

## H<sup>-</sup> Formation Process in a Multicusp Ion Source

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The H<sup>-</sup> formation process has been investigated in a magnetically filtered multicusp source operated at a modest plasma density. By use of a mixture of xenon and hydrogen gas, it is found that the production of H<sup>-</sup> ions in the tandem discharge geometry is consistent with a model of dissociative attachment of low-energy electrons to vibrationally excited hydrogen molecules.

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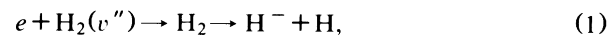
In recent years, H<sup>-</sup> ions have found important applications in high-energy accelerators and in neutral-beam heating of fusion plasmas.<sup>1</sup> There are different techniques for producing the H<sup>-</sup> ions.<sup>2-4</sup> The most attractive scheme is the direct extraction of H<sup>-</sup> ions from a hydrogen discharge. This technique requires no cesium and it utilizes the existing large-area positive-ion source technology. The H<sup>-</sup> ions generated by volume processes have lower average energy than those formed by surface conversion or by charge-exchange processes. For this reason, intensive research and development of volume H<sup>-</sup> sources are now being conducted in various accelerator and fusion laboratories.<sup>5</sup>

In the past, attempts have been made to extract volume-produced H<sup>-</sup> ions from the plasma of a duoplasmatron, a magnetron, or a Penning-type discharge source. In 1983, a novel method of extraction of H<sup>-</sup> ions directly from a multicusp source was reported by Leung, Ehlers, and Bacal.<sup>6</sup> From this prototype source H<sup>-</sup> beams with current density as high as 38 mA/cm<sup>2</sup> have been produced successfully in an experiment performed by York *et al.*<sup>7</sup> In order further to improve the extractable H<sup>-</sup> current density, it is essential to understand the production process of the H<sup>-</sup> ions in these type of negative-ion sources. Several theoretical models have been developed in an effort to explain the H<sup>-</sup> yield.<sup>8</sup> It is generally assumed that the H<sup>-</sup> ions are formed by the two-step dissociative attachment process described in the following paragraphs. In this Letter, we report the first experimental investigation which identified the dominant process for production of the H<sup>-</sup> ions in the multicusp ion source for low discharge power.

The multicusp plasma generator has demonstrated its ability to produce large volumes of uniform and quiescent plasmas with high gas and electrical efficiency.<sup>9</sup> Figure 1 shows a schematic diagram of the generator when it is operated as a H<sup>-</sup> ion source. The source chamber (20 cm diam by 24 cm long) is surrounded externally by ten columns of samarium-cobalt magnets which form a longitudinal line-cusp configuration for primary-electron and plasma confinement.<sup>10</sup> The magnet columns are connected at the end flange by four extra rows of similar magnets. The open end of the

chamber is enclosed by a two-grid extraction system. A steady-state hydrogen plasma is produced by primary electrons emitted from two tungsten filaments, and the entire chamber wall serves as the anode for the discharge.

In order to enhance the H<sup>-</sup> yield, a water-cooled permanent magnet *filter*<sup>6</sup> is installed, and it divides the entire source chamber into an arc discharge and an extraction region. This filter provides a narrow region of transverse magnetic field ( $B_{\max} \approx 70$  G) which is strong enough to prevent the energetic primary electrons from entering the extraction chamber. Excitation and ionization of the gas molecules are performed by the primaries in the discharge region. Both positive and some negative ions, together with cold electrons, are present in the extraction chamber and they form a plasma with very low electron temperature ( $T_e \leq 1$  eV) in the extraction zone. More H<sup>-</sup> ions can be generated in the extraction region via processes such as the dissociative attachment of electrons to vibrationally excited H<sub>2</sub><sup>11,12</sup>



or the recombinational attachment of H<sub>2</sub><sup>+</sup> and H<sub>3</sub><sup>+</sup> ions with electrons<sup>13,14</sup>

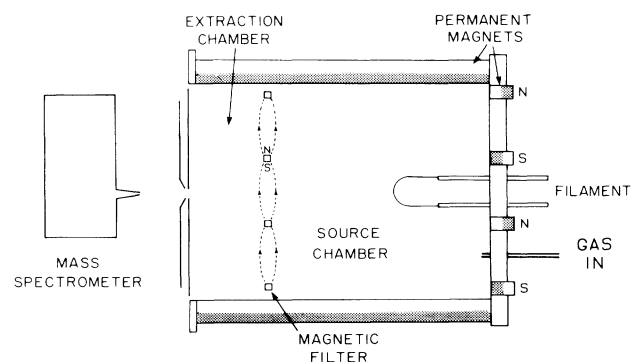


FIG. 1. Schematic diagram of the multicusp ion source equipped with a magnetic filter.

A recent experiment shows that the injection of additional electrons with energy  $E \approx 1$  eV into the extraction-chamber plasma can increase the  $H^-$  yield substantially.<sup>15</sup> The result seems to preclude the polar dissociation process<sup>16</sup> ( $e + H_2 \rightarrow H^- + H^+ + e$ ) which has its maximum rate above 30 eV and exhibits a threshold near 17 eV. It is also unlikely that the  $H^-$  are formed by recombinational attachment of electrons to  $H_3^+$  ions because this process has a maximum cross section in the energy range of 4 to 10 eV.<sup>14</sup> Thus, the observed  $H^-$  enhancement at low electron energy is consistent with either dissociative recombination of  $H_2^+$  or dissociative attachment of  $H_2(v'')$ , which both have the highest reaction rate at very low electron energy.

In order to identify which is the dominant  $H^-$  production process, the source must be operated with either  $H_2^+$  ions or neutral  $H_2$  in the extraction chamber. The former condition is difficult to achieve, but the latter can be accomplished by employment of the gas-mixing technique, that is, by introducing a gas which has a threshold ionization energy lower than that of  $H_2$  ( $E_i = 15.4$  eV). If a plasma can be generated with primary-electron energy lower than 15.4 eV, then only neutral  $H_2$  but no  $H_2^+$  ions will be present in the ion source. However, low-energy electrons together with the ions of the supporting gas will form the plasma in the extraction region.

In this experiment, xenon ( $E_i = 12.1$  eV) was chosen as the supporting gas because it has a relatively high ionization cross section ( $\sigma_i = 10^{-16}$  cm<sup>2</sup>) even at electron energy as low as 15 eV,<sup>17</sup> and it does not react chemically with hydrogen. The source chamber was filled with hydrogen and xenon to partial pressures of  $2.5 \times 10^{-4}$  Torr and  $1.1 \times 10^{-4}$  Torr, respectively. Positive or negative ions were extracted from the source through a small ( $0.1 \times 1.0$ -cm<sup>2</sup>) aperture. A compact magnetic deflection

mass spectrometer,<sup>18</sup> located just outside the extractor, was used for relative measurement of the extracted  $H^-$  ions as well as for the analysis of positive-ion species. Plasma parameters were obtained by small Langmuir probes located at the center of the source and extraction chambers.

The presence of the filament heater voltage can introduce a spectrum of energies for the emitted electrons. Since the discharge voltage  $V_d$  in this measurement was applied between the anode and the negative terminal of the filament heater power supply, the maximum energy  $E$  acquired by the primary electrons is  $e(V_d + V_p)$ , where  $e$  is the electron charge and  $V_p$  is the plasma potential.

A mixture of hydrogen and xenon plasma was initially generated with a discharge power of 40 V, 3 A, producing a density of  $1.7 \times 10^{11}$  cm<sup>-3</sup> at the center of the source chamber. As  $V_d$  was gradually reduced, the filament heater current had to be increased in order to maintain a constant discharge current of 3 A. The lowest  $V_d$  which could maintain a discharge was about 11 V. Figure 2 shows the distribution of the positive hydrogen ion species for  $V_d = 11, 15,$  and 40 V. All the three ion species ( $H^+, H_2^+, H_3^+$ ) are present for discharge voltages of 15 and 40 V. For  $V_d = 11$  V, no positive hydrogen ion species can be detected because the maximum energy of the primaries is only 15 eV when the plasma potential ( $V_p \approx +4$  V) is taken into account. Thus, the positive ions in the plasma are essentially  $Xe^+$  ions.

However, the mass spectrometer output signal in Fig. 3 shows the presence of  $H^-$  ions even when  $V_d$  is reduced to 11 V. The extracted  $H^-$  ions in this case can only be generated from the neutral  $H_2$  and most probably by dissociative attachment of low-energy electrons to the higher vibrational levels belonging to the ground electronic state of the molecule,  $H_2(X^1\Sigma_g^+)$ . The cross sections for the excitation of the vibrational levels of  $H_2(X^1\Sigma_g^+)$  by electron collision have been calculated by

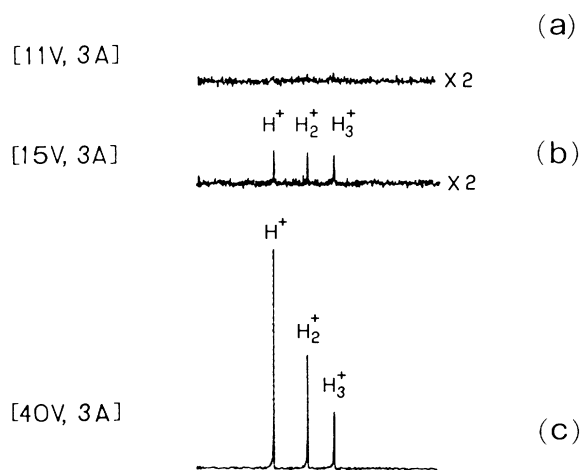


FIG. 2. Spectrometer output signal showing the positive hydrogen ion species distribution when the source is operated with a discharge power of (a) 11 V, 3 A; (b) 15 V, 3 A; and (c) 40 V, 3 A.

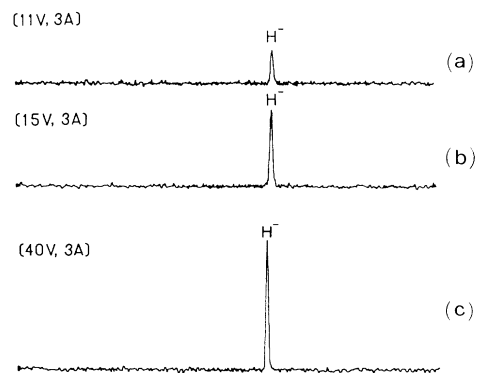


FIG. 3. The  $H^-$ -ion spectrometer signal obtained when the source is operated with a discharge power of (a) 11 V, 3 A; (b) 15 V, 3 A; and (c) 40 V, 3 A.

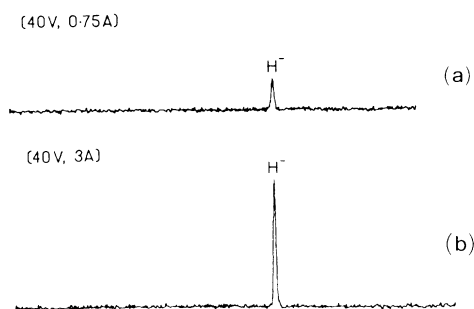


FIG. 4. The  $H^-$  ion spectrometer signal obtained when the source is operated with a discharge power of (a) 40 V, 0.75 A, and (b) 40 V, 3 A.

Hiskes.<sup>19</sup> They are in the range of  $10^{-18}$ – $10^{-17}$   $\text{cm}^2$  for incident electron energies between 15 and 50 eV.

According to Fig. 3, the  $H^-$  signal obtained for a discharge power of 11 V, 3 A is approximately one-fourth of that produced by 40 V, 3 A. Langmuir-probe measurement also showed that the source plasma density decreased by the same amount as the discharge power was reduced from 40 V, 3 A to 11 V, 3 A. The drop in  $H^-$  yield could then be simply due to the reduction of electron density in the source and extraction chamber, or the energy variation of the electron excitation cross section. Indeed, when the discharge power was adjusted to 40 V, 0.75 A, both the electron density and the  $H^-$  output signal (Fig. 4) were nearly the same as those obtained for the 11 V, 3 A discharge, except that the positive hydrogen ion species reappeared again in the spectrum as illustrated in Fig. 5.

The rate of production of vibrationally excited  $H_2(v'')$  by primary electrons in a plasma with volume  $V$  is  $N_0 N_p \sigma v V$ , where  $N_0$  is the density of ground-state  $H_2$  molecules,  $\sigma$  is the cross section for vibrational excitation by electronic collision, and  $N_p$  and  $v$  are the density and velocity of the primary electrons, respectively. At low source pressure, when ionization and excitation processes are not important, the balance equation for the primaries can be written as<sup>20</sup>

$$I_d \approx e N_p V / \tau_c, \quad (4)$$

where  $I_d$  is the discharge current and  $\tau_c$  is the magnetic confinement time of the primary electrons. It is justified to use this approximation in this experiment because the confinement time  $\tau_c$  for the primary electrons ( $\tau_c = 2$  and  $0.75 \mu\text{s}$  for 15- and 45-eV electrons, respectively) is shorter than the ionization and excitation time  $\tau_{ie}$  ( $\tau_{ie} = 16$  and  $2 \mu\text{s}$  for 15- and 45-eV electrons respectively). If  $L$  is the total line-cusp length,  $B$  is the magnetic field at the cusp, and  $r$  and  $E$  are the primary electron Larmor radius and energy, respectively, then<sup>20</sup>  $\tau_c = 2V/rvL = VeB/EL$ . From Eq. (4), the primary electron density  $N_p \approx BI_d/LE$ . By use of this expression for  $N_p$  and the values of  $\sigma$  reported by Hiskes,<sup>19</sup> the rates of

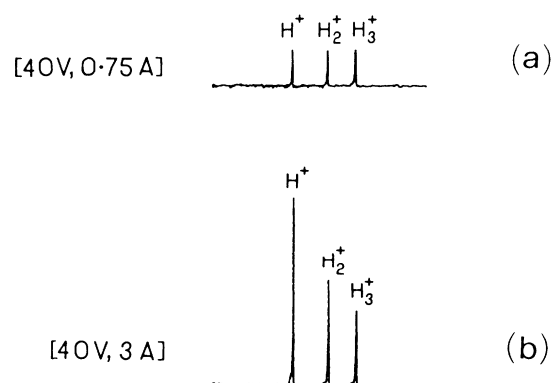


FIG. 5. Spectrometer output signal showing the positive hydrogen ion species distribution when the source is operated with a discharge power of (a) 40 V, 0.75 A, and (b) 40 V, 3 A.

production of vibrationally excited  $H_2$  are found to be the same for the two different discharge conditions of 11 V, 3 A and 40 V, 0.75 A. Since the plasma electron density in the extraction chamber is about the same, the rate of generating  $H^-$  via dissociative attachment process should be equal.

The above analysis demonstrates that positive hydrogen ions do not play an important role in the formation of  $H^-$  in modest-discharge-power operations. However, in the case of a pure hydrogen discharge, the positive hydrogen ions do provide the space charge necessary to neutralize the  $H^-$  in the extraction region. In order to enhance the  $H^-$  ion in a volume source, it is essential to supply large quantities of vibrationally excited  $H_2(v'')$  and low-energy electrons, together with the proper amount of positive ions. The filter-equipped multicusp generator arrangement does provide the ideal source configuration for the formation and extraction of  $H^-$  ions.

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