Isotope Effect of H^-/D^- Volume Production in Low-Pressure H_2/D_2 Plasmas - Negative Ion Densities versus Plasma Parameters -

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Abstract. Isotope effect on H^-/D^- volume production is studied in a rectangular arc chamber. Axial distributions of H^-/D^- ion densities in the source are measured directly using a laser photodetach.ment method. Relationship between H^-/D^- production and plasma parameter control with using a magnetic filter (MF) is discussed. Furthermore, relative intensities of extracted negative ion currents are discussed compared with the negative ion densities in the source. Production and control of D_2 plasmas are well realized with the MF including good combination between the filament position and field intensity of the MF. Extracted H^- and D^- currents depend directly on negative ion densities in the source.

INTRODUCTION

Sources of H^- and D^- negative ions are required for generation of efficient neutral beams with energies in excess of 150 keV. 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" $\geq$ 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]:

$$H_2\,(X^1\Sigma_g, v''=0) \quad + \quad e_f \quad \rightarrow \quad H_2^*(B^1\Sigma_u, C^1\Pi_u) \quad + \quad e_f', \qquad (1a)$$
$$H_2^*(B^1\Sigma_u, C^1\Pi_u) \quad \rightarrow \quad H_2\,(X^1\Sigma_g, v'') \quad + \quad h\nu, \qquad (1b)$$
$$H_2\,(v'') \quad + \quad e_s \quad \rightarrow \quad H^- \quad + \quad H. \qquad (2)$$

Production process of D^- ions is believed to be the same as that of H^- ions. To develop efficient D^- ion sources, namely to extract D^- ions with high current density, it is important to clarify production and control of deuterium (D_2) plasmas, and to understand difference in the two step process of negative ion production between H_2 plasmas and D_2 plasmas. Cesium seeding into this source is used to enhance negative ion currents and to reduce extracted electron currents. However, there are few studies on optimization of volume-produced D^- ions. Then, 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")/D_2(v") is discussed [3] by observing the photon emission, i.e. VUV emission associated with the process (1b) [4, 5]. To clarify the relationship between plasma parameters and volume production of negative ions, H^- or D^- ions in the source are measured [6, 7] by the laser photodetachment method [11].

In this paper, plasma parameter control by varying the magnetic field intensity of the MF is presented [8, 9]. Influence of these plasma parameter distributions on H^-/D^- production is discussed with using estimated rate coefficients and collision frequencies based on measured plasma parameters [9, 10]. Estimating negative ion densities in the source with the use of laser photodetachment technique, we discuss the relationship between negative ions in the source and extracted negative ion currents. [8]

EXPERIMENTAL SET-UP

Figure 1 shows a schematic diagram of the ion source [6-10]. The rectangular arc chamber is 25 cm × 25 cm 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 the source region from side walls 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), and the MF separates the extraction region from the source region. PG potential is kept earth potential throughout the present experiments both for H_2 and D_2 plasmas.

Plasma parameters are measured by Langmuir probes. A magnetic deflection type ion analyzer is also used for relative measurements of the extracted H^- or D^- current. H^- or D^- densities in the source are measured by the laser photodetachment method [11]. A light pulse from a Nd:YAG laser (wavelength 1064 nm, duration of laser pulse 9 ns, repetition 10 Hz) is introduced from the side wall window of the chamber and passes through the source plasmas. The laser light axis can move across the MF.

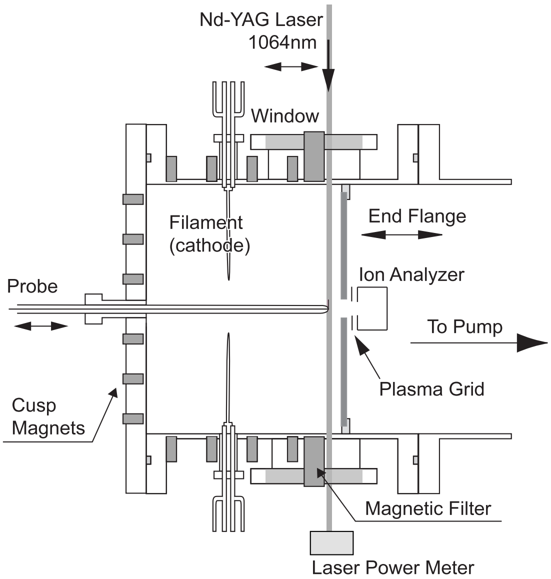

Fig. 1 Schematic diagram of the ion source. The probe, the laser path, and power meter used in photo-detachment experiments are also shown.

EXPERIMENTAL RESULTS AND DISCUSSION

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 with n_e keeping higher. To realize above-mentioned 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. In this purpose, plasma parameter control is studied by varying the intensity of the MF.

Figures 2 and 3 show axial distributions of plasma parameters (n_e and T_e) in H_2 and D_2 plasmas, respectively. By varying the intensity of the MF, axial distributions of n_e and T_e in both H_2 and D_2 plasmas are changed strongly in the downstream region (from z = 8 to -2 cm) [8-10]. Production and control of D_2 plasmas are almost the same characteristics as that of H_2 plasmas.

In Figs. 2 and 3, for the MF with 150 G (B_{MF} = 150 G), not only T_e but also n_e are decreased far from the MF, i.e. z = 8 cm, in the source region. On the other hand, decreasing points of n_e and T_e are shifted to downstream region for the case of 80 G and 60 G. In this source, due to the external MF, width of the half-maximum of magnetic field intensity is wider (about 16cm in this case) than the case of rod filter [5]. Namely, varying the intensity of the magnetic filter indicates also varying the strength of magnetic field distribution in both source region and extraction region. Thus, the external MF has the merit of control of plasma parameters gradually. T_e control can be done precisely with keeping n_e high in the extraction region.

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 1eV in the extraction region. Then, plasma conditions are good for H^- production, 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 ones in H_2 plasmas. T_e in the extraction region is decreased below 1 eV in both H_2 and D_2 plasmas. Plasma conditions are good for H^- and D^- production. The stronger MF field is required for control of T_e in D_2 plasmas. Therefore, plasma productions of H_2 and D_2 plasmas are different from each other. Namely isotope effect of plasma production is observed.

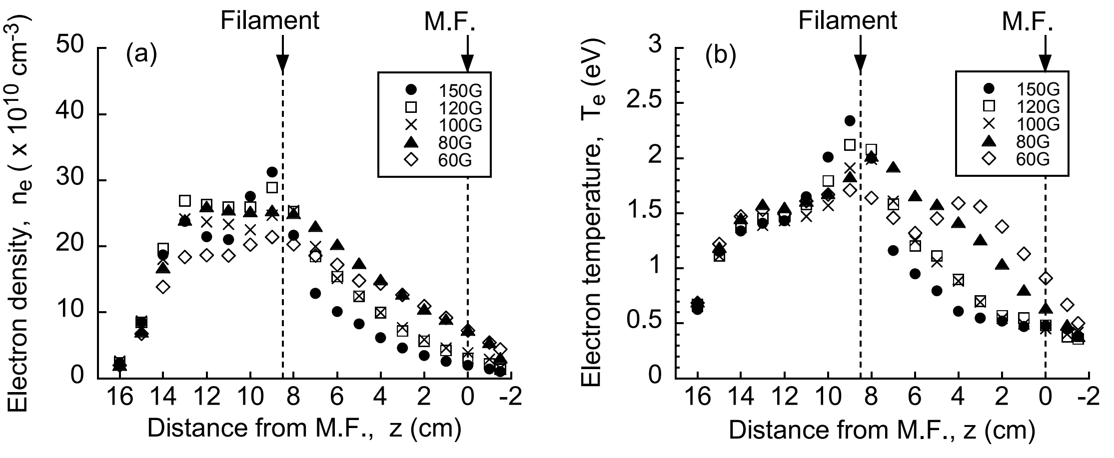

Fig. 2 Axial distributions of plasma parameters (a) n_e and (b) T_e in H_2 plasmas. Experimental conditions are as follows: V_d = 70 V, I_d = 5 A, p(H_2) = 1.5 mTorr. Parameter is the magnetic field intensity of the MF.

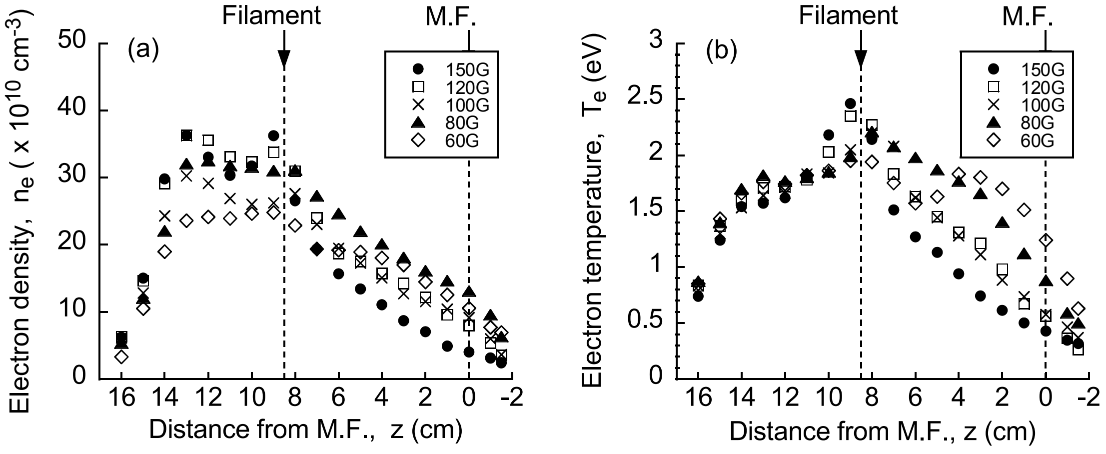

Fig. 3 Axial distributions of plasma parameters (a) n_e and (b) T_e in D_2 plasmas. Experimental conditions are as follows: $V_d = 70$ V, $I_d = 5$ A, $p(D_2) = 1.5$ mTorr. Parameter is the magnetic field intensity of the MF.

As shown in Figs. 2 and 3, plasma parameters in the extraction region depend strongly on the MF intensity. Figure 4 shows pressure dependence of extracted negative ion currents from (a) H_2 and (b) D_2 plasmas [8]. The negative ion currents are also depending strongly on the MF intensity. In both cases, there are some optimum pressures. With increasing gas pressure, negative ion currents (i.e. the H^- current, I_{H^-} and the D^- current, I_{D^-}) increase in their magnitude, reach the maximum value, and then, decrease. With decreasing the intensity of the MF, optimum pressure p_{opt} shifts to higher pressure. For D^- production, p_{opt} is from 2 to 3.5 mTorr. On the other hand, for H^- production, p_{opt} is from 1.5 to 2 mTorr. Optimum pressure in D_2 plasmas is slightly higher than one in H_2 plasmas.

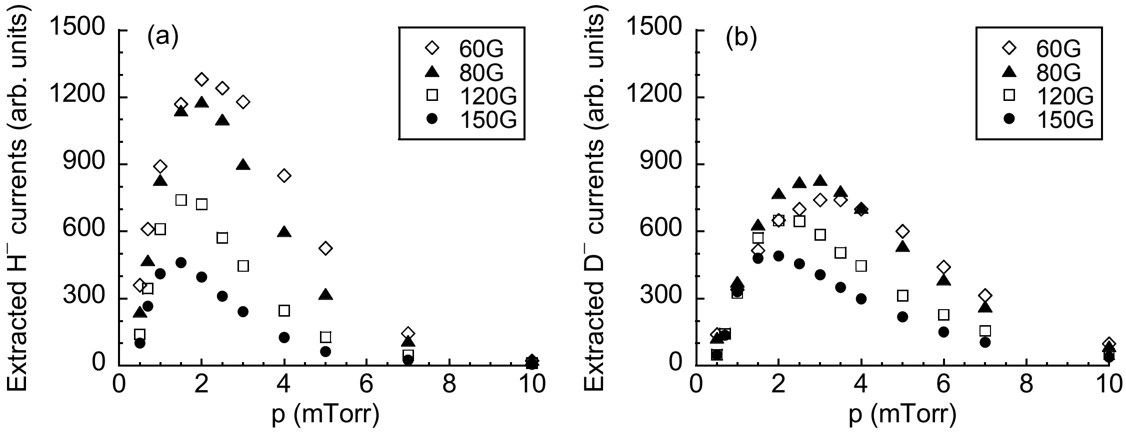

Fig. 4 Pressure dependence of extracted (a) H^- and (b) D^- currents. Experimental conditions are as follows: $V_d = 70$ V, $I_d = 5$ A, and $V_{ex} = 1.5$ kV. Parameter is the magnetic field intensity of the magnetic filter.

H^- density distributions across the MF are measured and its dependence on plasma parameters are studied. Figure 5 shows axial distributions of H^- ion densities, where B_{MF} = 150 G and 80 G, respectively [9, 10]. Plasma parameters corresponding to these H^- ion densities are shown in Fig. 2. Spatial distributions of H^- densities are varied by changing plasma parameters. When B_{MF} = 150 G, H^- density distribution decreases toward to the extraction hole (i.e. z = -2 cm). On the other hand, when B_{MF} =80 G, H^- density distribution remains nearly constant value although n_e decreases toward to the extraction hole. In front of the extraction hole (i.e. plots at z = -1.5 cm), H^- density with 80 G is higher than that with 150 G by a factor about 2. As is shown in Fig. 4, extracted H^- currents from the source are also the same ratio. Extracted H^- currents depend on H^- densities in front of the extraction hole.

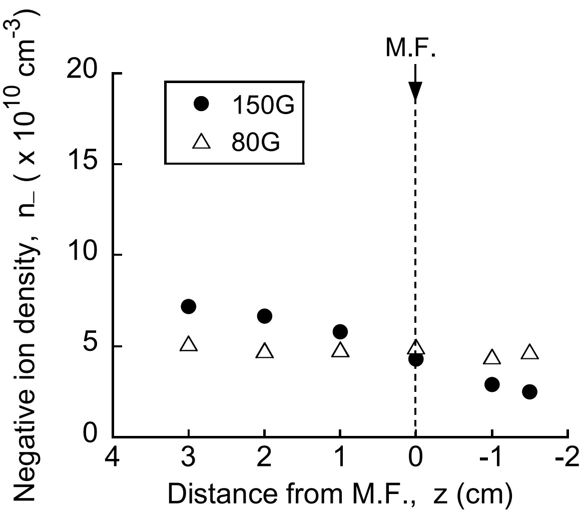

Fig. 5 Axial distributions of H^- ion densities. Experimental conditions are as follows: V_d = 70 V, I_d = 5A, $p(H_2)$ =1.5 mTorr. Parameter is the magnetic field intensity of the MF. Corresponding plasma parameters are shown in Fig. 2 (with B_{MF} = 150 G and 80G).

Relationship between these plasma parameter distributions and H^-/D^- production is not well clarified. The variations of H^- and D^- production due to changes in plasma parameter distributions are discussed by taking into account main collision processes for production and destruction. Dissociative attachment (DA: $H_2(v") + e \rightarrow H^- + H$) is main process for H^- production and electron detachment (ED: $H^- + e \rightarrow H + 2e$) is main process for H^- destruction. These two processes are also applicable to the main process in D_2 plasmas for D^- production and destruction. In the following discussion, it is assumed that only H_2(v"=8) or D_2(v"=12) is present. H_2(v"=8) and D_2(v"=12) have almost the same internal energy [12]. The values of rate coefficient, $<\sigma v>_{DA}$ for DA and $<\sigma v>_{ED}$ for ED, and collision frequency, $n_e<\sigma v>_{DA}$ and $n_e<\sigma v>_{ED}$ are estimated by using measured values of T_e and n_e shown in Figs. 2 and 3.

Figure 6 shows axial distributions of rate coefficients and collision frequencies of DA and ED processes, respectively [9, 10]. With changing T_e distributions, as shown in Fig. 6(a), distributions of ED processes are changed strongly while DA processes keep nearly the same value. It is found that T_e control by varying the intensity of the MF reduce ED process remarkably. As shown in Fig. 6(b), by taking into account both T_e and n_e changes, the difference between DA with 150 G and with 80 G is caused by n_e in this region (n_e with 80 G is higher than that with 150 G). The distribution patterns of H^- densities are mainly determined by ED process in range of T_e = 0.5 to 1.5 eV. H^- density with 150 G in Fig. 5 is scarcely decreased by ED process because T_e keeps sufficiently below 1 eV (almost 0.5 eV). The pattern of H^- density distribution with 150 G is nearly the same as that of n_e distribution. On the other hand, H^- density with 80 G is decreased strongly by ED process because T_e is nearly equal to or above 1 eV in the upstream region from the MF. Thus, the pattern of H^-

density distribution with 80G is difference from that of n_e distribution.

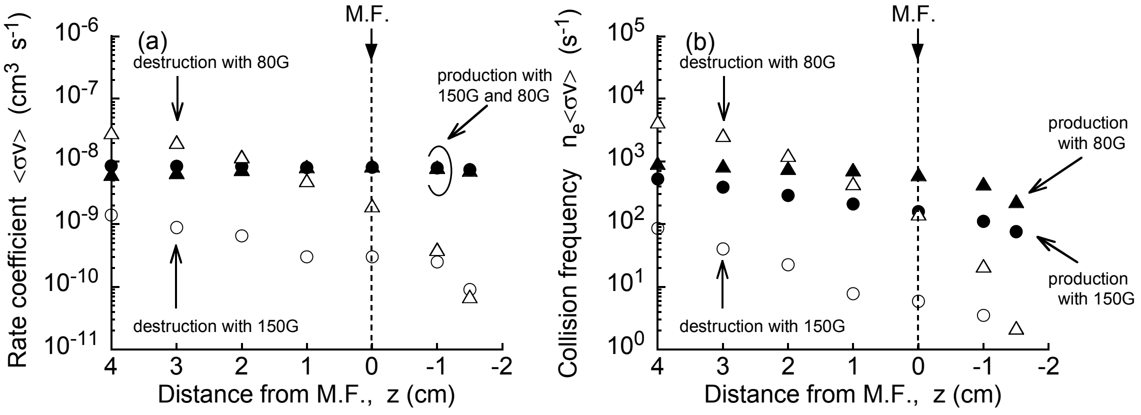

Fig. 6 Axial distributions of (a) rate coefficient and (b) collision frequency estimated by measured T_e and n_e in H_2 plasmas (closed circle; H^- production with 150G, closed triangle; H^- production with 80G, open circle; H^- destruction with 150G, closed triangle; H^- destruction with 80G). Corresponding plasma parameters are shown in Fig. 2.

D^- density distributions are compared to H^- density distributions in the same discharge condition. Figure 7 shows axial distributions of negative ion densities, where B_{MF} = 80 G, $p(H_2) = p(D_2)$ = 1.5 mTorr, respectively [9, 10]. Axial distribution of D^- density is lower than that of H^- density. According to the plasma conditions shown in Figs. 2 and 3, T_e in D_2 plasma is higher than that in H_2 plasma. With discussion described above, influence of D^- destruction by ED process on D^- density is higher although n_e in D_2 plasma is also higher. As shown in Fig. 4, extracted D^- current is also lower than H^- current, and the ratio of H^- to D^- current is almost the same as the ratio of H^- to D^- density in front of the extraction hole. Therefore, extracted D^- current is mainly determined by D^- density in front of the extraction hole. Detailed discussions in relation to negative ions in the source and extracted negative ion currents will be discussed below.

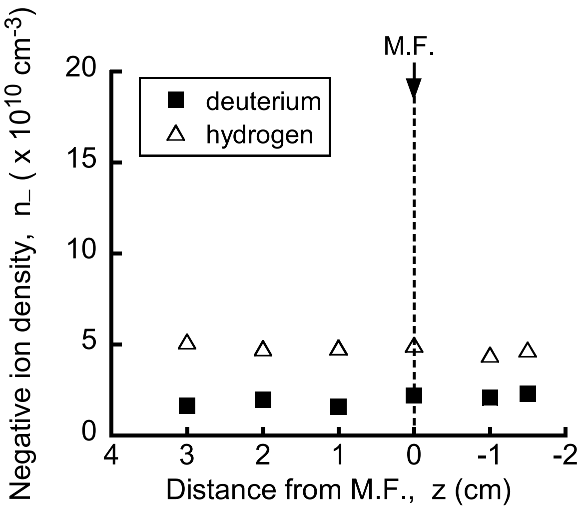

Fig. 7 Axial distributions of H^- and D^- ion densities. Experimental conditions are as follows: V_d = 70 V, I_d = 5 A, $p(H_2$ or $D_2)$ = 1.5 mTorr and B_{MF} = 80 G. Corresponding plasma parameters are shown in Fig. 2 (for H_2 plasma) and Fig. 3 (for D_2 plasma).

The relationship between the behavior of negative ions (corresponding to negative ion densities) in the source and the extracted negative ion currents are not well examined. Figure 8 shows axial distributions of negative ion densities in the source, where the field intensity of the MF is 80 G, p(H_2)= 1.5 mTorr and p(D_2)= 3 mTorr, respectively [8]. These two different pressure conditions are corresponding to the results in Fig. 4. As shown in Fig. 8, the negative ion densities in front of the extraction hole in D_2 plasmas nearly equal to that in H_2 plasmas. On the other hand, according to the results in Fig. 7, I_D- at 3 mTorr with 80G is lower than I_H- at 1.5 mTorr, where the same extraction voltage V_{ex} is applied for H^- extraction and D^- extraction, respectively. Considering the factor of √2 due to mass difference, √2 times I_D- is nearly equal to I_H-. Then D^- ions in the source are expected to be the same as H^- ions. Results in Fig. 8 support this.

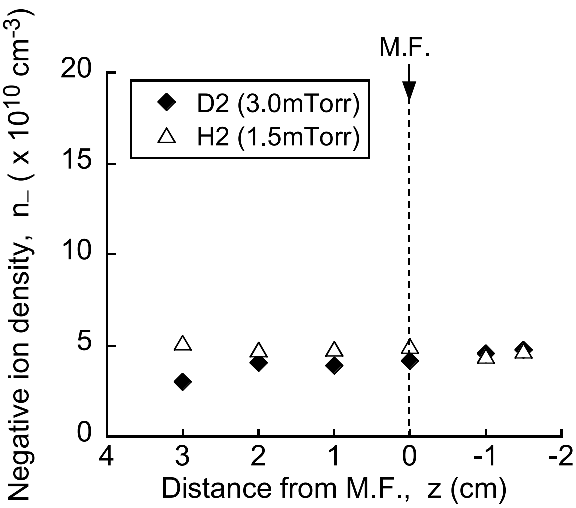

Fig. 8 Axial distributions of H^- and D^- ion densities. Experimental conditions are as follows: V_d= 70 V, I_d = 5 A, p(H_2) = 1.5 mTorr, p(D_2) = 3 mTorr, B_{MF} = 80 G and V_{ex} = 1.5 kV.

SUMMARY

Production and control of plasma parameters in H_2 and D_2 plasmas are performed by varying the intensity of the MF. The values of T_e and n_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. The stronger MF field is required for control of T_e in D_2 plasmas. Therefore, plasma production between H_2 and D_2 plasmas is different from each other. Namely isotope effect of plasma production is observed. H^- and D^- densities have different spatial distributions corresponding to those different plasma parameters. Extracted H^- and D^- currents are mainly determined by H^- and D^- densities in front of the extraction hole, respectively. According to the discussions based on estimated rate coefficient and collision frequency of main collision processes, it is reconfirmed that T_e in the extraction region should be reduced below 1 eV with n_e keeping higher for enhancement of H^- and D^- production. For further studying enhancement of D^- production, simultaneous measurements of VUV emission and negative ion density in the source is necessary.

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