Isotope effect of H^-/D^- volume production in low-pressure H_2/D_2 plasmas
- measurement of VUV emissions and negative ion densities -

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Isotope effect on H^-/D^- volume production is studied by measuring both VUV emission and negative ion density in the source. In a double plasma type source, under some discharge conditions, extracted D^- currents are nearly the same as H^- currents, although VUV emission intensity (corresponding to production of vibrationally excited molecules) in D_2 plasmas is slightly lower than that in H_2 plasmas. Considering the factor $\sqrt{2}$ due to mass difference, D^- ion density in the extraction region of the source is higher than H^- ion density. In another experiment with a rectangular arc chamber, axial distributions of H^-/D^- ion densities in the source are measured directly using a laser photodetachment 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.

1. 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~ 1 eV) to highly vibrationally excited hydrogen molecules H_2 (v") (effective vibrational level v"≧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]:

$$H_2 (X^1 \Sigma g, v"=0) + e_f \rightarrow H_2^*(B^1 \Sigma u, C^1 \Pi u) + e_f' \quad (1a)$$

$$H_2^*(B^1 \Sigma u, C^1 \Pi u) \rightarrow H_2 (X^1 \Sigma g, v") + h\nu \quad (1b)$$

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

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], for the first time, 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] by the laser photodetachment method [7]. In the present paper, with the use of a double plasma (DP) negative ion source [5, 8], we study further isotope effect of H^-/D^- production in volume negative ion sources. By observing the VUV emission from plasmas, we compare $D_2(v")$ production with $H_2(v")$ production and discuss further enhancement of D^- production. 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 the extracted negative ion current.

2. Measurement of VUV Emission Intensities

In this section , we discuss the relationship between $H_2(v")$/ $D_2(v")$ production and H^-/D^- production in beam-excited plasmas, by taking into account VUV emission intensities.

Figure 1 shows a schematic diagram of the double plasma type negative ion source [3, 5, 8]. The chamber made of stainless steel is divided by a mesh grid ($z = 0$ cm) into two regions, i.e. a driver plasma region (the left hand side) and a target plasma region (the right hand side). The target plasma region is a conventional multicusp negative ion source equipped with both a magnetic filter and a plasma grid.

The magnetic filter (MF) is composed of four water-cooled Sm-Co magnets rods, and provide a limited region of transverse magnetic field of about 70 G on the center between the two rods. This field divides the target chamber into the source region (i.e. plasmas with injected high-energy electrons) and the extraction region (i.e. plasmas with low electron temperature T_e). The MF is strong enough to prevent all energetic electrons in the source region from entering into the extraction region. Cold electrons, however, together with positive ions can penetrate the filter and form diffused plasmas with low T_e [9].

In the driver chamber, plasmas are produced by arc discharge between hot filaments and the chamber anode, which is grounded. Electrons in the plasmas are extracted and injected into the target chamber as an electron beam with controlled beam energy eV_B. In the target chamber, hydrogen or deuterium gas is introduced and then ionized by the injected electron beam. In this region, the photon emissions related to the $H_2(v")$ or $D_2(v")$ production, i.e. the process (1b), are measured by the VUV spectrometer. The spectrometer was normally operated at a resolution of 0.1 nm.

Plasma parameters (electron density n_e, electron temperature T_e, space potential V_s and so on) are measured by Langmuir probes. A magnetic deflection-type ion analyzer is used for relative measurement of the extracted H^- or D^- negative ion currents. The plasma grid potential is kept earth potential.

Figure 2 shows the typical VUV spectra (a) from the hydrogen and (b) from the deuterium plasmas. Strong intensity (121.8 nm in H_2 plasma and 121.7 nm in D_2 plasma) of VUV spectra is Lyman α of atomic hydrogen and deuterium. According to the numerical simulation [2], $H_2(v"\geqq5)$ are more effective for H^- production. In Fig.2 (a), spectra leading to production of $H_2(v"\geqq5)$ are ranged from 117.5 to 130 nm and from 135 to 165 nm [4]. Internal energy of molecules $D_2(v"\geqq8)$ are almost the same as that of $H_2(v"\geqq5)$. Therefore, concerning production of vibrational molecules, discussion on VUV spectra from H_2 plasmas can be applicable to that from D_2 plasmas. Namely, production of highly vibrationally excited deuterium molecules $D_2(v")$ is related to the emission with the same wavelength range, i.e. 117.5~165 nm. By taking into account above discussion, we integrate the VUV spectra (110~165 nm) of H_2 and D_2 plasmas to compare $H_2(v")$ production with $D_2(v")$ production. Integration of VUV spectra excludes Lyman- α [10].

Concerning production of H_2 and D_2 plasmas, axial distributions of plasma parameters (i.e. n_e and T_e) are shown in Fig. 3. Both patterns of n_e and T_e distributions in D_2 plasmas are nearly the same as ones in H_2 plasmas. However, values in n_e with D_2 plasmas is lower than one with H_2 plasmas, and T_e in D_2 plasmas is higher than one in H_2 plasmas.

Figure 4 shows the pressure dependence of the extracted negative ion currents. In both cases, there is a certain optimum pressure, namely from 3 to 4 mTorr. With increasing gas pressure, negative ion currents (i.e. the H^- current, Γ_H and the D^- current, Γ_D) increase in their magnitude, reach the maximum value, and then, decrease. Optimum pressure in D_2 plasmas is slightly higher than one in H_2 plasmas. When the value of extraction voltage is the same for both cases, Γ_D is usually reduced approximately by factor $1/\sqrt{2}$ compared with Γ_H due to mass difference. For reference, points corresponding to $\sqrt{2}$ times Γ_D are also plotted. These points are larger than the points of Γ_H. It suggests that D^- density in the source is nearly equal to or higher than H^- density.

Figure 5 shows the dependence of negative ion currents on discharge power, where p = 3 and 4 mTorr. D^- currents increase almost linearly with discharge power, similar to H^- currents.

When $p(H_2) = p(D_2) = 3$ mTorr, under the same discharge power, Γ_H is higher than Γ_D. However, when $p(H_2) = p(D_2) = 4$ mTorr, Γ_H is nearly equal to Γ_D. For reference, points corresponding to $\sqrt{2}$ times Γ_D are also plotted. These points are higher than the Γ_H.

Figure 6 shows integrated intensities of VUV emissions corresponding to the results in Fig. 5. The ratio of intensity from D_2 plasmas to one from H_2 plasmas keeps nearly the constant value although intensity from D_2 plasmas is lower than one from H_2 plasmas. The mean values of the ratio are 0.79 in (a) and 0.88 in (b), respectively. By taking into account that plasma parameter conditions in D_2 plasmas are the same as those in H_2 plasmas, the ratio of the VUV emission spectra is suitable for the results of negative ion currents shown in Fig. 5. D^- density in the source can be higher than H^- density. In the future, detailed discussion will be continued with measuring H^- and D^- densities in this source. The same discussion is presented in section 3.

3. Measurement of Negative Ion Densities

In this section, we further discuss the relationship between H^-/D^- production (i.e. H^-/D^- densities in the source) and both plasma parameters and extracted negative ion currents.

Figure 7 shows a schematic diagram of the ion source [6]. The rectangle arc chamber of the ion source is 25×25 cm in cross section and 19 cm in height. Four tungsten filaments are installed from the side walls of the chamber. The line cusp magnetic field consists of permanent magnets which surround the chamber. The external MF is composed of a pair of permanent magnets, and the field (dipole magnetic field) separates the extraction region from the source region with high temperature bulk plasmas produced by arc discharge between filament cathodes and the chamber anode.

Plasma parameters are measured by Langmuir probes. Negative ions in the source are measured by the laser photodetachment method [7]. A magnetic deflection-type ion analyzer is also used for relative measurements of the extracted H^- or D^- currents.

Figure 8 shows axial distributions of plasma parameters (n_e and T_e) for four different magnetic filters. In the present case, due to the external MF, the width of the half-maximum of the MF field intensity is wider than that in Fig. 1. For example, when the MF with 150 G is used, the intensity of the MF at the filament position is about 80 G.

Plasma parameters, especially in the downstream region (from z = 8 to -2 cm) , are changed strongly by varying the intensity of the MF. On negative ion volume production, optimum condition for plasma parameters is that T_e in the extraction region should be reduced below 1 eV with keeping n_e high. According to the numerical results [2,11], optimum value of T_e is about 0.8 eV. For the MF with 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, for the MF with 60 G, decrease in n_e is limited rather higher density, but at the same time, decrease in T_e is also limited above 1 eV in the extraction region, i.e. z = 2-1 cm. Then, plasma condition is not so good for H^- formation. At any rate, production and control of plasmas should be well done with the MF, including good combination of filament position and the MF with a certain intensity.

Production and control of D_2 plasmas has the same characteristics. For reference, Figure 9 shows axial distributions of plasma parameters (n_e and T_e) for H_2 and D_2 plasmas. Both patterns of n_e and T_e distributions in D_2 plasmas are nearly the same as ones in H_2 plasmas except that values of n_e and T_e are slightly higher than ones in H_2 plasmas.

Figure 10 shows pressure dependence of the extracted negative ion currents. The negative ion currents depend strongly on the intensity of the MF. Apparently, there are some optimum pressures the same as shown in Fig. 4. With decreasing the intensity of the MF, optimum pressure p_{opt} shifts to the higher pressure. For D^- production, p_{opt} is 3 mTorr. On the other hand, for H^- production, p_{opt} is from 1.5 to 2.

The relationship between the behavior of negative ions in the source and the extracted negative ion currents is not well examined. Then, H^- ions and D^- ions densities in the source are obtained by the laser photodetachment method [7, 12], where L-shaped probe is 1mm in diameter and 6mm in length, and Nd-YAG Laser ($\lambda = 1064$ nm) is used (duration of laser pulse 9 ns, repetition 10 Hz). Figure 11 shows axial distributions of photodetached electron signals and obtained 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. These two different pressure conditions are corresponding to the results in Fig. 10. As is shown in Fig. 11, the photodetached electron signals or the negative ion density in front of the extraction hole in D_2 plasmas is nearly equal to that in H_2 plasmas. On the other hand, according to the results in Fig. 10, I_D at 3 mTorr with the MF (80 G) is lower than Γ_H at 1.5 mTorr, where the same extraction voltage V_{ex} is applied for H^- extraction and D^- extraction, respectively. Considering the factor $\sqrt{2}$ due to mass difference, $\sqrt{2}$ times Γ_D is nearly equal to Γ_H. Then D^- ions in the source are expected to be the same as H^- ions. Results in Fig. 11 support this.

4. Summary

Production and control of D_2 plasmas are studied. Plasma parameters are changed as the same manner as ones in H_2 plasmas by varying the magnetic field intensity of the MF. Then, we have confirmed that production and control of D_2 plasmas are well done with the MF, including good combination between the filament position and field intensity of the MF. To discuss isotope effect of H^- /D^- volume production, VUV emission and negative ion density in the source are measured. In beam-excited plasmas, VUV emission from D_2 plasmas is slightly lower than that from H_2 plasmas. Optimum condition for D^- production is different from that for H^- production. It is also found that, under some plasma conditions, D^- density is higher than H^- density. According to the results in the rectangular ion source, extracted H^- and D^- currents depend directly on negative ion densities in the source, respectively. 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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Figure captions

Fig.1 Schematic diagram of the double plasma type negative ion source.

Fig.2 Typical VUV spectra from (a)hydrogen and (b)deuterium plasmas. Experimental conditions are as follows: discharge voltage of driver plasma V_d = 50 V, discharge current I_d = 4.1A, gas pressures $p(H_2) = p(D_2)$ = 3 mTorr, beam acceleration voltage V_B = 100 V and beam current I_B = 1.5 A.

Fig. 3 Axial distributions of plasma parameters, (a) electron density n_e and (b) electron temperature T_e. Experimental conditions are as follows: V_d = 50 V, I_d = 4.1A, $p(H_2)$ = $p(D_2)$ = 3 mTorr, V_B = 100 V and I_B = 1.5 A.

Fig. 4 Pressure dependence of extracted H^- and D^- currents. Experimental conditions are as follows: V_d = 50 V, $p(H_2)$ = 1.5 - 4 mTorr, $p(D_2)$ = 1.5 - 5 mTorr, V_B = 100 V, I_B = 1.5A in (a) and I_B = 2 A in (b). Extraction voltage V_{ex} = 600V.

Fig. 5 Dependence of negative ion currents on discharge power Wd. Experimental conditions are as follows: V_d = 50 V, $p(H_2) = p(D_2)$ = 3 mTorr in (a), $p(H_2) = p(D_2)$ = 4 mTorr in (b), V_B = 100 V, I_B = 0.5 - 2A, and V_{ex} = 600V.

Fig. 6 Integrated intensity of VUV emission spectra from H_2 and D_2 plasmas, corresponding to the results in Fig. 5.

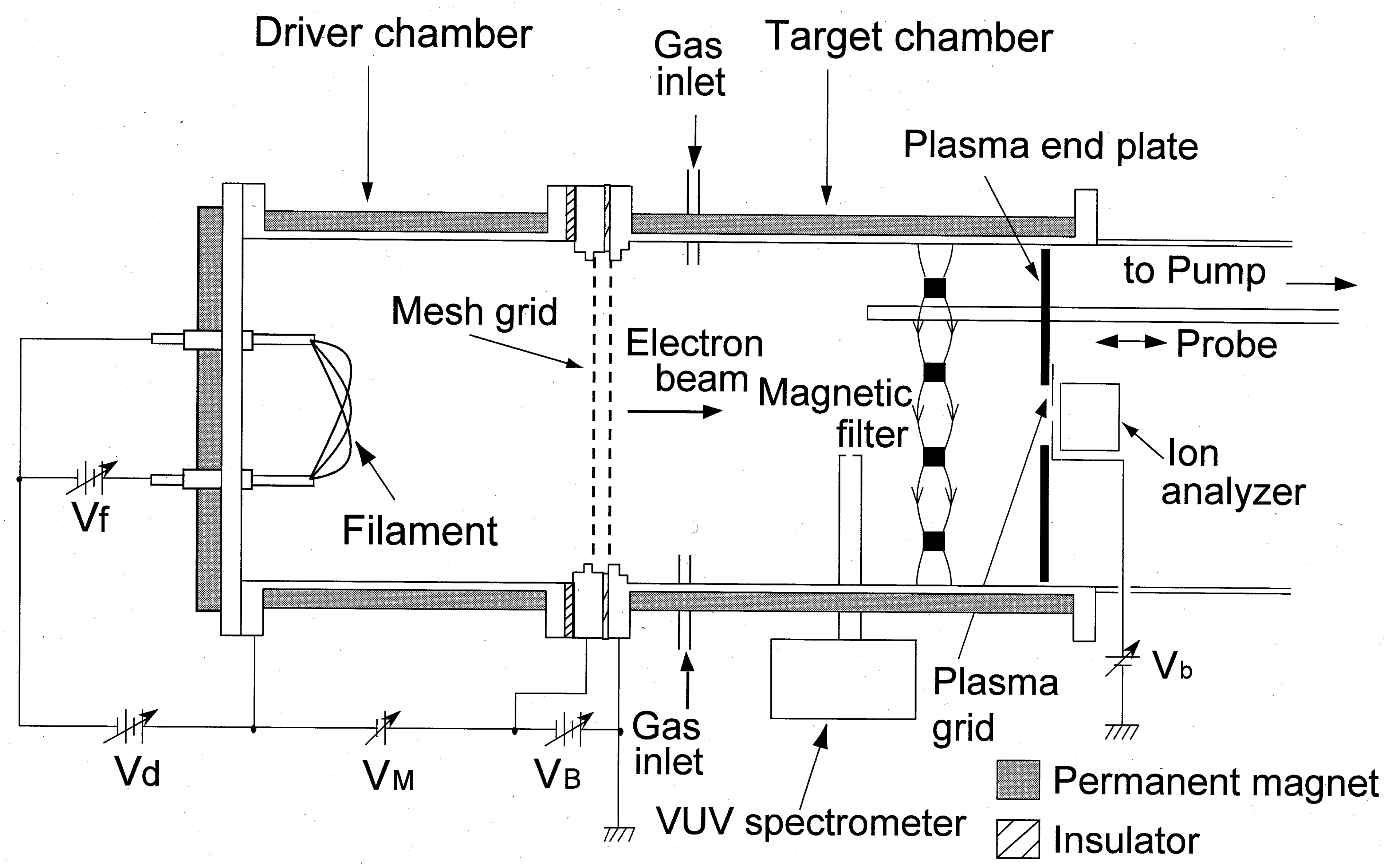
Fig. 7 Schematic diagram of the rectangular negative ion source. The probe, the laser path, and the power meter used in photodetachment experiments are also shown.

Fig.8 Axial distributions of plasma parameters (a) n_e and (b) T_e. Experimental conditions are as follows: $V_d = 70$ V, $I_d = 5$A, and $p(H_2) = 1.5$ mTorr.

Fig.9 Axial distributions of plasma parameters (a) n_e and (b) T_e for H_2 and D_2 plasmas. Experimental conditions are as follows: $V_d = 70$ V, $I_d = 5$A, $p(H_2) = p(D_2) = 1.5$ mTorr and intensity of the magnetic filter $B_{MF} = 80$ G.

Fig. 10 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 intensity of the magnetic filter.

Fig. 11 Axial distributions of photodetached electron signal $\Delta\Gamma$ (a) and negative ion densities n_- (b). 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.



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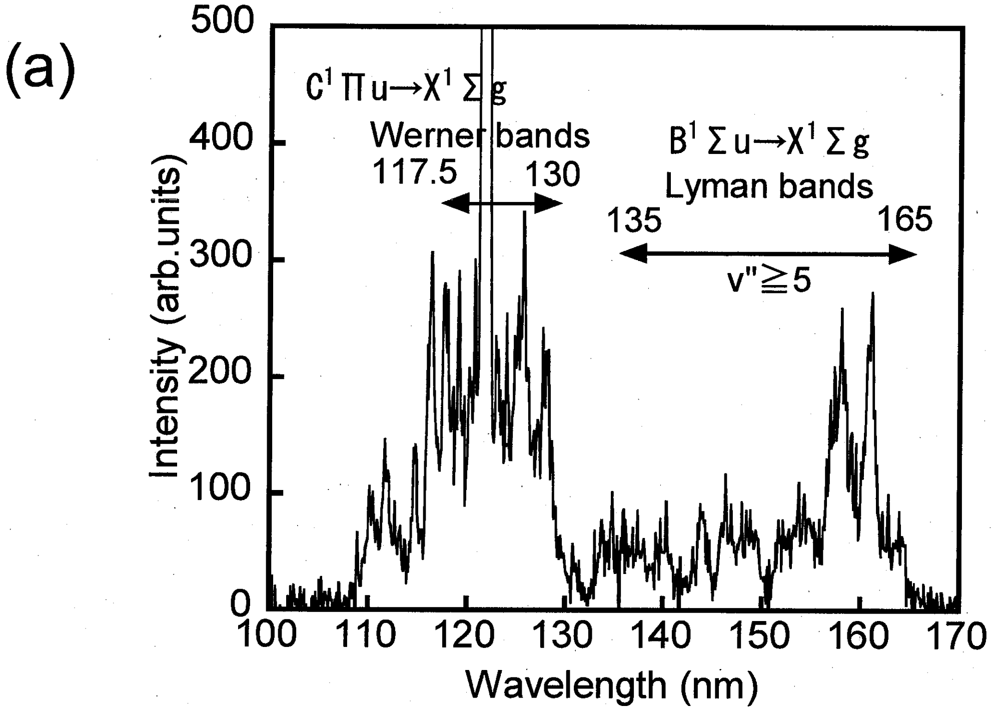

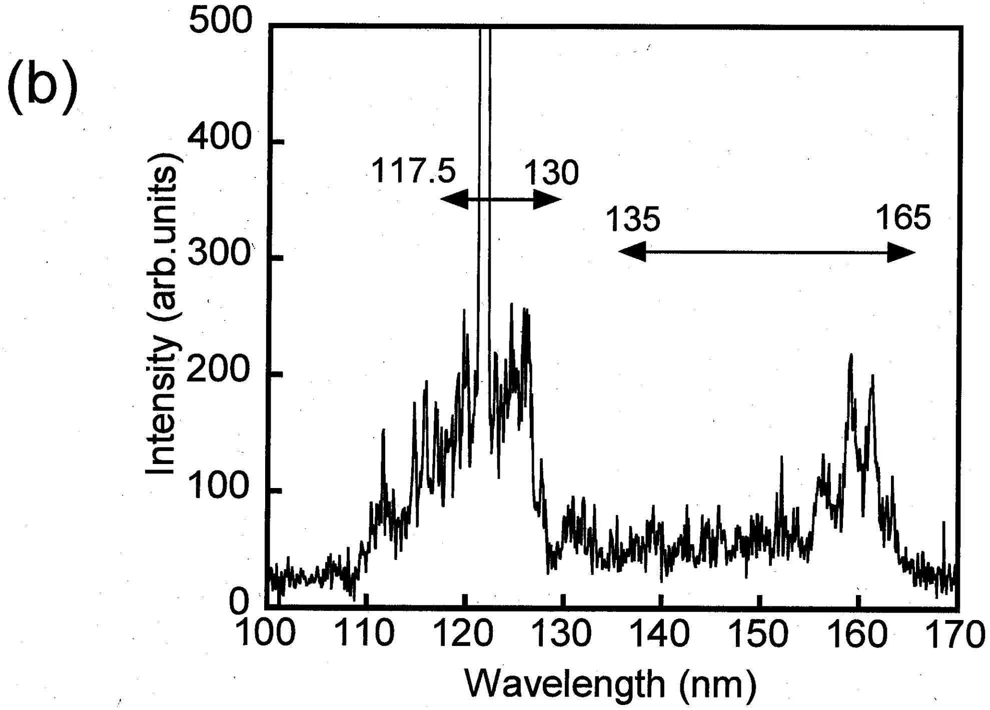

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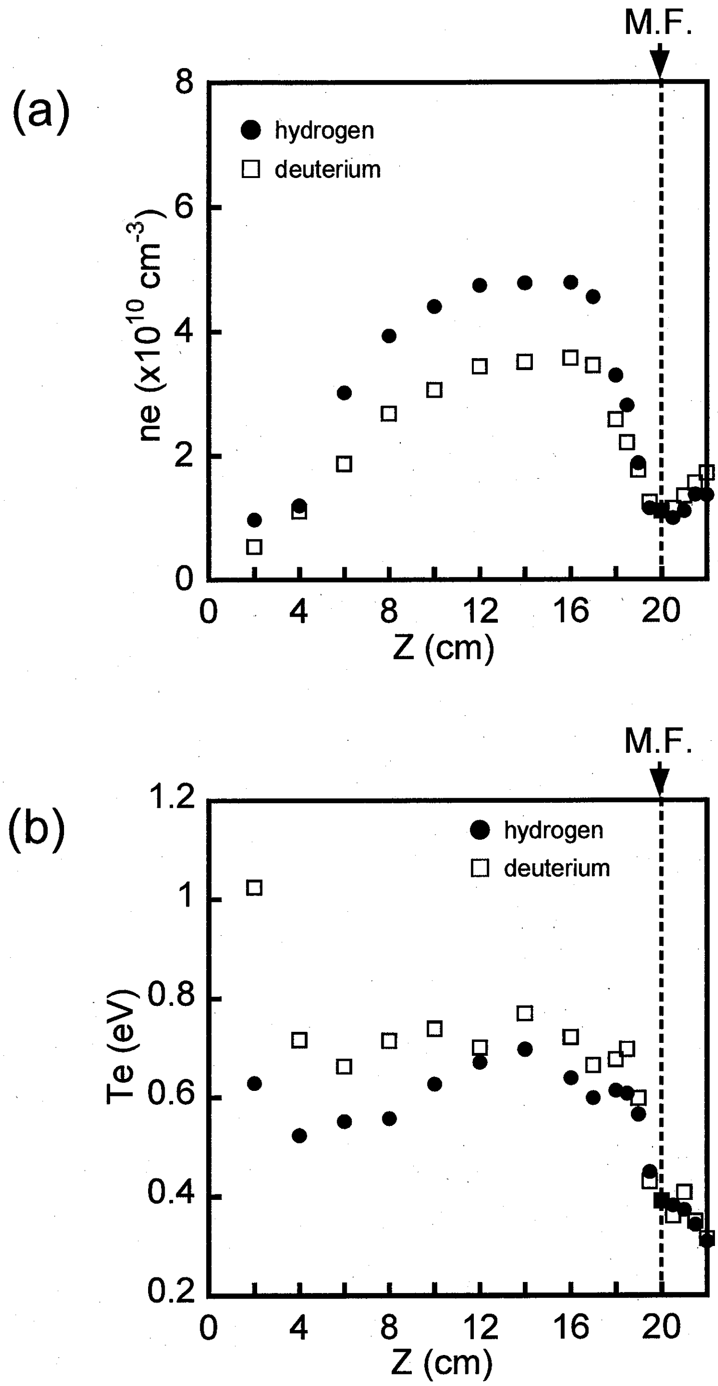

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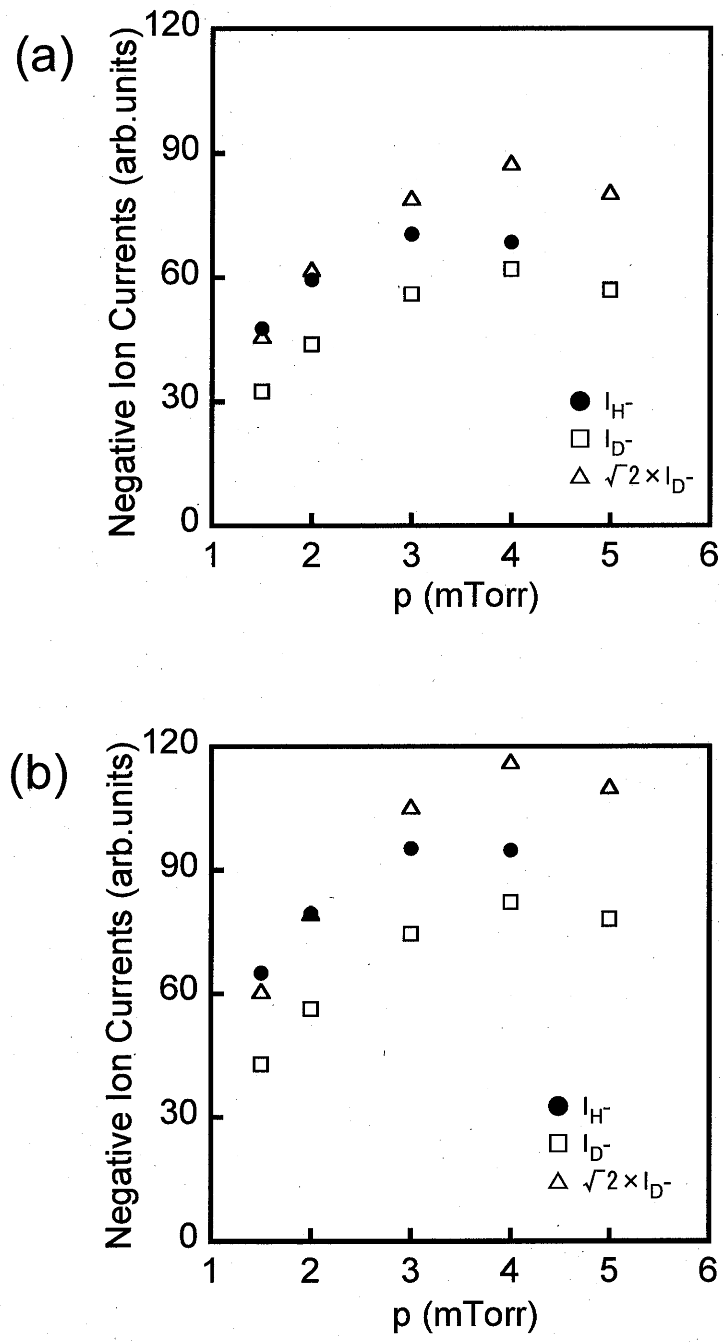

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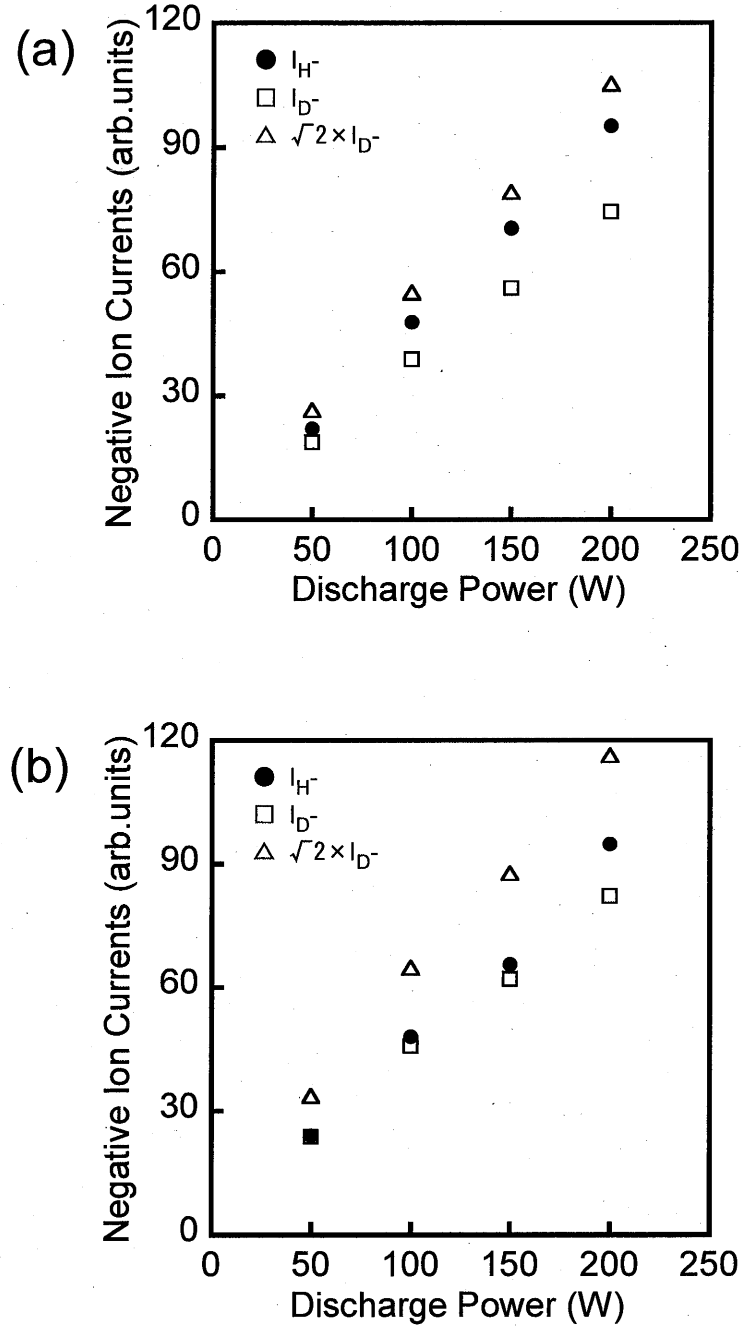

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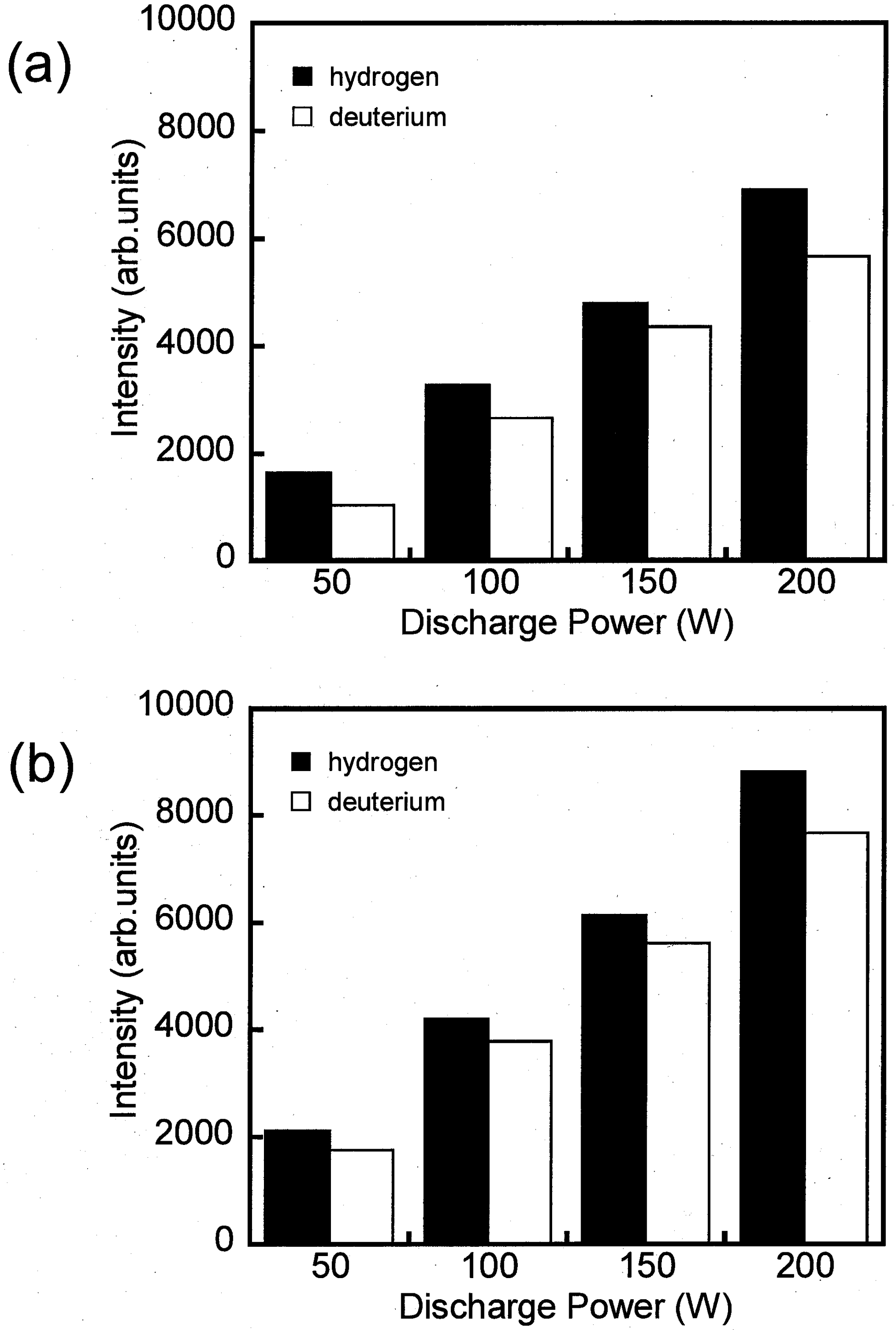

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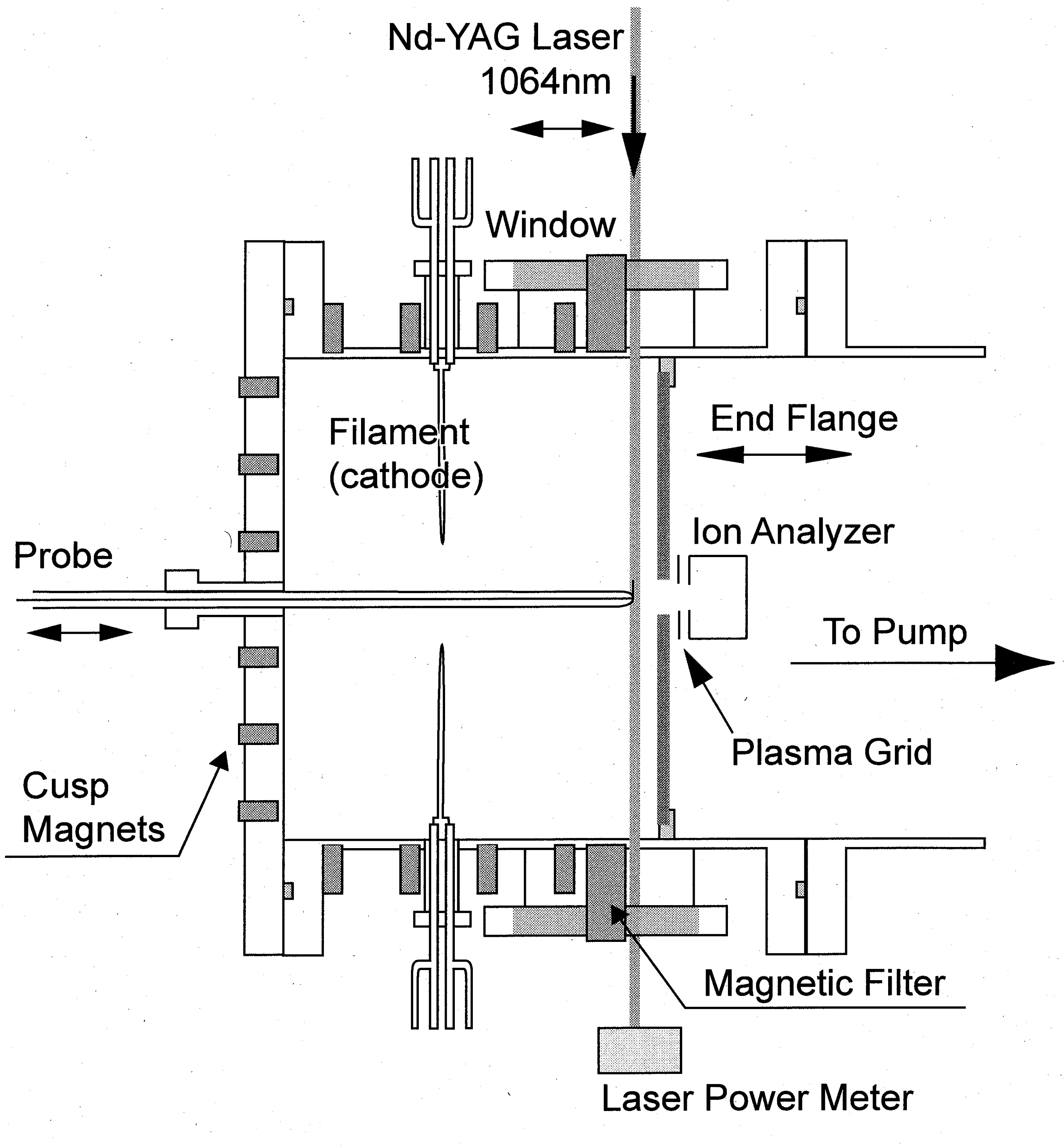

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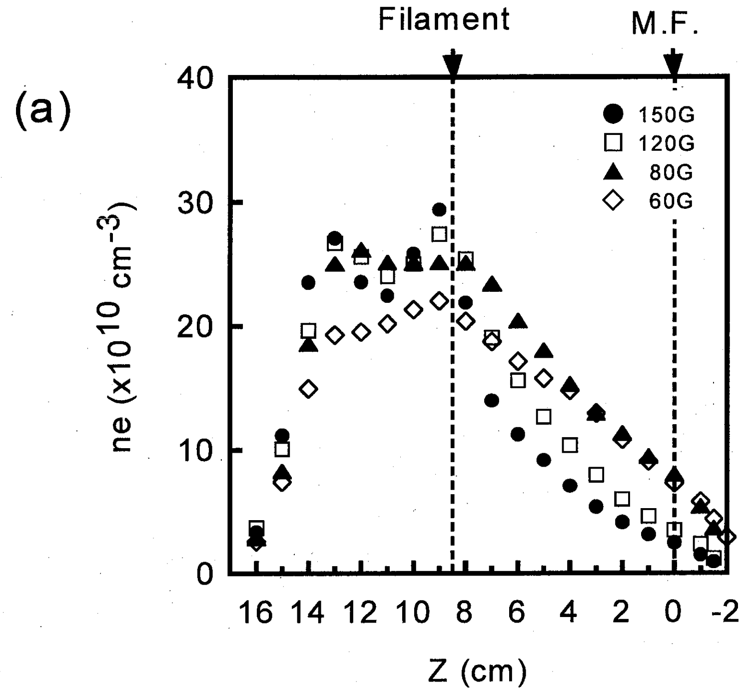

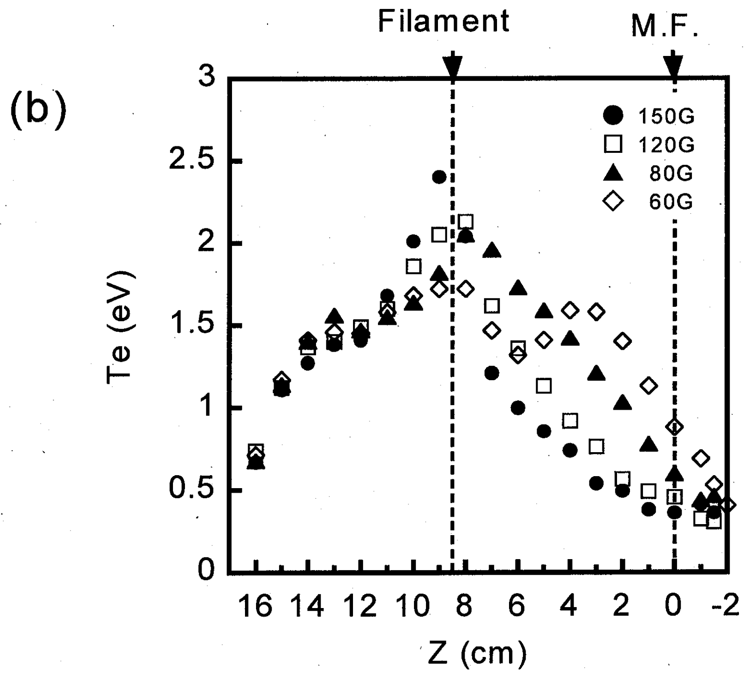

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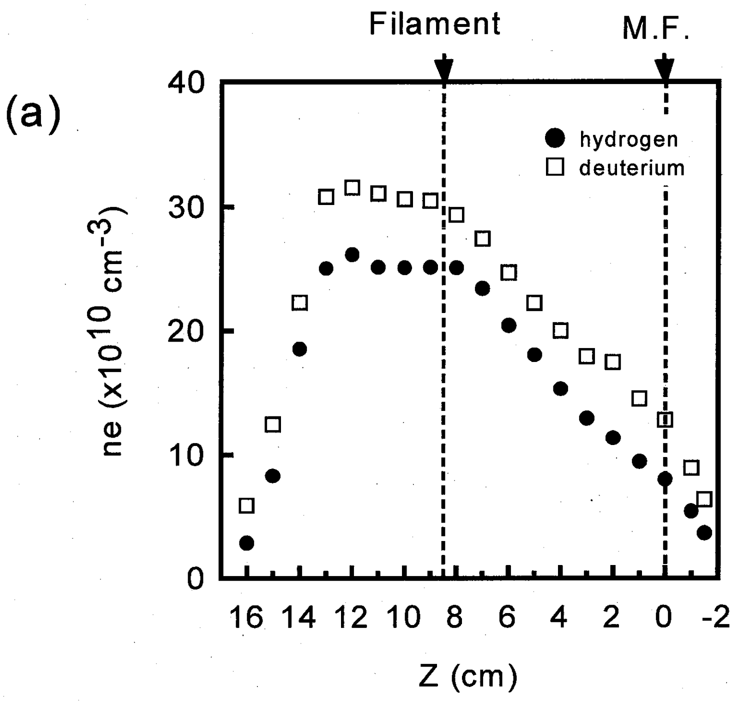

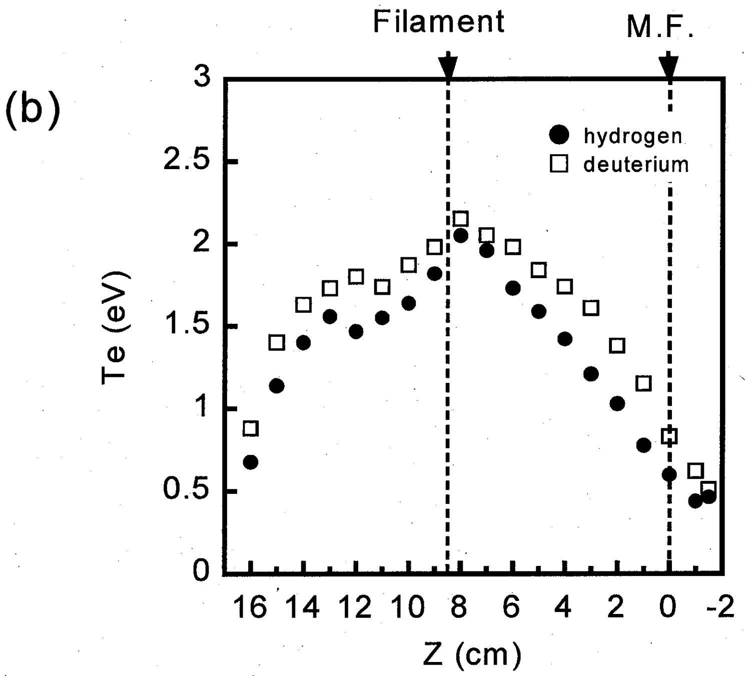

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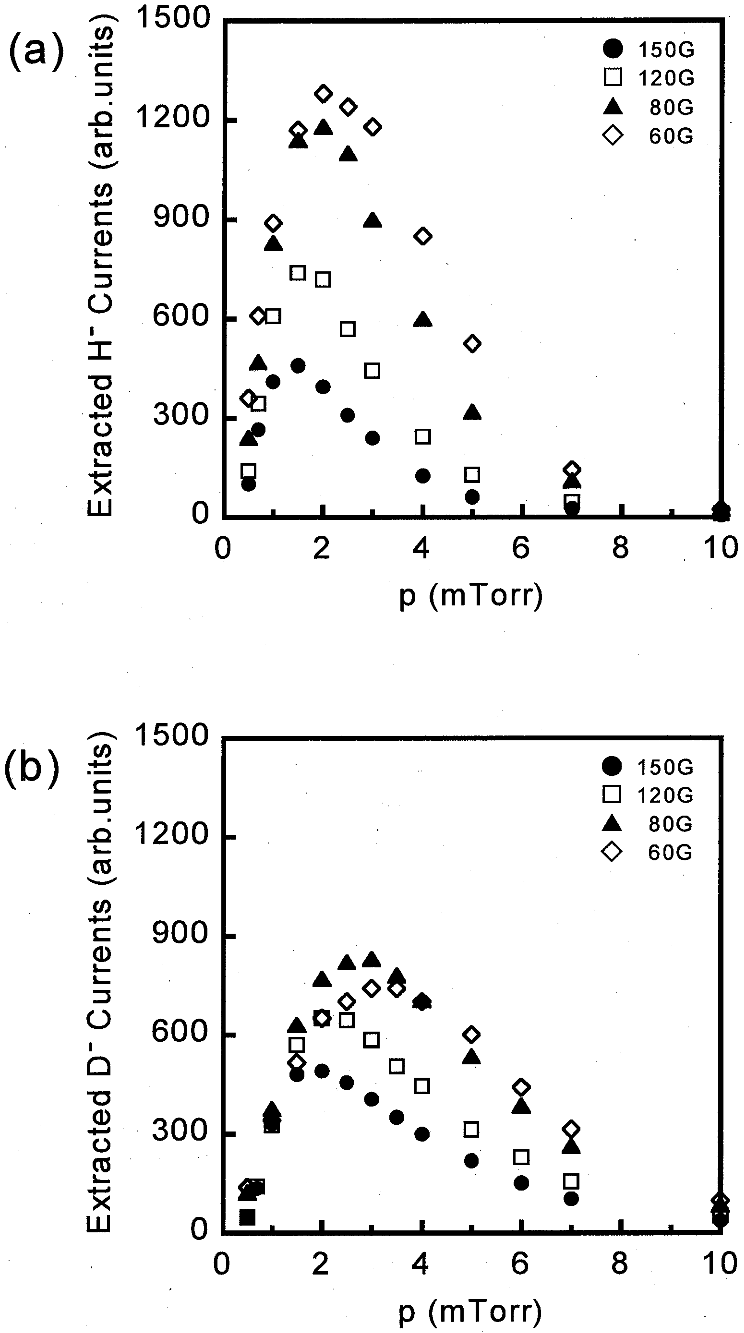

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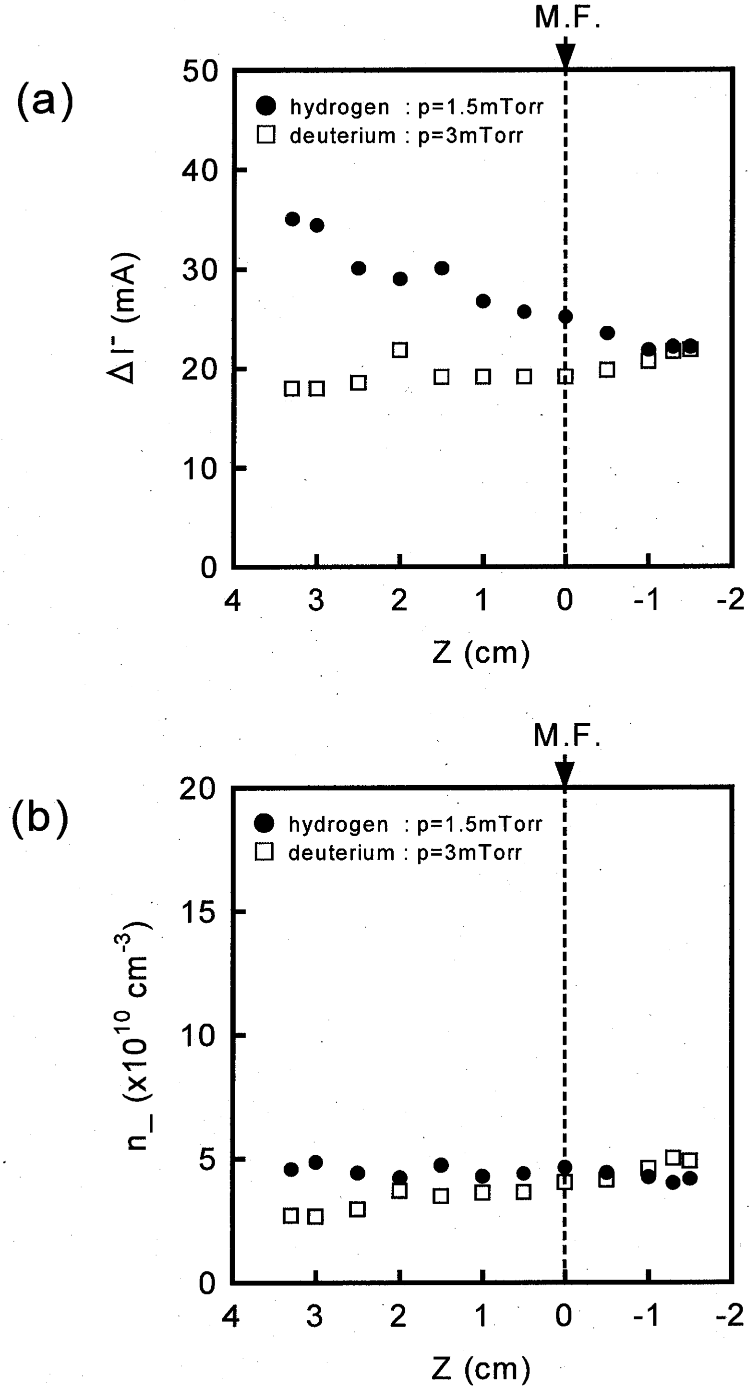

Fig. 11 O. Fukumasa