

## VOLUME H- ION PRODUCTION EXPERIMENTS AT LBL\*

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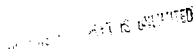
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**MASTER**




VOLUME H<sup>-</sup> ION PRODUCTION EXPERIMENTS AT LBL\*

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## ABSTRACT

H<sup>-</sup> ions formed by volume processes have been extracted from a multicusp ion source. It is shown that a permanent magnet filter together with a small positive bias voltage on the plasma grid can produce a very significant reduction in electron drain as well as a sizable increase in H<sup>-</sup> ions available for extraction. A further reduction in electron current is achieved by installing a pair of small magnets at the extraction aperture. An H<sup>-</sup> ion current density of 38 mA/cm<sup>2</sup> was obtained with a discharge current of approximately 350 A. Different techniques to increase the H<sup>-</sup> ion yield have also been investigated.

## INTRODUCTION

In recent years, neutral beam injection has proven to be an effective way to heat plasmas in fusion devices to thermonuclear temperatures.<sup>1,2</sup> Higher energy neutral beams will be required for plasma heating and for current drive in some future fusion reactors.<sup>3</sup> The high neutralization efficiency of H<sup>-</sup> or D<sup>-</sup> ions makes these negative ions the favorite to form atomic beams with energies in excess of 150 keV.<sup>4</sup> There are several approaches for producing H<sup>-</sup> or D<sup>-</sup> ions. A self-extraction negative ion source based on surface conversion of positive ions has already been operated successfully to generate a steady-state H<sup>-</sup> ion beam current greater than 1 A.<sup>8</sup> Several experiments have been conducted to extract H<sup>-</sup> ions directly from a hydrogen discharge plasma.<sup>9-11</sup> This technique of generating H<sup>-</sup> ions has the advantage over the surface and double charge exchange processes in that it requires no cesium and it uses presently developed large area positive ion source geometries which have demonstrated good ion optics for large positive ion current. However, one must find methods to handle the electron problem in order to make the negative ion source practical.

This paper presents a novel method of extracting volume produced H<sup>-</sup> ions directly from a multicusp ion source. This type of plasma generator has demonstrated its ability to produce large volumes of uniform and quiescent plasmas with a high H<sup>+</sup> or D<sup>+</sup> ion fraction and with good gas and electrical efficiency.<sup>12,13</sup> We show that the addition of a magnetic filter<sup>14</sup> to the source will not only enhance the H<sup>-</sup> ion yield but sizably reduce the extracted electron component. It is also shown that the electron current can be further reduced substantially by installing a pair of thin permanent magnets at the extraction aperture. The H<sup>-</sup> ion beam current was found to increase almost linearly with the discharge current. An H<sup>-</sup> current density of 38 mA/cm<sup>2</sup> was obtained with a discharge current of approximately 350 A. Attempts have also been

made to increase the  $H^-$  ion yield by optimizing the discharge voltage; by injecting very low energy primary electrons into different chambers; by increasing the electrostatic containment potential; and by using some special source geometries.

#### EXPERIMENTAL SETUP

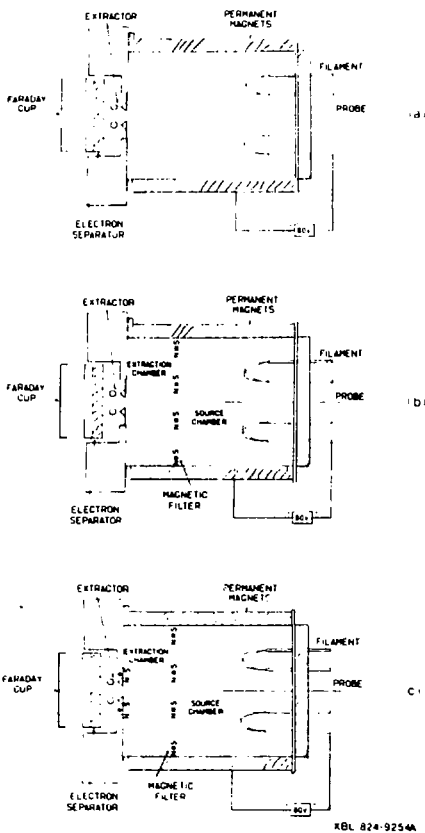


Fig. 1 Schematic diagram of (a) the multicusp ion source, (b) the multicusp ion source with a filter, and (c) a magnetically filtered multicusp source equipped with an E X B electron suppressor.

Figure 1(a) is a schematic diagram of the test multicusp ion source geometry. The device is a cylindrical stainless-steel chamber (20-cm diameter by 24-cm long) surrounded externally by ten columns of samarium-cobalt magnets ( $B_{max} \approx 3.6$  kG). These magnets form continuous line-cusps parallel to the source axis and they are connected at the end plate by four extra rows of magnets. The open end of the chamber is enclosed by a three-grid extraction system. When operated as a  $H^-$  ion source, the second and third grids were connected to ground. The first or plasma grid was masked down to a small ( $0.15 \times 1.3$  cm<sup>2</sup>) extraction slot and was biased at a potential equal to or more positive than the anode. A steady-state hydrogen plasma was produced by primary electrons emitted from four 0.05-cm diam. tungsten filaments and the entire chamber wall served as the anode for the discharge. The data presented in the next section were obtained with a modest discharge current of 1 A and a discharge voltage of 80 V.

Figure 1(b) shows a

schematic of the source when a permanent magnet filter is included. This filter provides a limited region of transverse magnetic field which is made strong enough to prevent all energetic primary electrons in the source chamber from crossing into the extraction chamber. Ions, because of their much larger mass, can penetrate the filter, and the interesting feature of the magnetic filter is that the electrons which accompany these ions to form the plasma in the extraction region are very cold ( $T_e \approx 0.4$  eV).

Recent experiments have shown that the addition of a magnetic filter to a multicusp ion source can improve the  $H^-$  fraction, the source operability, and the plasma density profile at the extraction plane.<sup>15,16</sup> In order to increase the geometric transparency and to provide adequate cooling, the filter was constructed by inserting square permanent magnet rods into copper tubes through which a square broach had been passed. Since the magnets rested on the four broached grooves, their orientation was fixed and water was then run through the remaining space to provide cooling.

During normal operation, the pressure outside the source was maintained at  $1 \times 10^{-4}$  Torr as measured by an ionization gauge. The actual pressure inside the source chamber was approximately  $1.5 \times 10^{-3}$  Torr. Plasma parameters were obtained by Langmuir probes located at the center of the source chamber and in front of the plasma grid in the extraction chamber.

To extract  $H^-$  ions, a negative potential ( $\sim 1$  kV) was applied to the source chamber with respect to ground. The small extracted beam was then analyzed by two diagnostic techniques. (1) A compact magnetic deflection mass spectrometer,<sup>17</sup> located just outside the extractor was used for relative measurement of the extracted  $H^-$  ions and for the analysis of the extracted ion species. However, this measurement could not determine the total current of  $H^-$  ions or electrons in the extracted beam. (2) A permanent magnet mass separator, located just behind the last grid of the extractor was used with a Faraday cup to measure the extracted  $H^-$  ion and electron currents. After passing through the slit, the electrons were deflected onto a grooved graphite collector by the weak magnetic field produced by a pair of thin ceramic magnets. The  $H^-$  ions which were only slightly affected by the magnetic field of the electron separator proceeded into the Faraday cup. A small positive bias potential on the cup was used to suppress secondary electrons. With this arrangement, it was possible to measure the ratio of extracted  $H^-$  ion current to electron current as well as to determine the extracted  $H^-$  ion current density for various operational conditions.

## EXPERIMENTAL RESULTS

### (a) Source without filter

The source was first operated with a hydrogen plasma in the geometry shown in Fig. 1(a). It was found that the extractable  $H^-$  ion current was extremely small when the plasma grid was left floating electrically. The Langmuir probe characteristics in Fig. 2 illustrate that the potential  $V_p$  at the source center is

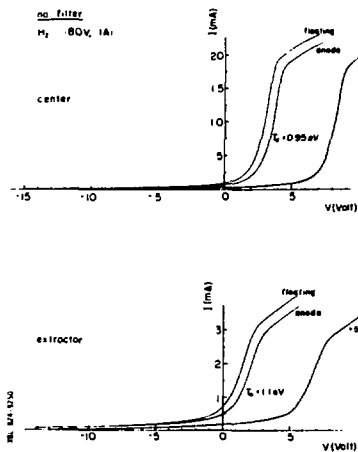


Fig. 2 Langmuir probe traces still 1.5 V more positive than obtained at the center and near that near the extractor. As a the extractor of a conventional result, only  $2 \mu\text{A}$  of  $\text{H}^-$  ion multicusp ion source for three current was extracted from the different plasma grid potentials. source with a discharge current

of 1 A (Fig. 3(a)). However, this negative ion current was accompanied by about 17 mA of electron current as shown in Fig. 3(b). Thus, the ratio of extracted negative ion current to electron current is 1/9000. By reversing the polarity of the extractional power supply,  $245 \mu\text{A}$  of positive hydrogen ion current was extracted for the same arc conditions (Fig. 3(c)). Therefore, the ratio of  $I^-/I^+$  was approximately 1/120 or 0.8%.

When the plasma grid was biased at a potential more positive than the anode ( $V_b > 0$ ), the plasma potentials also increased by about the same amount as shown by the probe traces in Fig. 2. Thus, the potential difference between the plasma and the grid and the gradient of the source plasma potential remained unchanged. There was no significant change in other plasma parameters such as  $T_e$  and density at the center or near the extractor of the source chamber, or in the extracted  $\text{H}^-$  ion or electron current.

#### (b) Source with magnetic filter

Figure 1(b) is a schematic of the source with the magnetic filter in place. Two kinds of permanent magnets have been used for the same filter geometry. Figure 4 shows the measured magnetic field across the plane of the filter between two adjacent magnet rods. It can be seen that both the magnitude and the integrated flux of the B field increase by a factor of two when the filter magnets are changed from ceramic to samarium-cobalt of the same size and shape.

When the source was operated with the "weak" ceramic magnet

positive ( $\sim 4 \text{ V}$ ) with respect to the chamber wall or anode, and that  $V_p$  at the source center is about 1.5 V more positive than that near the extractor. This potential gradient together with the fact that the plasma grid was floating approximately  $-50 \text{ V}$  relative to the anode, made it impossible for  $\text{H}^-$  ions formed in the center of the source to reach the extractor. These negative ions are electrostatically trapped within the source plasma by the positive potential well.

When the grid was connected to the anode, the potential of the plasma near the extractor was  $+3 \text{ V}$  relative to the grid and  $V_p$  at the source center was still 1.5 V more positive than obtained at the center and near that near the extractor. As a the extractor of a conventional result, only  $2 \mu\text{A}$  of  $\text{H}^-$  ion multicusp ion source for three current was extracted from the different plasma grid potentials. source with a discharge current

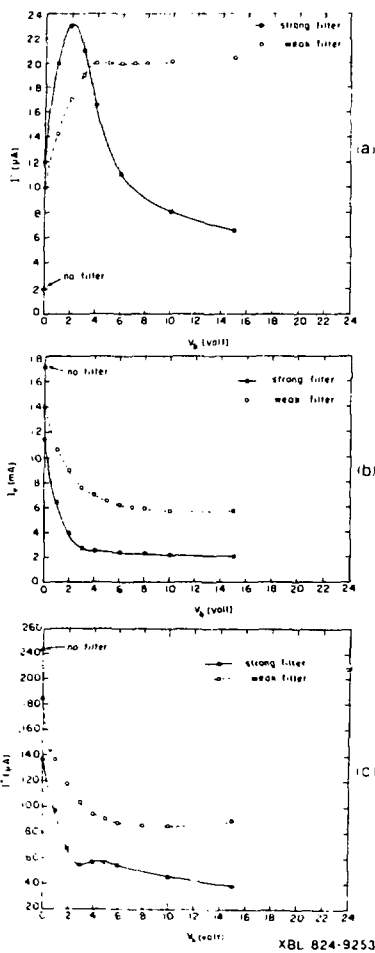


Fig. 3 (a) The extracted  $H^-$  ion current, (b) the extracted electron current, and (c) the extracted positive hydrogen ion current as a function of the plasma grid bias voltage for the strong and weak filters.

filter, the data in Fig. 3(a) shows that the extracted negative ion current  $I^-$  was about  $10 \mu A$  when the plasma grid was biased at anode potential, but  $I^-$  increased with grid bias voltage  $V_b$ , saturating at about  $20 \mu A$  at  $V_b = +5$  V. On the other hand, the extracted electron current  $I_e$  was  $14$  mA with the grid at anode potential, but it decreased to  $6.5$  mA at  $V_b = +5$  V (Fig. 3(b)). As a result, the ratio of  $I^-/I_e$  became  $1/300$  at  $V_b = +5$  V.

When the "strong" samarium-cobalt magnet filter was used, it was found that the extracted negative ion current  $I^-$  increased from  $12$  to  $23 \mu A$  as the grid bias  $V_b$  was changed from  $0$  to  $+2.5$  V. However, unlike the "weak" filter,  $I^-$  decreased rapidly as the plasma grid was biased higher than  $+2.5$  V as illustrated in Fig. 3(a). The extracted electron current  $I_e$  was about  $11.5$  mA with the grid biased at anode potential and it then decreased to  $2.8$  mA at  $V_b = +2.5$  V (Fig. 3(b)). Thus,

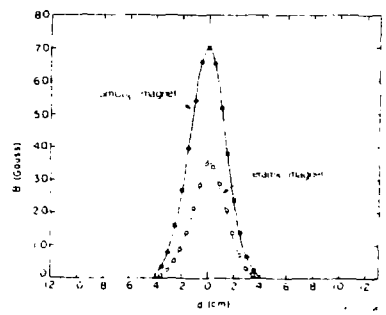


Fig. 4 A plot of the magnetic fields across the plane of the samarium-cobalt and the ceramic magnet filter in between two magnet rods.

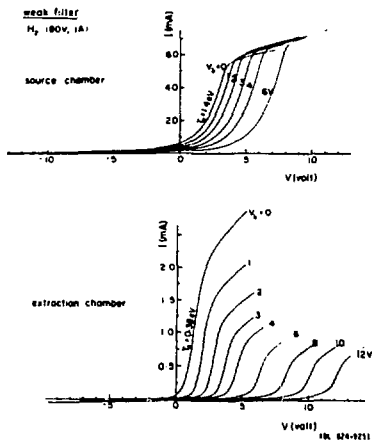


Fig. 5 Langmuir probe traces obtained in the source and extraction chambers for different plasma grid bias voltages for the case of a weak ceramic magnet filter.

by employing the strong samarium-cobalt magnet filter and by biasing the plasma grid at +2.5 V, the ratio of  $I^-/I_e$  was improved from 1/9000 to 1/200. The extracted negative ion current density  $J^-$  for discharge current of 1 A was estimated to be 0.12 mA/cm<sup>2</sup>.

We have previously shown that the density of electrons in the extraction chamber and, therefore, the extractable electron current  $I_e$  is closely related to the number of positive ions that can penetrate the magnetic filter.<sup>14,15</sup> The exact process as to how these low energy electrons penetrate the filter is not yet fully understood, but we are convinced that the relative plasma potentials of the two chambers is most important. For

both the weak and strong filters, the Langmuir probe measurements in Fig. 5 and 6 show that the plasma potential  $V_D$  of the source chamber is approximately 1.5 V more positive than that of the extraction chamber when  $V_D = 0$ . This potential gradient tends to draw positive ions into the extraction chamber and they in turn are able to bring the cold electrons with them. On the other hand,  $H^-$  ions formed in the source chamber will find it difficult to cross this potential barrier. It is also possible that some  $H^-$  ions are produced in the extraction chamber via processes such as dissociative attachment of vibrationally excited  $H_2$  18,19

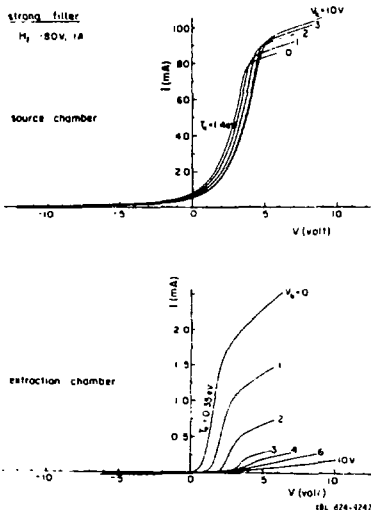


Fig. 6 Langmuir probe traces obtained in the source and extraction chambers for different plasma grid bias voltages for the case of a strong samarium-cobalt magnet filter.

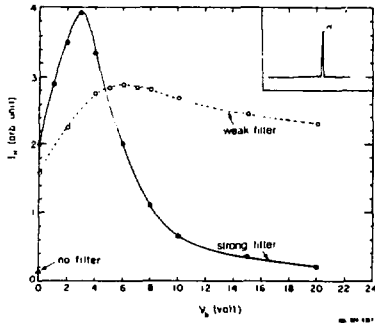


Fig. 7 The spectrometer signal for the  $H^-$  ion as a function of the plasma grid bias voltage for the strong and weak filters.

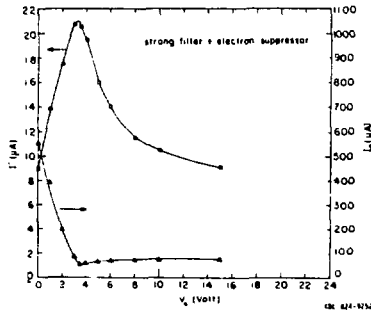


Fig. 8 The extracted  $H^-$  ion current as a function of the plasma grid bias voltage in the presence of a strong filter and an E X B electron suppressor.

$H^-$  ions are no longer electrostatically trapped and can now be extracted.

In the case of the strong filter, a further increase in the grid bias voltage  $V_b$  results in a drop of  $I^-$  as shown in Fig. 3(a). It is difficult to determine the plasma potential in the extraction chamber for  $V_b = +4$  V from the probe traces in Fig. 6. This potential may become positive relative to the potential of the source chamber plasma. In that case, the number of positive ions and electrons that leak through the filter is much reduced. The

or the dissociative recombination of  $H_2^+$  and  $H_3^+$ .<sup>20,21</sup> These  $H^-$  ions, instead of moving towards the extractor, would be accelerated back into the source chamber by the plasma potential gradient.

As the grid bias voltage  $V_b$  increases, the difference in plasma potential between the two chambers decreases and it then becomes more difficult for the positive ions and their associated cold electrons to cross the filter into the extraction region. As a result, the extracted positive ion current  $I^+$  (Fig. 3(c)) and the extracted electron current (Fig. 3(b)) are reduced simultaneously for both filters. No further reduction in  $I^+$  or  $I_e$  is observed once the potentials of the two chamber plasmas become almost identical and this happens when  $V_b$  is increased to approximately +8 and +4 V for the weak and strong filter, respectively. At this point, the  $H^-$  ions formed in the source chamber can cross the filter with ease while those produced in the extraction chamber are not attracted to the source chamber side. In addition, there is almost no difference in potential between the grid and the plasma. Consequently, volume-produced



extracted  $H^-$  ion current could then decrease due to the lack of positive ions needed to satisfy the requirement for charge neutrality. It is also possible that the production of  $H^-$  ions in the extraction chamber, which requires the presence of thermal electrons, is reduced.

The extracted beam has also been analyzed by means of a compact magnetic-deflection mass spectrometer when the source was operated with and without a magnetic filter. A typical  $H^-$  ion signal is displayed on the top corner of Fig. 7. The amplitude of this sharp  $H^-$  ion peak is plotted as a function of the plasma grid bias voltage in Fig. 7 for the weak and strong filters and also for operation without the filter. It can be seen that the results show almost the same characteristics as the Faraday cup current presented in Fig. 3(a).

When the spectrometer was tuned for higher masses, we found that the impurities were mainly  $OH^-$  and  $O_2^-$  ions. The total impurity content in the extracted beam was about 1%.

#### (c) Strong filter with E X B electron suppression

With the use of the strong samarium-cobalt magnet filter, the electron current extracted from the multicusp source is still about 100 times the  $H^-$  ion current. Thus, an attempt was made to further reduce the electron current by means of an E X B geometry. Figure 1(c) shows two tiny ceramic magnets (0.2 cm x 0.25 cm x 3 cm) placed on each side of the plasma grid electrodes that approximate a Pierce configuration. The maximum B field produced by this pair of magnets is about 350 G with thickness of approximately 0.5 cm. The extraction electric fields cause the electrons to E x B drift vertically in a cycloidal motion, and they are thus separated from the beam. The much heavier  $H^-$  ions pass through the extraction gap with little effect.

Figure 8 shows the extracted  $H^-$  ion current and the electron current when this E X B electron suppression scheme was used with the strong filter. There is no significant change in the  $H^-$  ion current when the plasma grid is biased at +3 V, but the electron current is reduced by nearly a factor of 50. A further reduction in the electron current was obtained by placing a small wire (biased at +12 V relative to the plasma grid) at one end of the extraction slot to intercept the drifting electrons so that they would not leak out of the extractor. With this arrangement, the ratio of  $I^-/I_e$  has been improved to almost unity.

### SCHEMES TO INCREASE THE $H^-$ ION YIELD

#### (a) By optimizing the discharge voltage

The dependence of the extracted  $H^-$  ion current on the discharge voltage has been investigated for the case of the strong filter. With the plasma grid biased at anode potential, and for a constant discharge current of 5 A, Fig. 9 shows that the extracted  $H^-$  ion current (as indicated by the mass spectrometer signal) increases almost linearly as the discharge voltage was varied from 40 V to 100 V. Above 110 V, the  $H^-$  ion current levels off and

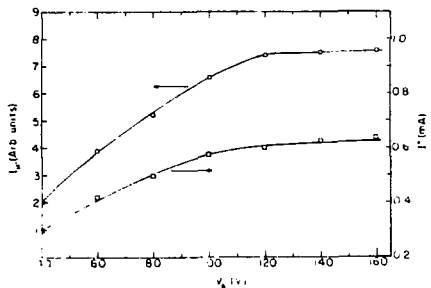


Fig. 9  $H^-$  ion current and the extracted positive ion current as a function of the discharge voltage with a constant discharge current of 5 A.

remains essentially constant for discharge voltages as high as 160 V. Thus the  $H^-$  ion yield increases by ~40% as  $V_d$  is changed from 80 V to 120 V. When the power supply polarities were reversed for positive ion extraction, the positive hydrogen ion current also increased in the same manner as the  $H^-$  ion current when the discharge voltage was varied (Fig. 9). This result shows that the increase in  $H^-$  ion yield for high discharge voltage is mostly due to the increase in plasma production in the source chamber. Without the magnetic filter, the optimum discharge voltage for this source normally occurs

at ~80 V. This change in the optimum discharge voltage in the case of the strong filter may be due to a better containment of high energy primary electrons in the source chamber.

(b) By using a magneto-electrostatic containment scheme

By including a magnetic filter, the multicusp ion source becomes essentially a "complete" multicusp generator. As a result, The plasma potential distribution in the source chamber is uniform both in the radial and axial directions.<sup>22</sup> The axial uniform  $V_p$  profile extends to the extraction chamber if a positive bias voltage is applied to the plasma grid. Thus, the positive ions will no longer "free-fall" down to this grid as in the case of positive ion source operation. However, there will be a substantial plasma leakage to the side walls due to a higher plasma potential. In a previous experiment, we demonstrated that the ion loss to regions between the line-cusps can be reduced by

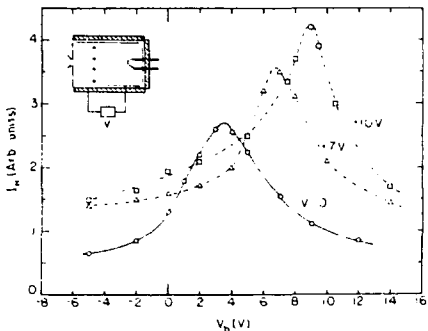


Fig. 10  $H^-$  ion yield as a function of plasma grid bias for three different bias potentials on the strip electrodes.

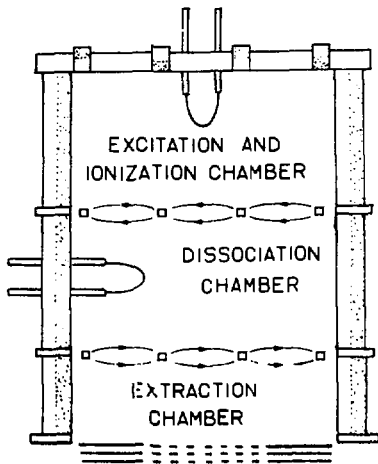


Fig. 11 A triple chamber  $H^-$  ion generator.

biased at the anode potential. From the probe traces obtained in the source chamber, we find the source plasma density also increases by approximately the same amount. Thus the increase in the extracted  $H^-$  ion current is mainly due to better confinement of the plasma.

(C) By using a triple plasma system

Hydrogen molecules can be excited into a high vibrational state by collision with energetic electrons. It is generally believed that these vibrationally excited  $H_2$  molecules play an important role in the formation of  $H^-$  ions. In a two chamber system, the plasma electron density in the extraction chamber is low when a positive bias is applied on the plasma grid. Thus the rate of  $H^-$  production in the extraction chamber due to the reaction  $e + H_2(v^*) \rightarrow H^- + H$  is reduced. For this reason, most of the  $H^-$  ions extracted from the filtered source are formed in the source chamber.

A new triple chamber  $H^-$  ion source has been proposed both by LBL and LLNL.<sup>24</sup> In this geometry (Fig. 11), the neutral molecules are vibrationally excited by energetic electrons in the first (excitation and ionization) chamber. These molecules together with some plasma ions and electrons then migrate into the second (dissociation) chamber. It has been determined theoretically that cold thermal electrons with  $T_e \approx 1$  eV are required to optimize the  $H^-$  ion production. This condition can be easily achieved by injecting a large quantity of very low energy electrons from

installing electrode-strips in between magnet columns.<sup>23</sup> When these electrodes are biased positively with respect to the anode, they reflect the positive ions back to the plasma volume, resulting in an increase of plasma density. This magneto-electrostatic plasma containment scheme was investigated in the test source operated with a strong filter. Figure 10 shows the  $H^-$  ion yield (as indicated by the spectrometer signal) as a function of the plasma grid bias voltage for three different strip electrode bias voltages. When the strips are biased at +10 V relative to the anode, the optimum  $H^-$  yield is about 53% higher than the case when they are

cathodes installed in this chamber.  $H^-$  ions formed are then drawn into the third (extraction) chamber by applying the proper bias voltage on the plasma grid of the extractor in the same manner as the two chamber system. The idea of this triple plasma device will be tested experimentally in the near future.

#### HIGH ARC POWER SOURCE OPERATION

Recently,  $H^-$  ions were extracted from this same magnetically-filtered cusp source but it was operated at much higher current and in a pulse mode on a high voltage test-stand at Los Alamos National Lab.<sup>25</sup> The accelerated beam was mass-analyzed for accurate  $H^-$  current and emittance measurements. A plot of the  $H^-$  beam current and current density as a function of the discharge current is shown in Fig. 12. The  $H^-$  ion beam current increases almost linearly with  $I_d$ . At an arc current of 350 A, an  $H^-$  current density of 38 mA/cm<sup>2</sup> was obtained. The source pressure was adjusted between 2.5 to 4.5 x 10<sup>-3</sup> Torr. The total impurity content was found to be less than 2% and the  $I^-/I_e$  ratio varied from 1/3 at low extracted current to 1/12 at the highest current observed. The brightness of the source is 0.58 A/cm<sup>2</sup>- $\mu$ rad<sup>2</sup> at a current density of 38 mA/cm<sup>2</sup>.

These results demonstrate that volume-produced  $H^-$  ions extracted from a magnetically-filtered, multicusp source can provide high quality  $H^-$  beams with sufficient current density to be useful for both neutral beam injection and accelerator applications. Work will continue to scale the source operation up to larger extraction area and perhaps with multiple beamlets. In addition, the magnet geometry at the exit aperture must be optimized to achieve electron suppression without degeneration of ion optics. Should

this succeed, one could operate a large area multicusp source to provide  $H^-$  ions in much the same manner as is now used to provide positive hydrogen ions for neutral beam systems.

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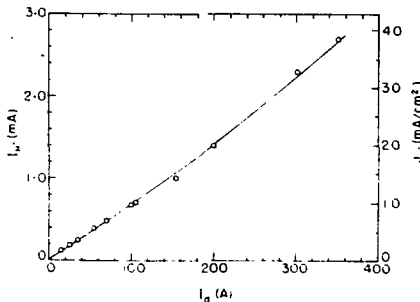


Fig. 12 The extracted  $H^-$  beam current and current density from a 3-mm diam. aperture as a function of discharge current.

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