Title

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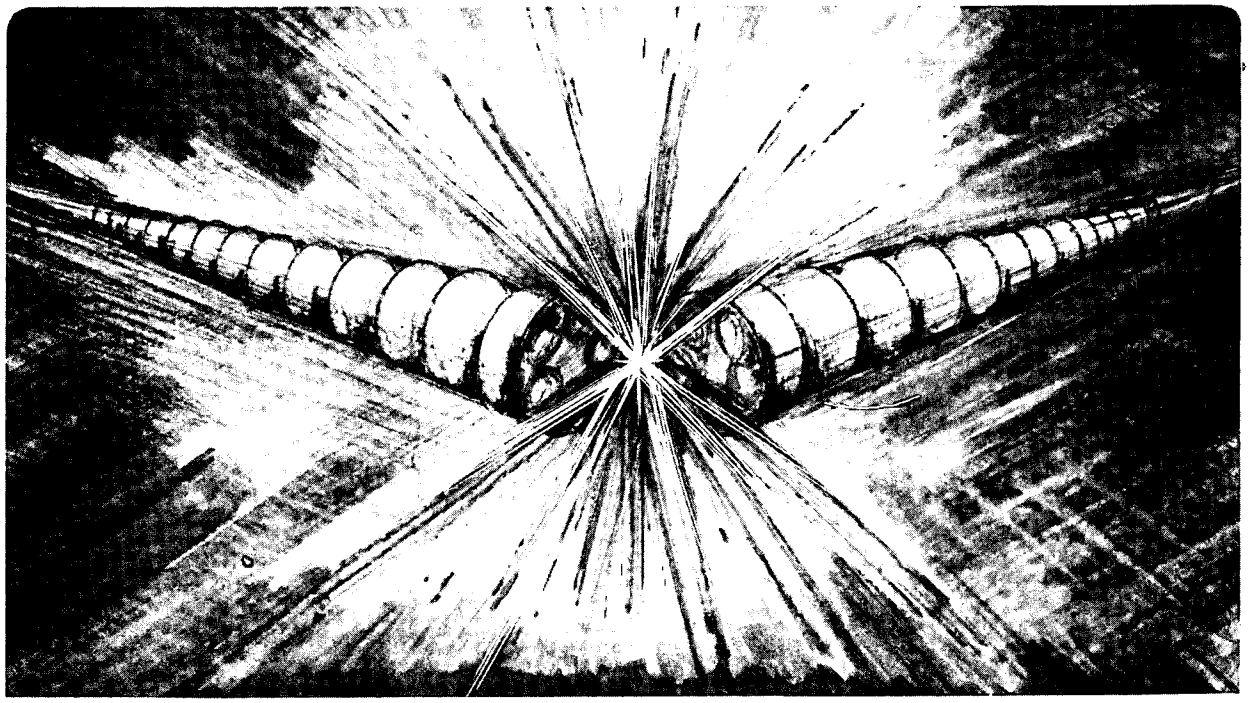

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Production of H^- Ions with Addition of Cesium or Xenon to a Hydrogen Discharge in a Small Multicusp Ion Source*

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Abstract

The effect on H^- ion production of adding cesium or xenon to a hydrogen discharge, in a small magnetically filtered multicusp ion source, has been investigated. Addition of cesium vapor to the hydrogen discharge resulted in a factor of sixteen increase in H^- output relative to the uncesiated discharge for the same operating parameters. Likewise, the addition of xenon gas to a hydrogen discharge resulted in a factor of 2.7 increase in H^- output over pure hydrogen operation at optimum H_2 source pressure, while maintaining the same arc parameters. Operation of the source with the plasma electrode at optimum bias voltage was essential to obtain this result.

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I. INTRODUCTION

Sources of H^- and D^- ions are required to generate efficient neutral beams with energies in excess of 150 keV[1]. The magnetically filtered multicusp ion source has been shown to be a promising source of high quality, high current density H^- ion beams[2]. Efforts to improve the efficiency of this type of H^- source by optimizing the chamber length[3] and chamber wall material[4] have been successful. To further improve the efficiency of this source, the effects of adding cesium or xenon to the hydroden discharge were studied.

Previous work on cesiated H^- ion sources has been concentrated on surface production type ion sources[5], but some recent work has been done on "cesiated" volume produced H^- ion sources[6,7,8]. These results, showing large increases in H^- output, imply that other source geometries may also enhance H^- output with the addition of cesium. The effect of cesium on the H^- ion yield in the filtered multicusp source has not been carefully studied. The experimental results detailed in this paper demonstrate that a substantial gain in H^- output can be achieved with the addition of cesium.

Mixing xenon with hydrogen in a filtered multicusp source discharge has been tested previously[9]. The reason for including xenon addition in this work is to compare xenon addition to cesium addition for the same ion source and filter geometry. Both species have large masses and consequently large ion gyroradii, large ionization cross sections, and lower thresholds for ionization relative to H_2. Differences in H^- output when either cesium or xenon are added may explain the function of cesium in volume H^- ion sources.

II. EXPERIMENTAL SETUP

The multicusp ion source is fabricated from a cylindrical water cooled copper chamber (2.5 cm diameter by 5 cm long) with the open end enclosed by a two-grid ion extraction system. A schematic diagram of the ion source is shown in Ref. 10. When operating with cesium, a sheet metal liner is used as the inner wall of the ion source, and an oven is attached via a valve. The liner is heated by the discharge to temperatures high enough to prevent condensation of the cesium vapor.

The source chamber is surrounded externally by 16 columns of small ceramic magnets to form a longitudinal line-cusp configuration for primary-electron and plasma confinement. The use of 16 columns of magnets, as opposed to a smaller number, allows a larger 'field-free' region ($B < 10$ gauss) where the filament is placed and primary electrons are emitted. The magnet columns on the cylindrical wall are connected at the end flange by two rows of samarium-cobalt magnets that are also in a line-cusp configuration.

A samarium-cobalt magnetic filter near the plane of extraction divides the chamber into an arc discharge and an extraction region. The filter magnets provide a transverse magnetic field ($B \approx 250$ gauss at the center) which serves to prevent energetic primary electrons from reaching the extraction region. However, positive ions and low energy electrons can diffuse across the filter into the extraction region.

A two-electrode acceleration system is attached to the open end of the chamber. The extraction aperture is 1.6 mm in diameter giving an extraction area of 2×10^{-2} cm^2. The source is biased positive for positive-ion extraction and negative for negative-ion extraction. The

second electrode is electrically grounded. A plasma is produced by primary electrons emitted from a 0.5-mm-diameter hairpin tungsten filament. The chamber wall serves as the anode for the discharge. The plasma electrode can be biased independently of the anode to optimize H^- ion extraction. This electrode is also operated at high temperature to prevent condensation of cesium.

Located downstream from the second electrode is a compact magnetic deflection spectrometer[11] for measurement of the ion species in the extracted beam. A Faraday cup was also available to sample the H^- ion beam current. In this case, a permanent magnet mass separator[12] was used to remove electrons from the extracted beam.

III. EXPERIMENTAL RESULTS

A. Source operation with hydrogen and cesium

For source operation with cesium vapor, an oven containing metallic cesium is connected to the ion source via a valve as shown schematically in Fig. 1. Initially, the oven is heated to 400 ^oC with the valve closed to breakdown an oxide layer that may form on the surface of the cesium during loading of the oven. The oven is then cooled to below 150 ^oC and the valve is opened. During this time and throughout the experiment, heater tapes maintain the temperature of the valve and transport tubing at ~ 300 ^oC to minimize cesium condensation. The oven is then heated to temperatures greater than 150 ^oC to drive cesium from the oven into the discharge chamber.

The ion source was first operated without cesium to determine source performance when only hydrogen gas is used. The mass spectrometer was

used to measure the positve ion species distribution and the H^- signal level. Figure 2(a) shows the positive ion species in the extracted beam for an arc voltage of 80V and an arc current of 2A. It can be seen that H_3^+ is the dominant positive ion species in the beam, with the distribution being 5% H^+, 12% H_2^+, and 83% H_3^+. The negative ion spectrometer signal is shown in Fig. 3(a). In this case, H^- ions are the main negative ion species in the discharge, and no other negative ion species was detected.

Cesium was introduced to the discharge by opening the valve to the cesium oven. The H^- output signal was monitored while maintaining the same discharge parameters. Fig. 4 shows the H^- output signal as a function of the oven temperature. With the oven temperature adjusted at or below 150 ^oC, no significant change in the H^- ion signal is observed. As the oven temperature exceeds 170 ^oC, the H^- signal increases steadily with temperature until a plateau is reached at ~300 ^oC. The maximum enhancement of the H^- signal with cesium is over sixteen times that for operation with pure hydrogen.

To verify that cesium was indeed in the plasma, a positive ion beam was extracted from the source and Fig. 2(b) and (c) illustrate the resulting positive ion spectrum. Fig. 2(b) shows that the hydrogen ion species distribution changes to 4% H^+, 7% H_2^+, and 89% H_3^+, very similar to operation without cesium but with a slightly higher percentage of H_3^+ ions.

Cs^+ ions are not seen in the spectrum of Fig. 2(b) because they are too massive to be collected at this extraction voltage (187V). When the extraction voltage is lowered to 35V (Fig. 2(c)), the spectrum shows the presence of the Cs^+ ion peak, along with H_3^+ions. Indeed, cesium ions are the dominant positive ion species in the discharge because cesium has a

much larger ionization cross section, and a low threshold ionization energy (3.9eV). Because of its large mass, Cs^+ ions have a larger ion gyroradius than H_3^+ ions. Thus they can penetrate the magnetic filter much more easily. Fig. 3(b) shows the spectrometer signal for H^- with cesium in the discharge; this signal is much larger than that obtained for pure hydrogen operation (Fig. 3(a)). Again, H^- ions are the dominant negative ion species and no Cs^- ions have been detected.

After an hour of operation, the valve to the cesium oven was closed and the source was operated only with residual cesium. After several hours of additional operation, only a slight decrease in H^- output was observed. This indicates that neutral cesium leaves the ion source at a very slow rate, either through condensation at cold spots on the wall or through the extraction aperture. If the cesium is highly ionized, the potential barrier of negative ion extraction can keep the cesium ions from exiting through the extraction aperture. Thus, serious breakdown problems in high voltage accelerating structures can be minimized.

The source has also been operated with no arc voltage present. In this case only the filament was on. The H^- ion signal was still detected with an amplitude comparable to the pure hydrogen discharge case. The filament was driven with a voltage of 5V and a current of 20A. Therefore, cesium ionization can still occur either by electron impact or by surface ionization on the filament. However, vibrational excitation of the hydrogen molecule cannot proceed by the usual mechanism - electron impact excitation of an electronically excited state of H_2 which decays into a vibrationally excited state, because the electron energy is too small (<5eV). Vibrationally excitated H_2 molecules could be generated by recombination of hydrogen

atoms on a surface[13]. In this case, hydrogen atoms are produced by dissociation of H_2 on the tungsten filament.

There are several reasons why the addition of cesium can improve the H^- output of the filtered multicusp source[14]. Cesium has a large ionization cross-section at low electron energies relative to H_2. Hence, cesium is efficiently ionized in the discharge, resulting in a much higher plasma density for a given discharge power. This, coupled with its large gryoradius (6.5 cm at 250 gauss and E=1eV) compared to H_3^+ (1.0 cm at 250 gauss and E=1eV), will allow the cesium ions and low energy electrons to diffuse much more easily across the filter field and gives a much higher plasma density in the extraction region of the ion source. The presence of a large concentration of low energy electrons in the extraction region in turn, can greatly improve the conversion of vibrationally excited H_2 into H^- ions.

Since a molybdenum surface partially covered by cesium has a very low work function, the impact of positive ions or absorption of ultraviolet radiation may cause emission of additional electrons with energies in the range of 1 eV. In addition, cesium atoms may cool the electrons in the extraction region through inelastic collisions at low energy (1 - 10 eV). There is also a reaction between cesium atoms and H_3^+ ions to give vibrationally excited H_2:

$$Cs + H_3^+ \Rightarrow Cs^+ + H_2(v^*) + H \qquad (1a)$$

$$Cs + H_3^+ \Rightarrow Cs^+ + 3H \qquad (1b)$$

The cross-section and branching ratio for the above reactions are known at

higher energies (>15eV)[14], but not at the lower energies of interest (0-5eV). For energies of 15-1000 eV, the cross-section for 1(a) is greater than 10^{-14} (cm^2)[14]. Nevertheless, this reaction may also contribute to the increase in H^- output by providing more vibrationally excited molecules. Finally, it is also possible that the discharge chamber walls are not hot enough to prevent adsorption of a monolayer of cesium and thus can add H^- ions produced by surface conversion of H^+ ions.

B. Source operation with hydrogen and xenon

Source operation with hydrogen and xenon was investigated at a variety of hydrogen and xenon partial pressures. Fig. 5 shows the results of adding xenon to a hydrogen discharge at different hydrogen pressures. Here, the H^- output signal is plotted as a function of the ionization gauge reading obtained downstream from the ion source. For each point, the plasma electrode bias voltage was adjusted to provide the optimum H^- output. The curve marked by open squares denotes operation with hydrogen only. For the other curves, the first point represents pure hydrogen operation, with higher pressures the result of adding xenon only. Since the ionization gauge is ~6.5 times as sensitive to xenon as hydrogen, the real increase in pressure due to xenon to achieve the best H^- output is only about 6% over the starting pressure (2.2×10^{-6} torr). The best H^- output for hydrogen only is achieved at about 5×10^{-6} torr.

In order to verify the increase in H^- output recorded by the spectrometer, a Faraday cup was used to measure the total extracted negative ion current. The electrons in the beam were removed by a permanent magnet mass separator, while the H^- ions were collected by the

Faraday cup. Fig. 6 shows the H^- output versus pressure for both the spectrometer and the Faraday cup signal. There is very good agreement between the two except at the highest pressures. This may be due to the increase in stripping of the H^- ions inside the spectrometer.

The positive and negative ion species in the extracted beam were measured by the spectrometer for operation with and without xenon. Fig. 7(a) shows the positive ion species of the pure hydrogen discharge (6% H^+, 11% H_2^+, 83% H_3^+). When xenon is added to the discharge, the hydrogen species mix changes to 50% H^+, 12% H_2^+, and 38% H_3^+ (Fig. 7(b)). This spectrum is very different than that of Fig. 2(b) for cesium-hydrogen operation. The addition of xenon shifts the species mix to give a much larger percentage of protons in the beam.

To verify the presence of Xe^+ ions, the extraction voltage was lowered to 35V to allow Xe^+ ions to be collected by the spectrometer. Fig. 7(c) demonstrates that the Xe^+ ion is the dominant species, with H^+ and H_3^+ ion peaks also visible. Fig. 8 shows the spectrometer output signal for negative ion extraction, with Fig. 8(a) obtained for operation with hydrogen only, and Fig. 8(b) for xenon-hydrogen operation. For the case of a xenon-hydrogen discharge, no negative impurity ions were detected.

IV. Discussion

As in the case of cesium, xenon also provides a higher density of low energy electrons to the extraction region of the ion source. This increase in electron density enhances H^- ion production. It should be noted that the peak filter field strength used in these experiments is comparitively strong (B = 250 gauss at the center) . While both cesium and xenon addition

increase H^- output, cesium provides greater H^- enhancement even though the plasma electrode bias was not optimized in this experiment. There are several reasons why this is the case. Since cesium has a considerably lower ionization energy than xenon, cesium may provide a higher plasma density than xenon in the extraction region of the discharge. Also, cesium may cool the electrons in the extraction region more effectively than xenon. This would reduce H^- losses due to stripping by energetic electrons. Another possibility is the reaction given by equation 1(a), whereby H_3^+ ions are converted into vibrationally excited hydrogen molecules. However, more information about the cross section of this reaction in the energy range of interest is needed in order to determine the importance of this process. Additional surface production of H^- ions is also a possibility.

This experiment suggests that addition of cesium to higher power filtered multicusp ion sources may provide much larger H^- current densities than previously attained. Only minor modifications to the ion source are required for cesium operation, and with continuous negative ion extraction, very little cesium will escape from the source.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Fig. 1. A schematic drawing of the filtered multicusp ion source with the cesium oven attached.

Fig. 2. Spectrometer output showing the positive ion species in the extracted beam for (a) pure hydrogen operation, (b) operation with hydrogen and cesium, and (c) operation with hydrogen and cesium at lower extraction voltage.

Fig. 3. Spectrometer output showing the negative ion species in the extracted beam for (a) pure hydrogen operation and (b) operation with hydrogen and cesium (background hydrogen pressure is the same in both cases).

Fig. 4. A graph of the H^- yield as a function of the cesium oventemperature.

Fig. 5. A graph of the H^- yield as a function of the unnormalized ion gauge reading downstream from the ion source. The open squares represent pure hydrogen operation. The closed diamond represent 1.3×10^{-6} H_2 plus xenon; the heavy bordered square 2.2×10^{-6}; the open diamond 4.1×10^{-6} H_2 plus xenon; the closed square 6×10^{-6} H_2 plus xenon.

Fig. 6. A graph of the H^- yield as a function of the unnormalized ion gauge reading for both the spectrometer and the Faraday cup.

Fig. 7. Spectrometer output showing the positive ion species in the extracted beam for (a) pure hydrogen operation, (b) hydrogen with xenon, and (c) hydrogen with xenon at low extraction voltage.

Fig. 8. Spectrometer output showing the negative ion species in the extracted beam for (a) pure hydrogen operation and (b) operation with hydrogen and xenon (background hydrogen pressure is the same on both cases).

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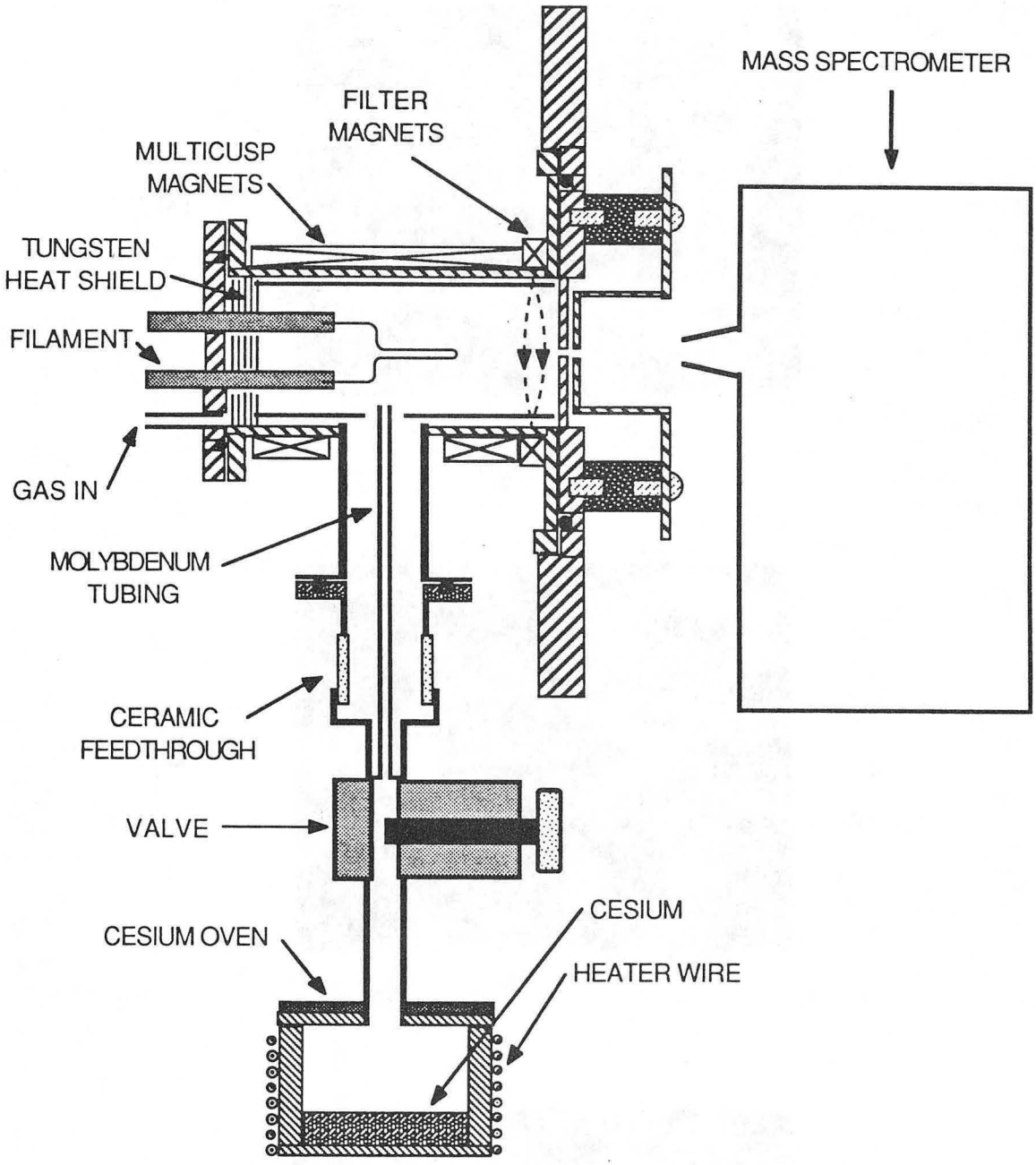

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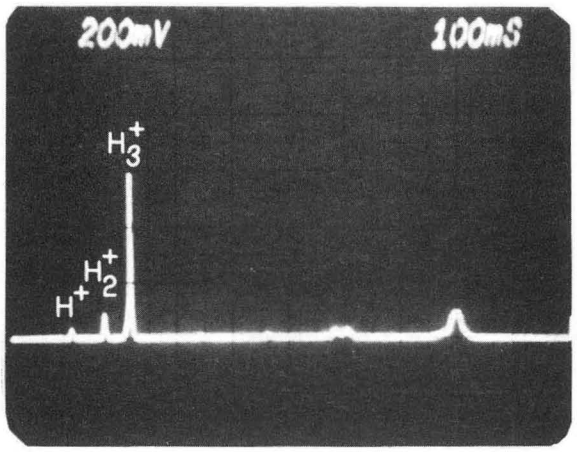

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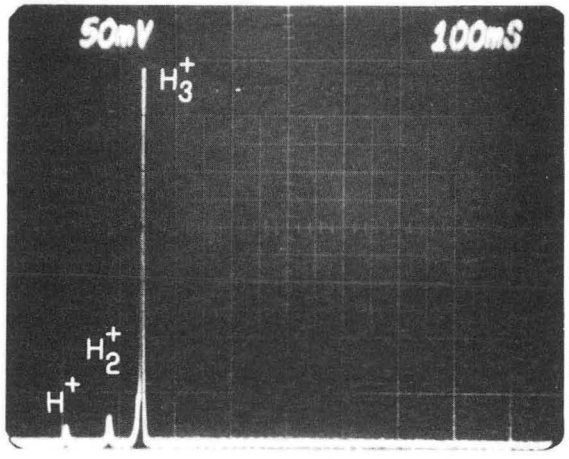

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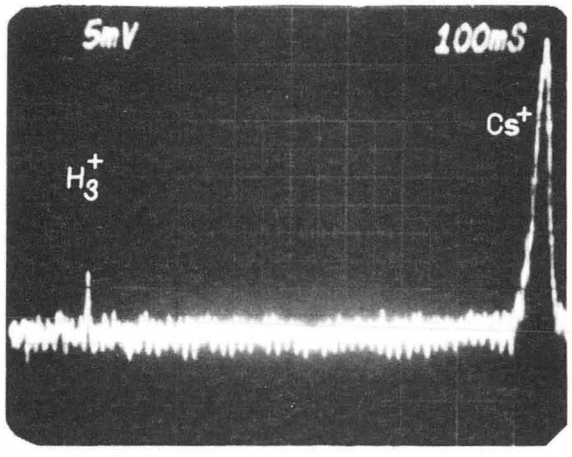

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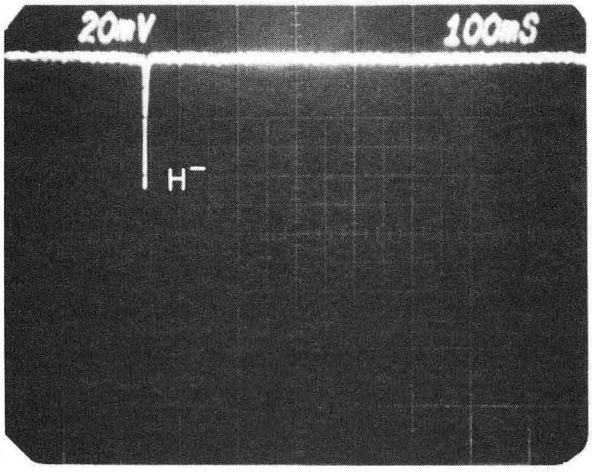

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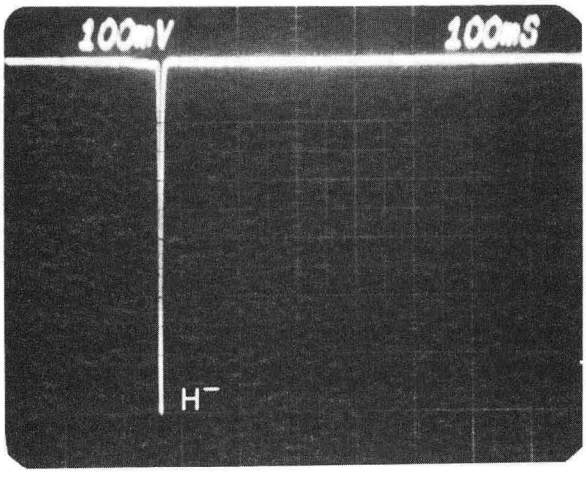

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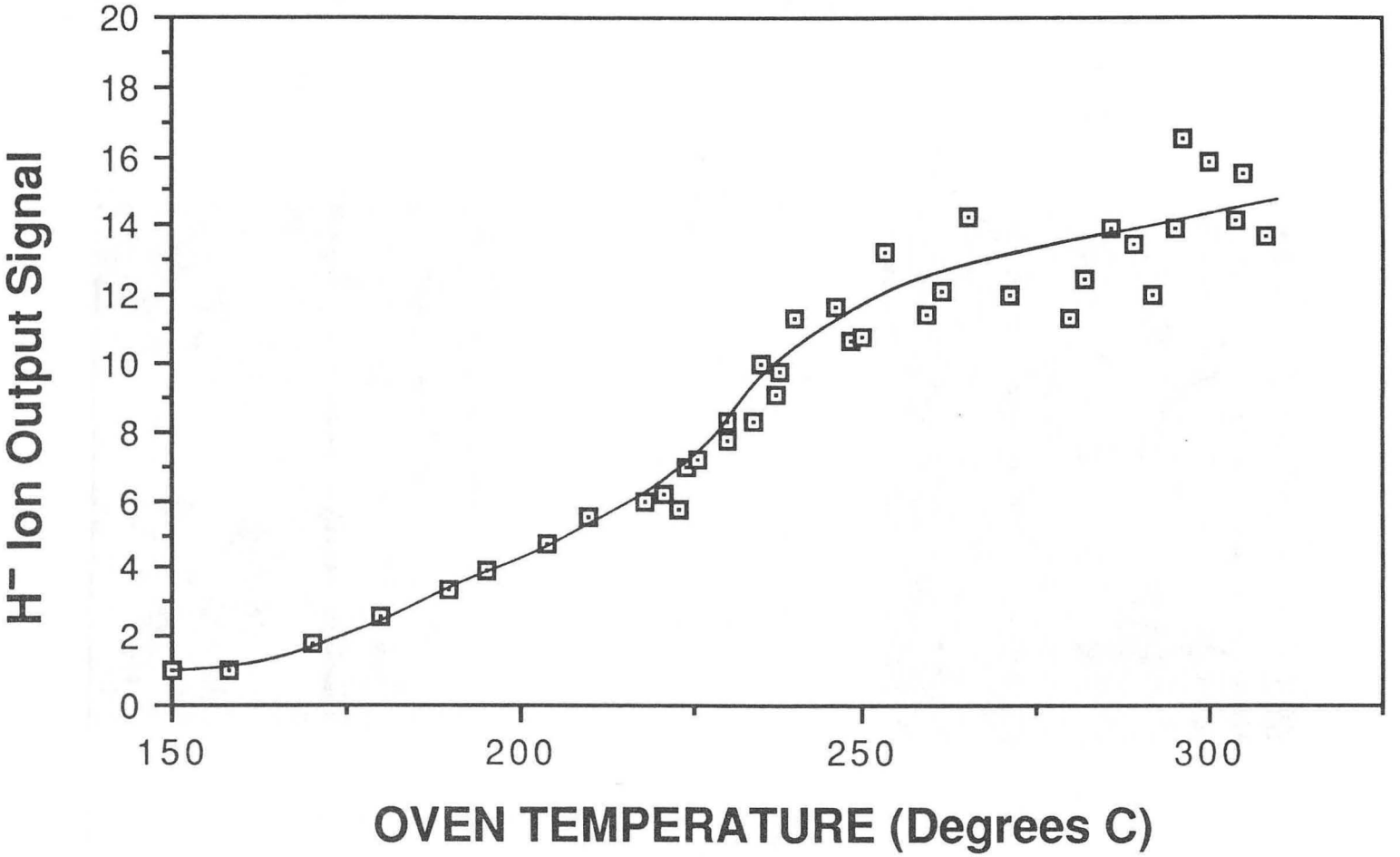

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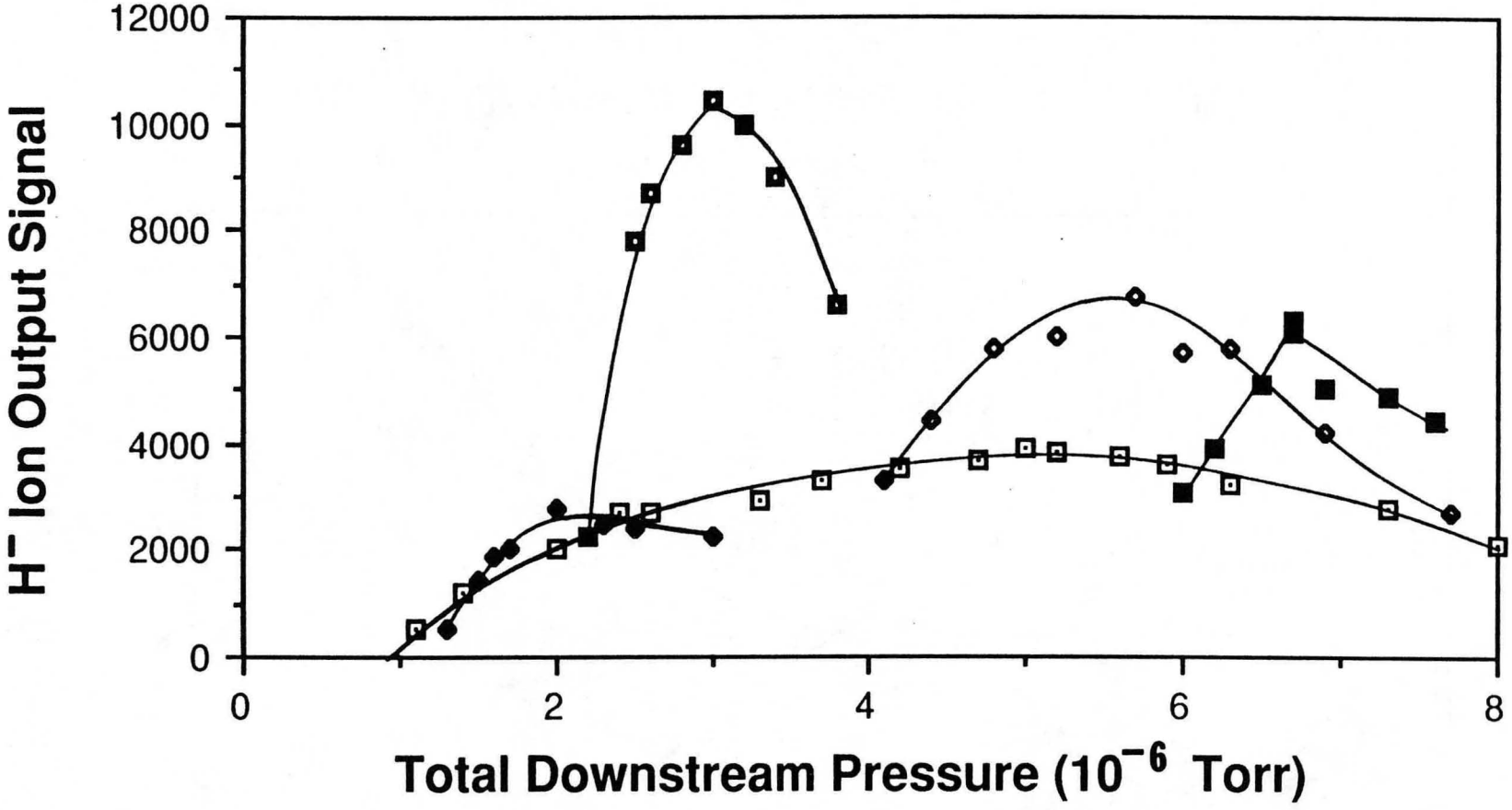

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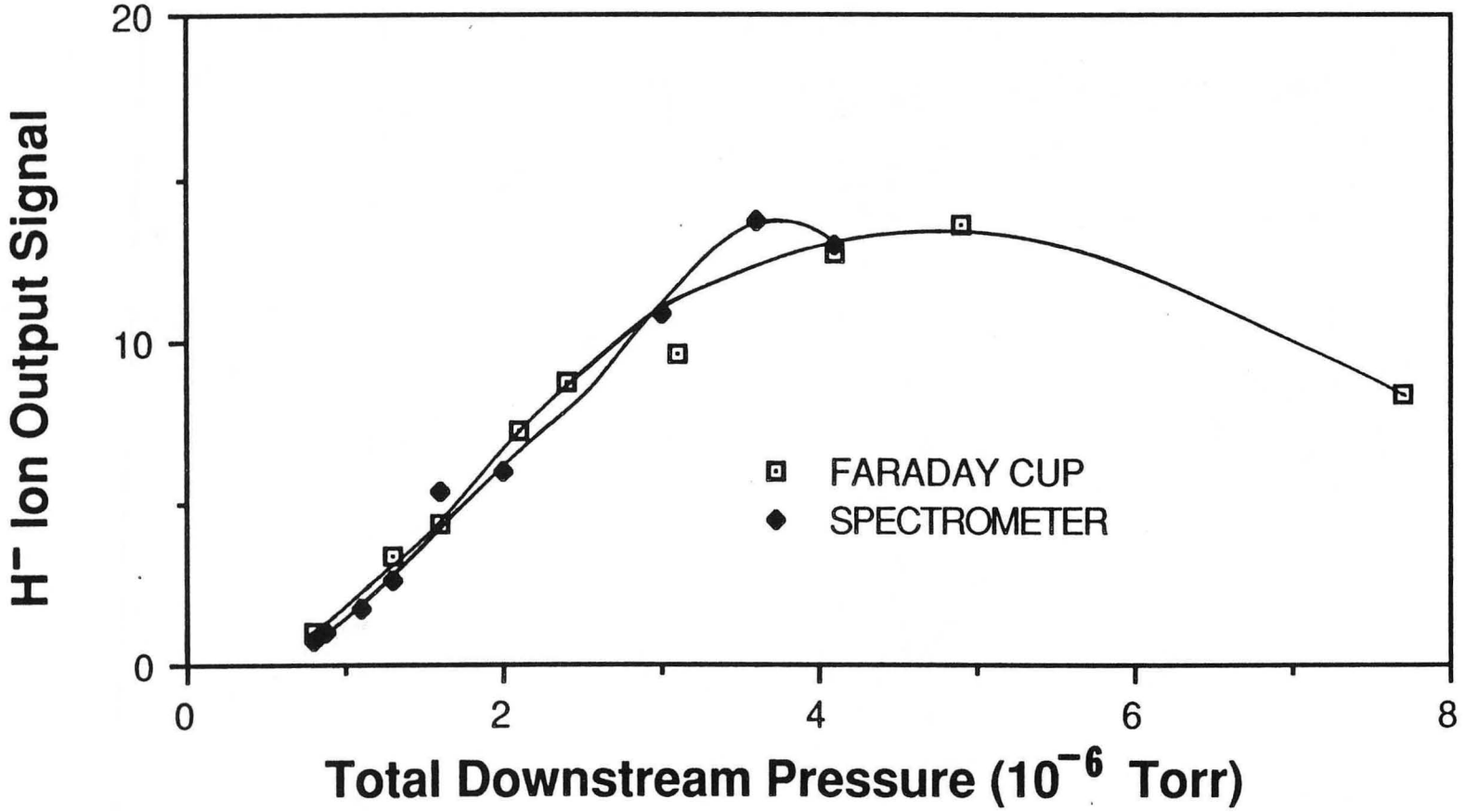

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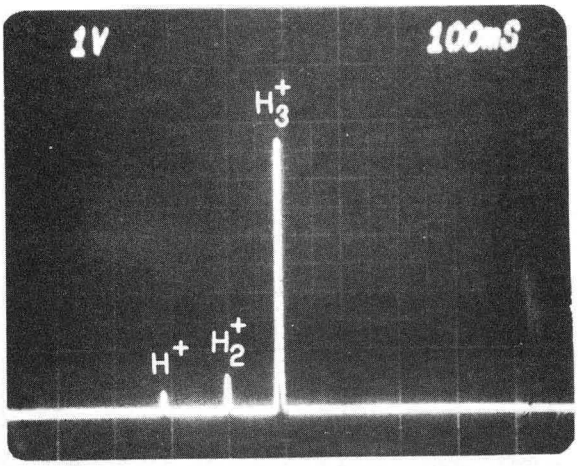

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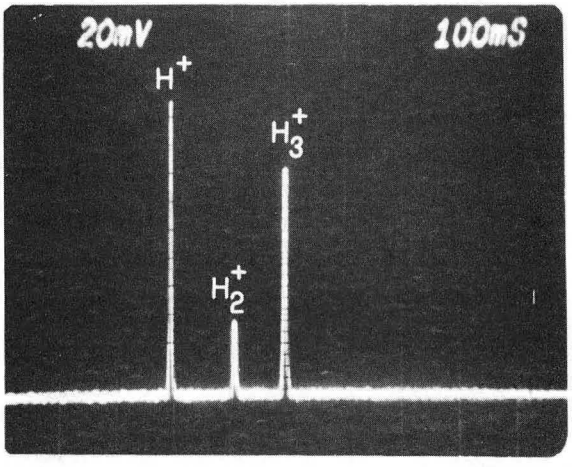

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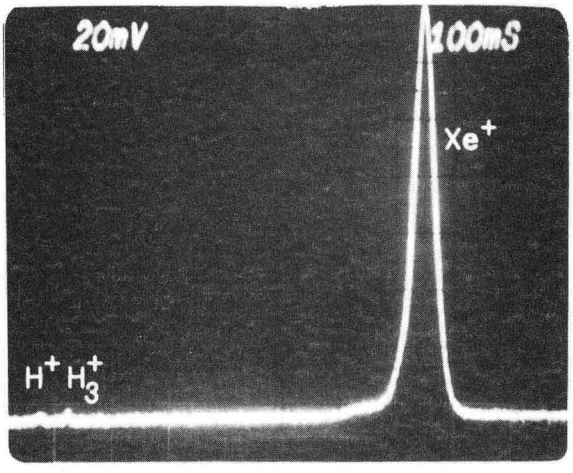

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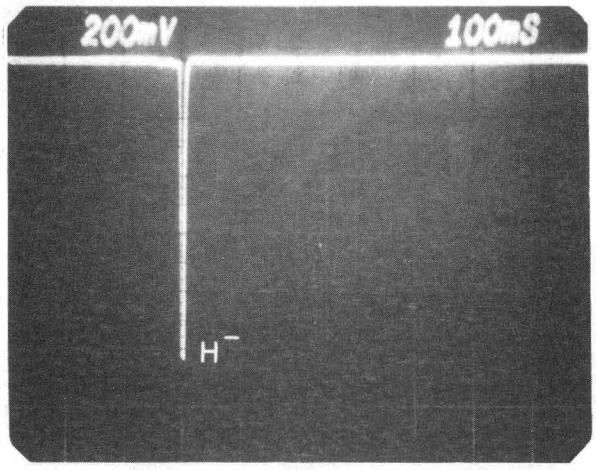

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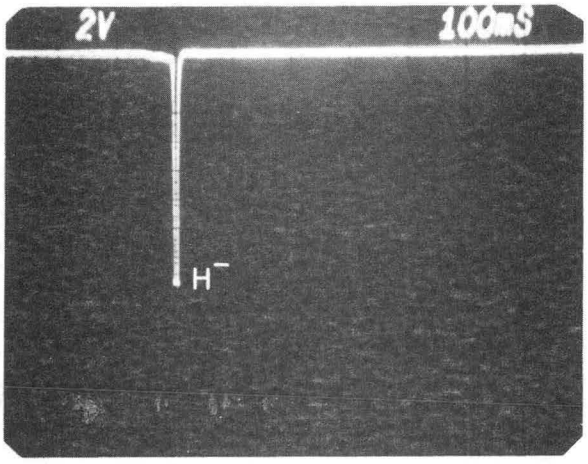

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Figure 8

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