen discharge can modify the plasma parameters substantially. Since xenon is easy to ionize, the background electron density and temperature are higher for the same discharge power. As a result, more vibrationally excited $H_2(v'')$ can be formed which in turn can enhance H^- production[5]. Because xenon ions are massive, they can penetrate the filter much easier than hydrogen ions[9]. A positive bias on the plasma electrode will eliminate a large fraction of electrons near the extraction aperture. However, the amount of cold electrons in the filter region can still be higher than in the case of pure hydrogen discharge operated with no plasma electrode bias[9]. Thus, the number of H^- ions arriving at the exit aperture can be the same or higher, even though the electron output current is reduced by a factor of 4.

E. Effect of Adding Cesium to a Hydrogen Discharge

Surprisingly, recent experimental findings show that the H^- yield from a filter-equipped multicusp source can be increased substantially if the hydrogen discharge is seeded with cesium[10]. As a result, H^- beams with current densities exceeding 1 A/cm^2 can now be easily obtained from the small multicusp source when cesium is introduced into the hydrogen discharge[2].

We have studied several multi-aperture geometries with cesium added to the discharge. In each case, the same H^- current enhancement was observed[2]. More important, it was also found that the extracted electron current decreased as more cesium was added[2]. An oscilloscope picture illustrating the effect of cesium on the H^- and electron current is shown in Fig. 9. When sufficient cesium is introduced into the discharge, the H^- current is improved by about a factor of 4, while the electron signal is reduced by a factor of 2. Hence, the e/H^- ratio is reduced by a factor of 8 for the same discharge power.

Figure 10 is a graph of the e/H^- ratio versus discharge current for the seven-aperture insert. Source operation with pure hydrogen produced a high e/H^- ratio that increased with discharge current. Addition of cesium to the discharge, however, reduced the ratio from 120 to 30 at high discharge power. If a 9-mm-long collar was used at the extraction aperture in addition to cesium, the ratio was further reduced to approximately 10.

It has been demonstrated that surface-generated H^- ions are responsible for the large enhancement (> a factor of 5) of the H^- output current when cesium is added to the hydrogen discharge[6]. The reduction in the e/H^- ratio, however, is not well understood. It may be closely related to the change in plasma potential inside the source. A more detailed discussion about this effect is presented in Sec. G.

F. <u>Effect of Optimizing the Filter Rod Separation</u>

The small multicusp source is equipped with a pair of movable, water-cooled filter rods. The strength of the magnetic field can be changed by adjusting the filter rod separation. The dependence of the H^- and electron current on the filter rod separation d for a constant discharge power of 150 V, 120 A has been reported in Ref. 2. It was found that an optimum filter separation (~ 5.7 cm) exists for the H^- current. However, the extracted electron current increases monotonically with the filter separation. There is no optimum filter separation for the electron current because the weaker the filter field, the higher will be the electron density and temperature in the extraction region.

Figure 11 shows the e/H^- ratio as a function of rod separation for discharge currents of 120 and 300 A. The discharge voltage was maintained at 160 V and the size of the extraction aperture used in this study was 2.26 mm diameter. As d is reduced from 6 to 3 cm, the e/H^- ratio is 50 and 100 for discharge current of 120 and 300 A respectively. The H^- current, on the other hand, decreases by about 24% from its optimum value for the case of the 300 A discharge.

When the source is operated with an admixture of cesium in hydrogen, the dependence of the extracted electron current on the filter separation is similar to the case of a pure hydrogen plasma. However, no optimum filter separation has been observed for the H^- current. The larger the filter separation, the higher is the extractable H^- current.

A plot of the e/H^- ratio as a function of filter separation for a discharge power of 160 V, 300 A is shown in Fig. 12. Indeed, the e/H^- ratio is much reduced with the addition of cesium to the source discharge (see Sec. E). As the filter separation is varied from 6 to 3 cm, the ratio is reduced further from 20 to 3 while the H^- current drops by approximately a factor of two.

G. Effect of Reducing the Source Plasma Potential

The flow of positive ions, and hence plasma electrons, to the extraction region can be controlled by changing the potential gradient between the plasma electrode and the source plasma. To accomplish this, one can apply a positive bias on the plasma electrode. (This technique has already been described in Sec. A.) An alternative approach is to modify the plasma potential V_p in the source chamber.

In normal source operation, V_p assumes a value which is several volts more positive than the anode. If V_p can be made less positive, the flow of positive hydrogen ions to the plasma electrode will decrease which in turn will reduce the electron density in the extraction region. It has been demonstrated that a negative plasma potential can be formed in a multicusp ion source by the low-energy electron injection technique.[11] The same scheme can also be employed to suppress the electrons by optimizing the plasma potential.

Figure 13 shows the arrangement of the small source when the low-energy electron injection technique was applied. A steady-state hydrogen plasma was produced by 80 eV primary electrons emitted from one set of tungsten filaments. A second set of tungsten filaments was used to supply additional low energy primary electrons into the source plasma. If the energies of the injected electrons are lower than the ionization energy of the hydrogen gas, then they cannot give rise to ionization process, but they can be confined very efficiently by the multicusp fields. The presence of a large quantity of these low-energy primaries will reduce the plasma potential in the source chamber.

The effect of adding 8 eV primary electrons to a background hydrogen plasma generated by a 80 V, 0.5 A discharge is summarized in Table I. As the discharge current of the second filament set increases to 5.5 A, the plasma potential at the center of the source chamber becomes less positive relative to the anode walls or the plasma electrode. The H^- current increases but the electron current drops. The e/H^- ratio is reduced drastically from 533 to 7. The H^- current increases by about a factor of two which is approximately equal to the increase in the source plasma density.

The results of this investigation suggest that the large improvement in the e/H^- ratio when cesium is added to the hydrogen plasma (see Sec. E) could also be due to a reduction in the plasma potential. In fact, it has been observed that V_p did change from +4 to +1.5 V (relative to the anode) when barium was added to the hydrogen plasma of the small multicusp source.[6] In both cases, a large number of low-energy electrons could be emitted from the anode walls (since they become low work-function surfaces) to the plasma volume, resulting in a drop of V_p.

The above low-energy electron injection experiment was performed in a low-power steady-state discharge. For high-density operation, a large number of filaments would be required to provide the necessary cathode area for space-charge limited emission at low voltages, and thus this method would be difficult to employ. Nevertheless, we have tested the small multicusp source in a pulsed mode by injecting 120 A of ~ 13 eV electrons into a hydrogen plasma generated by a 90 V, 75 A discharge. The extracted electron current was reduced by a factor of 5 with no degradation in the H^- output current. The increase in total discharge power was only 23%.

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References

1. K. N. Leung, K. W. Ehlers, C. A. Hauck, W. B. Kunkel, and A. F. Lietzke, Rev. Sci. Instrum. 59, 453 (1988).
2. K. N. Leung, C. A. Hauck, W. B. Kunkel, and S. R. Walther, Rev. Sci. Instrum. 60, 531 (1989).
3. K. N. Leung, K. W. Ehlers, and M. Bacal, Rev. Sci. Instrum. 54, 56 (1983).
4. P. Allison, IEEE Trans. on Nucl. Sci. Vol. NS-32, No. 5 (1985) p.2556.
5. K. N. Leung and W. B. Kunkel, Phys. Rev. Lett. 59, 787 (1987).
6. K. N. Leung, S. R. Walther, and W. B. Kunkel, Phys. Rev. Lett. 62, 764 (1989).
7. K. N. Leung, K. W. Ehlers, and R. V. Pyle, Rev. Sci. Instrum. 56, 364 (1985).
8. T. S. Green, SPIE Vol. 1061 Microwave and Particle Beam Sources and Directed Energy Concepts (1989) p.628.
9. K. N. Leung and K. W. Ehlers, Rev. Sci. Instrum. 55, 342 (1984).
10. S. R. Walther, K. N. Leung, and W. B. Kunkel, J. Appl. Phys. 64, 3424 (1988).
11. 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 small multicusp ion source equipped with a collar at the extraction aperture.

Fig. 2 The extracted H^- and electron current as a function of plasma electrode bias voltage for a constant discharge current of 220 A.

Fig. 3 H^- output current as a function of discharge current for three different aperture geometries. (The total extraction areas are 8, 5.7, and 4.9 mm^2 for the single, 7 and 19 apertures respectively).

Fig. 4 Extracted electron current as a function of discharge current for three different aperture geometries.

Fig. 5 H^- output current as a function of discharge current for different collar lengths. Diameter of the collar is maintained at 11.6 mm.

Fig. 6 Extracted electron current as a function of discharge current for different collar lengths. Diameter of the collar is maintained at 11.6 mm.

Fig. 7 H^- output current as a function of discharge current for three different collar diameters. Length of the collar is maintained at 9 mm.

Fig. 8 Extracted electron current as a function of discharge current for three different collar diameters. Length of the collar is maintained at 9 mm.

Fig. 9 Oscilloscope traces showing the extracted electron and H^- currents, the discharge current and voltage for (a) a pure hydrogen discharge, and (b) a cesium-hydrogen discharge. (Note: the scale for I_e and I_{H^-} in (a) is 2.5 and 0.4 times that of (b), respectively).

Fig. 10 A plot of the e/H^- ratio as a function of discharge current for three different discharge conditions.

Fig. 11 A plot of the e/H^- ratio vs filter rod separation with the source operating in 120 and 300 A of discharge current.

Fig. 12 A plot of the e/H^- ratio vs filter rod separation when cesium is added to the source.

Fig. 13 A schematic diagram of the ion source when operated with two independent tungsten filament cathodes.

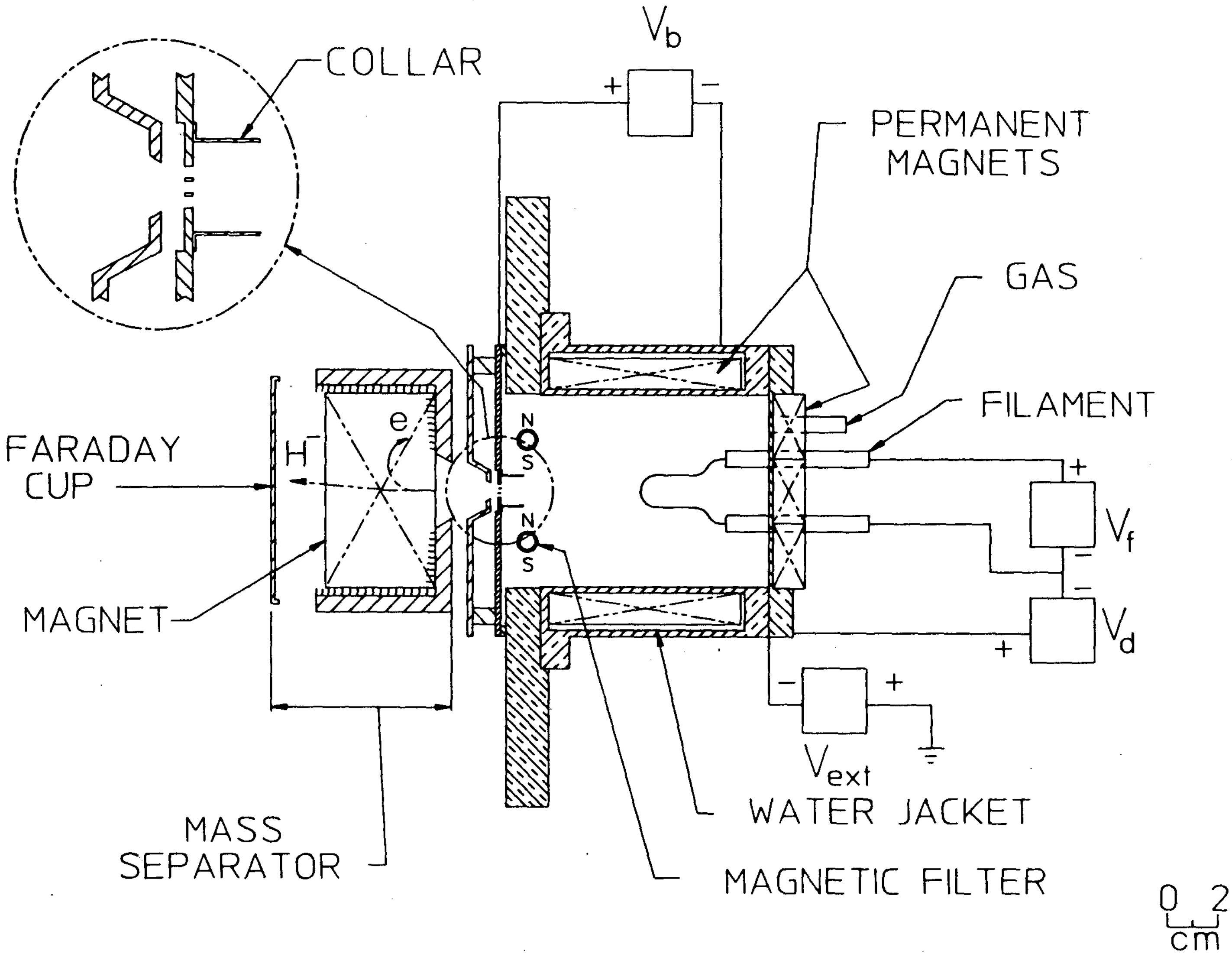

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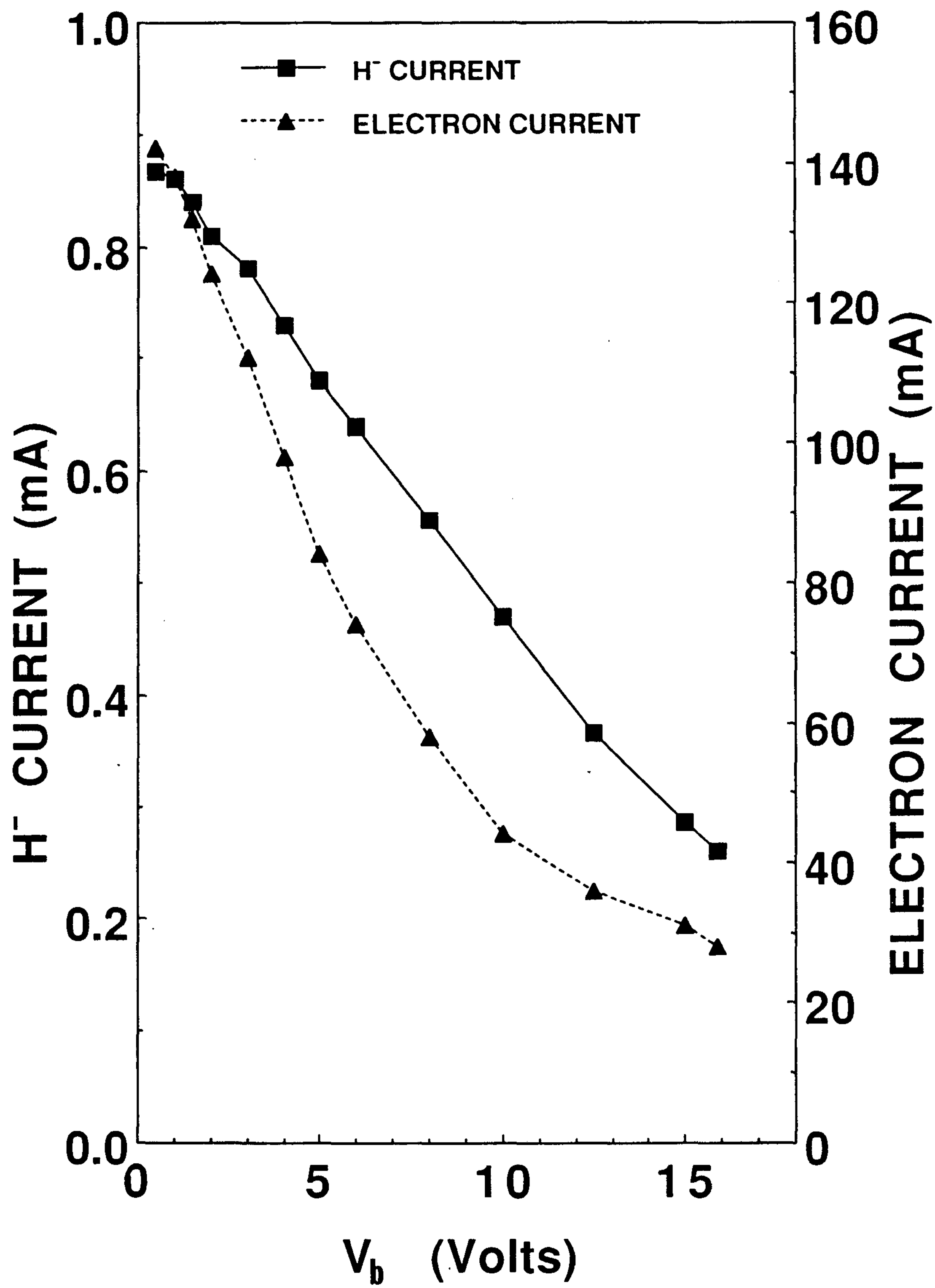
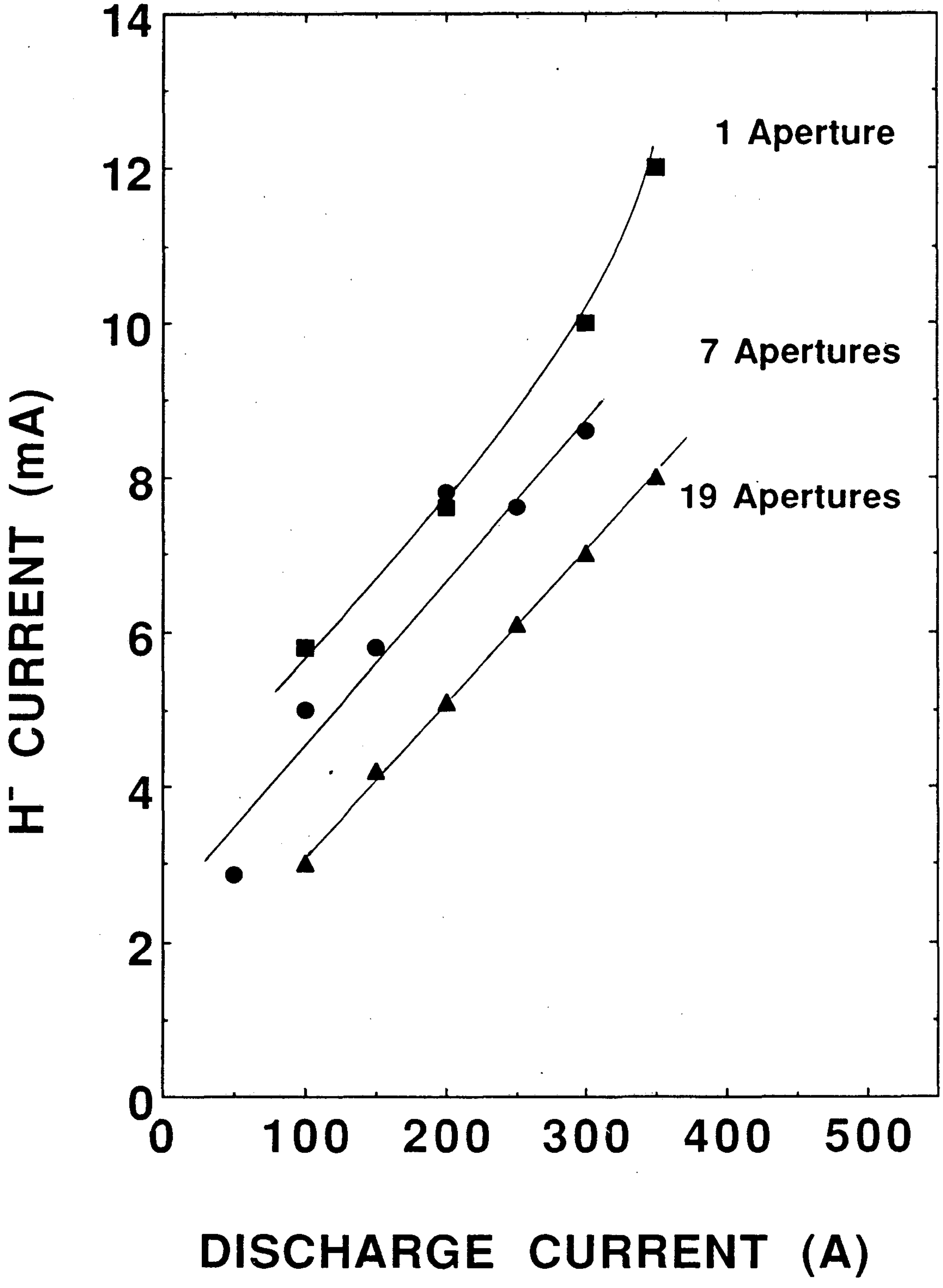
Fig. 1



XBL 896-2452

Fig. 2



XBL 896-2453

Fig. 3

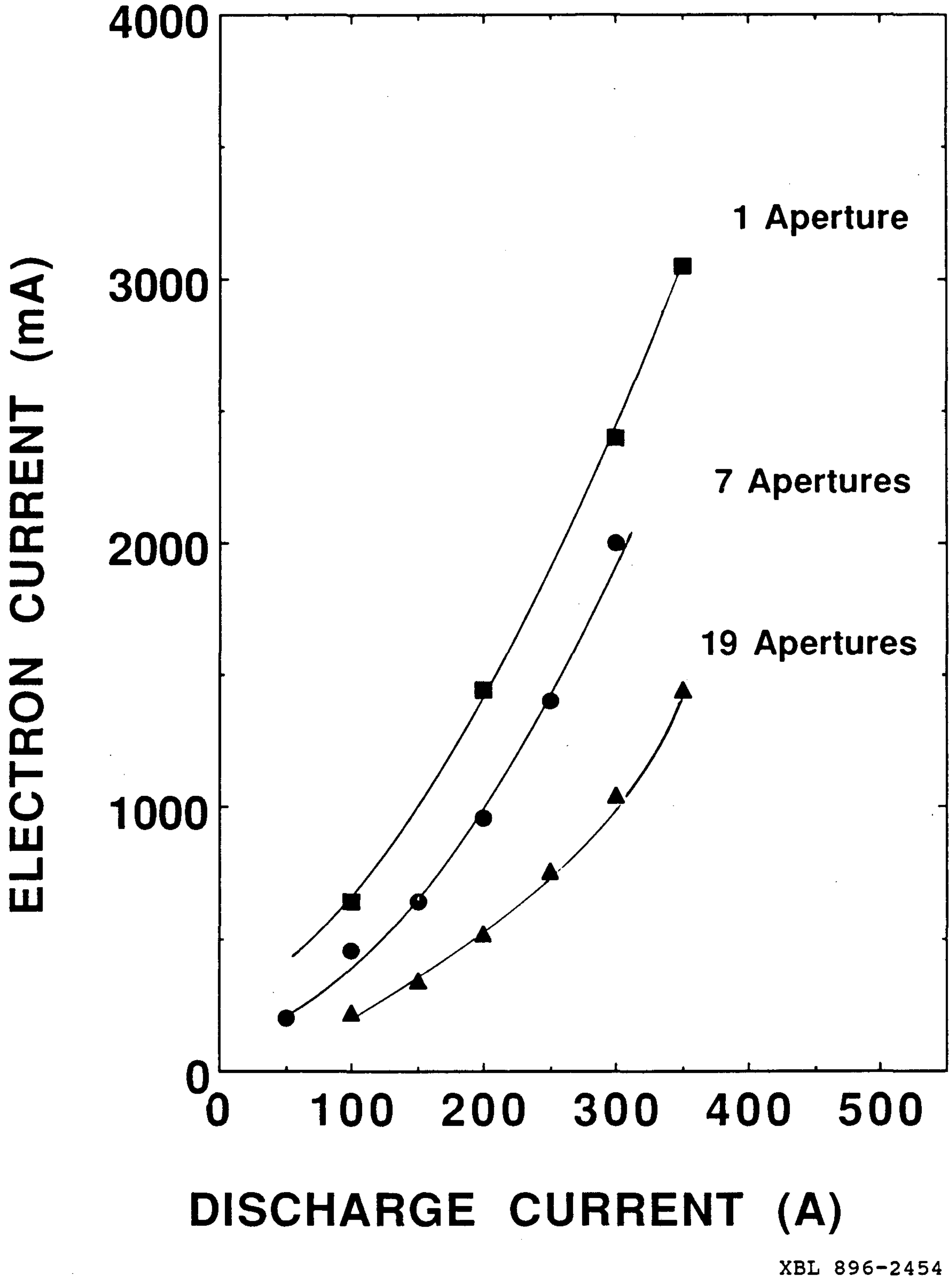

4000
3000
2000
1000
0
0
100
200
300
400
500
ELECTRON CURRENT (mA)
DISCHARGE CURRENT (A)
1 Aperture
7 Apertures
19 Apertures
XBL 896-2454

Fig. 4

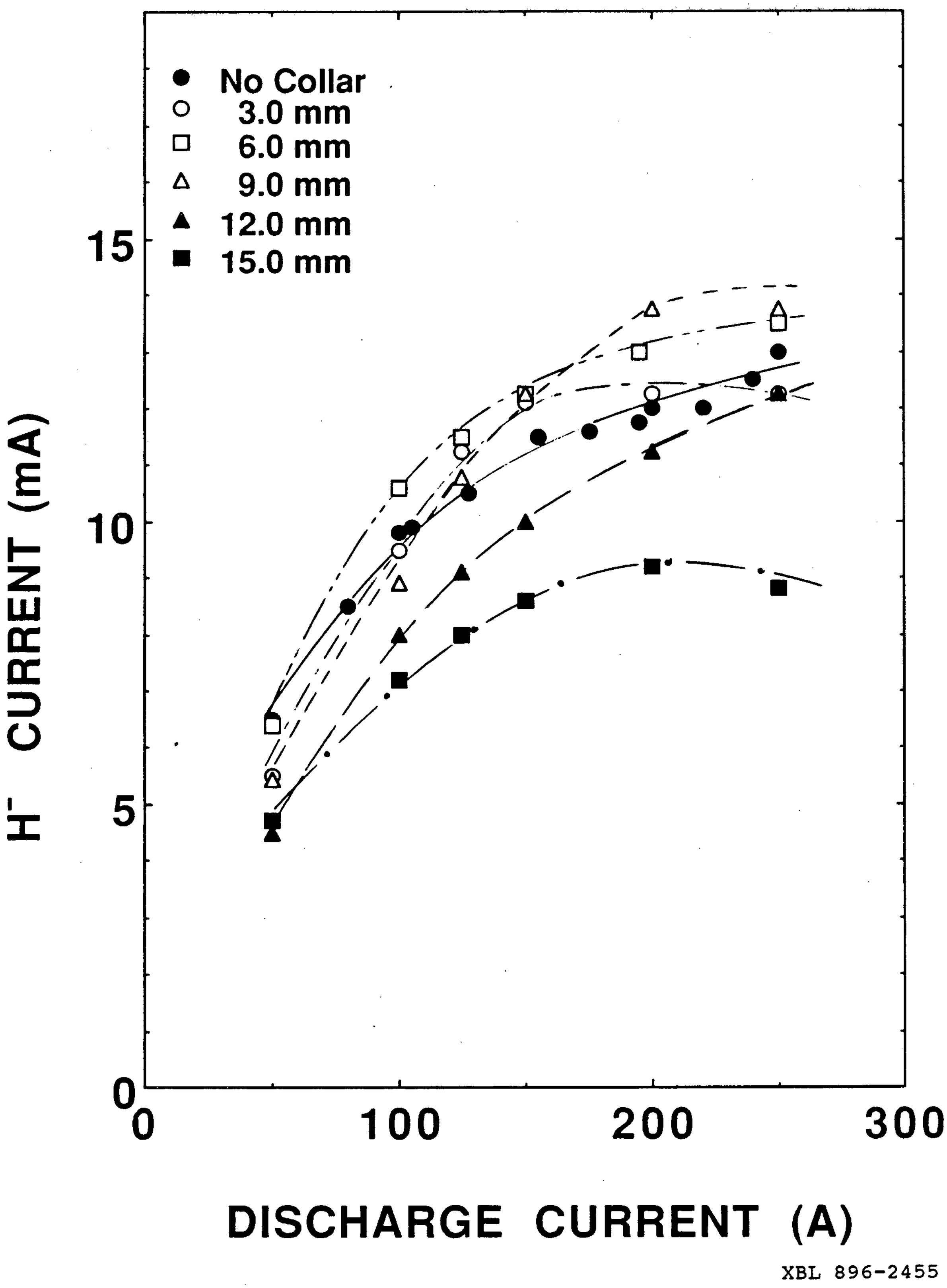
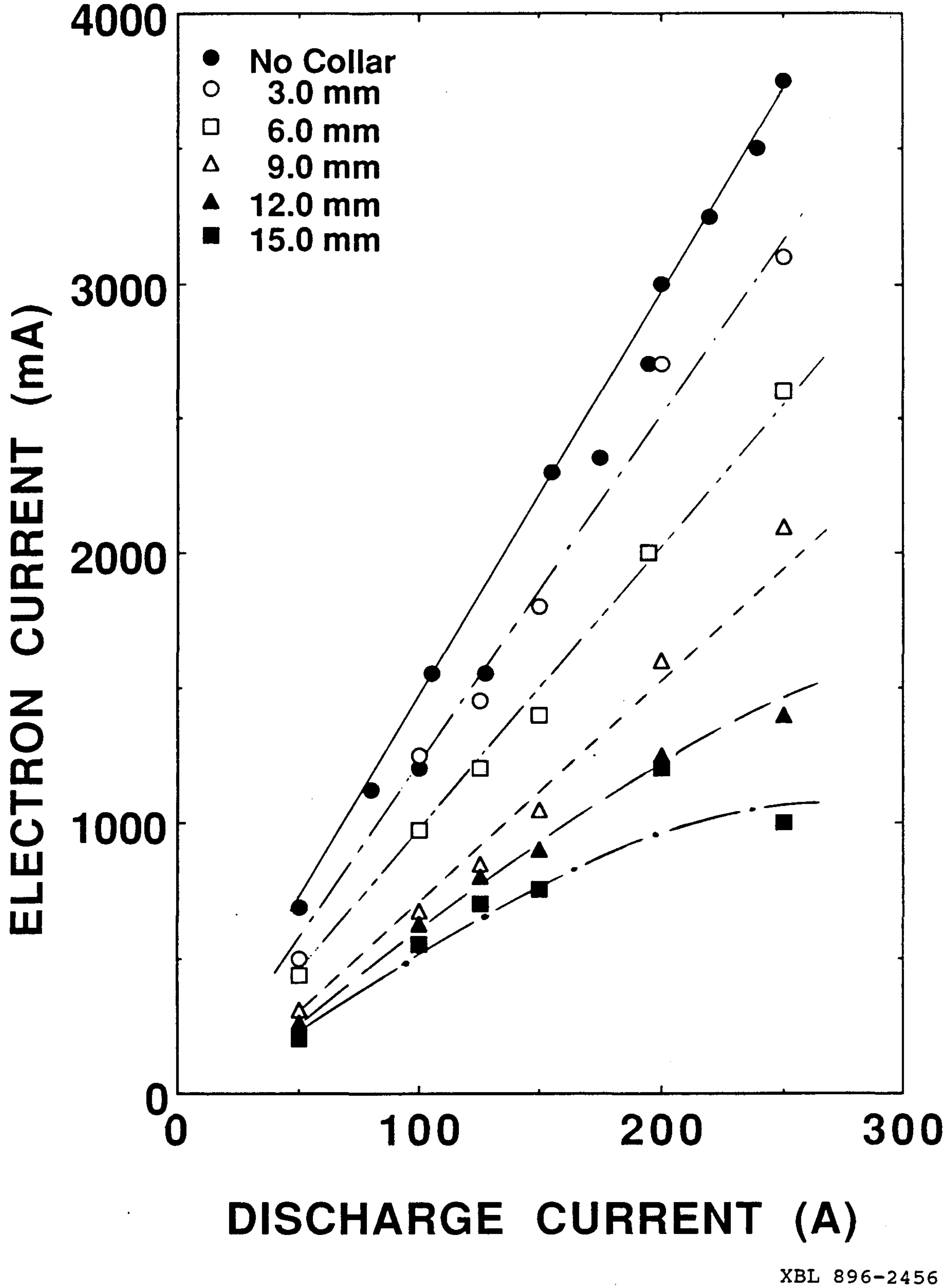
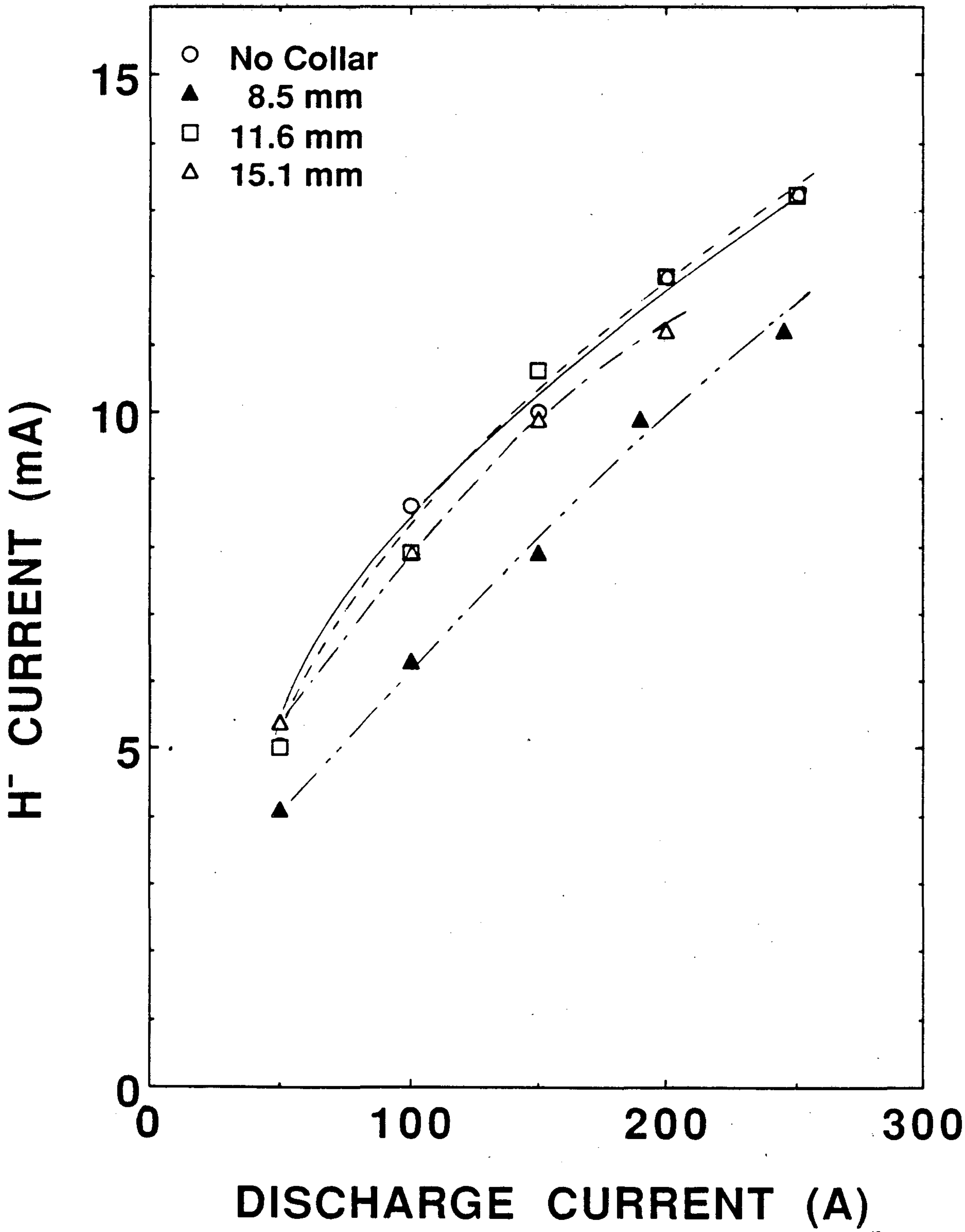

No Collar
3.0 mm
6.0 mm
9.0 mm
12.0 mm
15.0 mm
15
10
5
0
0
100
200
300
H⁻ CURRENT (mA)
DISCHARGE CURRENT (A)
XBL 896-2455

Fig. 5



4000
3000
2000
1000
0
0
100
200
300
No Collar
3.0 mm
6.0 mm
9.0 mm
12.0 mm
15.0 mm
ELECTRON CURRENT (mA)
DISCHARGE CURRENT (A)
XBL 896-2456

Fig. 6



XBL 896-2457

Fig. 7

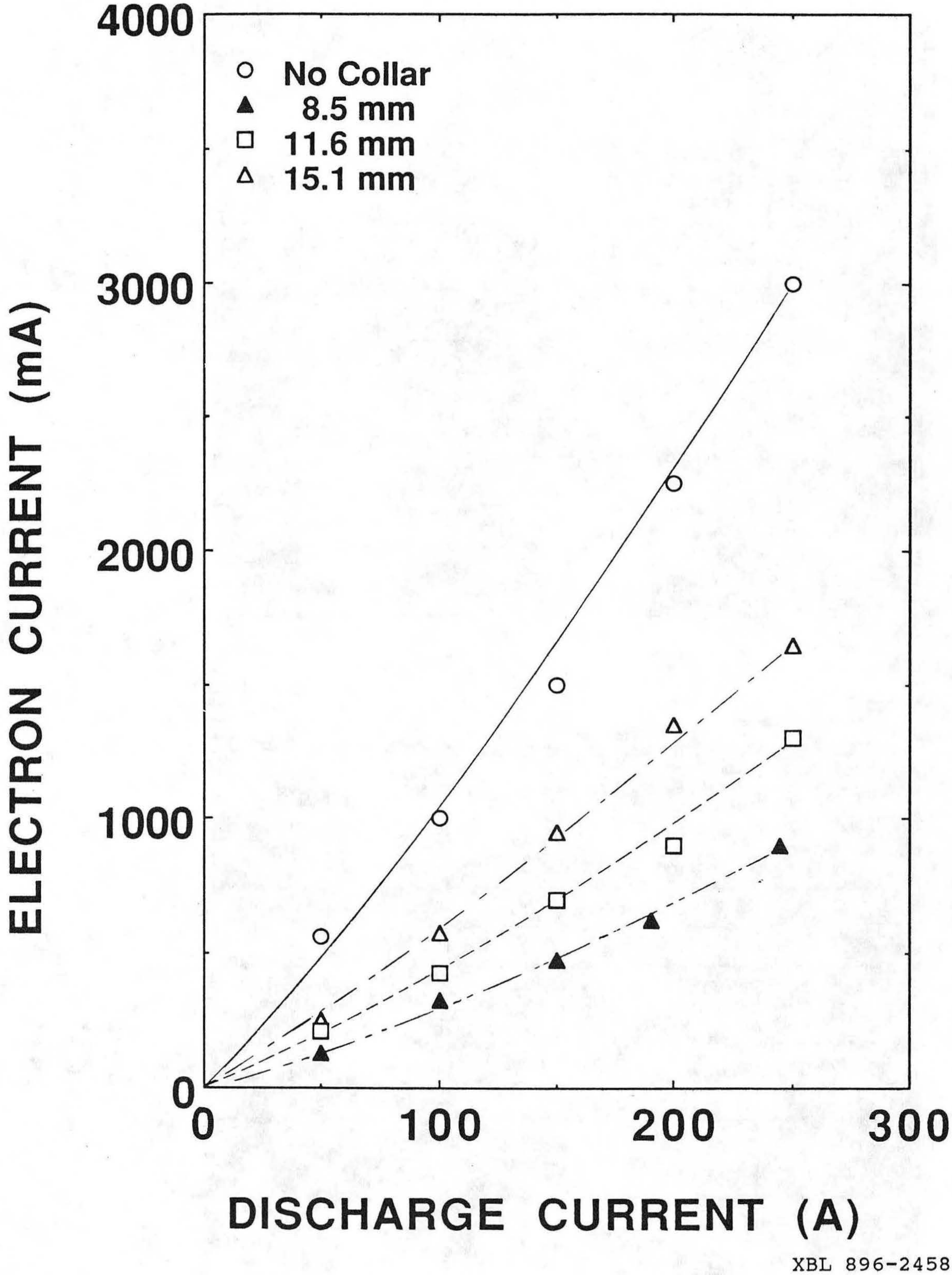
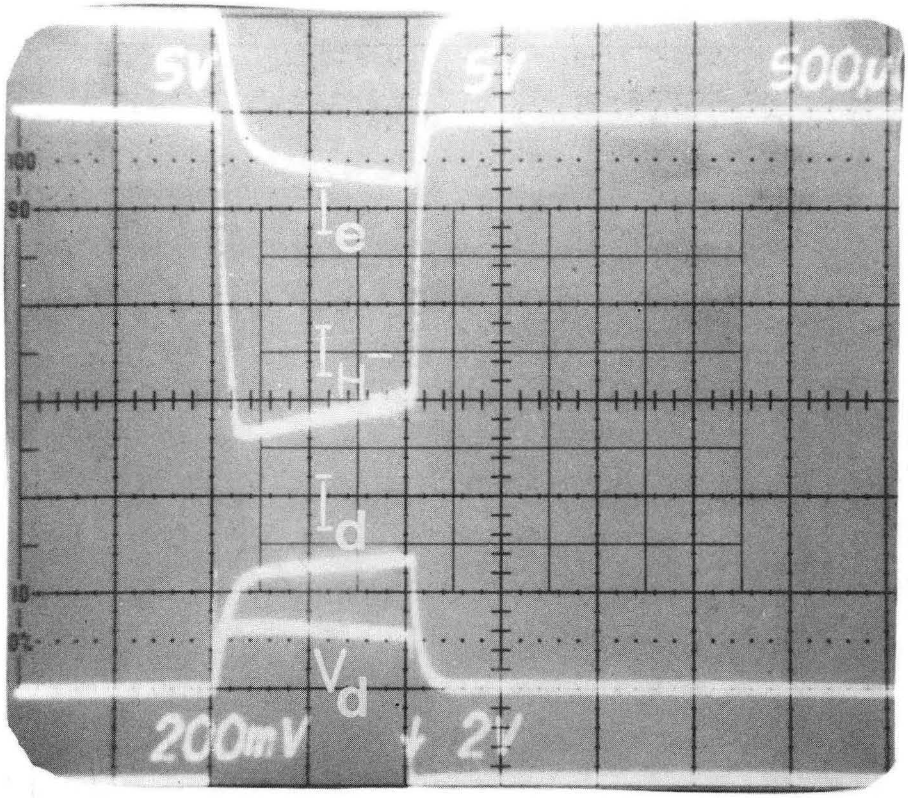
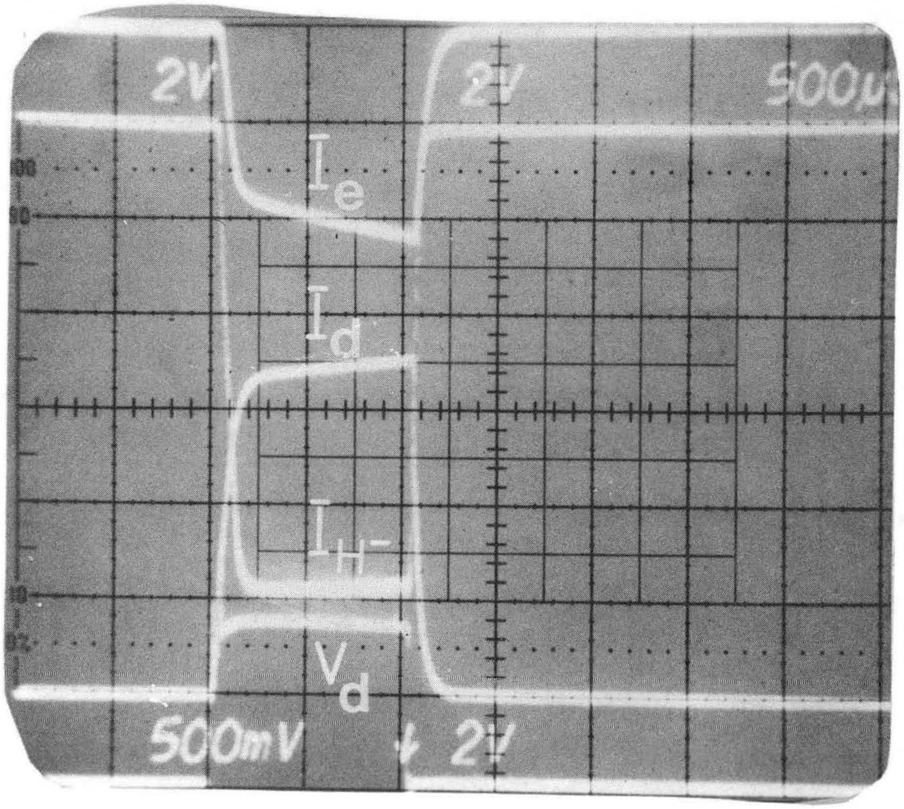

4000
3000
2000
1000
0
No Collar
8.5 mm
11.6 mm
15.1 mm
ELECTRON CURRENT (mA)
0
100
200
300
DISCHARGE CURRENT (A)
XBL 896-2458

Fig. 8

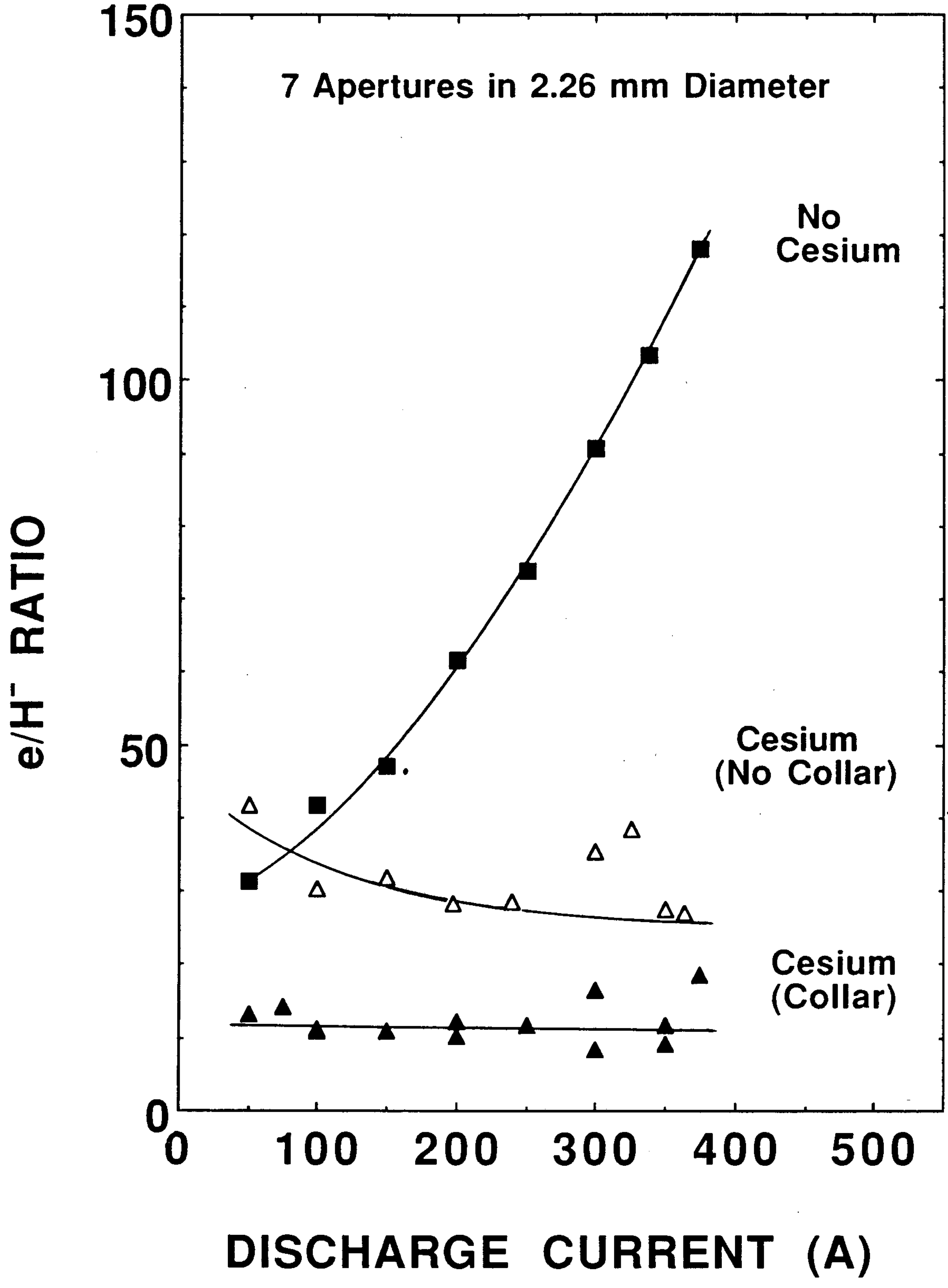


(a)



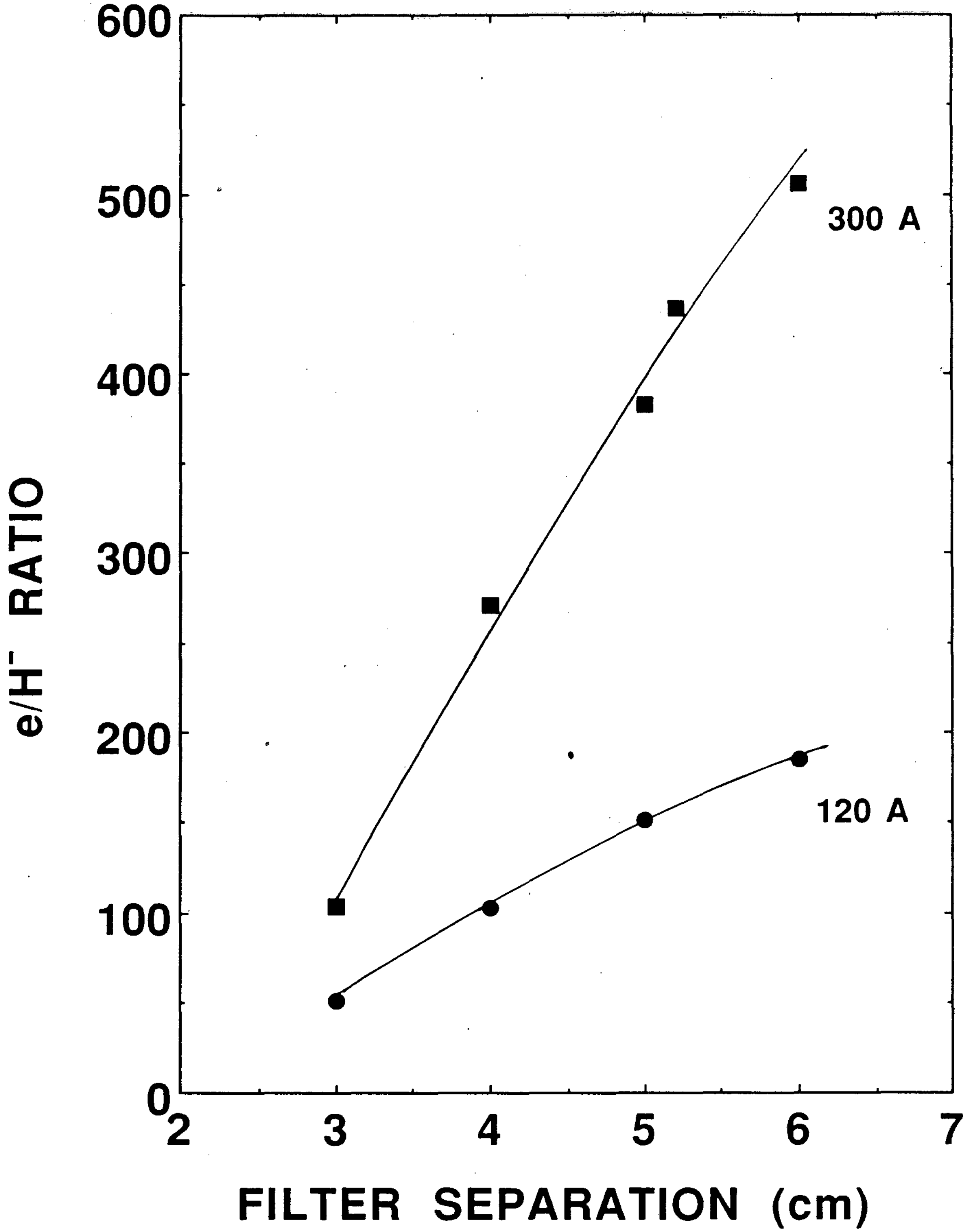
(b)

Fig. 9



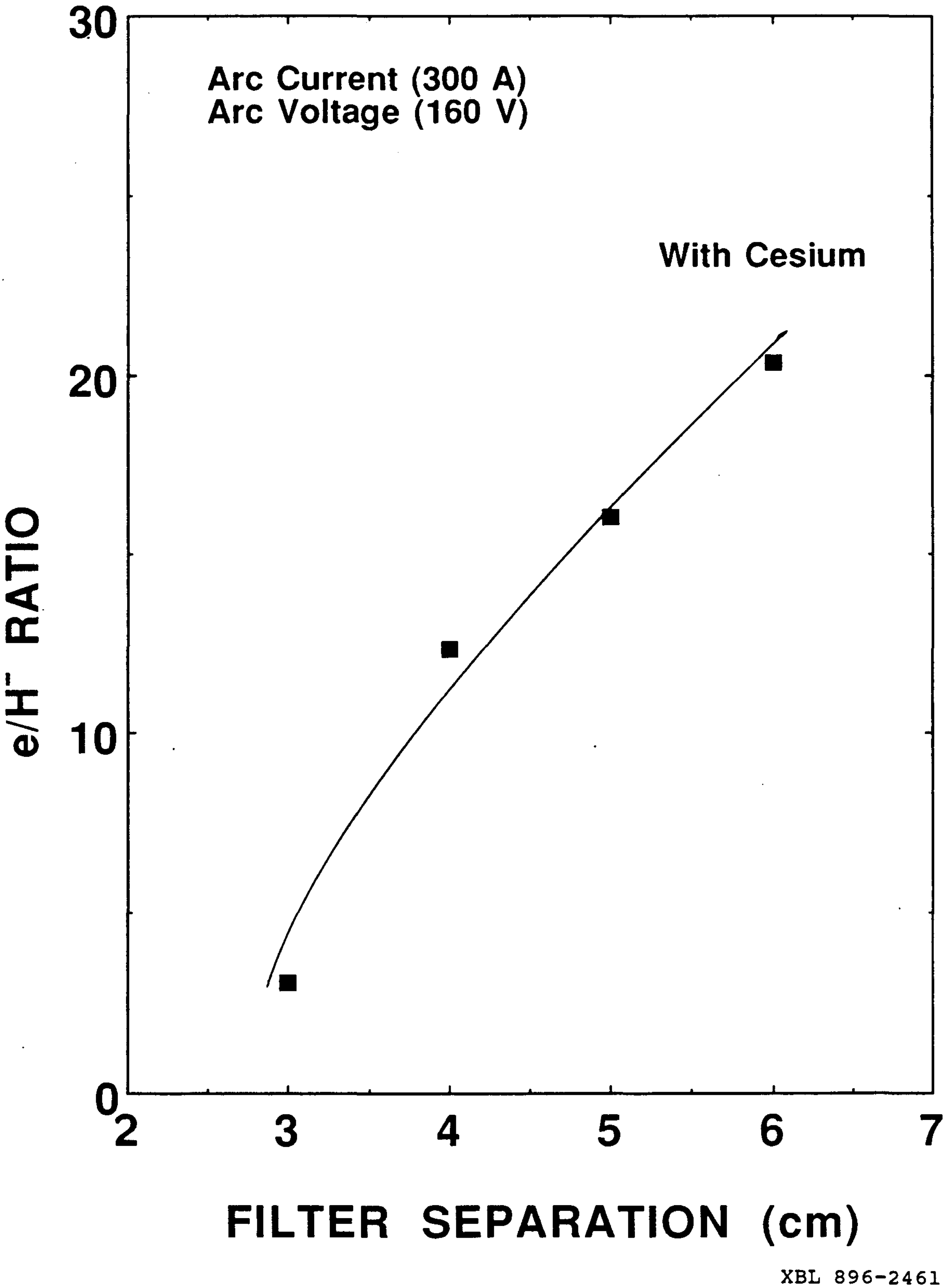
XBL 896-2459

Fig. 10



XBL 896-2460

Fig. 11



Arc Current (300 A)
Arc Voltage (160 V)
With Cesium
e/H⁻ RATIO
0
10
20
30
2
3
4
5
6
7
FILTER SEPARATION (cm)
XBL 896-2461

Fig. 12

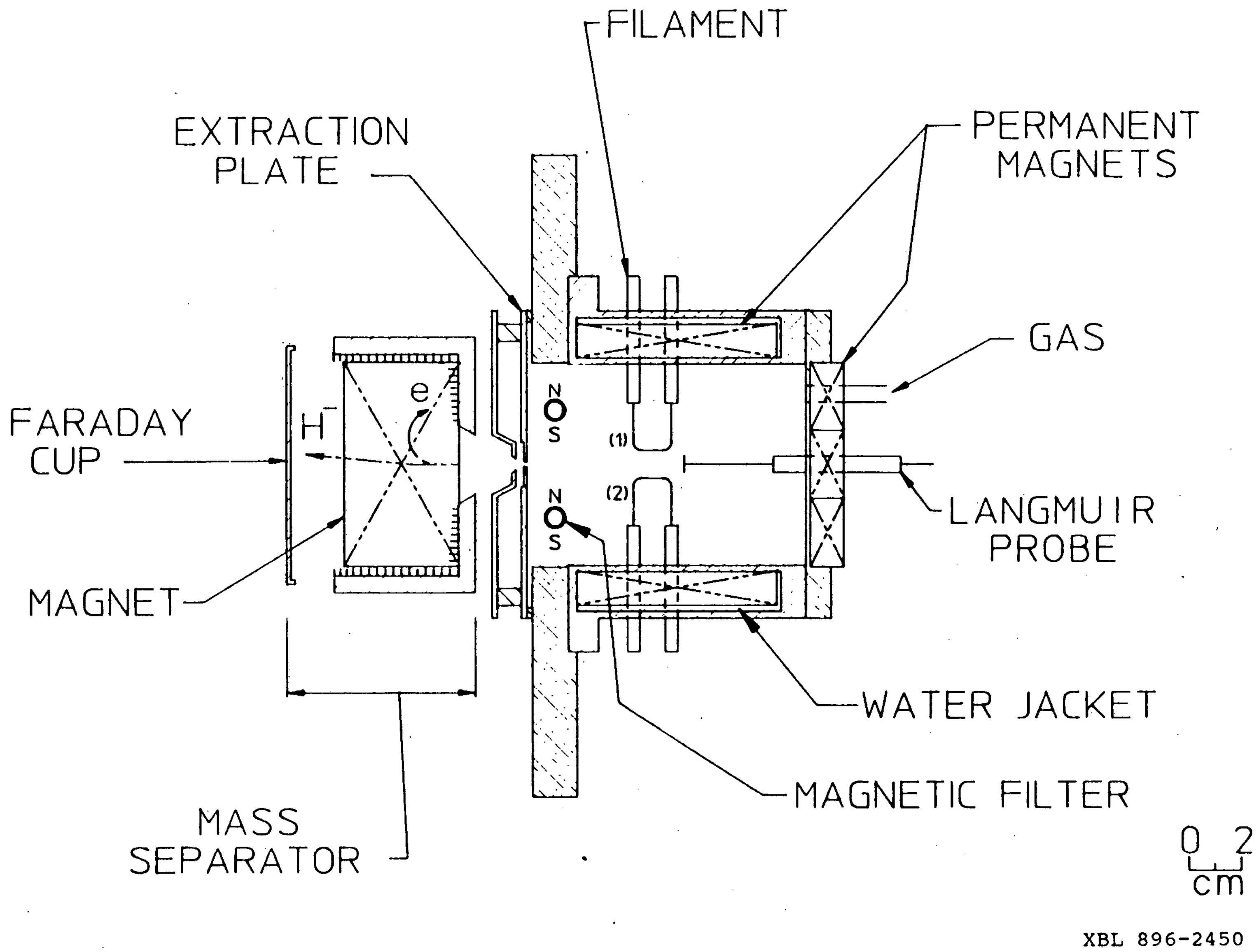

FILAMENT
EXTRACTION PLATE
PERMANENT MAGNETS
GAS
FARADAY CUP
H⁻
e
N
S
(1)
(2)
LANGMUIR PROBE
MAGNET
WATER JACKET
MAGNETIC FILTER
MASS SEPARATOR
0 2
cm
XBL 896-2450

Fig. 13

Table I. Extracted beam and plasma parameters before and after the addition of low-energy electrons.

Discharge Power	I_{H^-} (μA)	I_e (μA)	I_e/I_{H^-}	V_p (V)	T_e (eV)	N_e (cm^{-3})
80 V, 0.5 A	1.2	640	533	+3.1	1.1	5.4×10^{11}
+(8 V, 4.0 A)	1.6	120	75	+2.3	2.5	8.5×10^{11}
+(8 V, 4.5 A)	2.0	100	50	+2.1	2.7	9.2×10^{11}
+(8 V, 5.0 A)	2.5	27	11	+1.8	2.5	1.0×10^{12}
+(8 V, 5.5 A)	2.7	20	7	+1.5	2.3	1.0×10^{12}

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