Relationship between production and extraction of D^-/H^- negative ions in a volume negative ion source

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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). Production and control of D_2 plasma with the MF is nearly the same as that of H_2 plasmas. 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}), although the values of n_e and T_e in D_2 plasmas are slightly higher than that of H_2 plasmas. With choosing the optimum combination of gas pressure and B_{MF}, plasma conditions are well controlled for volume production of D^-/H^- ions. With decreasing B_{MF} from 150 Gauss to 80 Gauss, negative ion production increases in its value, and D^- production (or density) is nearly the same as H^- production at the optimum gas pressure. Depending on B_{MF}, however, extraction of D^- current is limited in low level compared to that of H^- current although D^- production is nearly the same as H^- production. Optimum gas pressure for D^- production is slightly higher than that for H^- production.

Keywords: Volume negative ion source, Isotope effect of D^-/H^- production, extraction of negative ion, Plasma parameter control, Magnetic filter

1. Introduction

Sources of H^- and D^- negative ions are required for efficient generation of neutral beams with energies above ≈100 keV/nucleon. In pure hydrogen (H_2) discharge plasmas, most of the H^- ions are generated by 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” ≥ 5 – 6). Namely, H^- ions are produced by the following two-step process: [1, 2]

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

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

$$H_2 (v'') + e_s \rightarrow H^- + H, \quad (2)$$

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 excited electronic states ($B^1\Sigma_u$ 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^- ion 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. In Cesium (Cs)-seeded H_2 plasma, the extracted electron currents decrease, and the extracted negative ion currents increase. 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 D_2 or H_2 discharge plasmas.

For this purpose, we are interested in estimating densities of highly vibrationally excited molecules and negative ions in the source. The previous results are as follows [6-8]; H^- production in the extraction region is remarkably changed corresponding to the variation of electron density n_e and T_e in the extraction region. Optimum field intensity B_{MF} of magnetic filter (MF) and gas pressure for D^- production is slightly higher than that for H^- production. The extracted H^- and D^- currents are mainly determined by H^- and D^- densities in front of the extraction hole, respectively.

In this paper, plasma parameters are controlled by using the usual magnetic filter method[8] although we have shown recently that mesh grid bias method is also useful to optimize plasma conditions for negative ion volume production [9.10]. To study further the isotope effects of D^-/H^- production and D^-/H^- extraction, we discuss the relationship between negative ions in the source and the extracted negative ion currents, including the measurements of plasma parameters and VUV emission associated with the process (1b) [11,12].

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2. Experimental set-up

Figure 1 shows a schematic diagram of the ion source. The rectangular arc chamber is 25 × 25 cm in cross section and 19 cm in height. Four tungsten filaments 0.7 mm in diameter and 20 cm in length are installed in the source region from the side walls of the chamber. H_2 and D_2 plasmas are produced by a DC arc discharge between the chamber anode and the filament cathode. Produced plasmas are confined by the line cusp magnetic field. The line cusp magnetic field is produced by permanent magnets which surround the chamber. The external magnetic filter (MF) is composed of a pair of permanent magnets in front of the plasma grid (PG). Figure 2 shows profiles of the field intensities for four different MFs along the axis of the ion source. These MFs gradually separate the extraction region from the source region with filaments.

H^- or D^- densities in the source are measured by the laser photodetachment method [13]. In this method, a photodetached electron from the negative ion by means of a pulsed laser beam (A light pulse from a Nd:YAG laser :100 mJ cm^{-2} pulse, wavelength 1064 nm, duration of laser pulse 9 ns, repetition 10 Hz) is collected by the cylindrical tungsten L-probe (1 mm in diameter, 6 mm long) placed along the axis of the laser beam. The probe is biased at +20 V relative to the anode and therefore it attracts the detached electrons. These detached electrons create a probe current pulse, $\Delta\Gamma$, whose height is proportional to the negative ion density. This probe is also used to measure plasma parameters. On the other hand, negative currents are extracted through a single hole with 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 and extracted electron current.

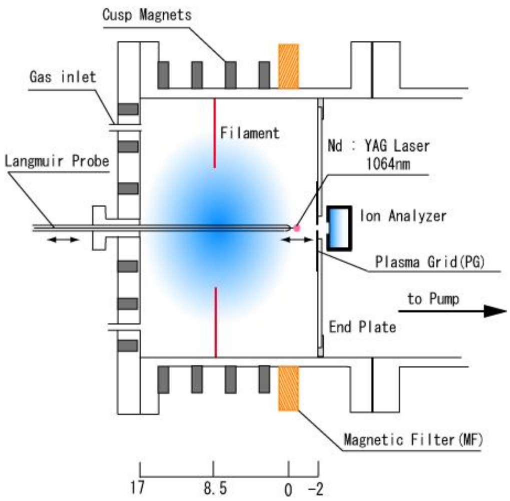

Fig.1 Schematic diagram of the ion source.

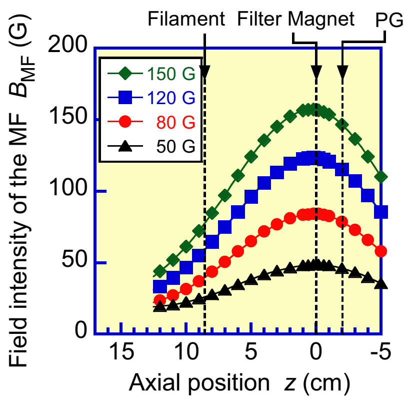

Fig.2 Axial distributions of field intensities for four different magnetic filters (MF), B_{MF}

3. Experimental results and discussion

3.1 Production and control of plasmas

On D^-/H^- 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 D^-/H^- production by dissociative attachment and to reduce D^-/H^- destruction by electron detachment including collisions with energetic electrons, plasma parameters are controlled by changing the field intensity B_{MF} of the MF.

As is shown previously [6, 7], as a whole, the axial

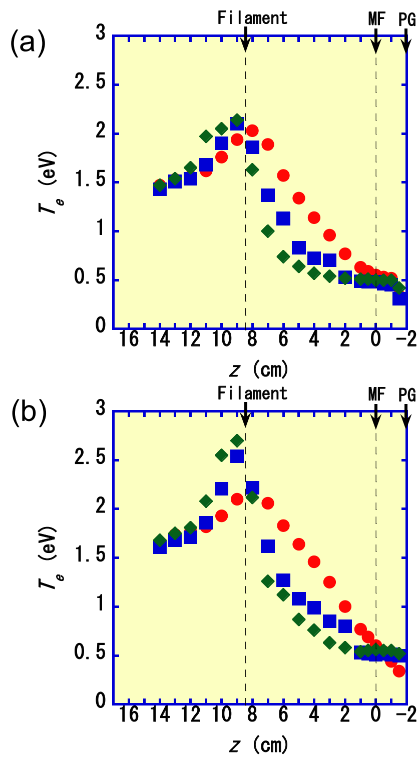

Fig.3 Axial distributions of electron temperature T_e in (a) D_2 and (b) H_2 plasmas. Parameter is the magnetic field intensity B_{MF} of the MF, namely B_{MF}= 80 Gauss (●), 120 Gauss (■) and 150 Gauss (◆). Experimental conditions are as follows: discharge voltage V_d = 70 V, discharge current I_d = 10A, gas pressure p (H_2) = 2 mTorr and p (D_2) = 4 mTorr

profiles of n_e and T_e in deuterium (D_2) and hydrogen (H_2) plasmas have nearly the same patterns with each other. In general, for the same discharge conditions, both n_e and T_e in D_2 plasmas are higher than ones in H_2 plasmas. 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 D_2 and H_2 plasmas, respectively.

However, these plasma conditions are well controlled by choosing a good combination of gas pressure and B_{MF}. To clarify this point in details, we show the axial distributions of T_e and n_e in D_2 and H_2 plasmas, respectively, in Figures 3 and 4. Here, gas pressures are set to about optimum conditions, respectively (see Fig.5). Parameter is B_{MF}. When B_{MF} = 80 Gauss, values of n_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 D_2 and H_2 plasmas. The plasma conditions are good for D^- and H^- volume productions.

3.2 Production and extraction of negative ions

Plasma parameters in the extraction region depend on the B_{MF}, and therefore plasma conditions for negative ion volume production are also varied [6-8]. Then, the extracted negative ion currents are found to be strongly dependent on the B_{MF}. Because, extraction probability of negative ions depends on its birth point, i.e. the distance from the extraction electrode (i.e. the PG in our case) [14]. To increase the extraction of negative ion currents, the production of negative ions near the PG should be enhanced by optimizing the plasma conditions.

By changing B_{MF}, plasma parameters in the downstream region (i.e., z = 4 to -2 cm) are varied. Then, negative ion production, i.e. the measured $\Delta\Gamma$, is varied in both D_2 and H_2 plasmas. However, the variation of $\Delta\Gamma$ in D_2 plasmas is lower than that in H_2 plasmas although variation of plasma parameters in both plasmas is nearly the same. At any rate, negative ion production in the vicinity of the PG is nearly equal with each other.

Figure 5 shows the pressure dependence of negative ion densities in (a) D_2 and (b) H_2 plasmas. In both cases, the negative ion densities are varied due to the change in plasma conditions with changing gas pressure p and B_{MF}. It is shown clearly that there are some optimum pressures. With increasing p, 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 4 to 5 mTorr. On the other hand, for H^- production, p_{opt} is from 3 to 2 mTorr. Optimum pressure in D_2 plasmas is slightly higher than one in H_2 plasmas.

In Fig.6, corresponding plasma parameters (n_e) are shown as a function of p. With increasing p, at first n_e in D_2 plasmas is increased slightly and then keeps nearly constant and n_e in H_2 plasmas has nearly the same manner although values of n_e is lower than ones in D_2 plasmas.

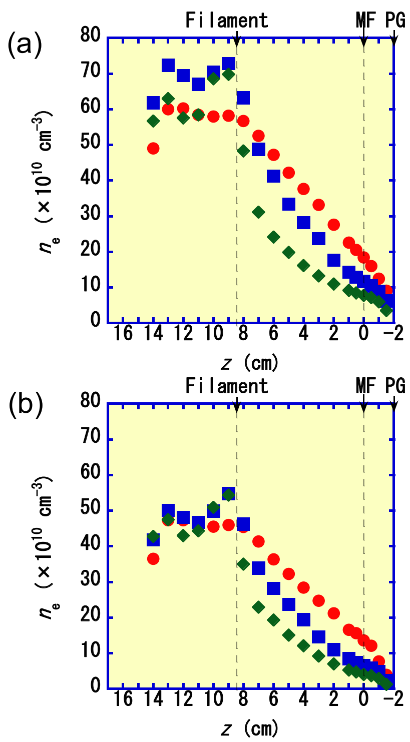

Fig.4 Axial distributions of electron density n_e in (a) D_2 and (b) H_2 plasmas. Parameter B_{MF} and experimental conditions are the same as in Fig.3.

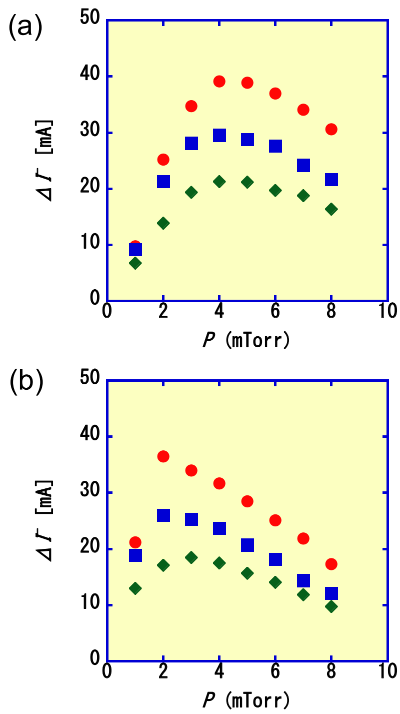

Fig.5 Pressure dependence of negative ion densities in the vicinity of the extraction electrode (i.e. the PG): (a) D_2 plasma and (b) H_2 plasma. Parameter is B_{MF}, i.e. B_{MF} = 80 Gauss (●), 120 Gauss (■), 150 Gauss (◆). Experimental conditions are as follows: V_d = 70 V, I_d = 10 A and measurement point of $\Delta\Gamma$ z = -1.5 cm.

Values of T_e is both D_2 and H_2 plasmas (not shown here) are nearly equal to each other and are decreased gradually with p, i.e. from 0.6 eV to 0.3 eV. According to these variation of plasma parameters, negative ion production rate (i.e. disassociative attachment) keeps nearly the same value and then could not be well explained the pressure dependence of negative ion production shown in Fig. 5.

There is a report about pressure dependence of H^- production. The population of vibrationally excited molecules attains a maximum at a certain optimum pressure due to their quenching in collisions with molecules at higher pressure [15]. Moreover the total H^- loss rate increases strongly for elevated pressures and the associative detachment process with atomic hydrogen becomes the main loss process for H^-. We will further study this point in D_2 plasmas.

The corresponding extracted negative ion currents, I_{D-} and I_{H-}, are shown in Fig.7. As a whole, pressure dependences of the extracted currents have the same feature as ones of negative ion production shown in Fig. 5 although details are slightly changed. When B_{MF} = 150 Gauss, extracted negative ion currents at optimum pressure are nearly equal with each other. With decreasing B_{MF}, however, I_{D-} is limited in low level compared with I_{H-} although negative ion production in the source is increased. This is partly because n_e in the extraction region becomes high with decreasing B_{MF} (see Fig.6) and then extraction of I_{D-} becomes inefficient compared with that of I_{H-}. However, effect of B_{MF} on negative ion extraction is not well clarified. Details are now under study.

On negative ion production, intensity of the VUV emission caused by the process (1b) is measured [7, 8]. 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 p and the B_{MF}. It is noted that the integrated intensity of the VUV emissions and the negative ion densities vary in opposite directions, respectively, when the B_{MF} is varied. With increasing the B_{MF}, fast electron density in the source region is increased and then the collisions with process (1a) are also increased. Then, the intensity of VUV emission increases with the B_{MF} as ones observed in our experiments [7, 8].

Our present picture on negative ion production is as follows: In the present low-pressure case, 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 D_2 (v”) and H_2 (v”) are transported to the extraction region, although D_2 (v”) and H_2 (v”) are mainly produced by the collisions between the ground state molecules and fast primary electrons in the

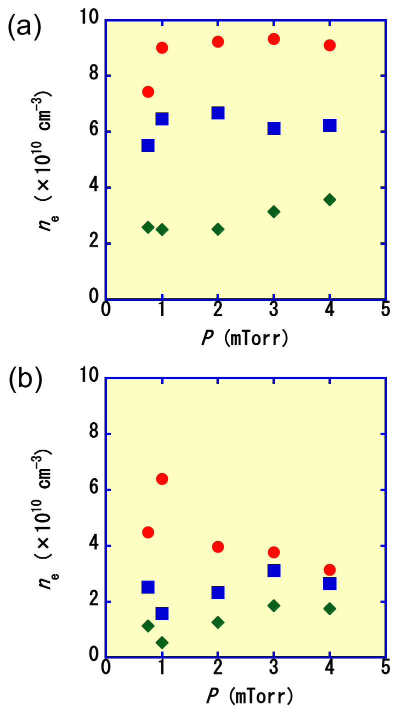

Fig.6 Pressure dependence of electron density in the vicinity of the PG: (a) D_2 plasma and (b) H_2 plasma. Parameter is B_{MF}, i.e. B_{MF} = 80 Gauss (●), 120 Gauss (■) and 150 Gauss (◆). Experimental conditions are as follows: V_d = 70 V, I_d = 10 A and z = -1.5 cm.

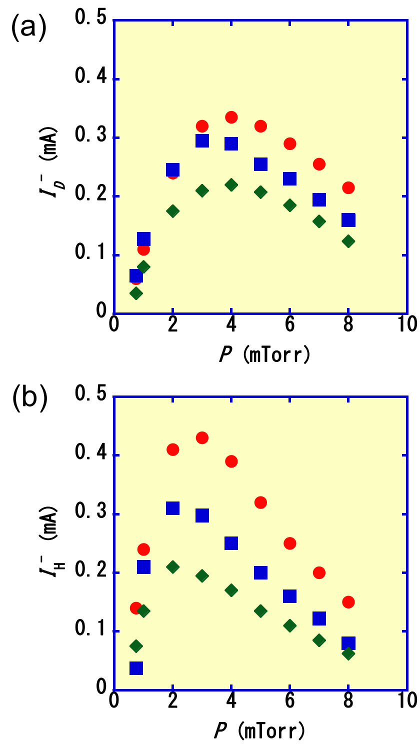

Fig.7 Pressure dependence of extracted D^- current in (a) and H^- current in (b), corresponding to the negative ion densities shown in Fig.5. Experimental conditions are the same as in Fig.5, where extraction voltage V_{ex} = 1.5 kV.

source region. The negative ions are produced by the process (2) of slow plasma electrons to D_2 (v”) and H_2 (v”) in the extraction region. Namely, negative ion production is rate-determined by the plasma parameters in the extraction region.

Pressure dependence of D^- production shown in Fig.5 is not well clarified although destruction of D^- is enhanced with increasing p. Pressure dependence of VUV emission and effect of B_{MF} on VUV emission are studied near future.

4. Summary

Production and control of D_2 plasmas are performed by varying the intensity of the MF. Axial profiles of n_e and T_e in D_2 and H_2 plasmas have nearly the same patterns although values of n_e and T_e in D_2 plasmas are slightly higher than ones in H_2 plasmas. T_e in D_2 plasmas cannot be decreased and is kept above 1 eV in the extraction region with the same MF intensity for optimizing H_2 plasmas. Therefore, plasma production and/or transport in D_2 plasmas are different from those in H_2 plasmas. Namely, an isotope effect of plasma production is observed. D^- and H^- densities have different spatial distributions corresponding to those different plasma conditions. The extracted D^- and H^- currents are mainly determined by D^- and H^- densities in the vicinity of the extraction hole, respectively. According to the present experiment and discussion, it is reconfirmed that T_e in the extraction region should be reduced below 1 eV while keeping n_e higher for enhancement of D^- production.

In the future, we will discuss further the isotope effect of D^- and H^- production including Cs injection and the atomic density. We will also try to control plasma parameters with using the mesh grid bias method.

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