D^- DENSITY DISTRIBUTION AND ITS DEPENDENCE ON PLASMA PARAMETERS IN VOLUME NEGATIVE ION SOURCES

Shigefumi Mori and Osamu Fukumasa

Department of Electrical and Electronic Engineering,
Faculty of Engineering, Yamaguchi University
Tokiwadai 2-16-1, Ube, Yamaguchi 755-8611, Japan

Abstract:

To understand H^-/D^- negative ion formation mechanism, isotope effects of plasma production and H^-/D^- production in volume negative ion sources are studied. Axial distributions of H^- and D^- densities in the source are measured directly by laser photodetachment method. In particular, experimental results concerning dependence of H^-/D^- density distributions on plasma parameters are presented and discussed. Isotope effect of plasma production in H_2 and D_2 discharge is observed. H^- and D^- densities have different spatial distributions, respectively, corresponding to those different plasma parameter conditions.

Keywords:

H^-/D^- density distribution, magnetic filter, plasma parameter control, volume negative ion source

1. Introduction

Negative ion based neutral beam injector (N-NBI) is the most promising candidate for heating and current drive in future fusion reactors. The magnetically filtered multicusp ion sources of H^- and D^- negative ions are required for generation of efficient neutral beams with energies of in excess of 150 keV. In tandem volume sources, 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 $v" \geq 5\text{-}6$). 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 two-step process [1,2]. 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 study production and control of deuterium (D_2) plasmas, and to understand difference in the two-step process of negative ion production between H_2 and D_2 plasmas. Most of the experimental investigations have concentrated on the study of H_2 plasmas. Therefore, there are few studies on optimization of volume-produced D^- ions. Then, we focus on understanding the negative ion production mechanism in the volume negative ion source [3-5].

We have studied relationship between H^- [3] and D^- [4,5] productions and plasma parameters across the magnetic filter (MF). In this paper, plasma parameter control by varying the magnetic field intensity of the MF is presented. Influence of these plasma parameter distributions on H^-/D^- production is discussed with using estimated rate coefficients and collision frequency based on measured plasma parameters.

2. Experimental set-ups and procedure

Figure 1 shows a schematic diagram of the ion source [4,5]. 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 with energetic primary electrons emitted from filaments. 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 [6]. 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.

3. Experimental results and discussion

3.1 Plasma parameter control by varying the intensity of MF

On H^-/D^- volume production, desired condition for plasma parameters is as follows: T_e in the extraction region should be reduced below 1eV with n_e keeping higher. MF is used to realize above-mentioned condition, namely to enhance H^-/D^- production by dissociative attachment and to reduce H^-/D^- destruction by collisional electron detachment including collision with energetic electrons. For this purpose, plasma parameter control is studied by varying the magnetic field intensity of the MF, B_{MF}. In the present study, B_{MF} is variable from 60 G to 150 G on the center axis of the chamber. 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 [4]. Namely, varying the intensity of the magnetic filter indicates also varying the strength of magnetic field distribution in both source region and extraction region.

Figures 2 and 3 show axial distributions of plasma parameters (T_e and n_e) in H_2 and

D_2 plasmas, respectively. By varying the intensity of the MF, axial distributions of T_e and n_e in both H_2 and D_2 plasmas are changed strongly in the downstream region [4,5]. Both patterns of T_e and n_e distributions are strongly dependent on the MF intensity. Production and control of D_2 plasmas are almost the same characteristics as that of H_2 plasmas.

For the MF with 150 G (B_{MF}= 150 G) in Figs. 2 and 3, T_e and n_e are decreased far from the MF in the source region. By decreasing the MF intensity, value of n_e is limited higher level in the downstream region. The external MF has the merit of controlling plasma parameters gradually. T_e control can be done precisely with keeping n_e high in the extraction region.

When B_{MF} = 80 G, values of T_e and n_e in D_2 plasmas are higher than ones in H_2 plasmas. T_e in the extraction region is decreased below 1eV in both H_2 and D_2 plasmas. Plasma conditions are good for H^- and D^- production. 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. According to these results, 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 productions of H_2 and D_2 plasmas are different from each other. Namely isotope effect of plasma production is observed.

3.2 Influence of plasma parameter distributions across the MF on H^- and D^- production/destruction

As shown in Figs. 2 and 3, by varying the intensity of the MF, axial distributions of T_e and n_e in both H_2 and D_2 plasmas are changed strongly in the downstream region. Relationship between these plasma parameter distributions and H^-/D^- production is not well clarified. Variation of H^- and D^- production due to changes in plasma parameter distributions across the MF are discussed by taking into account main collision processes for production and destruction.

For main production and destruction processes of H^- ions, dissociative attachment (DA: $H_2(v'') + e \rightarrow H^- + H$) process is for H^- production and collisional electron detachment (ED: $H^- + e \rightarrow H + 2e$) process is for H^- destruction. In DA process, it is assumed for simplicity 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 and have highest values of rate coefficient in the $H_2(v''=1\text{-}14)$ and $D_2(v''=1\text{-}19)$, respectively [7]. 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 measured T_e and n_e.

Figures 4 (a) and (b) show axial distributions of rate coefficient and collision frequency of DA and ED processes, respectively. These plots are based on measured T_e and n_e for two different MF as shown in Fig. 2. Due to changes in T_e distributions, as shown in Fig. 4(a), distributions of ED processes are changed strongly rather than that of DA processes. It is found that T_e control by varying the intensity of the MF reduce ED process remarkably across the MF. As shown in Fig. 4(b), by taking into account both T_e and n_e changes, distributions of DA processes are changed in the extraction region. The difference between DA with 150 G and that with 80 G is caused by n_e in this region (n_e with 80G is higher than that with 150G). On the other hand, distributions of ED processes are also changed similarly. It is reconfirmed that T_e in the extraction region should be reduced below 1eV with n_e keeping higher with the MF, including good combination of filament position and the MF with a certain intensity. Control of not only T_e but also n_e in the extraction region is very important for enhancement of H^- and D^- production.

3.3 H^- and D^- density distributions across the MF

Figure 5 shows axial distributions of H^- ion densities, where B_{MF} = 150 G and 80 G, respectively. Plasma parameters corresponding to H^- densities in Fig. 5 are shown in Fig. 2. In H_2 plasmas, H^- densities have different spatial distributions corresponding to those different plasma parameters. When $B_{MF} = 150$ G, H^- density distribution is similar to n_e distribution across the MF. In this case, according to the result in Fig. 4, H^- density is scarcely decreased by ED process because T_e keeps sufficiently below 1 eV (almost 0.5 eV). On the other hand, when B_{MF}=80 G, H^- density distribution is not similar to n_e distribution. In this case, H^- density is decreased strongly by ED process because T_e is nearly equal to or above 1 eV in upstream region from MF. In front of 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 of about 2. Extracted H^- currents from the source are also the same ratio. Extracted H^- currents depend on H^- densities in the source.

D^- density distributions are compared to H^- density distributions under the same discharge condition as follows: $B_{MF} = 80$ G, $p(H_2) = p(D_2) = 1.5$ mTorr, $V_d = 70$ V and $I_d = 5$ A, respectively. Figure 6 shows axial distributions of negative ion densities. D^- density is lower than that of H^- density across the MF. From viewpoint of plasma production in Figs. 2 and 3, T_e in D_2 plasma is higher than that in H_2 plasma. Concerning the discussion with main collision process in Sec. 3.2, influence of D^- destruction by ED process on D^- density is higher although n_e in D_2 plasma is also higher. 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.

4. 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, to enhance H^-/D^- yield, optimizing production and control of plasmas 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 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.

Acknowledgements

The authors would like to thank Y. Tauchi (Yamaguchi University) for his support in the experiments and Prof. H. Naitou (Yamaguchi University) for his variable discussions and encouragement. The authors also would like to thank Prof. Y. Takeiri and Dr. K. Tsumori (National Institute for Fusion Science) for their discussions. A part of this work was supported by the Grant-in-Aid for Scientific Research from Ministry of Education, Culture, Sports, Science and Technology, Japan. This work was also carried out as collaboration research program (the LHD project) of National Institute for Fusion Science.

References

[1] J. R. Hiskes, A. M. Karo, J. Appl. Phys. **56** (1984) 1927.

[2] O. Fukumasa, J. Phys. D: Appl. Phys. **22** (1989) 1668.

[3] S. Mori, Y. Tauchi, O. Fukumasa, M. Hamabe, Y. Takeiri, Abstract of 30th IEEE International Conference on Plasma Science (Jeju, Korea, June 2, 2003) p.209.

[4] O. Fukumasa, S. Mori, N. Nakada, Y. Tauchi, M. Hamabe, K. Tsumori, Y. Takeiri, Contrib. Plasma Phys. **44** (2004) 516.

[5] S. Mori, Y. Tauchi, O. Fukumasa, M. Hamabe, K. Tsumori, Y. Takeiri, Proceedings of Novel Materials Processing by Advanced Electromagnetic Energy Sources 2004 (Osaka, Japan, March 20, 2004) (to be published).

[6] M. Bacal, G. W. Hamilton, A. M. Bruneteau, H. J. Doucet, J. Taillet, Rev. Sci. Instrum. **50** (1979) 719.

[7] J. M. Wadehra, Appl. Phys. Lett. **35** (1979) 917.

Figure Captions

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

Fig. 2. Axial distributions of plasma parameters (a) T_e and (b) n_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) T_e and (b) n_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.

Fig. 4. 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 150 G, closed triangle; H^- production with 80 G, open circle; H^- destruction with 150 G, closed triangle; H^- destruction with 80 G). Corresponding plasma parameters are shown in Fig. 2.

Fig. 5 Axial distributions of H^- ion densities. 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. Corresponding plasma parameters are shown in Fig. 2 (with $B_{MF} = 150$ G and 80 G).

Fig. 6 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. Corresponding plasma parameters are shown in Fig. 2 (for H_2 plasma) and Fig. 3 (for D_2 plasma).

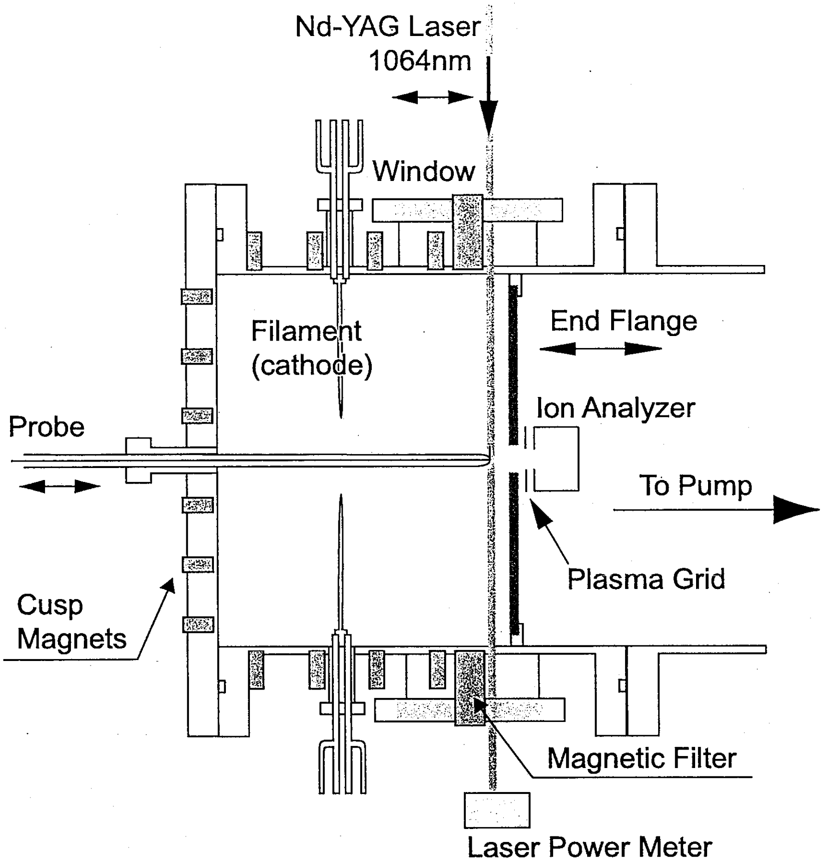
Nd-YAG Laser
1064nm
Window
Filament
(cathode)
End Flange
Ion Analyzer
Probe
To Pump
Plasma Grid
Cusp
Magnets
Magnetic Filter
Laser Power Meter

Fig. 1

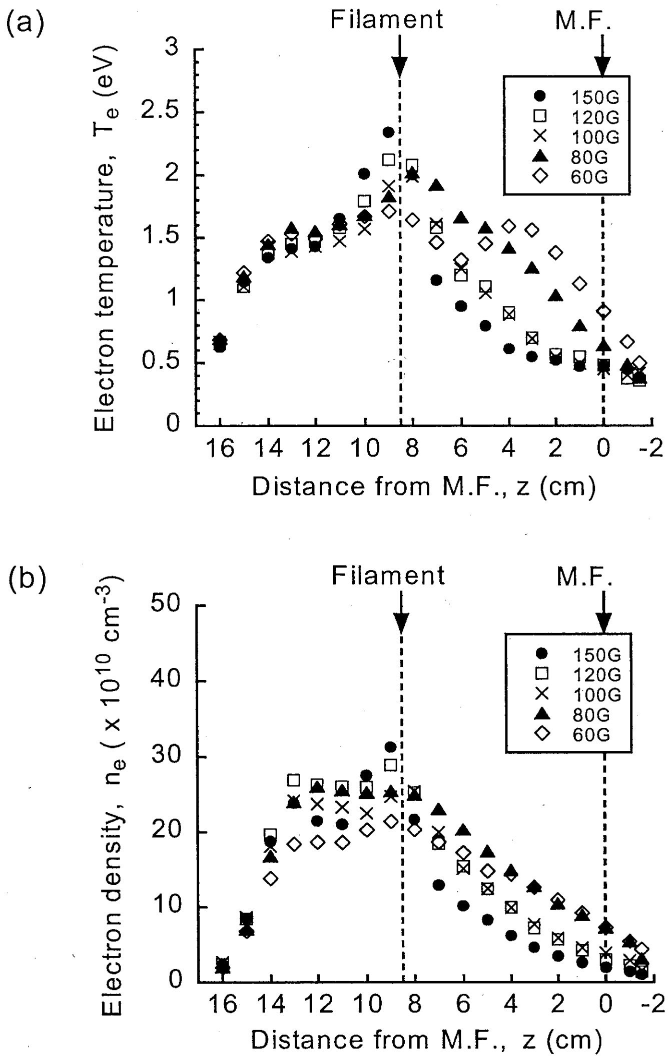
(a)
Filament
M.F.
Electron temperature, T_e (eV)
3
2.5
2
1.5
1
0.5
0
150G
120G
100G
80G
60G
16 14 12 10 8 6 4 2 0 -2
Distance from M.F., z (cm)
(b)
Filament
M.F.
Electron density, n_e (x 10^{10} cm^{-3})
50
40
30
20
10
0
150G
120G
100G
80G
60G
16 14 12 10 8 6 4 2 0 -2
Distance from M.F., z (cm)

Fig. 2

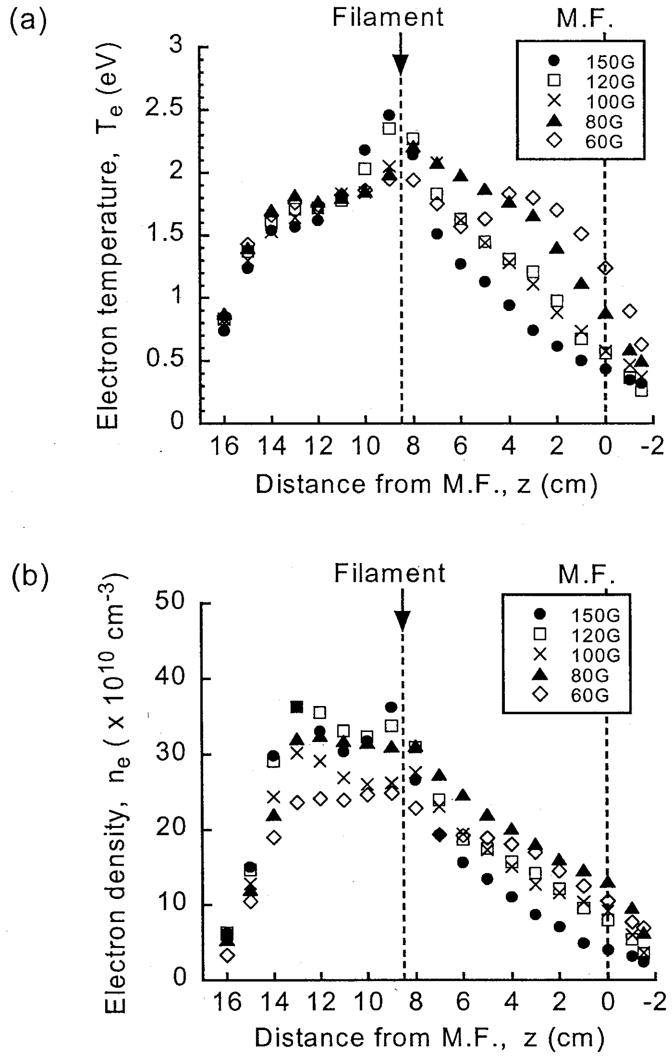
(a)
Filament
M.F.
Electron temperature, T_e (eV)
3
2.5
2
1.5
1
0.5
0
16 14 12 10 8 6 4 2 0 -2
Distance from M.F., z (cm)
● 150G
□ 120G
× 100G
▲ 80G
◇ 60G
(b)
Filament
M.F.
Electron density, n_e (x 10^{10} cm^{-3})
50
40
30
20
10
0
16 14 12 10 8 6 4 2 0 -2
Distance from M.F., z (cm)
● 150G
□ 120G
× 100G
▲ 80G
◇ 60G

Fig. 3

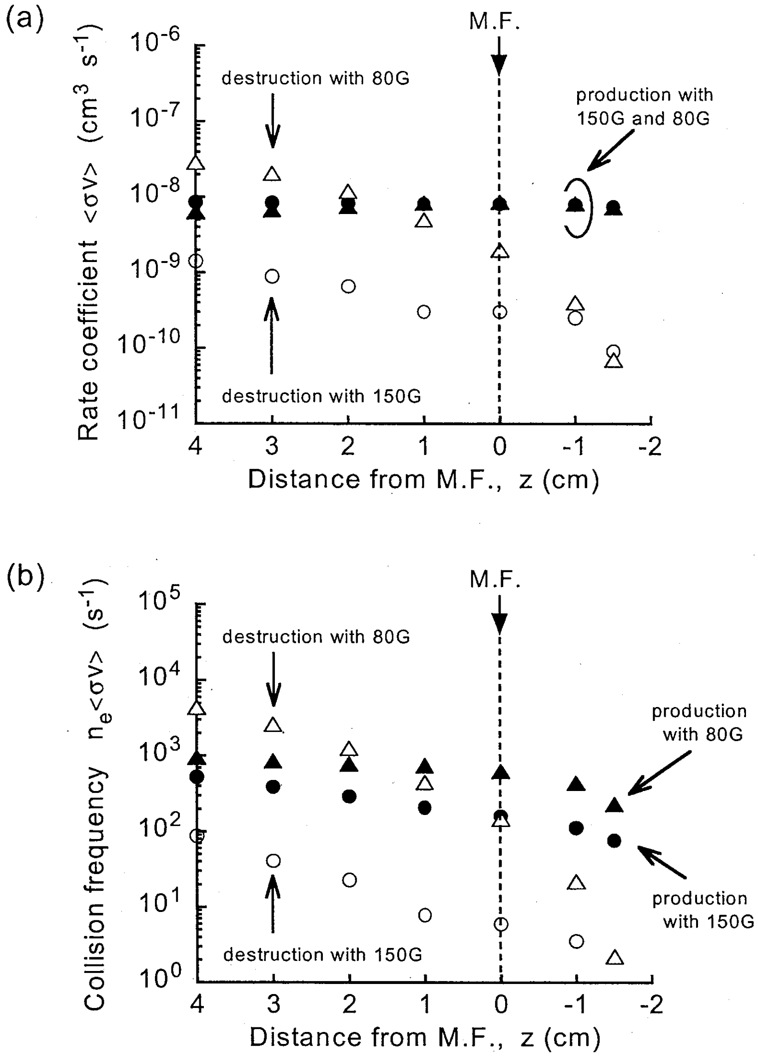
(a)
M.F.
Rate coefficient <σV> (cm3 s-1)
10-6
10-7
10-8
10-9
10-10
10-11
destruction with 80G
production with 150G and 80G
destruction with 150G
4
3
2
1
0
-1
-2
Distance from M.F., z (cm)
(b)
M.F.
Collision frequency ne<σV> (s-1)
105
104
103
102
101
100
destruction with 80G
production with 80G
production with 150G
destruction with 150G
4
3
2
1
0
-1
-2
Distance from M.F., z (cm)

Fig. 4

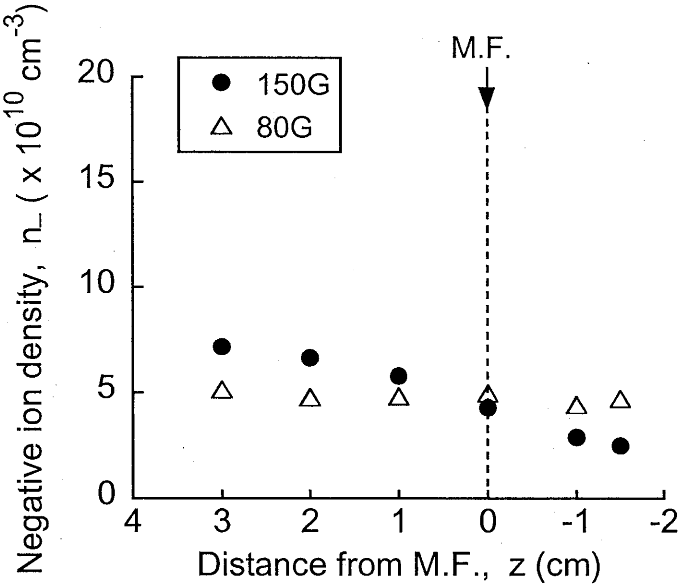
Negative ion density, n_- (x 10^{10} cm^{-3})
20
15
10
5
0
● 150G
△ 80G
M.F.
4
3
2
1
0
-1
-2
Distance from M.F., z (cm)

Fig. 5

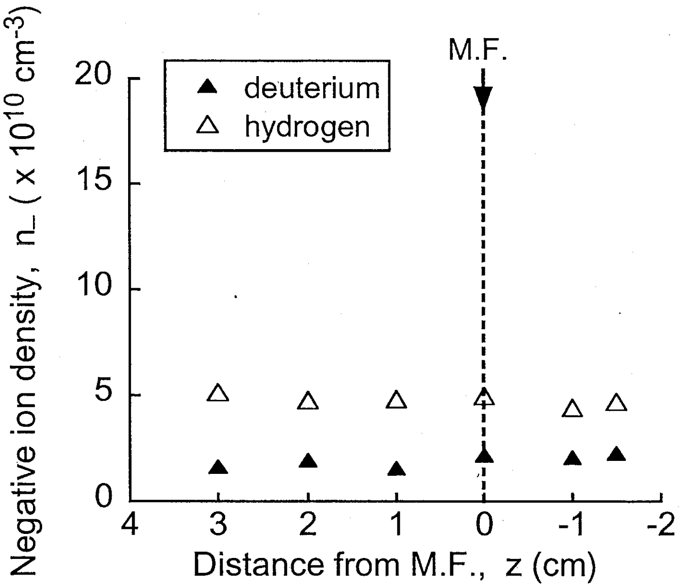
Negative ion density, n_ (x 10^10 cm^-3)
20
15
10
5
0
4
3
2
1
0
-1
-2
Distance from M.F., z (cm)
M.F.
▲ deuterium
△ hydrogen

Fig. 6