REVIEW OF SCIENTIFIC INSTRUMENTS **79**, 02A526 (2008)

Effects of external magnetic filter on behaviors of fast primary electrons in a volume negative ion source[a)]

Shigefumi Mori and Osamu Fukumasa[b)]
Graduate School of Science and Engineering, Yamaguchi University, Tokiwadai 2-16-1, Ube 755-8611, Japan

(Presented 29 August 2007; received 27 August 2007; accepted 8 October 2007; published online 21 February 2008)

The relationship between enhancement of hydrogen negative ion H^-, volume production, and behaviors of fast primary electrons is studied theoretically. Trajectories of fast primary electrons are calculated, including collisional effects with hydrogen molecules. Active region of fast electrons depends strongly on the field intensity of the magnetic filter (MF), B_{MF}, and filament position. Therefore, spatial distributions of ionization and vibrational excitation collision points are also affected with changing B_{MF}. Although number of vibrational excitation collision points is much smaller than that of ionization collision points due to different mean free path, the relative intensity is varied by changing energy of fast electrons. According to the results and discussions including transport of produced vibrationally excited molecules, for enhancement of H^- production, it is desired that fast electrons should approach the MF position and move into the downstream region as deep as possible without destruction of H^- ions. To realize these conditions, good combination between filament position and the intensity of the MF should be required. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2805381]

I. INTRODUCTION

Sources of H^- and D^- ions are required for efficient generation of neutral beams with energies above 100 keV/nucleon. The bucket (magnetic multicusp) ion source equipped with magnetic filter (MF) has been shown to be a promising source.

For H^- volume production in hydrogen (H_2) discharge plasmas, highly vibrationally excited molecules $H_2(v'' \geqslant 5)$ are indispensable and the following two-step process is dominant production mechanism:[1,2]

$$H_2(v''=0) + e_f(E_{fe} > 20 \text{ eV}) \rightarrow H_2(v'') + e_f', \quad (1)$$

$$H_2(v'' \geqslant 5) + e_s(T_e \sim 1 \text{ eV}) \rightarrow H^- + H, \quad (2)$$

where e_f means fast primary electrons and e_s means plasma electrons. The role of e_f is important for enhancement of negative ion production, i.e., collisional excitation of $H_2(v'')$ and production of high density plasmas.

The purpose of the present study is to understand the behaviors of e_f in the rectangular negative ion source equipped with external MF. Although there are some studies[3,4] on behaviors of e_f, discussion concerning production of $H_2(v'')$ and then H^- production is not reported. Taking into account our experimental study,[5,6] the following two articles are discussed: (1) movable regions of fast primary electrons e_f for different magnetic field intensities of the MF, B_{MF}, and filament positions, and (2) combination effect of B_{MF} and filament positions for controlling behaviors of fast electrons. Trajectories of e_f are calculated numerically by solving three-dimensional (3D) motion equation, including collisional effects with hydrogen molecules.

II. NUMERICAL MODEL

A. Simulation model

Figure 1(a) shows the schematic diagram of the model for our rectangular discharge chamber.[6] The coordinate is also shown in the figure. The origins of the x and y axes are at the center of the ion source (i.e., the center of the plasma grid) and the z axis is at the position of the filter magnets. The size of the discharge chamber is $25 \times 25 \times 19$ cm^3. The chamber walls are fully surrounded by bar magnets. The magnetic field is calculated by using the 3D analytical solution based on the magnetic charge model.[7] Typical distribution of the magnetic field strength in the y-z plane at $x = 0$ cm is shown in Fig. 1(b).

B. Tracing of an electron orbit

An equation of motion of e_f is solved three dimensionally by using the Runge-Kutta-Gill methods as shown in Eq. (3).

$$m dv/dt = q(v \times \mathbf{B}) + \mathbf{F}_{col}, \quad (3)$$

where m and q are a mass and a charge of an electron, respectively, B is the magnetic field, t is the time from an electron's occurrence, v is the electron's velocity, and $\mathbf{F}_{col}$ is the collision term, which is obtained by using the Monte Carlo method.[3,4,8] In this simulation, the elastic, ionization, excitation, and vibrational excitation collisions are considered. Primary electrons are launched isotropically from the four hairpin-type filaments with an initial energy of E_{fe} (i.e., 40, 50, 80, and 100 eV). Filament position z_f is also changed

---

[a)] Contributed paper, published as part of the Proceedings of the 12th International Conference on Ion Sources, Jeju, Korea, August 2007.

[b)] Author to whom correspondence should be addressed. Electronic mail: fukumasa@plasma.eee.yamaguchi-u.ac.jp. Fax: +81-836-85-9401.

0034-6748/2008/79(2)/02A526/4/$23.00

© 2008 American Institute of Physics

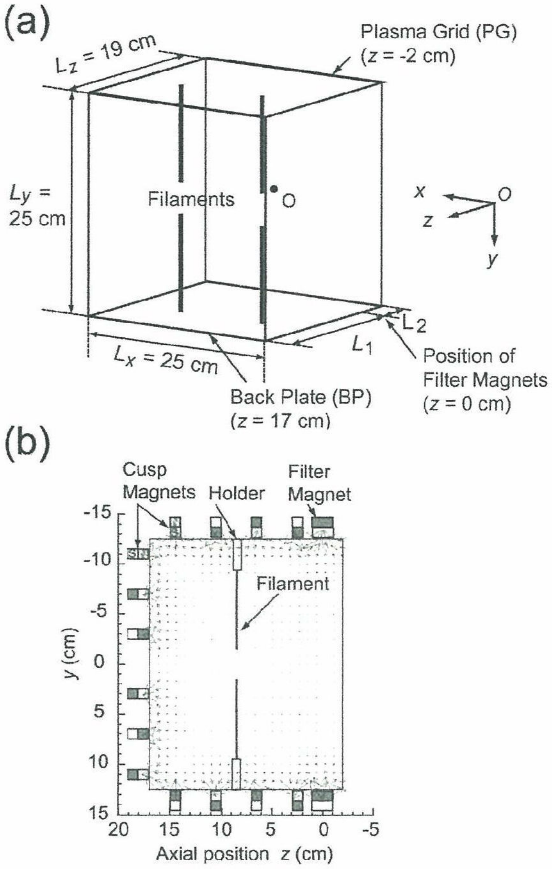


FIG. 1. Simulation model: (a) model for the rectangular discharge chamber and (b) arrangement of permanent magnets and distribution of the field strength in the y-z plane at $x=0$ cm.

along the z axis (i.e., z_f=4.5, 8.5, and 12.5 cm).

III. NUMERICAL RESULTS AND DISCUSSION

We have traced primary electron trajectories until the electron energy becomes smaller than a certain limit E_{limit} due to collision processes. The energy E_{limi} is taken to be 15 eV. Figure 2 shows trajectories of fast electrons for two different B_{MF}, where E_{fe}=80 eV and the number of test electrons is 4000. Here, trajectories of 30 test electrons are plotted. Movable region (i.e., active region) of fast electrons depends strongly on B_{MF}. It is clearly shown that decreasing B_{MF} allows the primary electrons to approach the extraction region. Namely, ionization and vibrational excitation occur more frequently in the downstream region (see Fig. 3) and also increase n_e as shown in our experiment.[5,6]

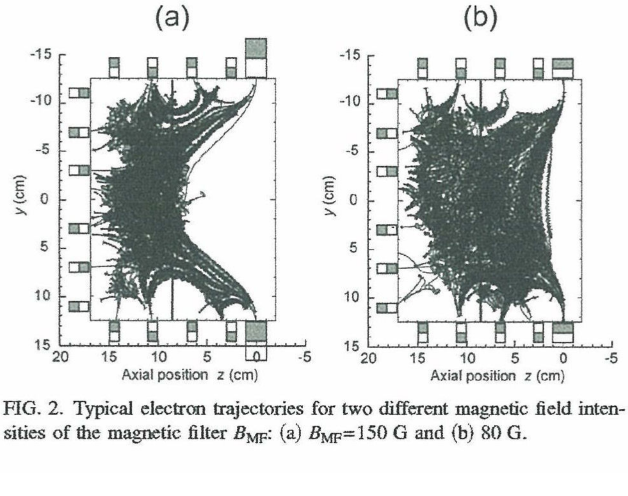


FIG. 2. Typical electron trajectories for two different magnetic field intensities of the magnetic filter B_{MF}: (a) B_{MF}=150 G and (b) 80 G.

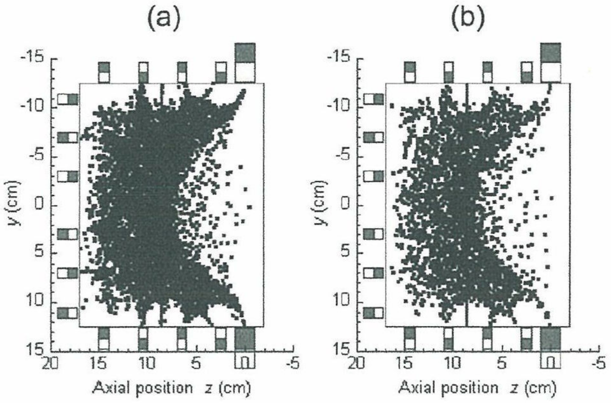


FIG. 3. Distribution of collision points: Ionization collision points (a) and vibrational excitation collision points (b) are plotted in the y-z plane when B_{MF}=150 G.

According to the motion of fast electrons, ionization and vibrational excitation collisions are taken place in the discharge chamber. Figures 3 and 4 show the distribution of collision points, i.e., ionization (a) and vibrational excitation (b), when B_{MF} are 150 and 80 G, respectively. Calculation conditions (E_{fe} and the number of test electron) are the same as the ones in Fig. 2. Distribution of these collision points is very similar to the trajectories of fast electrons shown in Fig. 2.

Figure 5 shows the number of collision point for the ionization N_i and for the vibrational excitation N_v as a function of z axis, where E_{fe}=40 eV and 8×10^4 test electrons are used. Collision points are focused in the vicinity of the filament position where z_f=8.5 cm. In the downstream region (i.e., z=8 to −2), the number of collision points has tendency to increase with decreasing B_{MF}. Because fast electrons approach easily near the MF position with decreasing B_{MF} as shown in Fig. 2, then plasma conditions in the extraction region are varied with B_{MF}.

As is shown clearly in Figs. 3–5, N_i is much larger than

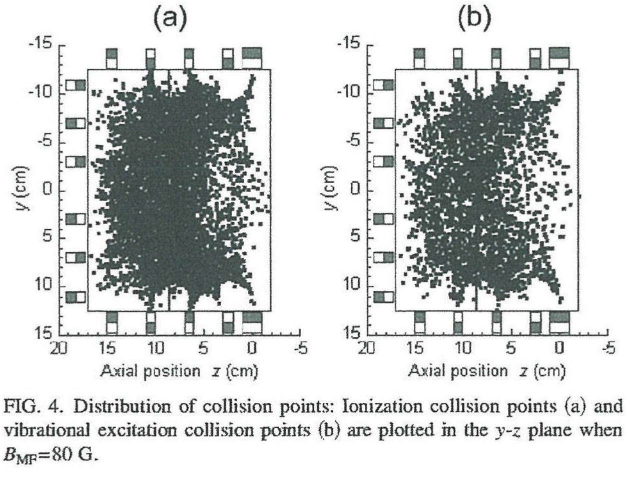
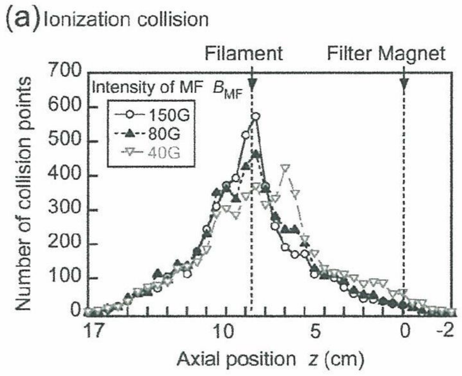


FIG. 4. Distribution of collision points: Ionization collision points (a) and vibrational excitation collision points (b) are plotted in the y-z plane when B_{MF}=80 G.



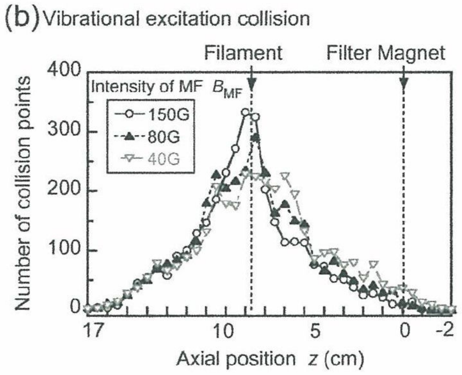
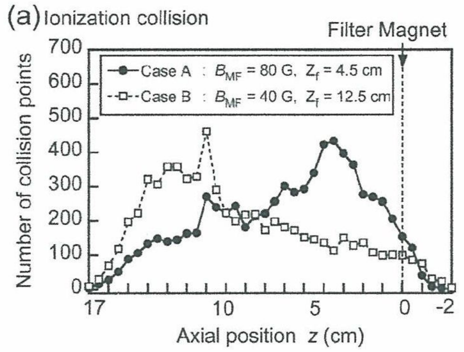


FIG. 5. Axial distribution of collision points for three different MFs: (a) ionization collision and (b) vibrational excitation collision points.



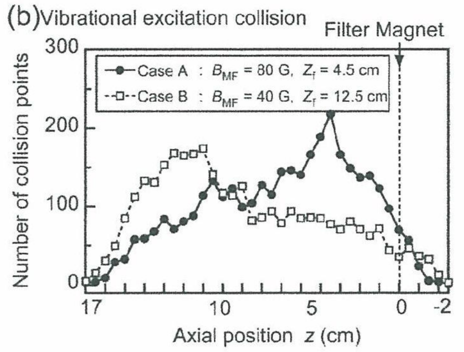


FIG. 7. Control of collision points with changing combination of the intensity of the MF and filament position: (a) ionization collision and (b) vibrational excitation collision points.

N_v. This difference is caused by mainly the difference of mean free path between the ionization collision and the vibrational excitation collision. With changing E_{fe}, however, the ratio of vibrational excitation collision points to ionization collision points (i.e., N_v/N_i) is varied. This is shown in Fig. 6. With decreasing E_{fe}, vibrational excitation collision becomes efficient.

Figure 7 shows axial distribution of collision point number for two different combinations of the B_{MF} and the filament position. As is shown clearly, plasma conditions in the extraction region are varied remarkably by changing the combination of the B_{MF} and the filament position. Recently, we have shown that the extraction probability of negative ions depends strongly on the upstream distance from the extraction electrode.[8] Then, for enhancement of extracted H^- ion current, H^- volume production should be increased and also optimized in the vicinity of the extraction electrode. In the source,[6] due to the external MF, the width of the half maximum of the B_{MF} is wide. Varying B_{MF} also indicates varying the strength of magnetic field distribution in both the source and extraction regions. Thus, the external MF has the merit of changing the plasma parameters in the extraction region. Optimum combination of B_{MF} and z_f should be required.

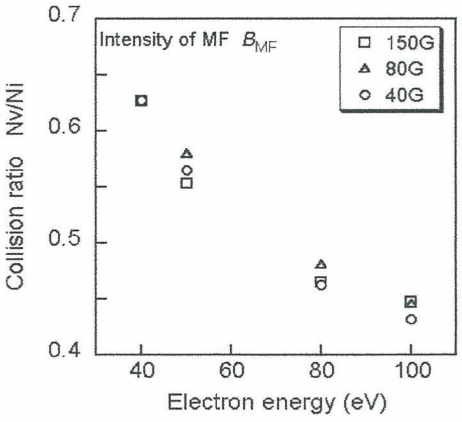


FIG. 6. Ratio of vibrational excitation collision to ionization collision as a function of primary electron energy.

Recently, to clarify the physical mechanism of the plasma spatial nonuniformity observed in tandem-type negative ion source,[9] the primary electron-transport process has been analyzed.[10] The primary electrons have been lost from the source region to the extraction region due to the magnetic drift in the filter magnetic region. We have also confirmed this drift in the present simulation (not shown here).[11]

IV. SUMMARY

Active region of fast electrons depends strongly on the field intensity of the MF, B_{MF}, and filament position. Therefore, spatial distributions of ionization and vibrational excitation collision points are also affected with changing B_{MF}. Although the number of vibrational excitation collision points is much lower than that of ionization collision points due to different mean free path, the ratio of collision number is varied by changing energy of fast electrons. According to the results and discussions including transport of produced vibrationally excited molecules, for enhancement of H^- production, it is desired that fast electrons should approach the MF position and move into the downstream region as deep as possible without destruction of H^- ions. To realize these conditions, good combination between filament position and the intensity of the MF should be required.

ACKNOWLEDGMENTS

The authors would like to thank T. Yoshimitsu for his support in numerical calculation. A part of this work was supported by the Grant-in-Aid for Scientific Research from Japan Society for the Promotion of Science.

[1] J. R. Hiskes and A. M. Karo, J. Appl. Phys. **56**, 1927 (1984).
[2] O. Fukumasa, J. Phys. D **22**, 1668 (1989).
[3] S. Asano, K. Tsumori, T. Okuyama, Y. Suzuki, M. Osakabe, Y. Oka, Y. Takeiri, and O. Kaneko, Rev. Sci. Instrum. **70**, 2338 (1999).
[4] M. Kashiwagi, S. Ido, and Y. Okumura, Rev. Sci. Instrum. **71**, 747 (2000).
[5] S. Mori and O. Fukumasa, Thin Solid Films **506–507**, 531 (2006).
[6] O. Fukumasa and S. Mori, Nucl. Fusion **46**, S287 (2006).
[7] Y. Ohara, M. Akiba, H. Horiike, H. Inami, Y. Okumura, and S. Yanaka, J. Appl. Phys. **61**, 1323 (1987).
[8] O. Fukumasa and R. Nishida, Nucl. Fusion **46**, S275 (2006).
[9] M. Hanada, T. Seki, N. Takado, T. Inoue, T. Morishita, T. Mizuno, A. Hatayama, T. Imai, M. Kashiwagi, K. Sakamoto, M. Taniguchi, and K. Watanabe, Fusion Eng. Des. **74**, 311 (2005).
[10] K. Katoh, N. Takado, A. Hatayama, M. Hanada, T. Seki, and T. Inoue, Rev. Sci. Instrum. **77**, 03A535 (2006).
[11] S. Mori and O. Fukumasa, Behaviors of fast primary electrons with collisional effects including production of vibrationally excited hydrogen molecules in a hydrogen negative ion source for a NBI system, IEEE Trans. FM. **127**, 747 (2007).