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K.N. Leung and W.B. Kunkel

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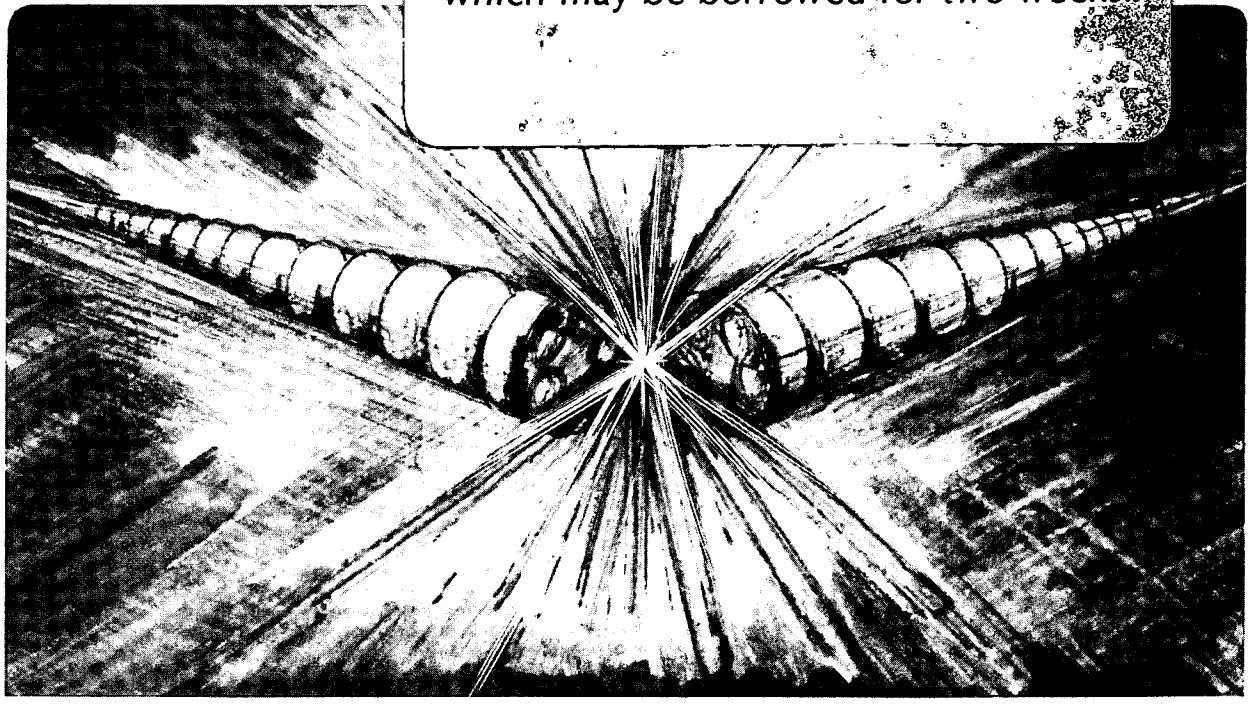

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H^- Formation in a Multicusp Ion Source*

K. N. Leung and W. B. Kunkel

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Abstract

The H^- production process has been investigated in a magnetically filtered multicusp source operated at a modest plasma density. By employing a mixture of xenon and hydrogen gas, it is found that dissociative attachment of low energy electrons to vibrationally excited hydrogen molecules is the dominant process for H^- formation in the tandem discharge geometry.

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In recent years, H^- ions have found important applications in high energy accelerators and in neutral beam heating of fusion plasmas.[1] There are different techniques for producing the H^- ions.[2-4] The most attractive scheme is the direct extraction of H^- ions from a hydrogen discharge. This technique requires no cesium and it utilizes the existing large area positive ion source technology. The H^- 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^- sources are now being conducted in various accelerator and fusion laboratories.[5]

In the past, attempts have been made to extract volume produced H^- ions from the plasma of a duoplasmatron, a magnetron, or a Penning-type discharge source. In 1983, a novel method of extracting H^- ions directly from a multicusp source was reported by Leung et al.[6] From this prototype source, H^- beams with current density as high as 38 mA/cm^2 have been produced successfully in an experiment performed jointly by the Los Alamos National Laboratory and the Lawrence Berkeley Laboratory.[7] In order to further improve the extractable H^- current density, it is essential to understand the production process of the H^- ions in these type of negative ion sources. In this letter, we report the first experimental investigation which identified the dominant process for producing the H^- 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.[8] Figure 1 shows a schematic diagram of the generator when it is operated as a H^- ion source. The source chamber (20 cm diam by 24 cm long) is surrounded externally by 10 columns of

samarium-cobalt magnets which form a longitudinal line-cusp configuration for primary electron and plasma confinement.[9] 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 served as the anode for the discharge.

In order to enhance the H^- yield, a water-cooled permanent magnet filter[6] 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^- ions can be generated in the extraction region via processes such as the dissociative attachment of electrons to vibrationally excited H_2[10,11]

$$e + H_2(v'') \rightarrow H_2^- \rightarrow H^- + H \qquad (1)$$

or the recombinational attachment of H_2^+ and H_3^+ ions with electrons[12,13]

$$e + H_2^+ \rightarrow H^- + H^+ \quad (2)$$

$$e + H_3^+ \rightarrow H^- + H_2^+ \quad (3)$$

A recent experiment shows that the injection of additional electrons with energy E ≈ 1 eV into the extraction chamber plasma can increase the H^- yield substantially.[14] The result seems to preclude the polar dissociation process[15] ($e + H_2 \rightarrow H^- + H$) 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.[13] 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.[15]

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 employing 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 15.8 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 ($\sigma_i \approx 10^{-16}$ cm^2) even at electron energy as low as 15 eV[16] and it does not react chemically with hydrogen. The source chamber was filled with hydrogen and xenon to a partial pressure of 2.5×10^{-4} Torr and 1.1×10^{-4} Torr respectively. Positive or negative ions were extracted from the source through a small 0.1 x 1.0 cm^2 aperture. A compact magnetic deflection mass spectrometer[17], 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 1.7×10^{11} cm^{-3} 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 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 Hiskes.[18] They are in the range of 10^{-18} - 10^{-17} 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. 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 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 producing 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, σ 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[19]

$$I_d = eN_p V/\tau_c \qquad (4)$$

where I_d is the discharge current and τ_c is the magnetic confinement time of the primary electrons. If L is the total line-cusp length, B is the magnetic field at the cusp, and r and E is the primary electron Larmor radius and energy respectively, then[19] $\tau_c = 2V/rvL = VeB/EL$. From Eq. (4), the primary electron density $N_p = BI_d/LE$. By using this expression for N_p and the values of σ reported by Hiskes in Ref. 18, the rates of producing 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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Figure Captions

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

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, 3A.

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.

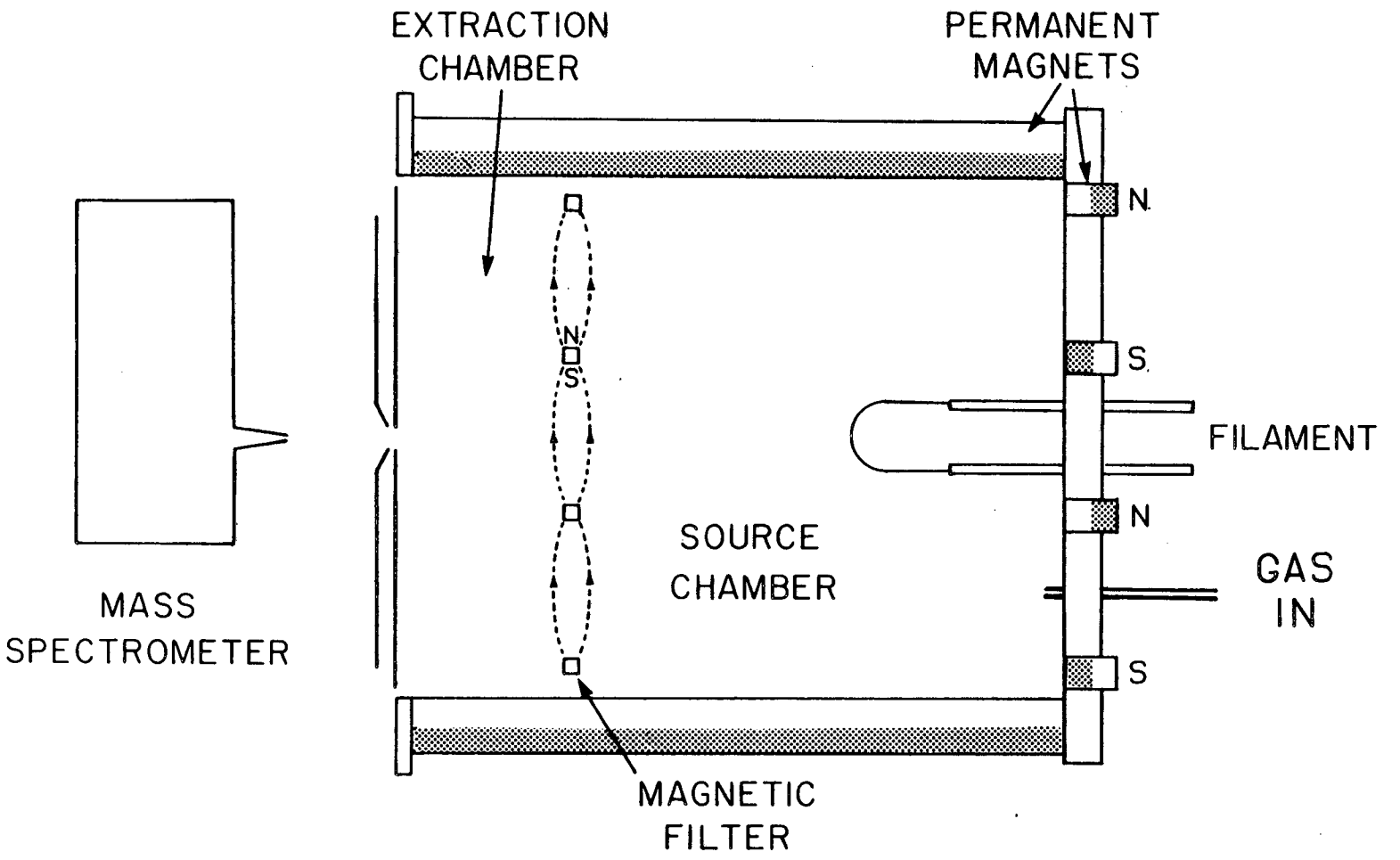

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Fig. 1

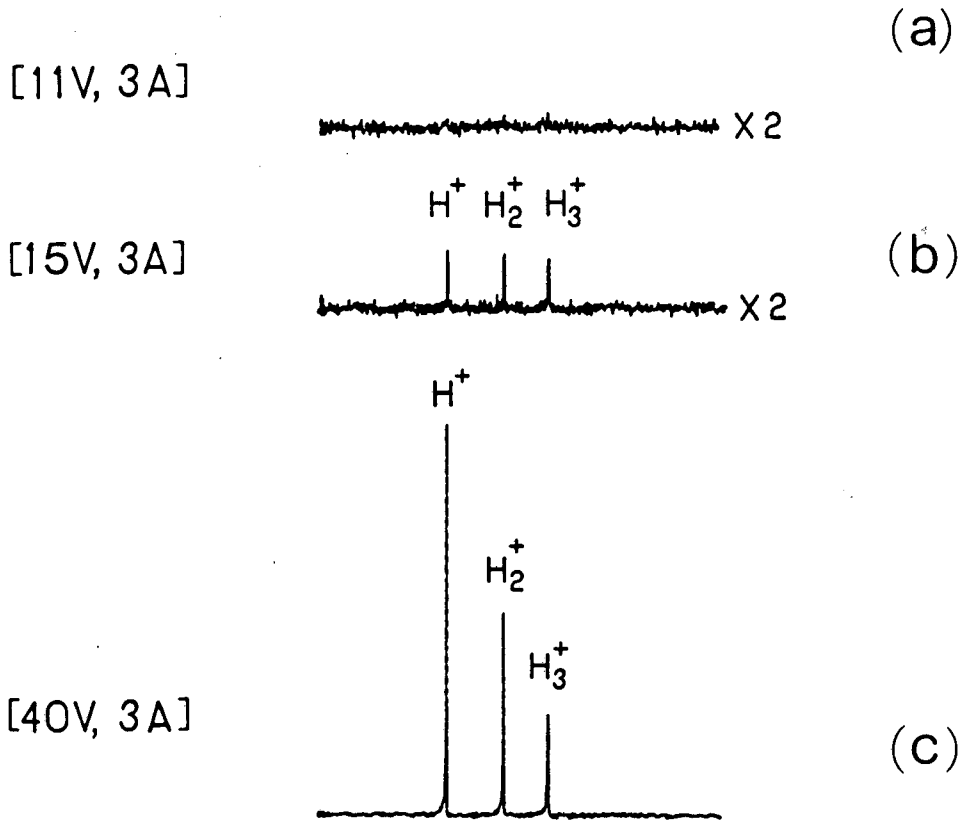

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Fig. 2

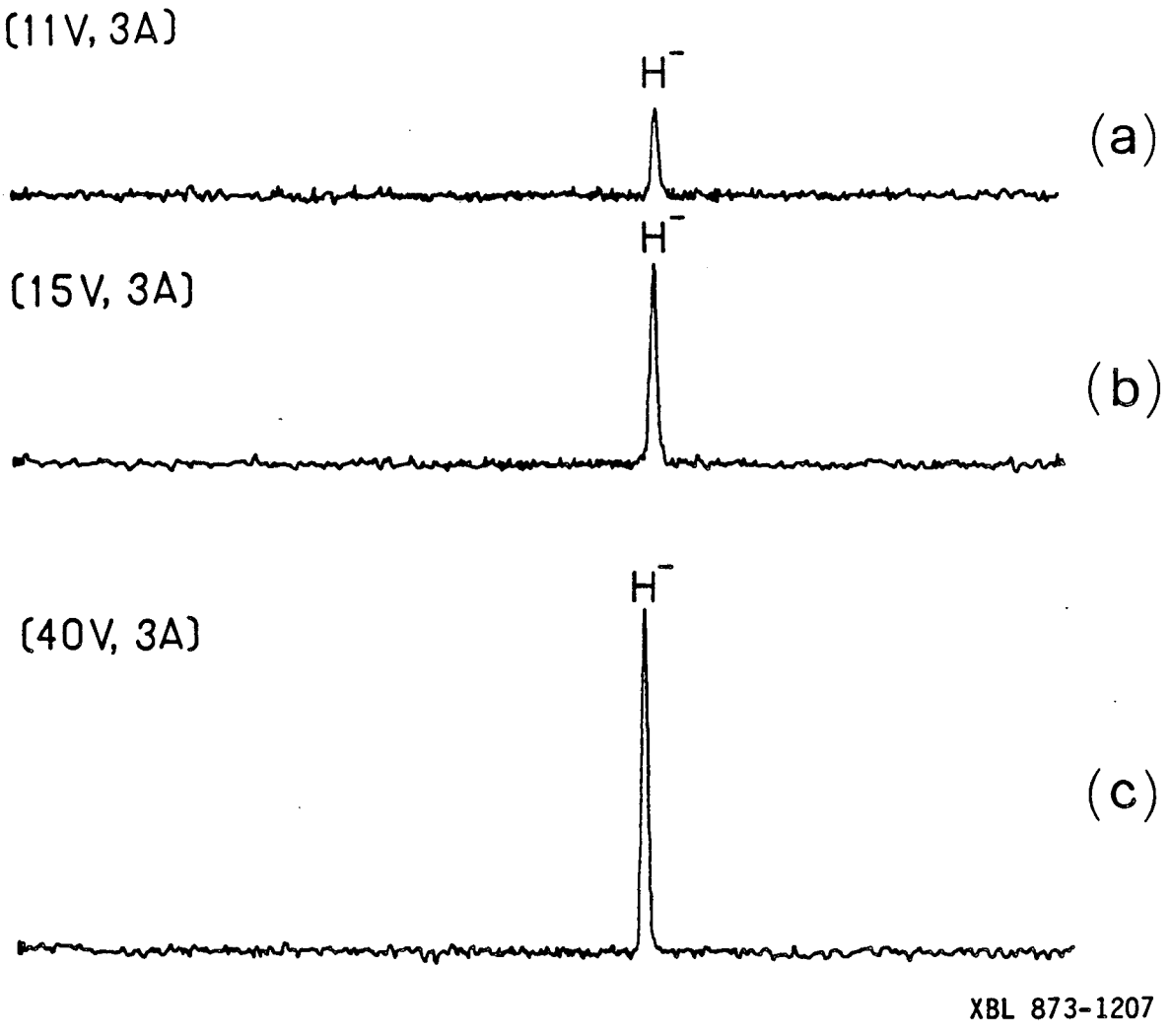

Fig. 3

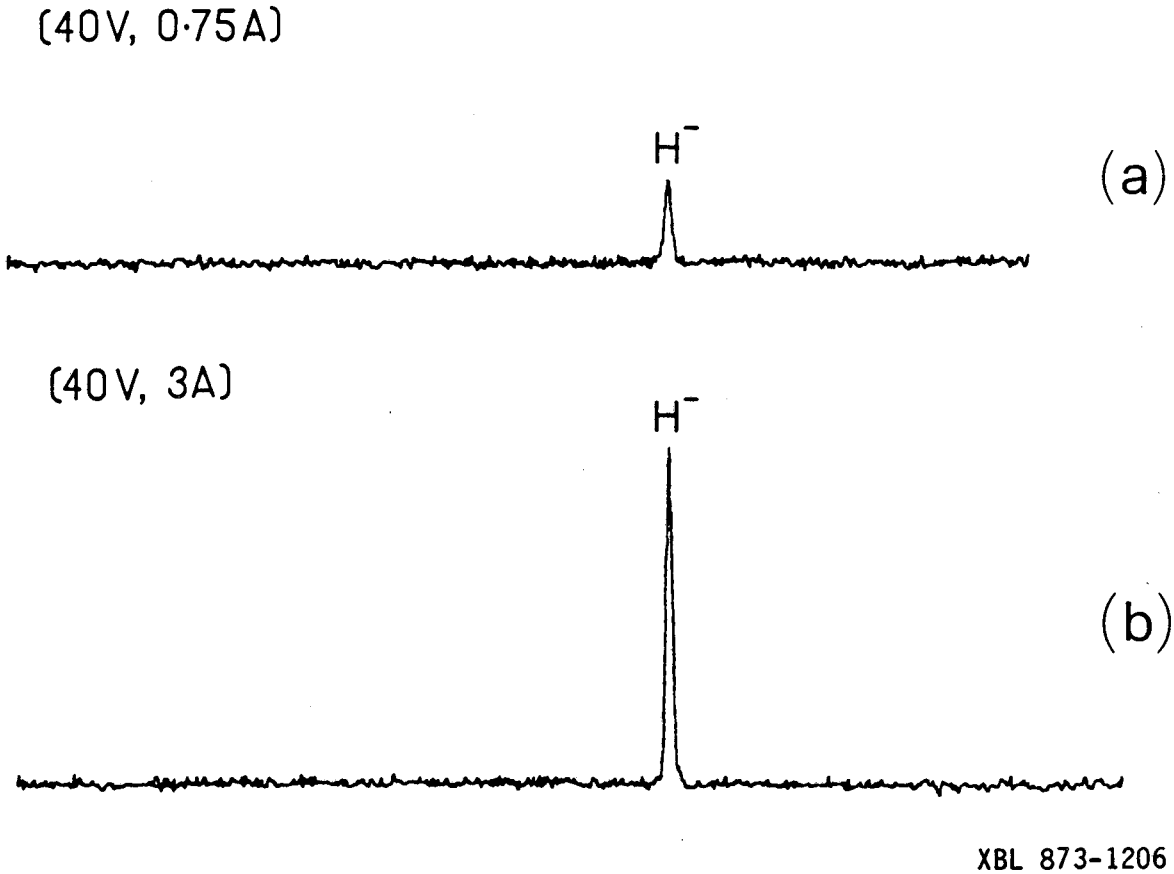

Fig. 4

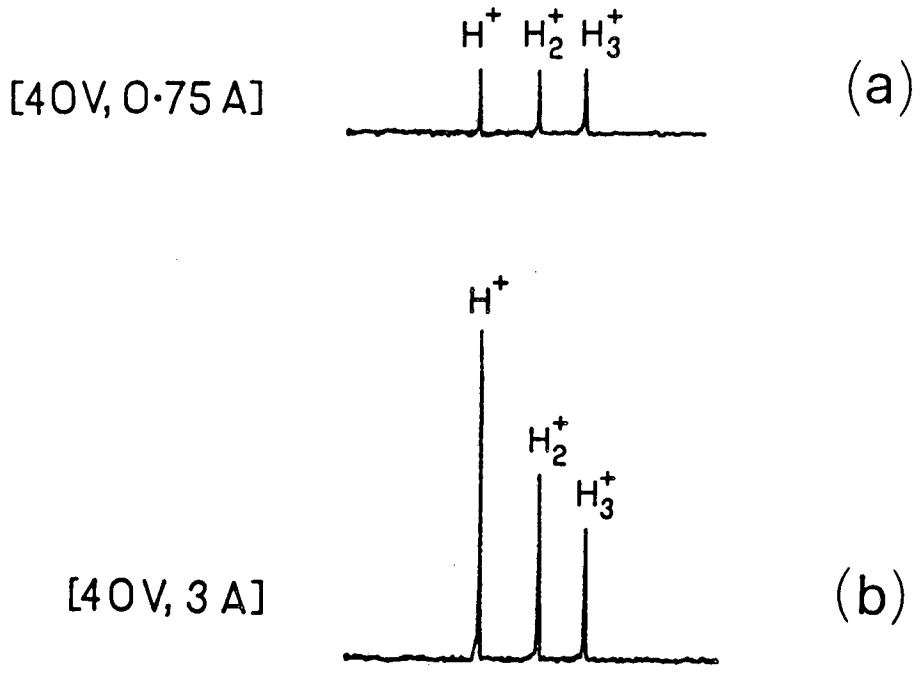

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Fig. 5

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720