# $D^-/H^-$ negative ion production versus plasma parameters in a volume negative ion source[a)]

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Pure volume production of $D^-$ negative ions is studied in rectangular negative ion source equipped with an external magnetic filter (MF). Plasma parameters ($n_e$ and $T_e$) in $D_2$ plasmas are varied mainly in the downstream region by changing the magnetic field intensity of the MF (i.e., $B_{MF}$). Production and control of $D_2$ plasma is nearly the same as that of $H_2$ plasmas, although the values of $n_e$ and $T_e$ in $D_2$ plasma are slightly higher than that of $H_2$ plasmas in both the source and the extraction regions. On $D^-/H^-$ production, however, it appears some different points. By varying the $B_{MF}$, $H^-$ production in the extraction region is remarkably changed corresponding to the variation of $n_e$ and $T_e$ in the extraction region. On the other hand, $D^-$ production is not so varied under the same discharge conditions in $H_2$ plasmas. This difference in $D^-$ production is not well explained only variation of $n_e$ and $T_e$ in $D_2$ plasmas. Optimum $B_{MF}$ and gas pressure for $D^-$ production is slightly higher than that for $H^-$ production. © *2008 American Institute of Physics.*
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## I. INTRODUCTION

Sources of $H^-$ and $D^-$ negative ions are required for efficient generation of neutral beams with energies above $\approx$100 keV/nucleon. The magnetically filtered multicusp ion source has been shown to be a promising source of high-quality multiampere $H^-$ ions. In pure hydrogen ($H_2$) discharge plasmas, most of the $H^-$ ions are generated by the dissociative attachment of slow plasma electrons $e_s$ (electron temperature $T_e \sim 1$ eV) to highly vibrationally excited hydrogen molecules $H_2(v'')$ (effective vibrational level $v'' \gtrsim 5-6$). These $H_2(v'')$ are mainly produced by collisional excitation of fast electrons $e_f$ with energies in excess of 15–20 eV. Namely, $H^-$ ions are produced by the following two-step process:[1,2]

$$H_2(X\,^1\Sigma_g, v''=0) + e_f \rightarrow H_2^*(B\,^1\Sigma_u, C\,^1\Pi_u) + e_f', \tag{1a}$$

$$H_2^*(B\,^1\Sigma_u, C\,^1\Pi_u) \rightarrow H_2(X\,^1\Sigma_g, v'') + h\nu, \tag{1b}$$

$$H_2(v'') + e_s \rightarrow H^- + H, \tag{2}$$

where $H_2$ $(X\,^1\Sigma_g)$ means the ground electronic state of the hydrogen molecule and $H_2^*$ $(B\,^1\Sigma_u)$ and $H_2^*$ $(C\,^1\Pi_u)$ mean the excited electronic states. The transitions from the $B\,^1\Sigma_u$ and $C\,^1\Pi_u$ levels to the ground state, $X\,^1\Sigma_g$, of $H_2$ are termed the Lyman and Werner bands, respectively, and are found in the vacuum ultraviolet (VUV) region.

The reaction-producing $D^-$ ions is believed to be the same as that for the production of $H^-$ ions. To develop efficient $D^-$ ion sources with high current density, it is important to clarify production and control of deuterium ($D_2$) plasmas and to understand the difference in the two-step process of negative ion production between $H_2$ plasmas and $D_2$ plasmas. Cesium (Cs) seeding of this type of ion source is often used as it enhances the extracted negative ion currents and reduces the extracted electron currents. There are some studies on optimization of volume-produced $D^-$ ion with or without Cs.[3–5] However, here we focus on understanding the negative ion production mechanisms in the "volume" ion source where negative ions are produced in low-pressure pure $H_2$ or $D_2$ discharge plasmas.

For this purpose, we are interested in estimating densities of highly vibrationally excited molecules and negative ions in the source. The production process of $H_2(v'')$ or $D_2(v'')$ is discussed[6] by observing the photon emission, i.e., VUV emission associated with the process (1b).[7,8] To clarify the relationship between plasma parameters and volume production of negative ions, the densities of $H^-$ or $D^-$ ions in the source are measured[9] by the laser photodetachment method.[10] The influence of plasma parameter distributions on $H^-$ or $D^-$ production is discussed using estimated rate coefficients and collision frequencies based on measured plasma parameters.[9,11,12] In this article, to study further the isotope effect of $D^-/H^-$ production, we discuss the relationship between negative ions in the source and extracted negative ion currents, including the results on VUV emission measurements.

## II. EXPERIMENTAL SETUP

Figure 1(a) shows a schematic diagram of the ion source.[9,11,12] The rectangular arc chamber is $25 \times 25$ cm$^2$ in cross section and 19 cm in height. Four tungsten filaments with 0.7 mm in diameter and 20 cm in length are installed in

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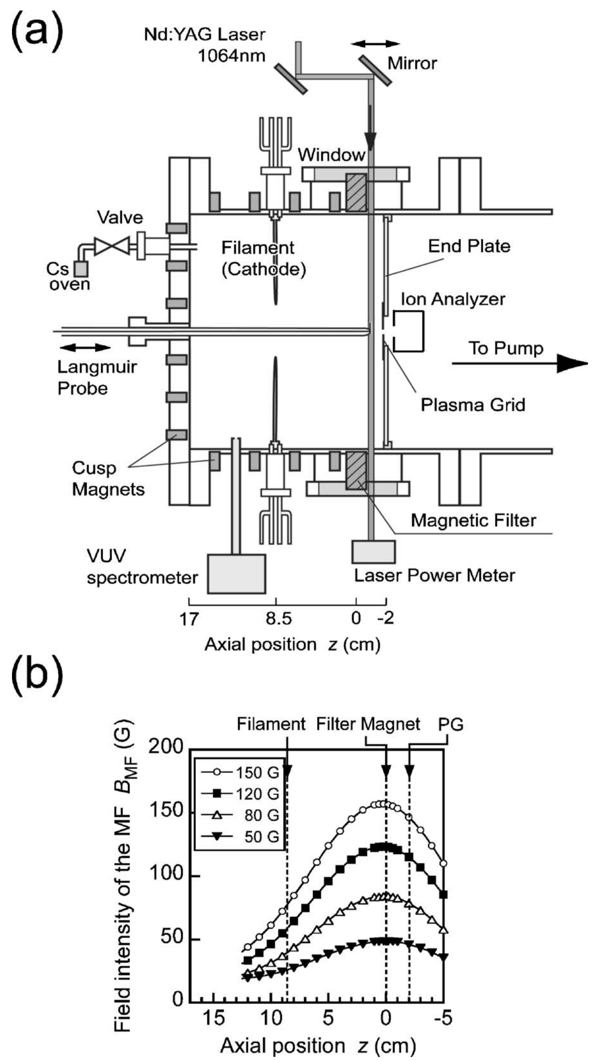


FIG. 1. (a) Schematic diagram of the ion source. The probe, the laser path, and power meter used in photodetachment experiments are also shown. (b) Axial distributions of field intensities for four different MFs.

the source region from the sidewalls of the chamber. The line cusp magnetic field is produced by permanent magnets which surrounded the chamber. The external magnetic filter (MF) is composed of a pair of permanent magnets in front of the plasma grid (PG). Figure 1(b) shows profiles of the field intensities for five different MFs along the axis of the ion source. In the present experiment, using these MFs, production and control of $H_2$ and $D_2$ plasmas to enhance negative ion volume production are studied. The end flange is kept at floating potential and the PG potential is kept at ground potential throughout the present experiments for both $H_2$ and $D_2$ plasmas.

In the source region, the VUV emission measurements related to the $H_2(v'')$ or $D_2(v'')$ production, i.e., the process (1b), are carried out by using the VUV spectrometer. The spectrometer was normally operated at a resolution of 0.1 nm. The optical pipe is equipped with collimators such that a rectangular plasma volume with a cross section of about $6 \times 3$ mm$^2$ is imaged. Emission intensity yields results averaged over the line of sight.

The plasma parameters are measured by an axially mov-

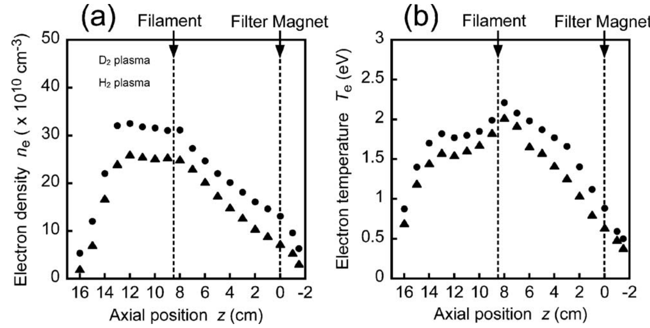


FIG. 2. Axial distributions of plasma parameters (a) $n_e$ and (b) $T_e$ in $H_2$ and $D_2$ plasmas. Experimental conditions are as follows: $V_d$=70 V, $I_d$=5 A, and $p(H_2)=p(D_2)=1.5$ mTorr.

able cylindrical Langmuir probe, supported by a quartz glass pipe with diameter of 3 mm. This probe is also used to measure negative ion density. Negative currents are extracted through a single hole of 5 mm in diameter on the PG. These currents are introduced into a magnetic deflection type ion analyzer for relative measurements of the extracted $H^-$ or $D^-$ current. On the other hand, $H^-$ or $D^-$ densities in the source are measured by the laser photodetachment method.[3,10]

## III. EXPERIMENTAL RESULTS AND DISCUSSION

### A. Production and control of $D_2$ plasmas

On $H^-/D^-$ volume production, desired condition for plasma parameters is as follows: $T_e$ in the extraction region should be reduced below 1 eV while keeping $n_e$ higher. To realize this condition, namely, to enhance $H^-/D^-$ production by dissociative attachment and to reduce $H^-/D^-$ destruction by electron detachment including collisions with energetic electrons, the MF is used. For this purpose, plasma parameter control is studied by varying the intensity of the MF, $B_{MF}$.

As is shown previously,[11,12] the axial profiles of $n_e$ and $T_e$ in hydrogen and deuterium plasmas are similar. For comparison, a typical example for axial distributions of $n_e$ and $T_e$ is shown in Fig. 2, where $B_{MF}$=80 G. In general, both $n_e$ and $T_e$ in deuterium plasmas are higher than the ones in hydrogen plasmas. When $B_{MF}$=60 G, $n_e$ is slightly higher than that for the case of 80 G. $T_e$ in $H_2$ plasma is equal to or lower than 1 eV, but $T_e$ in $D_2$ plasma is above 1 eV in the extraction region. Then, plasma conditions are good for $H^-$ production,

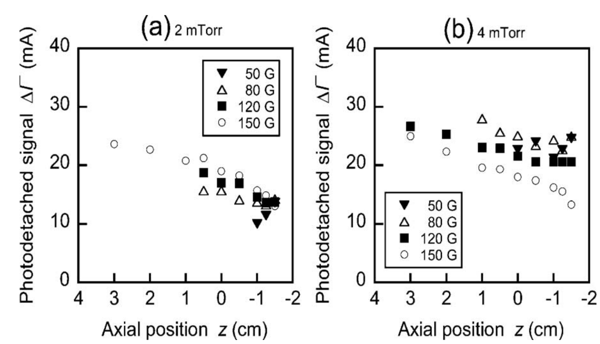


FIG. 3. Axial distributions of negative ion production in $D_2$ plasmas for two different gas pressures: (a) $p(D_2)$=2 mTorr and (b) 4 mTorr. Parameter is the intensity of the MF, $B_{MF}$.

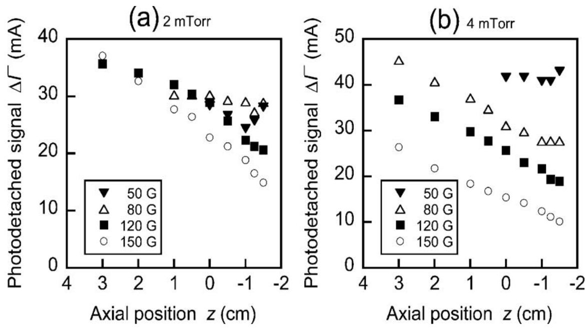


FIG. 4. Axial distributions of negative ion production in $H_2$ plasmas for two different gas pressures: (a) $p(H_2)=2$ mTorr and (b) 4 mTorr. Parameter is the intensity of the MF, $B_{MF}$.

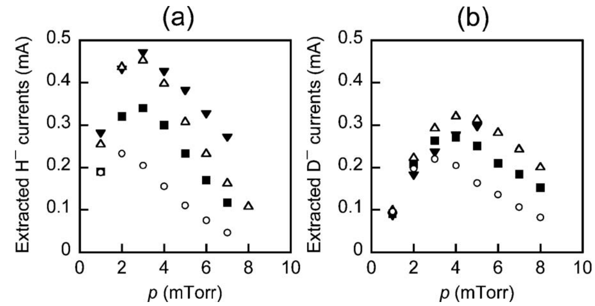


FIG. 6. Pressure dependence of extracted (a) $H^-$ and (b) $D^-$ currents, corresponding to the negative ion densities shown in Fig. 5, where extraction voltage $V_{ex}=1.5$ kV.

but not good for $D^-$ production. When $B_{MF}=80$ G, values of $n_e$ and $T_e$ in $D_2$ plasmas are higher than those in $H_2$ plasmas. $T_e$ in the extraction region is decreased below 1 eV in both $H_2$ and $D_2$ plasmas. The plasma conditions are good for $H^-$ and $D^-$ production. A stronger MF field is required for control of $T_e$ in $D_2$ plasmas. This indicates that plasma production and transport are different in $H_2$ and $D_2$ plasmas.

### B. Production and extraction of negative ions

Plasma parameters in the extraction region depend strongly on $B_{MF}$, and therefore plasma conditions for negative ion volume production are also varied.[11,12] As a consequence, the extracted negative ion currents are found to be strongly dependent on $B_{MF}$. The extraction probability of negative ions depends strongly on the distance from the extraction electrode.[13] To increase the extraction of negative ion currents, the production of negative ions near the extraction electrode should be enhanced by optimizing the plasma conditions.

Figures 3 and 4 show axial distribution of negative ion density in $D_2$ plasmas and in $H_2$ plasmas, respectively, for two different gas pressures. Parameter is $B_{MF}$. In these figures, not a negative ion density but a photodetached electron current $\Delta I^-$ is plotted.

By changing $B_{MF}$, plasma parameters in the downstream region (i.e., $z=8$ to $-2$ cm) are varied.[11,12] Then, negative ion production is varied and the measured $\Delta I^-$ is also varied in both $D_2$ and $H_2$ plasmas. However, the variation of $\Delta I^-$ in $D_2$ plasmas is lower than that in $H_2$ plasmas although variation of plasma parameters in both plasmas is nearly the same.

Figure 5 shows the pressure dependence of negative ion densities in (a) $H_2$ and (b) $D_2$ plasmas. In both cases, as described above, the negative ion densities are varied due to the change in plasma conditions with changing the magnetic field intensity $B_{MF}$ of the MF. As shown clearly, there are some optimum pressures. With increasing gas pressure, negative ion densities increase in their magnitude, reach the maximum value, and then, decrease. Decreasing the $B_{MF}$, the optimum pressure $p_{opt}$ shifts to higher pressure. For $D^-$ production, $p_{opt}$ is changed from 3 to 6 mTorr. On the other hand, for $H^-$ production, $p_{opt}$ is from 2 to 4 mTorr. Optimum pressure in $D_2$ plasmas is slightly higher than the one in $H_2$ plasmas.

The corresponding extracted negative ion currents are shown in Fig. 6. As a whole, pressure dependence have the same feature as the ones of negative ion production shown in Fig. 5 although details are slightly changed.

On negative ion production, intensity of the VUV emission caused by the process (1b) is measured. Typical example is shown in Fig. 7. VUV emission intensity is measured in both the source region ($z=8.5$ cm) and the extraction region ($z=3$ cm). The values of integrated intensities in the source region are increased with increasing gas pressure and $B_{MF}$. As shown in Fig. 5, the $H^-$ and $D^-$ densities vary with the $B_{MF}$. It is noted that the integrated intensity of the VUV emissions and the $H^-$ and $D^-$ densities vary in opposite directions, respectively, when the $B_{MF}$ is varied. Numerical calculations[14] show that the VUV emissions associated with the process (1b) are a function of fast primary

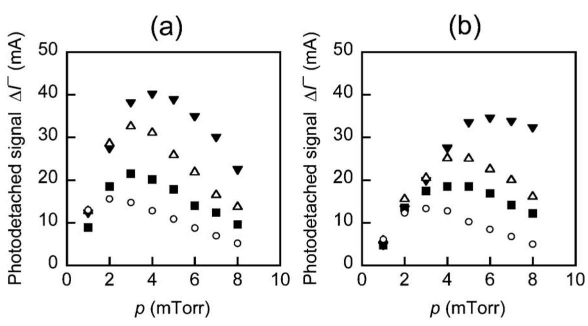


FIG. 5. Pressure dependence of negative ion densities in the vicinity of the extraction electrode: (a) $H^-$ density and (b) $D^-$ density. Parameter is the magnetic field intensity $B_{MF}$ of the MF, $B_{MF}$=50G(▼), 80G(△), 120G(■), and 150G(○). Experimental conditions are as follows: discharge voltage $V_d=70$ V and discharge current $I_d=10$ A.

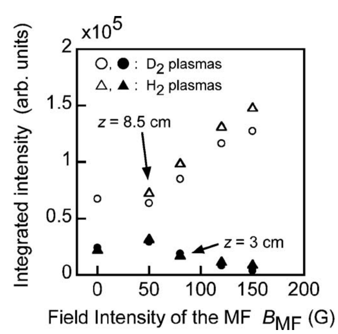


FIG. 7. The integrated intensities of VUV spectra for two different positions as a function of $B_{MF}$. Experimental conditions are as follows: $V_d=70$ V and $I_d=10$ A.

electrons, i.e., its density and behaviors. With increasing the $B_{MF}$, fast electron density in the source region is increased and then the collisions with process (1b) are also increased. Then, the intensity of VUV emission increases with the $B_{MF}$ as the ones observed in the present experiment.

According to the results shown in Figs. 5 and 6 and related discussions, our present picture on negative ion production is as follows: In the present experimental conditions with low-pressure, electron-neutral collision mean free paths for destruction of the vibrationally excited molecules (i.e., ionization and dissociation collisions) are a few tens of centimeters. Therefore, sufficient amount of $H_2(v'')$ and $D_2(v'')$ are transported to the extraction region, although $H_2(v'')$ and $D_2(v'')$ are produced by the collisions between the ground state molecules and fast primary electrons in the source region. The negative ions are produced by the process (2) of slow plasma electrons to $H_2(v'')$ and $D_2(v'')$ in the extraction region. Namely, negative ion production is rate determined by the plasma parameters in the extraction region.

## IV. SUMMARY

Production and control of $H_2$ and $D_2$ plasmas are studied by varying the intensity of the MF. The values of $T_e$ and $n_e$ in $D_2$ plasmas are slightly higher than the ones in $H_2$ plasmas under the same conditions. Then, a stronger MF field is required for control of $T_e$ in $D_2$ plasmas. Therefore, plasma production and/or transport in $H_2$ is different from that in $D_2$. $H^-$ and $D^-$ densities have different spatial distributions corresponding to those different plasma parameters. The extracted $H^-$ and $D^-$ currents are mainly determined by $H^-$ and $D^-$ densities in front of the extraction hole, respectively. $T_e$ in the extraction region should be reduced below 1 eV while keeping $n_e$ higher for enhancement of $H^-$ and $D^-$ production. For further studying of enhancement of $D^-$ production, results of simultaneous measurements of VUV emission and negative ion density in the source is presented. In the future, we will discuss further the isotope effect of $H^-$ and $D^-$ production including Cs injection and the atomic density.

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