Title
OPTIMIZATION OF H[SUB]-PRODUCTION FROM A SMALL MULTICUSP ION SOURCE

Authors
Leung, K.N.
Hauck, C.A.
Kunkel, W.B.

Publication Date
1988-08-01

LBL-25720
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

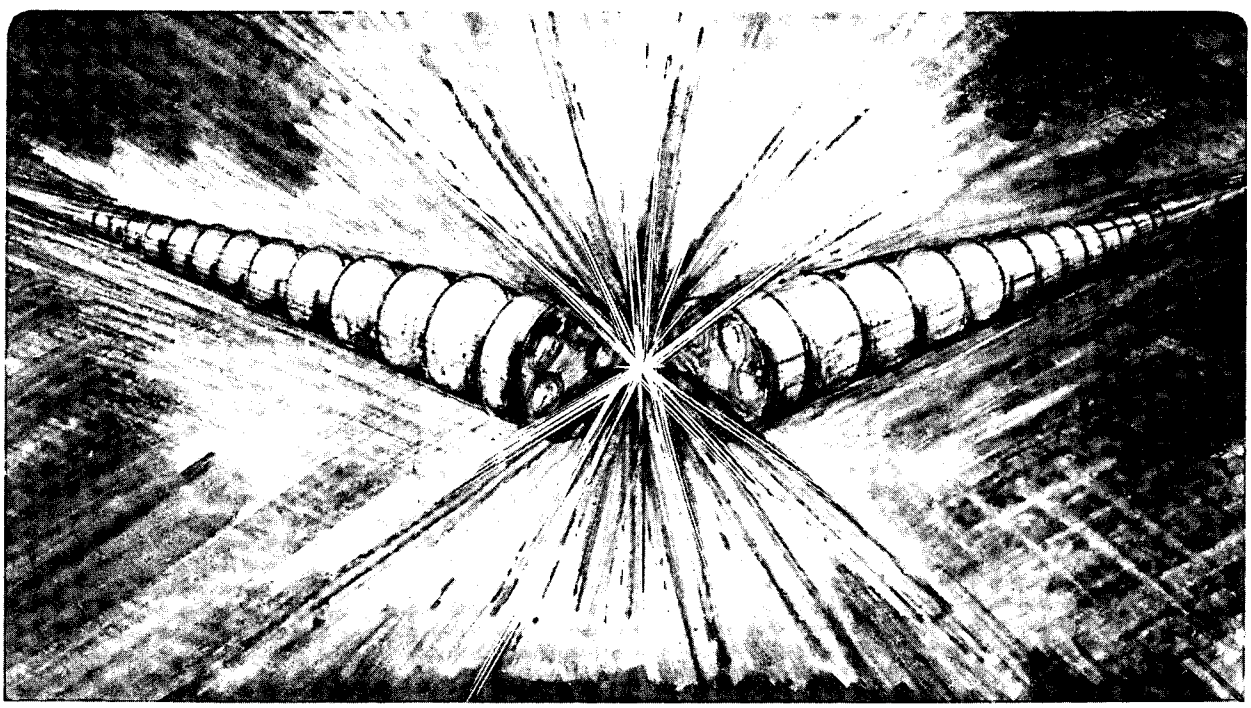
Accelerator & Fusion Research Division

Submitted to Review of Scientific Instruments

Optimization of H^- Production from a Small Multicusp Ion Source

K.N. Leung, C.A. Hauck, W.B. Kunkel, and S.R. Walther

August 1988



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

LBL-25720

Optimization of H^- Production from a Small Multicusp Ion Source*

K. N. Leung, C. A. Hauck, W. B. Kunkel and S. R. Walther

Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

Abstract

A small multicusp source has been developed to generate volume produced H^- ion beams in pulsed operation. To obtain high H^- current densities ($J^- > 250$ mA/cm^2), this source requires relatively high gas pressure and high discharge power. Experiments have been conducted to improve the arc and gas efficiencies, the beam pulse shape and the H^- to electron ratio in the extracted beam by optimizing the filter magnetic field, the thickness and axial position of the extraction aperture in the plasma electrode, and by mixing xenon or other elements with hydrogen in the discharge. The biggest improvement is achieved by adding *cesium* to the source, resulting in a five-fold increase in the extractable H^- current and a substantial drop in the e/H^- ratio. In order to improve the lifetime of the cathode, both filament and coaxial type LaB_6 cathodes have been developed and have been operated successfully in this H^- source.

* This work is supported by AFOSR (under Contract No. AFOSR-ISSA-88-003), AFSTC (under Contract No. FY-8303-8701-006), McDonnell Douglas Corp. (under Contract No. Y8E001), USASDC (under Contract No. W31PRD-8-D4030) and the Director, Office of Energy Research, Office of Fusion Energy, Development and Technology Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Introduction

H^- and D^- ions are being used in cyclotrons and tandem accelerators, in fueling storage rings of synchrotrons, and in generating high energy neutral beams for heating and for current drive in tokamak fusion reactors. There are two major types of H^- ion sources; surface-production sources and volume-production sources. The H^- ions generated by volume processes have lower average energy than those formed by surface conversion, resulting in a lower emittance of the extracted H^- beam. Unlike surface sources, volume H^- sources generally do not require cesium to operate. However, their optimum operating pressures are high and the amount of electrons accompanying the extracted H^- beam can be large. To address these problems, intensive research is now being conducted in many accelerator and fusion laboratories.

Recently, a small multicusp source has been fabricated, and operated in a pulsed mode to generate volume-produced H^- ions.[1] From this new source, H^- current densities higher than 250 mA/cm^2 have been extracted. To obtain these current densities, the source requires relatively high gas pressure and high discharge power. Experiments have been conducted to improve the arc and gas efficiencies, the shape of the beam pulse, and the H^- to electron ratio in the extracted beam by optimizing the filter magnetic field, the thickness and axial position of the extraction aperture in the plasma electrode, and by mixing various elements with hydrogen in the discharge. H^- current densities in excess of 1 A/cm^2 together with a substantial reduction in the e/H^- ratio were achieved when cesium was introduced into the hydrogen discharge. For

the purpose of steady-state operation, the lifetime of the cathode has to be greatly improved. Both filament and coaxial-type LaB_6 cathodes have been developed and operated successfully in this H^- source.

I. Experimental Setup

A schematic diagram of the small multicusp H^- source is shown in Fig. 1. The source geometry has already been described in a previous article.[1] In brief, the source chamber is a thin-walled (2-mm-thick) copper cylinder (7.5-cm-diam by 8-cm-long) surrounded by 14 columns of samarium-cobalt magnets for primary electron and plasma confinement. The permanent magnets in turn, are enclosed by an outer anodized aluminum cylinder. During pulsed high power discharges, adequate cooling of the magnets is provided by water circulating in between the two cylinders.

For experimental studies in Sec. IV, a thin molybdenum liner was installed against the inner walls of the source chamber and around the permanent magnet filter rods. Radiation from the tungsten filament and discharge heating by the plasma maintain a high liner temperature. As a result, cesium will not easily condense on the chamber walls. In this experiment, cesium vapor was introduced into the source through a transport pipe from an external oven. The temperatures of the oven and the transfer tubes were regulated by adjusting the heating current of the surrounding coil.

The open end of the source chamber was enclosed by a two-electrode acceleration system. H^- ions were extracted from the source through one

or multiple small apertures. A hydrogen plasma was generated by primary electrons emitted from a cathode located at the center of the source chamber. The entire source chamber, together with the filter rods, served as the anode for the discharge. In this study, the discharge voltage was maintained at ~150 V and the source pressure was varied between 15 to 50 mTorr to achieve the highest H^- yield.

During source operation, the H^- output current was optimized by varying the bias potential of the first (or plasma) electrode with respect to the anode. The maximum extraction voltage used in this experiment was ~16 kV. Electrons in the accelerated beam were separated from the H^- ions by a permanent magnet mass separator (Fig. 1). The B-field of the spectrometer 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.

II. Experimental Results with Pure Hydrogen Discharges

To study the H^- yield at high discharge power, the source was operated in a pulsed mode with the discharge voltage turned on and off by using an electronic switch. However, the cathode heater power and the extraction voltage were both operated in steady state. The pulse length was typically 1 ms long. As described in the previous article[1], the discharge voltage,

discharge current, and the collected electron current are nearly constant during the pulse. The extracted H^- current, however, behaves quite differently. It first reaches a maximum and then drops to a lower value at the end of the pulse. The H^- current (and the corresponding current density) presented in the following sections is the peak value during the discharge pulse.

A. Optimization of filament position

In order to achieve a quiescent discharge, the cathode must be placed inside the central "field-free" region of the multicusp source.[2] The dependence of H^- output as a function of axial filament position in this small multicusp source was investigated by employing a pair of moveable filament chucks. With this arrangement, the position of the filament could be easily varied with the source maintained at vacuum.

Figure 2 is a plot of the H^- current extracted from a 1-mm-diam aperture as a function of discharge current for three different filament positions. The distance from the filament tip to the surface of the back flange was varied from 57.5 to 67 mm. Although the variation in H^- current is small for the range of discharge current considered, the data demonstrates that the H^- output is the highest when the filament tip is 62 mm from the back flange.

When the filament is moved towards the back flange, primary electrons emitted from the filament can be trapped in the dipole fields generated by the permanent magnets on the back flange, resulting in a reduction of plasma density in the discharge volume and therefore the H^- output. On the other hand,

if the filament tip enters into the magnetic field of the filter, the H^- yield also decreases. This effect has been observed in a previous experiment performed in a large multicusp source.[3] The data presented in the following sections were all obtained with the filament installed in this optimum position, that is with the tip of the filament cathode at 62 mm from the back flange.

B. Optimization of filter rod separation

The small multicusp source has two permanent magnet filter rods. The strength of the magnetic field can be changed by adjusting the filter rod separation. H^- generation has previously been compared for only two rod separations (4 and 6 cm).[1] In order to optimize the filter magnetic field, a new mounting flange equipped with a pair of moveable, water-cooled, filter rods was fabricated. In this arrangement, the separation of the rods can be varied continuously while the source is in operation.

Figure 3 shows the extracted H^- current density as a function of rod separation for a constant discharge power of 150 V, 120 A. The size of the extraction aperture used in this study was 0.5 mm diameter. As the rod separation d (center to center) is increased from 3 to 5 cm, the current density increases linearly, reaches a maximum at d ~ 5.7 cm and then decreases. However, the extracted electron current (as shown in Fig. 4) increases monotonically for the range of rod separation considered. No optimum filter separation exists for the electron current because the weaker the filter field, the higher the electron density and temperature in the

extraction region. Since the electron current is very low for d ~ 3 cm, the ratio of the extracted electron to H^- current can be small for this filter separation.

For a given discharge power, there always exists an optimum filter field strength for the H^- output.[4] If the filter field is too strong, the plasma density is low in the extraction region, resulting in a lower H^- production rate. On the other hand, if the filter field is too weak, the rate of H^- loss via electron collisions becomes significant due to higher electron temperature. The balance between these two competing processes thus produces an optimum filter field which is equivalent to a rod separation of 5.7 cm for this particular discharge power. If the discharge current is increased from 100 to 300 A, the electron temperature T_e in the whole source chamber increases. In order to maintain the optimum H^- yield, the strength of the filter field must be increased or the separation of the filter rods must be reduced to about 5 cm. Results of the following sections were all obtained with the two filter rods separated by 5 cm.

C. Optimization of plasma electrode position

Previous experiments with the large multicusp source showed that the H^- output increased as the extractor approached the filter.[3] A similar study has also been performed with this small multicusp source. The source was operated with discharge current between 50 and 150 A and with the plasma electrode located at 0.38, 2.41 and 4.45 mm from the surface of the filter

rods. For the range of discharge current considered, the data in Fig. 5 shows that the extracted H^- current density is the highest when the plasma electrode is closest to the filter. The H^- yield increases by more than a factor of two as the extractor is moved from 4.45 mm to 2.41 mm from the edge of the filter rods.

Figure 6 is a plot of the electron to H^- ratio as a function of discharge current. The ratio is the highest when the plasma electrode is at 4.45 mm from the filter and is the lowest when it is at 2.41 mm from the filter. However, the variations in the H^- output and the electron to H^- ratio are small when the separation between the plasma electrode and the filter is below 2.41 mm. For this reason, the plasma electrode is positioned within this separation throughout the entire experimental investigation.

D. Optimization of aperture thickness in the plasma electrode

In order to optimize the thickness of the extraction aperture, several copper inserts with the same hole diameter but different thicknesses were fabricated. By replacing these inserts, the thickness of the aperture could be easily varied without changing the whole plasma electrode.

Figure 7 shows the extracted H^- current density as a function of discharge current when the thickness of a 0.5-mm-diam aperture is varied from 0.35 to 1.0 mm. It can be seen that the H^- current density decreases as the thickness of the hole increases. Variation of the electron output current as a function of aperture thickness is very similar to that of the H^- ion.

Figure 8 shows the result obtained when the experiment was repeated

with a 0.75-mm-diam aperture. In this case, only three thicknesses have been compared. The thinnest aperture again provides the highest extractable H^- current density. The data in Figs. 7 and 8 seem to suggest that as the aperture thickness is decreased, the extractable H^- current starts to saturate when the thickness is equal to the diameter of the aperture or when the aspect ratio of the aperture becomes unity. This result indicates that if small multiple apertures are employed in the plasma electrode for extraction, the thickness of the material around each hole should not exceed the aperture diameter.

H^- ions have been extracted through a 0.5 mm thick and 0.5 mm diameter aperture and with an optimized filter separation of 5 cm. Figure 9 is a plot of the H^- current density as a function of discharge current I_d at a constant discharge voltage of 150 V. It can be seen that H^- current densities as high as 365 mA/cm^2 have been achieved at I_d = 350 A. Thus, there is a substantial improvement in the extractable H^- current density when compared with the result obtained in a previous experiment.[1]

E. Source operation with gas puffing

The small multicusp source is normally operated in short pulses (1 ms duration and 5 pulses per second) with a continuous flow of hydrogen gas. For high power discharges, source pressure as high as 50 mTorr is required. A substantial saving in mass flow can be achieved if the hydrogen gas can also be supplied to the source in a pulsed mode.

Source operations with short gas puffs have been investigated using a

piezoelectric valve which has a fast turn-on time (< 50 μs) and repetition rates higher than 500 pulses per second. The oscilloscope traces in Fig. 10 illustrate the shape of the extracted H^- and electron current during a 1-ms discharge with gas input operated in dc (Fig. 10(a)) or pulsed mode (Fig. 10(b)). For gas puffing operations, the piezoelectric valve was opened prior to the discharge. With the gas switch-on time properly optimized (~ 250 μs before discharge is turned on), the shape of the H^- current is very uniform during the discharge pulse as shown by the oscilloscope trace in Fig. 10(b). Although the H^- peak current is higher for the dc gas input, the average H^- output current is about equal in both cases for the same discharge power.

F. Source operation with a mixture of hydrogen and xenon gases

The effect on H^- production when the source was operated with a mixture of hydrogen and other gases had previously been studied in the large multicusp source for low discharge power conditions.[5,6] This small multicusp source has been operated with an admixture of hydrogen and xenon in pulsed discharges at much higher power.

When the source was operated below the optimum hydrogen pressure and therefore with lower H^- output, two effects were observed when a substantial amount of xenon (28% of total pressure) was added to the hydrogen discharge. First, the H^- output could be optimized by applying a positive bias potential of several volts on the plasma electrode, resulting in a higher extracted H^- current than the case of pure hydrogen operation by approximately 38%. Second, the electron current was suppressed at the optimum plasma electrode

bias. As a result, the ratio of electron to H^- current was reduced significantly.

However, when the source was operated near optimum hydrogen pressure, adding xenon to the source did not improve the H^- output current. The oscilloscope traces in Fig. 11(a) and (b) illustrate the H^- and electron current with and without addition of xenon respectively. At the optimum bias voltage (+ 5 V), Fig. 11(b) shows that the H^- output is about the same as in Fig. 11(a) for the same discharge voltage and current. But the shape of the H^- current is more uniform and the extracted electron current is a factor of four lower at this optimum bias.

III. Source Operation with Different Types of Cathode

The small multicusp source was operated with one 1.5-mm-diam tungsten filament with a discharge current as high as 350 A. For 1 or 2 ms discharge duration, the lifetime of the filament is normally less than 14 thousand pulses. The tungsten filament eventually fails due to high temperature evaporation and severe sputtering by high ion flux. In order to prolong the filament lifetime, cathode materials other than tungsten have been investigated in this H^- source.

It has been known for some time that lanthanum hexaboride (LaB_6) is an excellent material for use as an electron emitter. Previous tests have demonstrated that directly heated LaB_6 filaments perform satisfactorily in different types of ion sources where tungsten or tantalum filaments are

normally employed.[7] Specially shaped hairpin LaB_6 filaments have been fabricated and tested in this small multicusp source. Figure 12 shows a LaB_6 filament installed in the molybdenum chucks on the back flange. The shape of this filament was properly designed so that electron emission occurred mainly at the filament tip, resulting in higher H^- ion yield. The total heater power required for this LaB_6 filament was ~500 W or only about 50% of the power needed for tungsten filament operation. The use of LaB_6 has also improved the lifetime of the cathode by about a factor of 3.

In addition to LaB_6 hairpin filaments, the small source has also been operated with a directly heated, coaxial LaB_6 cathode. Details of the coaxial type LaB_6 design have been reported in Ref. 8. The coaxial geometry requires only one feed-through on the back flange and is much stronger in structure than either the tungsten or LaB_6 filament. Since the magnetic field generated by the heater current is minimized, the coaxial cathode is able to emit electrons even at low discharge voltages. The heater power required for this coaxial LaB_6 cathode is approximately the same as that of the LaB_6 filament.

H^- yield from the small multicusp source has been compared for tungsten and LaB_6 filaments and the coaxial LaB_6 cathode for identical discharge conditions. The data in Fig. 13 shows that there is essentially no difference in the H^- output current for these three types of cathode when the discharge

current is varied from 50 to 550 A. The discharge voltage was maintained at 150 V for this experimental test.

IV. Experimental Results with Hydrogen-Cesium Operation

A recent experimental study on a smaller multicusp ion source, in steady state operation and at low discharge power, shows a very large increase in H^- output when cesium vapor is added to a hydrogen discharge.[9] To determine if the increased H^- output scaled in larger sources operated at high discharge power, this multicusp source was modified to operate with cesium. A cesium oven and a valve to regulate flow were mounted at the back flange of the ion source, as detailed in Fig. 1. A hot liner, consisting of molybdenum sheet metal, was installed over the entire inner surface of the source chamber including the filter rods. The insert on the plasma electrode was also thermally isolated. These modification allowed cesium vapor to be introduced into the source in a controlled manner, while radiation and plasma heating of the liner prevented the cesium from rapidly condensing on wall surfaces.

The experiment with the cesium-seeded plasma was first studied with a 1-mm-diam extraction aperture. Figure 14 shows the H^- current density obtained from the source as a function of discharge current and the amount of cesium added to the discharge. All measurements were performed at a constant discharge voltage of 150 V and at optimum source hydrogen pressure. When some cesium was added to the source, the H^- current density increased by about a factor of two relative to a pure hydrogen discharge. At this cesium

level, no difficulties were encountered during source operation and beam extraction. Further addition of cesium (Fig. 14) resulted in an overall improvement of H^- output by a factor of five and H^- current densities exceeding 1 A/cm^2 were obtained. The limiting factor in increasing the cesium density and therefore the H^- output current was electrical breakdown across the extraction electrodes. For a source specifically designed for cesium operation, these problems could be alleviated.

The scaling of H^- ion current as a function of extraction area is of great interest when considering ion sources for accelerator and fusion applications. To address this issue, two additional plasma electrode inserts were fabricated with different extraction areas. One insert contained seven apertures (each of 0.7-mm-diam) inside a 2.26-mm-diam circle and the other contained nineteen apertures (each of 0.9-mm-diam) inside of a 5.0-mm-diam circle. Thus, the nineteen aperture insert has an extraction area of about 16 times that of the single 1-mm-diam hole.

Figure 15 shows the extracted H^- current and current density as a function of discharge current when the seven aperture insert was used. The results are very similar to the single (1-mm-diam) aperture case. At a discharge current of 350 A, source operation with adequate cesium generated a H^- current density of ~1.2 A/cm^2. The corresponding H^- current was 33 mA.

Figure 16 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 of e/H^- from 200 to 20 at high discharge

power. This reduction may be in part due to a decrease in electron temperature in the extraction region.

Source operation with the nineteen aperture insert was very similar to the case of the single or seven aperture insert. In this measurement, the total extracted H^- current is improved to 150 mA at a discharge current of 350 A when cesium is added to the source plasma. The corresponding H^- current density is about 1.2 A/cm^2. The results of these experiments with cesium indicate that the H^- current scales directly with extraction area for the extraction geometries tested.

An oscilloscope picture illustrating the time dependence of the discharge current and voltage, and the extracted electron and H^- currents is shown in Fig. 17 for cesium operation with the nineteen aperture insert. During the 500 μs discharge pulse, the H^- current profile is very uniform. The reason for the improved pulse shape of the H^- current compared with pure hydrogen operation is not yet understood. It is likely that the addition of cesium to the source produces an effect similar to the case when xenon is mixed with hydrogen. Work is in progress to investigate the H^- production mechanism when the source plasma is seeded with cesium. Results of the study will be reported in the near future.

We would like to thank D. Moussa, M. D. Williams, G. J. DeVries, P. Purgalis, S. Wilde and members of their group for technical support. Fruitful discussion with members of the MFE Group is appreciated. This work is supported by AFOSR (under Contract No. AFOSR-ISSA-88-003), AFSTC (under Contract No. FY-8303-8701-006), McDonnell Douglas Corp. (under Contract No. Y8E001), USASDC (under Contract No. W31PRD-8-D4030), and the Director, Office of Energy Research, Office of Fusion Energy, Development and Technology Division, of the U.S. Dept. of Energy under Contract No. DE-AC03-76SF00098.

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. W. Ehlers and K. N. Leung, Rev. Sci. Instrum., 54, 1296 (1983).
3. K. N. Leung, K. W. Ehlers, and R. V. Pyle, Rev. Sci. Instrum., 56, 364 (1985)
4. Y. Okumura, K. N. Leung, and W. S. Cooper, Bull. Am. Phys. Soc. 31, 1507 (1986).
5. K. N. Leung, K. W. Ehlers, and R. V. Pyle, Rev. Sci. Instrum., 56, 2097 (1985).
6. O. J. Orient, A. Chutjian, and K. N. Leung, J. Appl. Phys. 62, 397 (1987).
7. K. N. Leung, P. A. Pincosy, and K. W. Ehlers, Rev. Sci. Instrum., 55, 1064 (1984).
8. K. N. Leung, D. Moussa, and S. B. Wilde, Rev. Sci. Instrum. 57, 1274 (1986).
9. S. R. Walther, K. N. Leung, and W. B. Kunkel, (accepted for publication in J. Appl. Phys.)

Figure Captions

Fig. 1 A schematic diagram of the ion source modified for operation with cesium.

Fig. 2 A plot of the extracted H^- ion current versus discharge current for three different filament positions.

Fig. 3 A plot of the extracted H^- ion current density as a function of the filter rod separation.

Fig. 4 A graph of the extracted electron current as a function of the filter rod separation

Fig. 5 A graph of the extracted H^- ion current density as a function of discharge current for different spacings between the plasma electrode and the edge of the filter rods.

Fig. 6 A plot of the electron to negative ion ratio as a function of discharge current for different spacings between the plasma electrode and the filter rods.

Fig. 7 A graph of the extracted H^- ion current versus discharge current for various thicknesses of the 0.5-mm-diam plasma electrode aperture.

Fig. 8 A graph of the extracted H^- ion current versus discharge current for various thicknesses of the 0.75-mm-diam plasma electrode aperture

Fig. 9 A plot of the extracted H^- ion current density versus discharge current for a 0.5-mm-diam, 0.5-mm-thick plasma electrode aperture.

Fig. 10 An oscilloscope trace showing the discharge current and voltage, and the extracted H^- ion and electron currents during a 1 ms discharge

pulse for (a) steady-state and (b) pulsed mode hydrogen gas input. (Note: the scale of the H^- signal in (b) is magnified by a factor of 2).

Fig. 11 An oscilloscope trace showing the discharge current and voltage, and the extracted H^- ion and electron currents during a 1 ms discharge pulse (a) without, and (b) with the addition of xenon to the hydrogen plasma.

Fig. 12 A picture showing the LaB_6 hairpin filament installed on the back flange of the ion source.

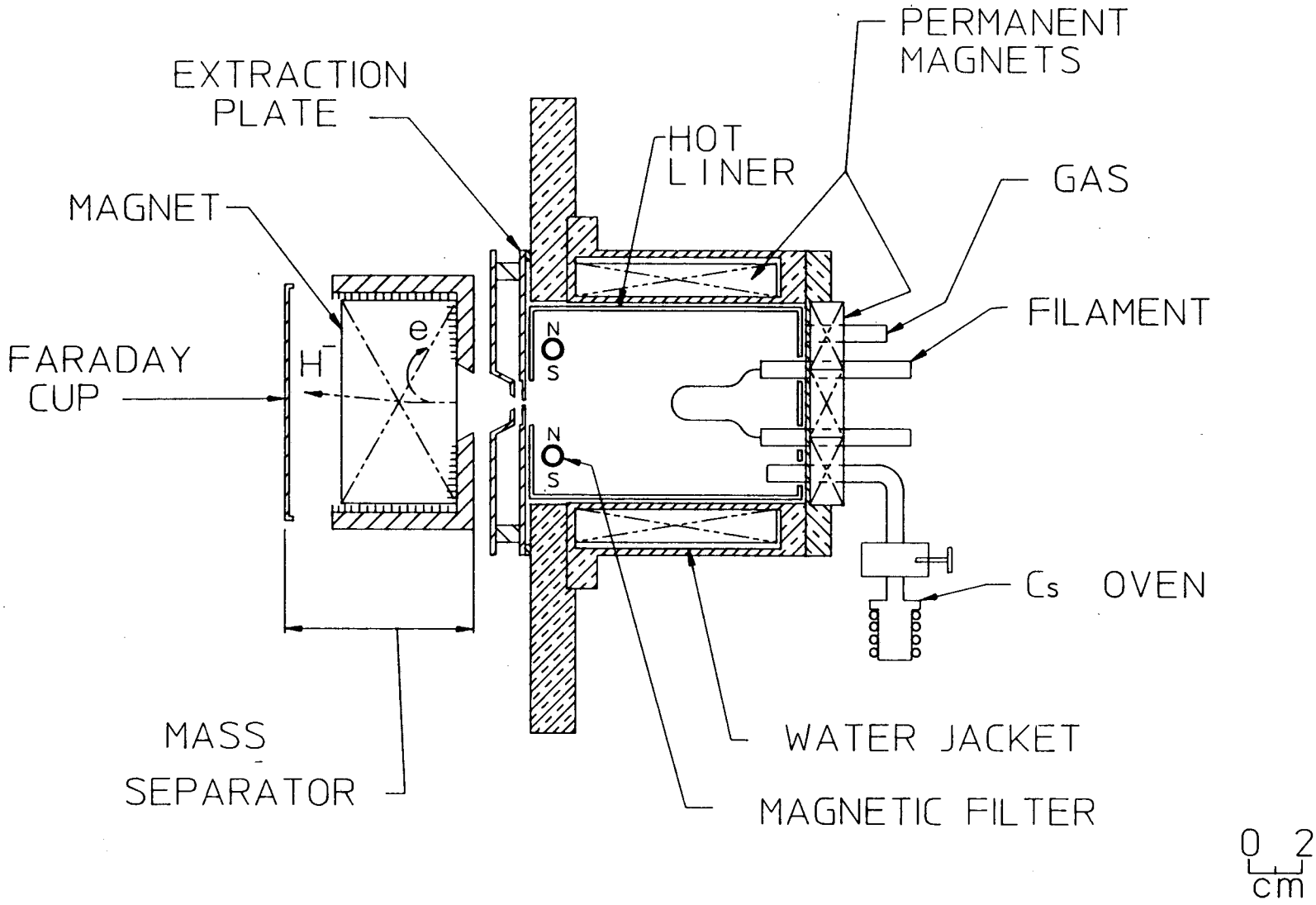
Fig. 13 A plot of the extracted H^- ion current density versus discharge current when the source is operated with either a tungsten or a LaB_6 hairpin filament, or with a LaB_6 coaxial type cathode.

Fig. 14 A graph of the extracted H^- ion current and current density versus discharge current for the single 1-mm-diam plasma electrode aperture operating with and without cesium in the source.

Fig. 15 A graph of the extracted H^- ion current and current density versus discharge current for the 7 aperture plasma electrode operating with and without cesium in the source.

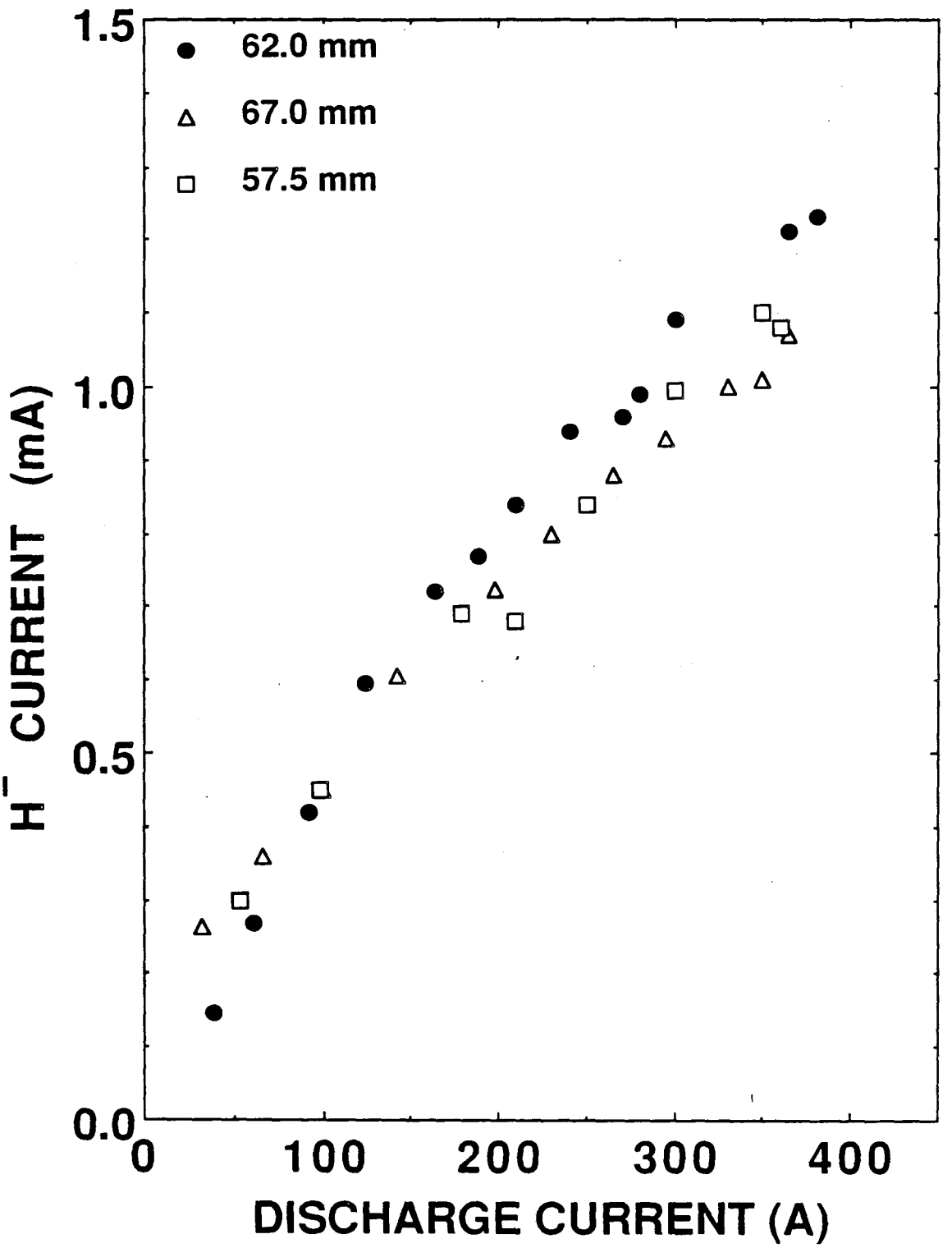
Fig. 16 A graph of the electron to H^- ion ratio versus discharge current for the 7 aperture plasma electrode operating with and without cesium in the source.

Fig. 17 An oscilloscope trace showing the discharge current and voltage, and the extracted H^- ion and electron currents during a 0.5 ms discharge pulse.



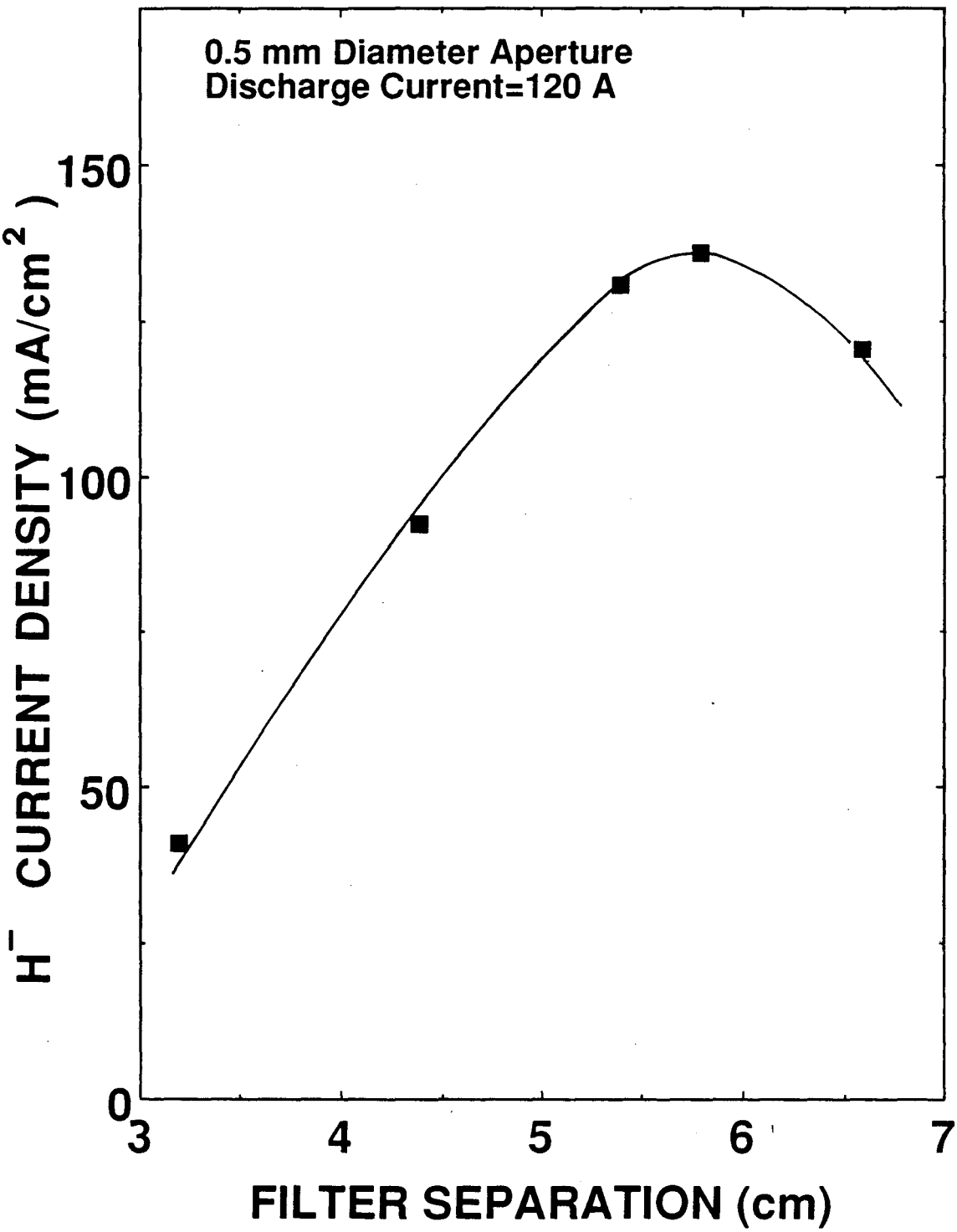
XBL 887-2636

Fig. 1



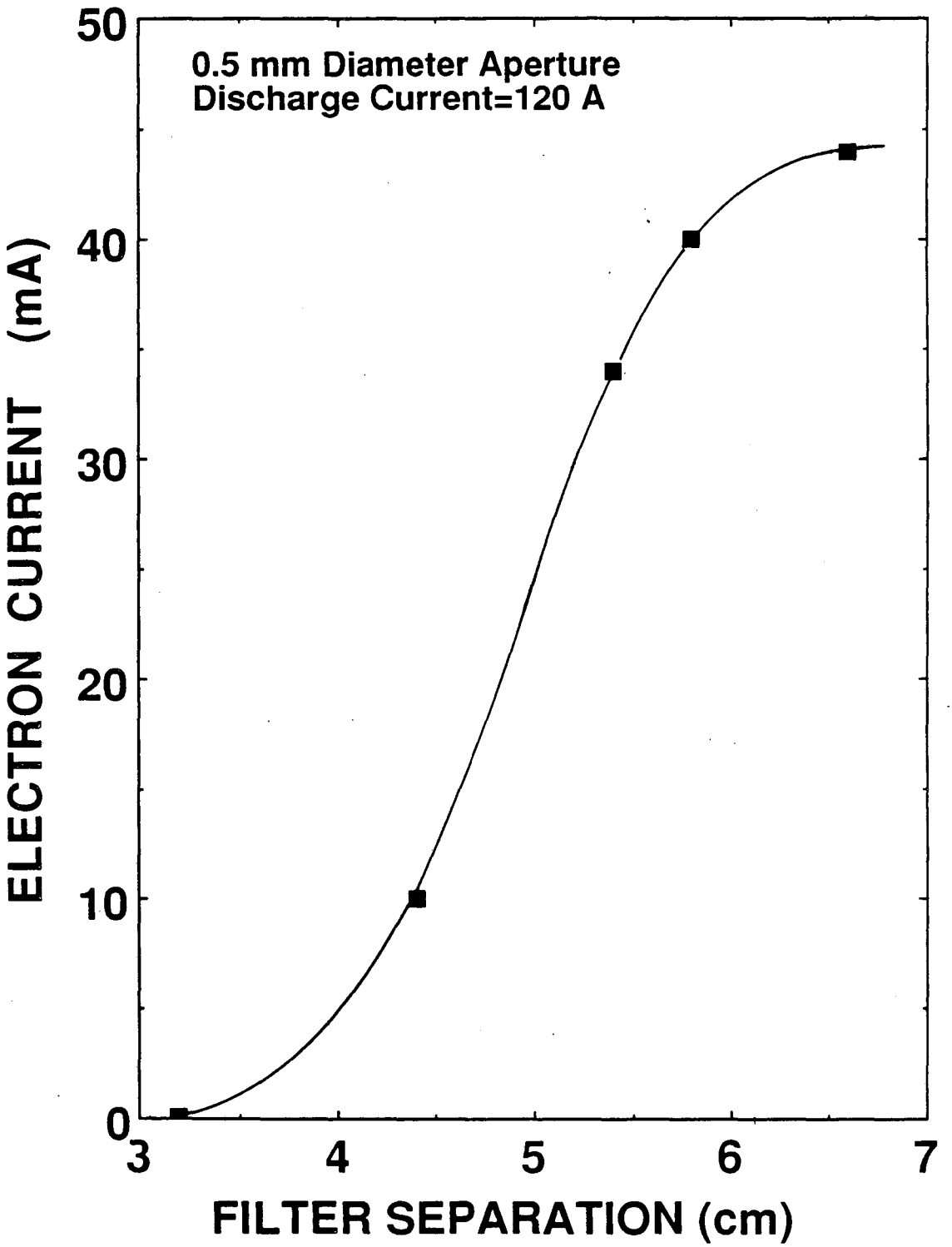
XBL 887-2638

Fig. 2



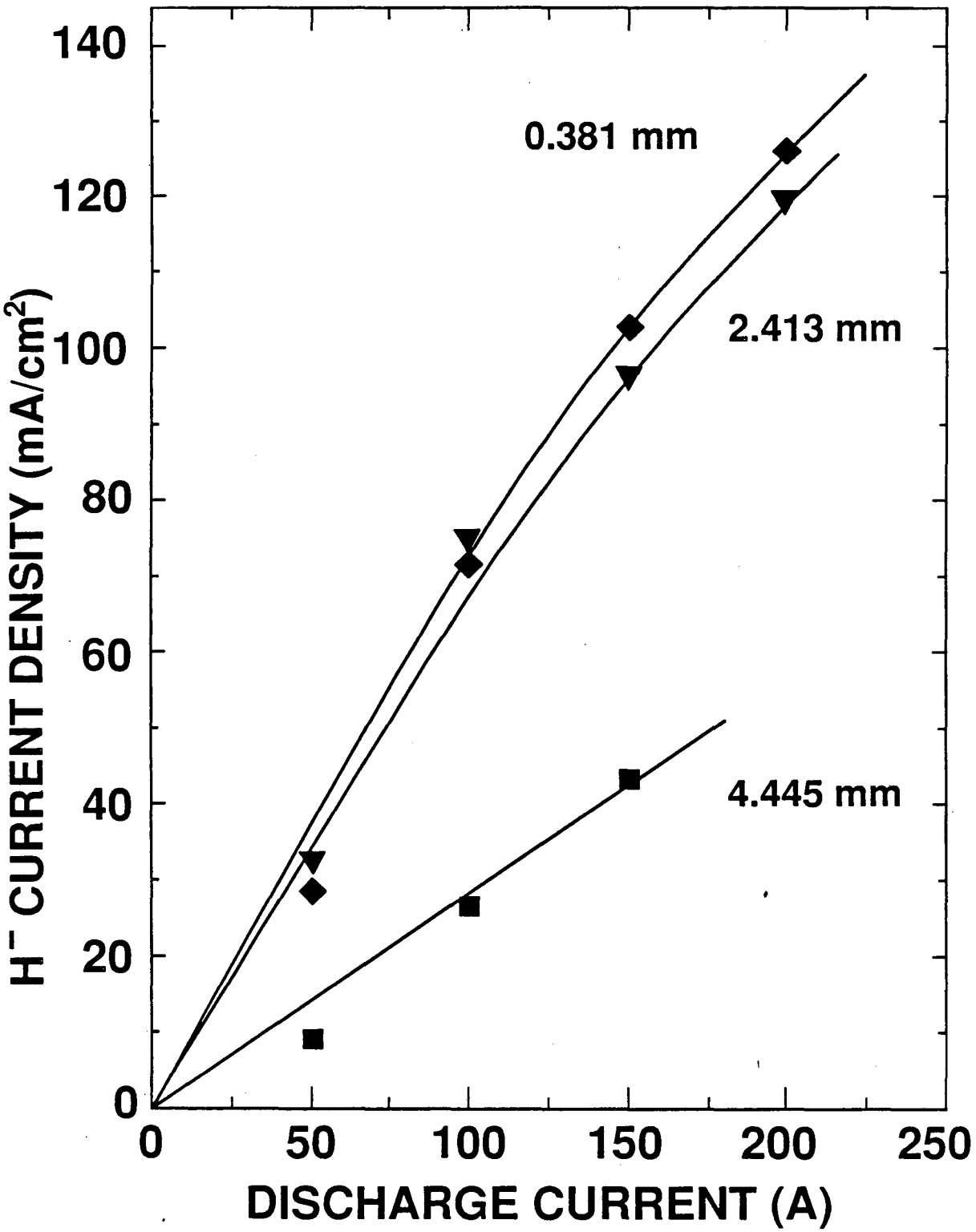
XBL 887-2639

Fig. 3



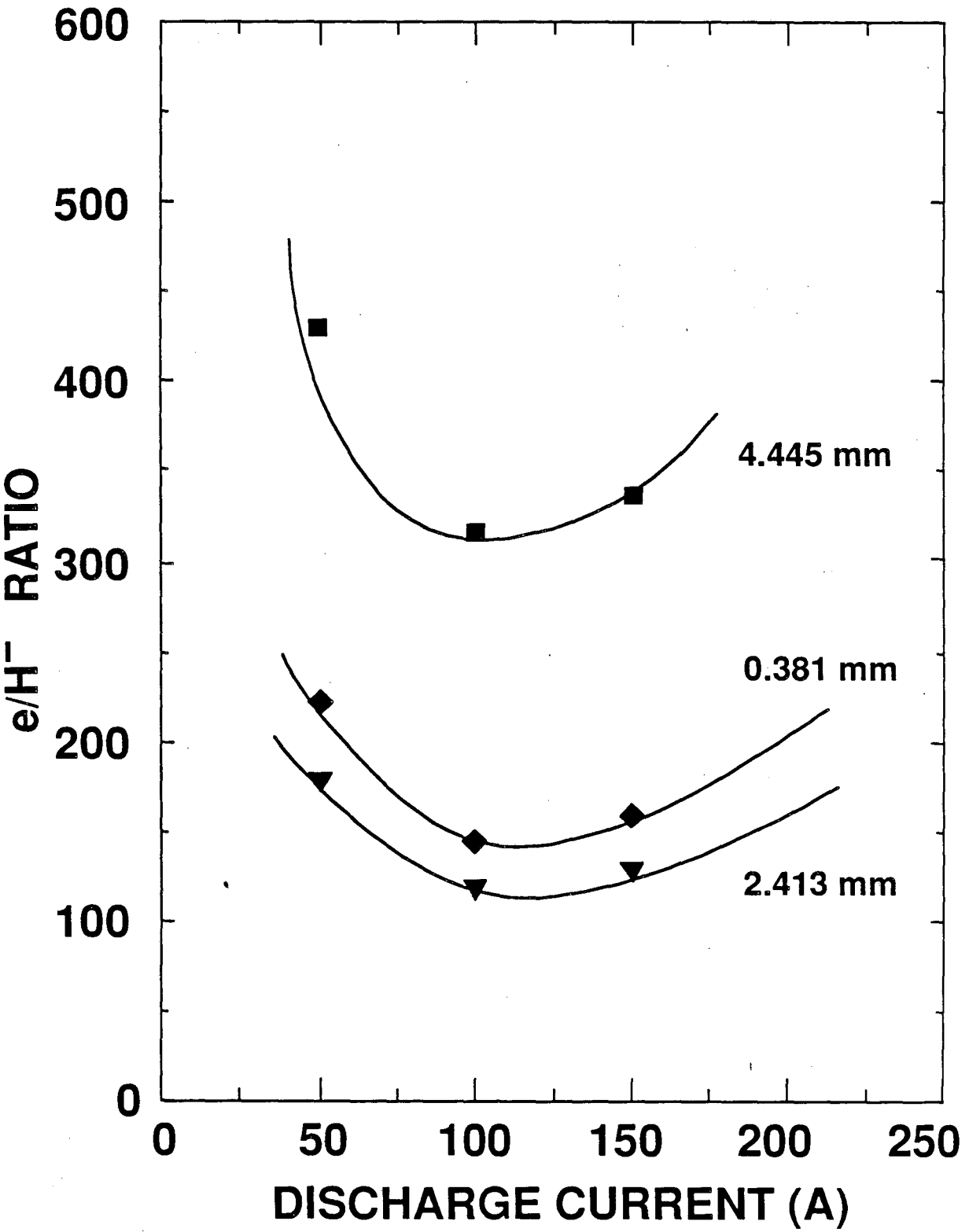
XBL 887-2640

Fig. 4



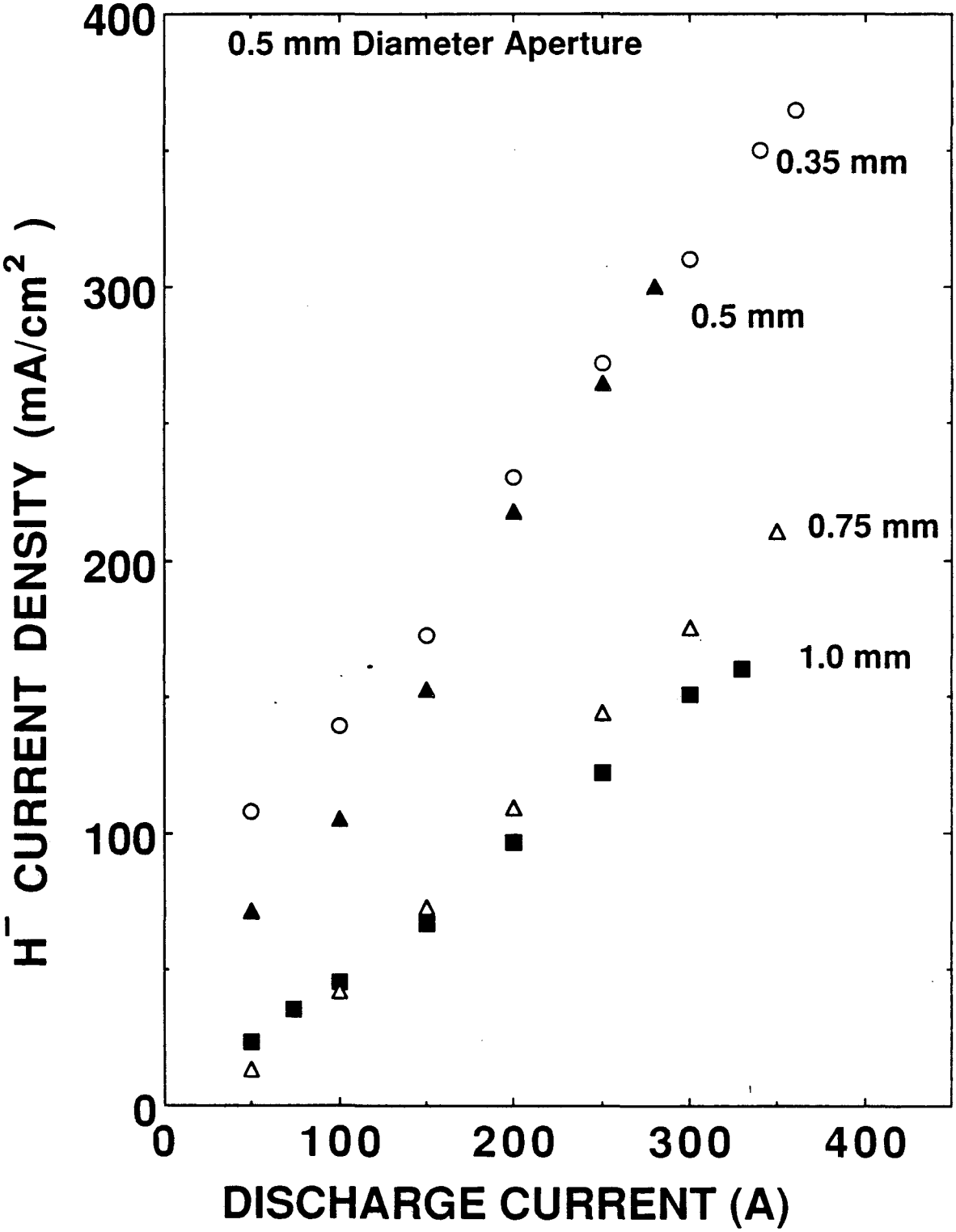
XBL 887-2644

Fig. 5



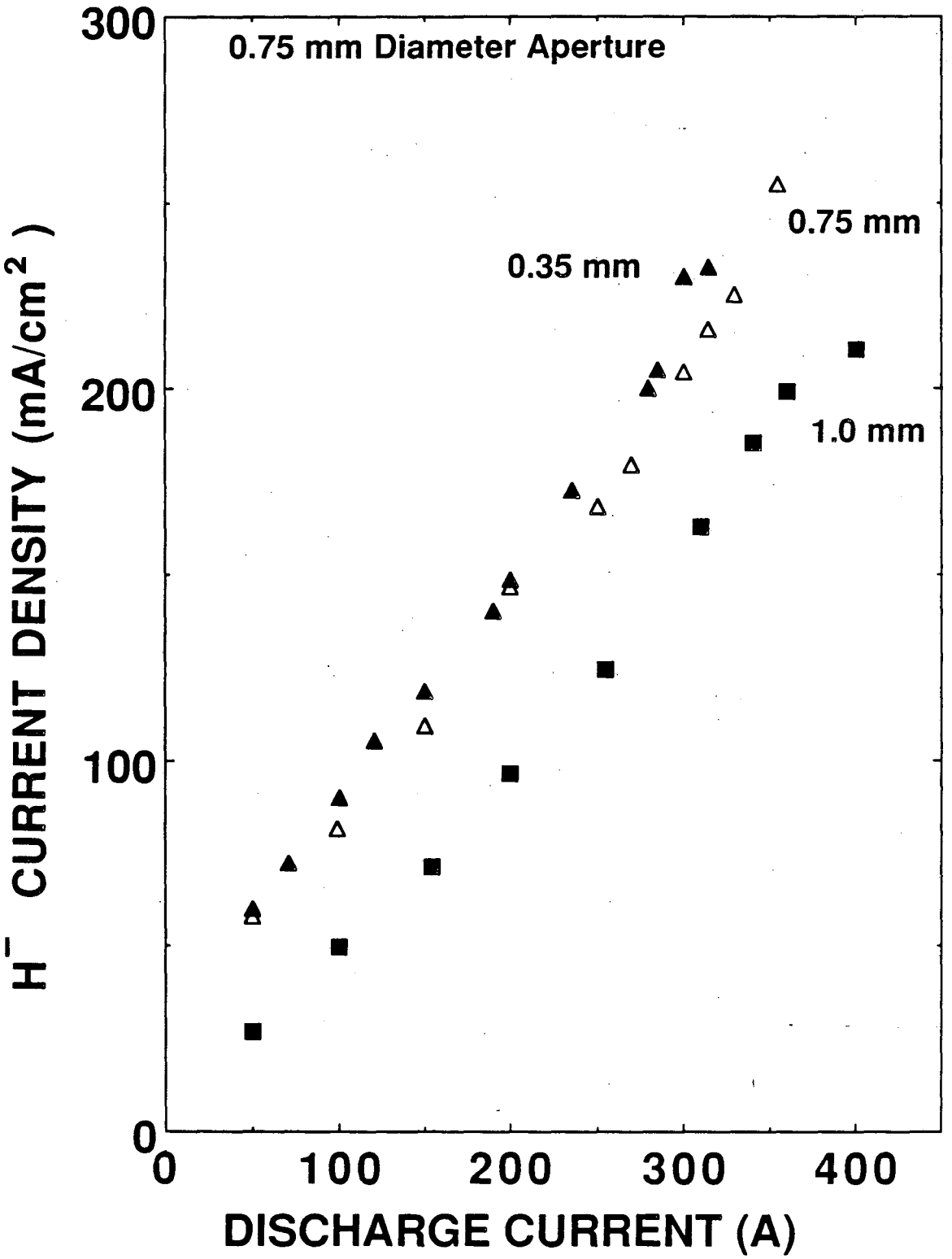
XBL 887-2645

Fig. 6



XBL 887-2641

Fig. 7



XBL 887-2642

Fig. 8

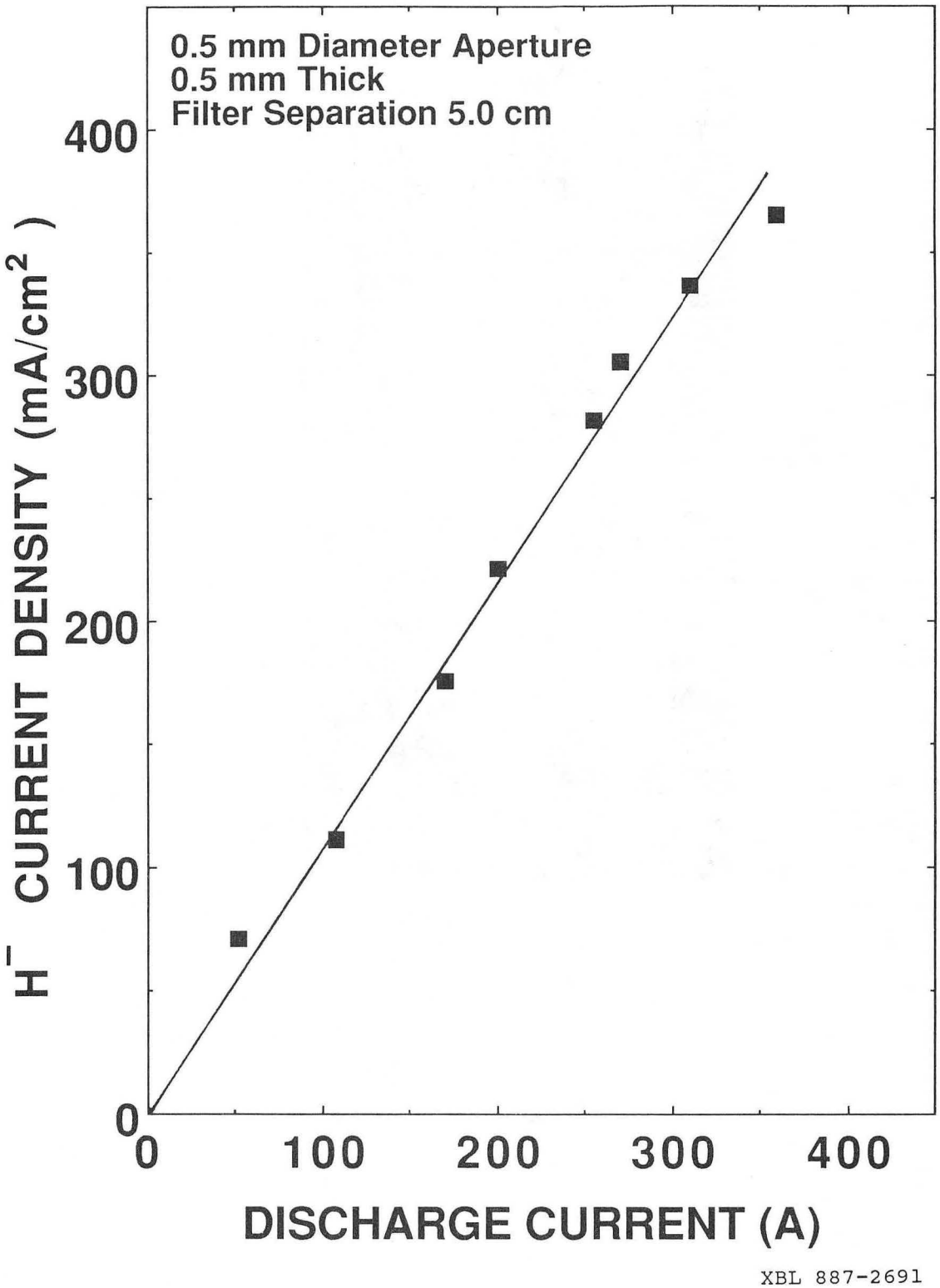
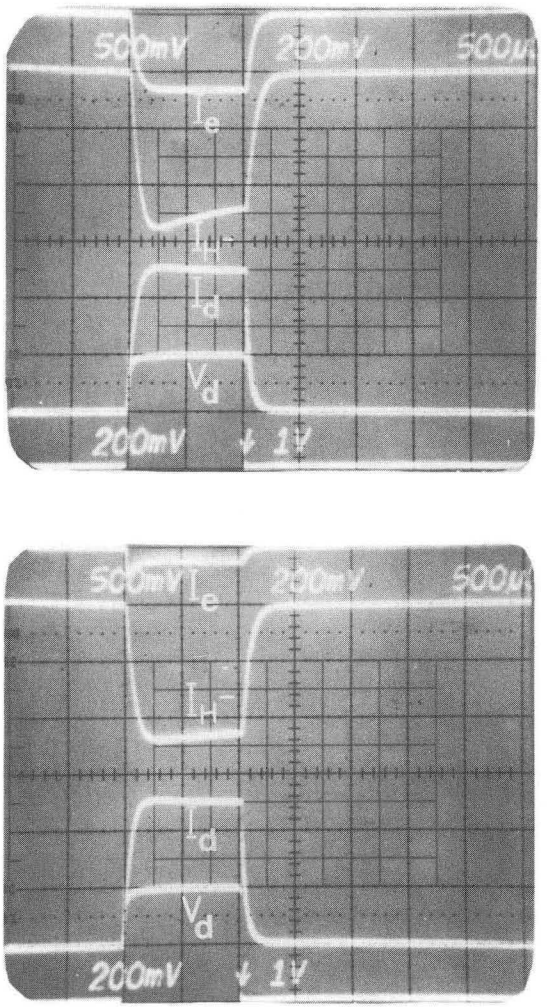
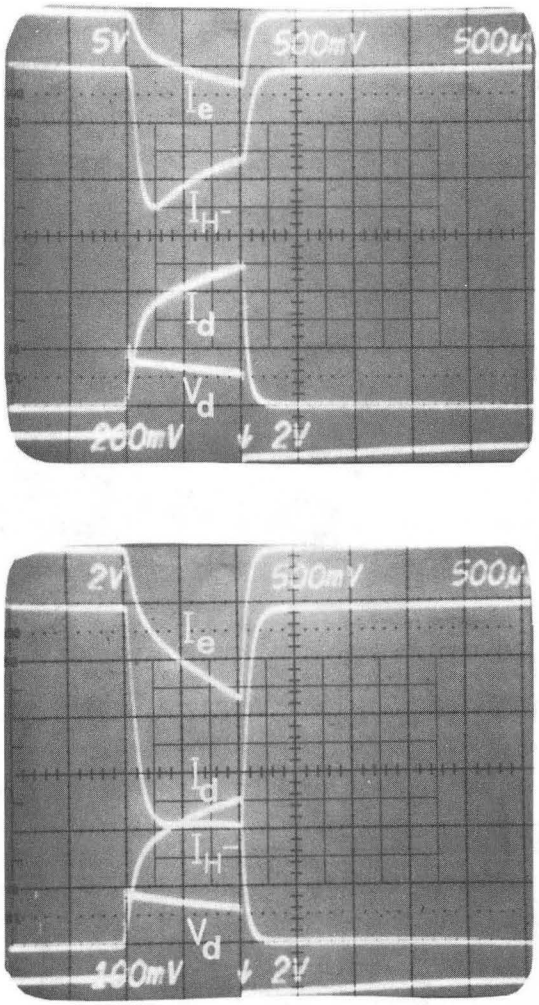

0.5 mm Diameter Aperture
0.5 mm Thick
Filter Separation 5.0 cm
H⁻ CURRENT DENSITY (mA/cm²)
0
100
200
300
400
0
100
200
300
400
DISCHARGE CURRENT (A)
XBL 887-2691

Fig. 9



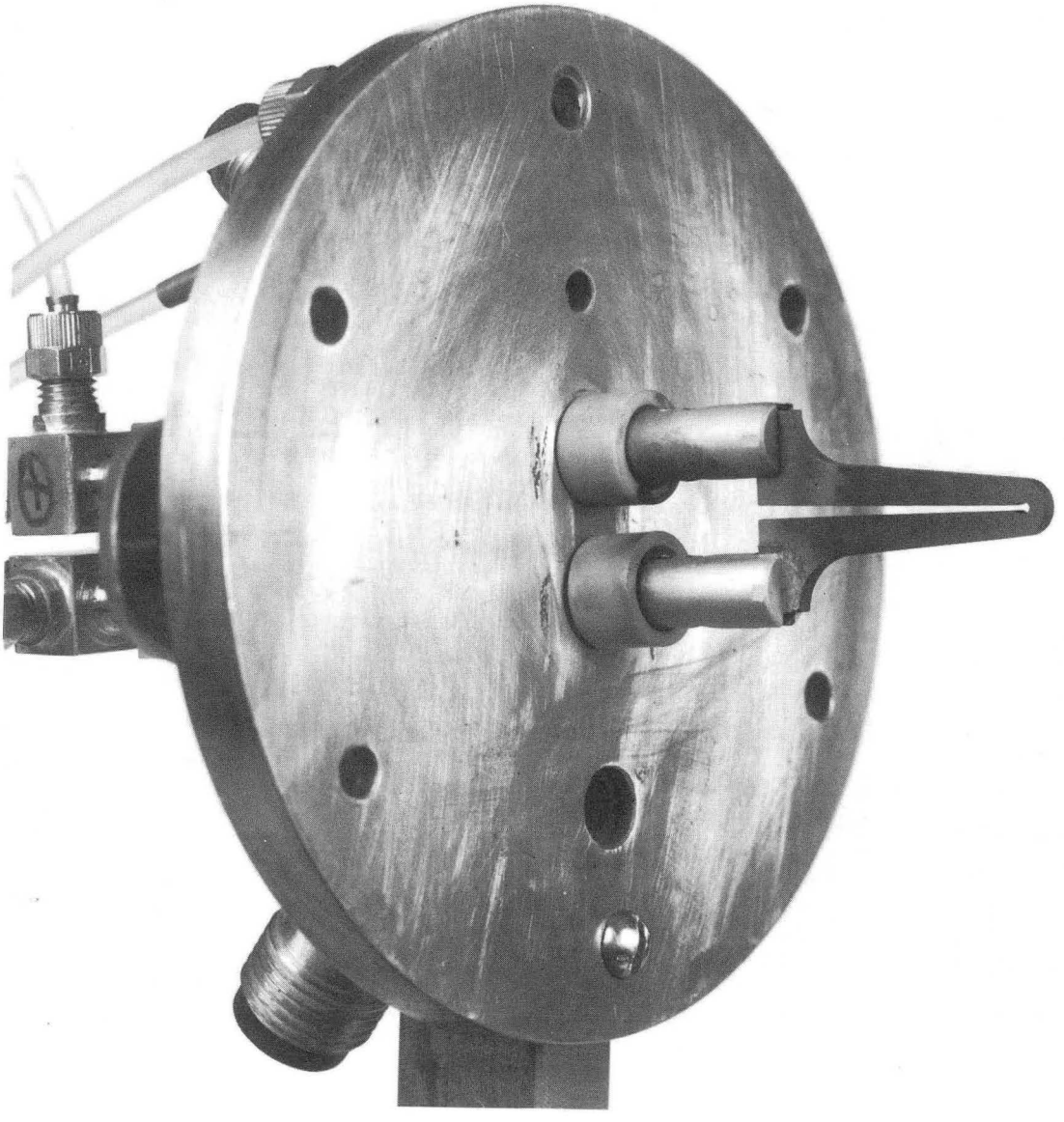
XBB 887-7246

Fig. 10



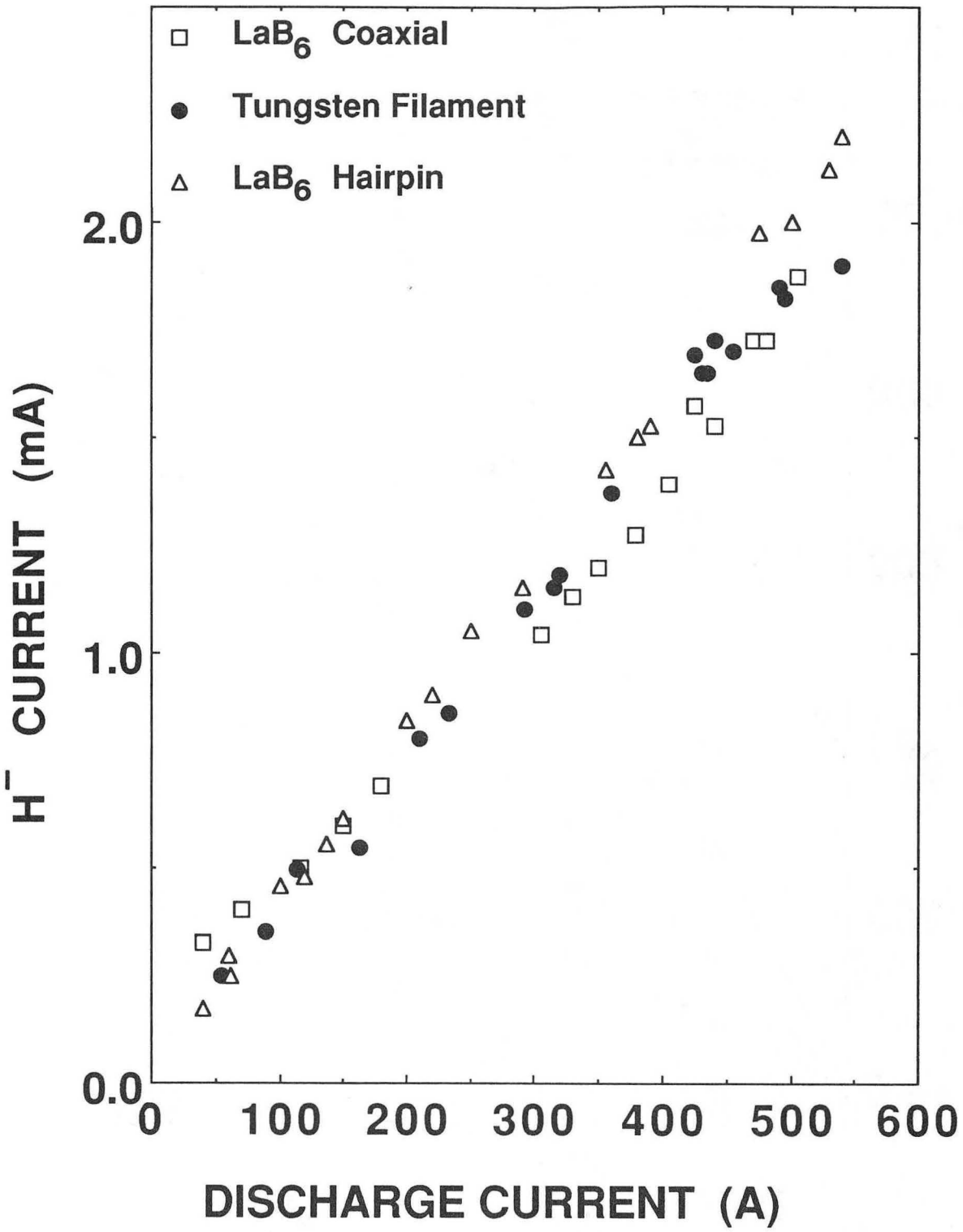
XBB 887-7247

Fig. 11



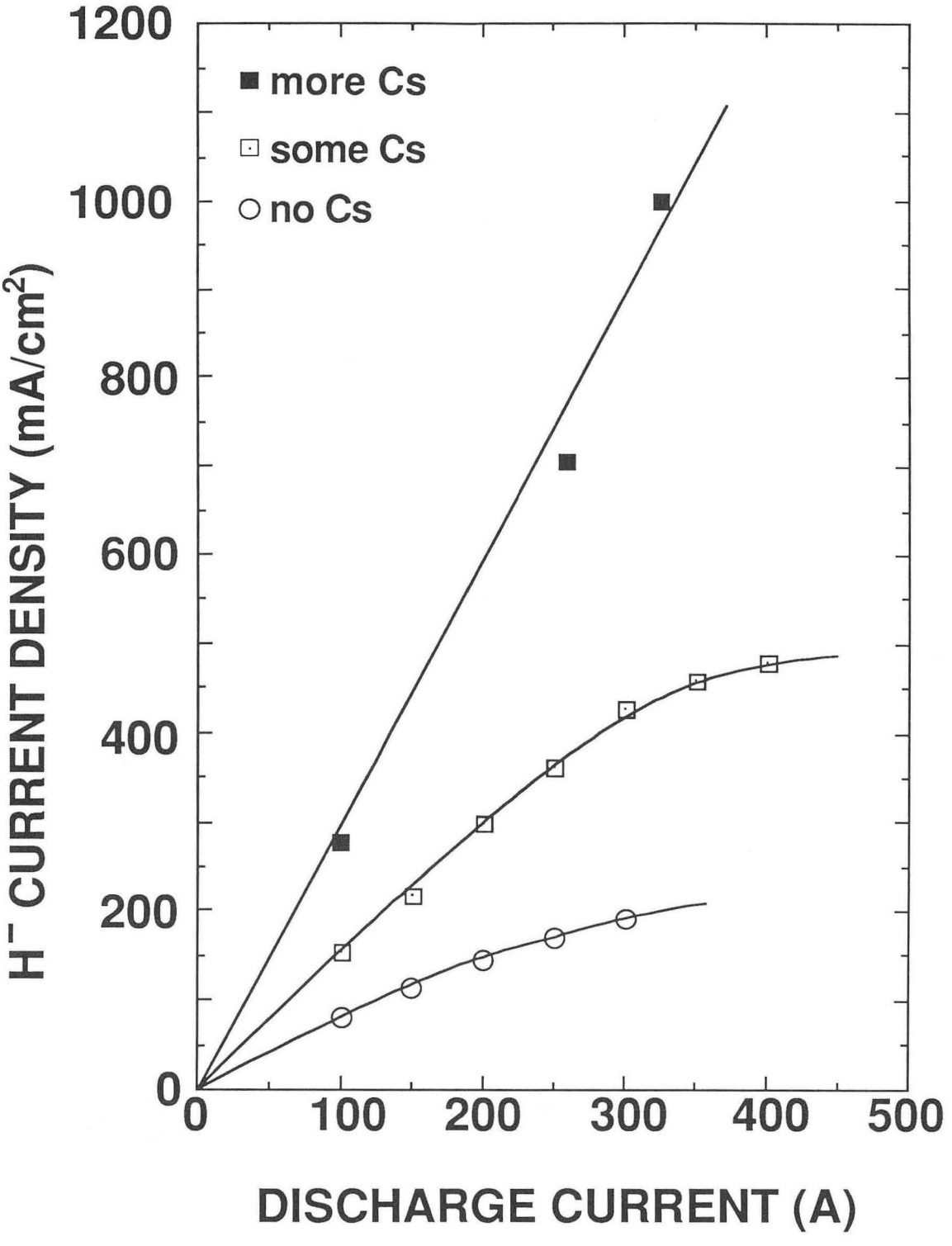
CBB 876-4931

Fig. 12



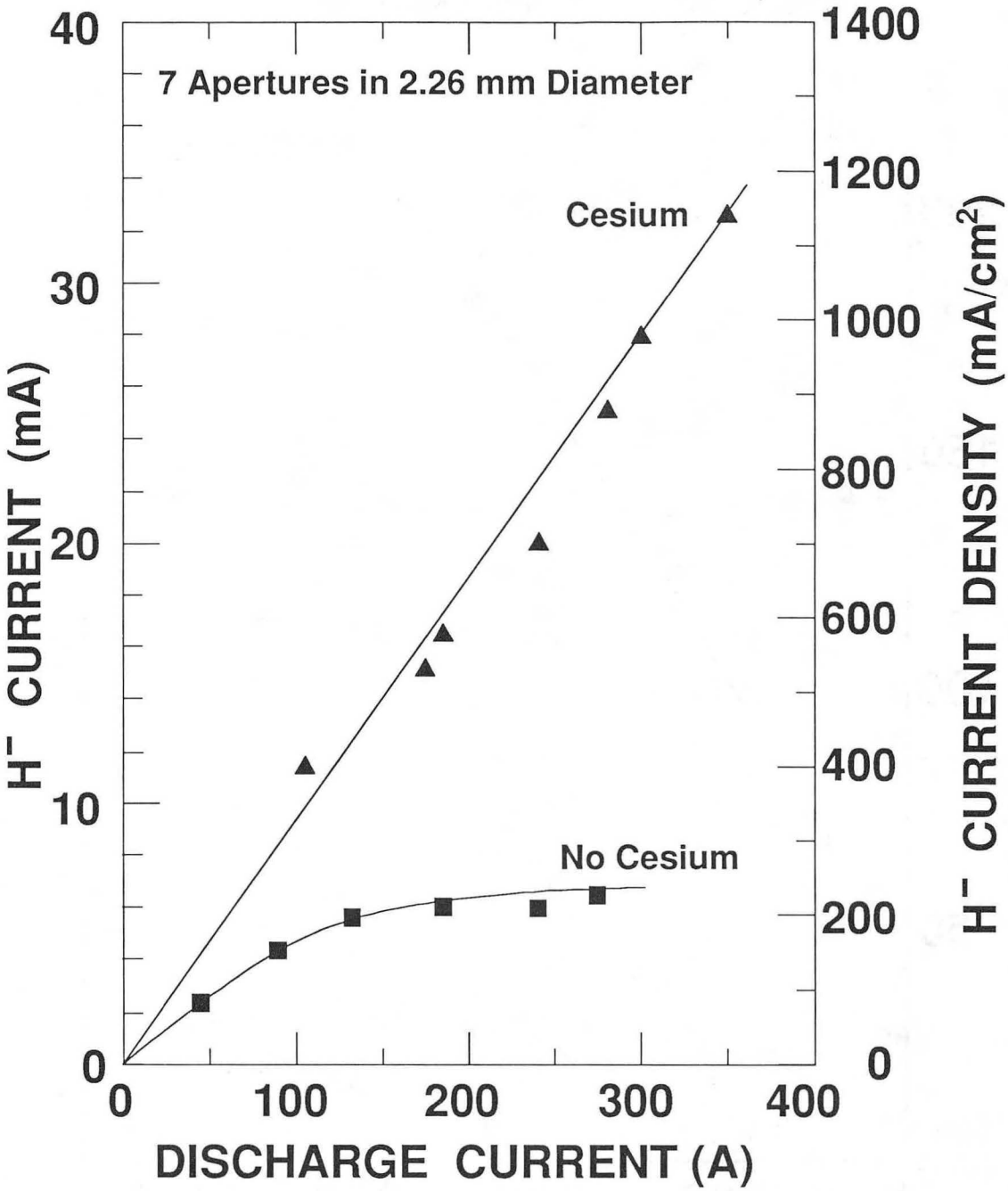
XBL 887-2637

Fig. 13



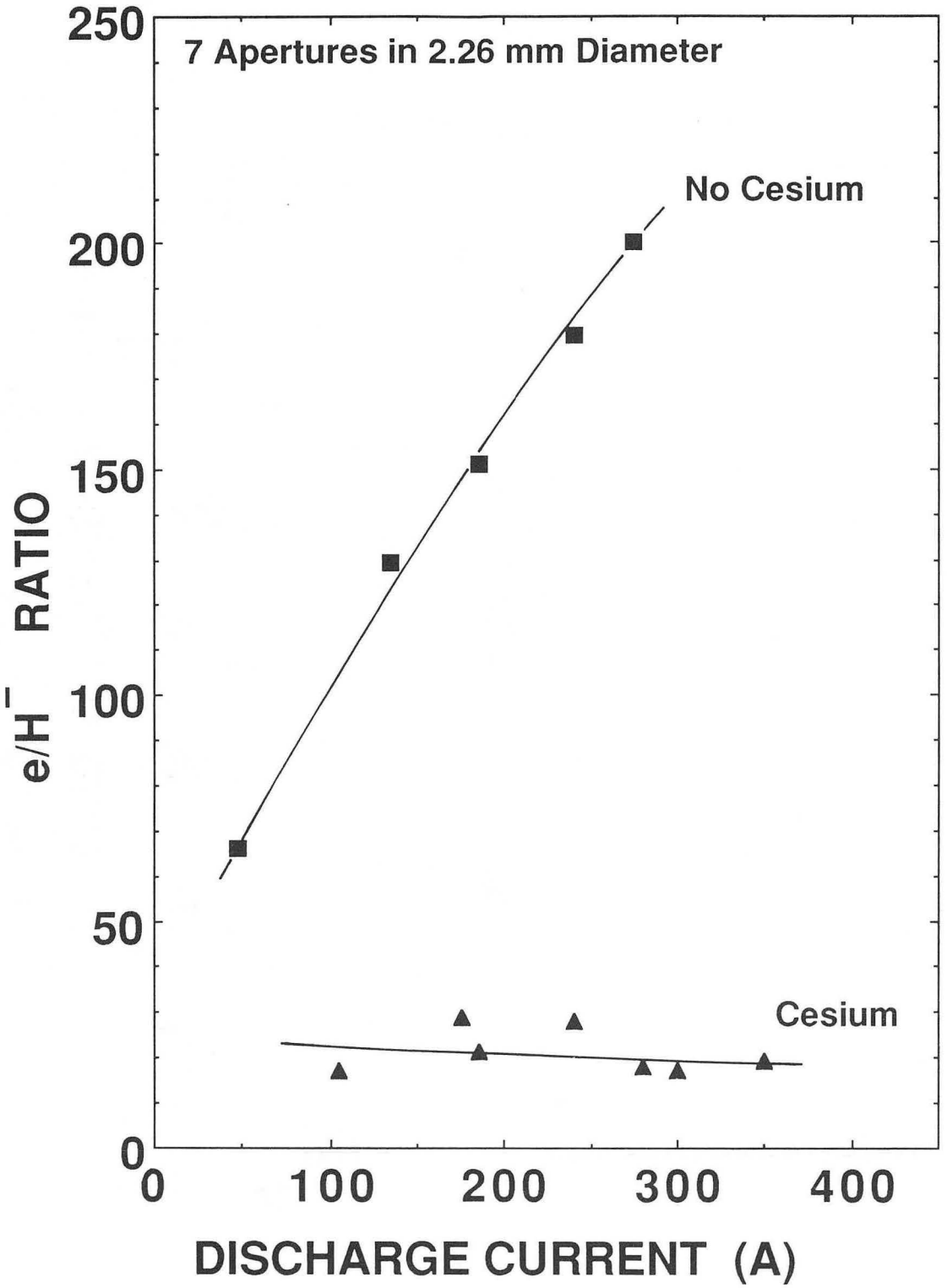
XBL 887-2646

Fig. 14



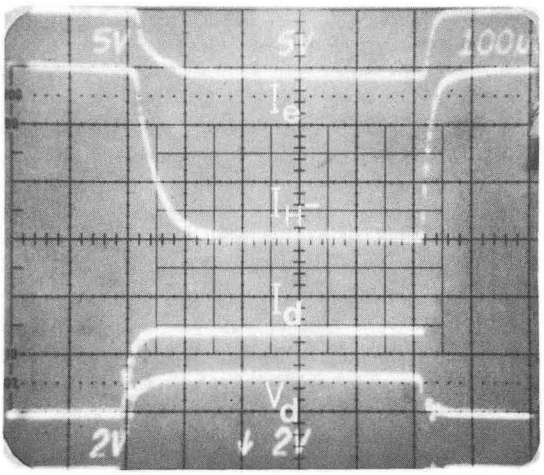
XBL 887-2667

Fig. 15



XBL 887-2650

Fig. 16



XBB 888-7355

Fig. 17

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
1 CYCLOTRON ROAD
BERKELEY, CALIFORNIA 94720