Parametric study of negative ion production in cesium seeded hydrogen plasmas

Osamu Fukumasa[a)] and Hideki Monji
Department of Electrical and Electronic Engineering, Faculty of Engineering, Yamaguchi University, Tokiwadai 2-16-1, Ube 755-8611, Japan

(Presented on 10 September 1999)

Effects of cesium vapor injection on H^- production in a tandem volume source are studied numerically as a function of plasma parameters. Model calculation is performed by solving a set of particle balance equations for steady-state hydrogen discharge plasmas. Here, the results with a focus on gas pressure dependence of H^- volume production are presented and discussed. Considering H^- surface production due to H atoms and positive hydrogen ions, enhancement of H^- production and pressure dependence of H^- production observed experimentally are qualitatively well reproduced in the model calculation, where stripping loss in the extraction and acceleration regions is taken into account. For pressure dependence of H^- production with cesium, i.e., decrease in optimum pressure, H atoms play an important role. For enhancement of H^- production, effect of so-called electron cooling is also briefly discussed. © *2000 American Institute of Physics.* [S0034-6748(00)55902-4]

I. INTRODUCTION

In pure hydrogen discharge plasmas, most of the H^- ions are produced by the two-step process[1–3] which involves dissociative attachment of slow plasma electrons, e (with electron temperature, T_e–1 eV) to highly vibrationally excited hydrogen molecules, $H_2(v'')$. Experimental investigations have revealed that the addition of cesium (Cs) or barium to a hydrogen discharge can enhance the H^- output current by a several factor and cause a substantial reduction in the electron-to-H^- ratio in the extracted beam.[4,5] It has also been reported[6,7] that the optimum pressure, p_{opt}, giving the highest H^- current for a certain arc current, I_a, is almost independent of I_a and that the value of p_{opt} decreases to 0.8–1.0 Pa when Cs vapor is seeded into a plasma source. Although these effects have been observed by many researchers, the mechanism of Cs catalysis in H^- production remains to be clarified.

To date, we have studied Cs effects on enhancement of H^- yield[8,9] and isotope effect.[10] In modeling Cs effects, based on some experimental results (for example, correlation between the H^- current and the work function of the plasma grid[11] and dependence of H^- current on barium washer voltage),[12] we have assumed that the dominant process of enhancement is surface production, where the surface has a low work function because of the Cs coverage. Enhancement of H^- yield are qualitatively well reproduced in the model calculation. In this article, to elucidate further the Cs effects, we will discuss characteristic features of enhancement of H^- yield as functions of plasma parameters, i.e., electron density n_e, hydrogen gas pressure p, and T_e.[9,13] Particularly, pressure dependence of extracted H^- current is explained by the model calculation. Here, atomic hydrogen H is the key parameter.

a)Electronic mail: fukumasa@plasma.eee.yamaguchi-u.ac.jp

II. SIMULATION MODEL

To study H^- production in a tandem two chamber system, we use the simulation model as shown in Fig. 1. Details are reported elsewhere.[3,9,13,14] Two chambers of volume $L\times L\times L_1$ (the first) and $L\times L\times L_2$ (the second) are in contact with each other in the region of magnetic filter, where $L=L_1+L_2=30\,\text{cm}$. We assume that fast electrons, e_f, are present only in the first chamber because the magnetic filter prevents e_f from entering the second chamber. We consider four ion species (H^-, H^+, H_2^+, and H_3^+), two electron species (e and e_f) and three species of neutral particles [H, $H_2(v'')$, and H_2]. Particles other than e and e_f are assumed to move freely between the two chambers without being influenced by the filter. The number of particles passing through the filter is represented by flux nv, when n and v are the particle density and velocity, respectively. Besides various collisional processes in hydrogen plasmas,[2] two kinds of reaction process at the wall surface are included in the present model.[8,9,10,13] One is H^- surface production caused by Cs injection. The following four processes are considered: $H_n^+ + \text{wall} \rightarrow nH^-$ $(n=1,2,3)$, and $H+\text{wall}\rightarrow H^-$. The other is effect of $H_2(v'')$ surface production due to wall recombination of H and neutralization of positive ions.

Surface production rates of negative ions are estimated as follows: The term representing wall loss of H atoms is expressed as $(\gamma_1+P_{\text{CSH}})N_H/\tau_H$, where γ_1 is a wall recombination coefficient, P_{CSH} indicates the probability of H^- formation at the wall, N_H is H density, and τ_H is a confinement time of H. Then, the H^- production rate at the wall surface is expressed as $P_{\text{CSH}}N_H/\tau_H$. We also assume that recombination of H to H_2 at the wall is written as $\gamma_1 N_H(2\tau_H)$. Therefore, production of $H_2(v'')$ is expresses as $P_0\gamma_1 N_H/(2\tau_H)$, where P_0 is the probability of finding $H_2(v'')$ in H_2 formed at the wall. In the same way, the rates of production of H^- and $H_2(v'')$ from positive ions at the wall are also estimated.

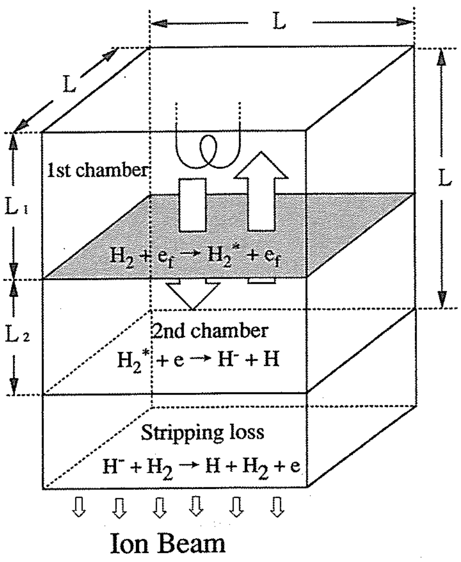

FIG. 1. Simulation model for the tandem two-chamber system.

For each chamber, 19 rate equations for H, $H_2(v''=1-14)$, H^-, H^+, H_2^+, and H_3^+ are derived by taking into account the earlier-mentioned reaction processes and the interaction between the two chambers. Thus, for the tandem two-chamber system, a set of 42 equations is solved numerically as a function of plasma parameters.

III. NUMERICAL RESULTS AND DISCUSSION

We will discuss the pressure dependence of H^- production or of the extracted H^- current.

Figure 2 shows the H^- densities, H^-, (2) in the second chamber as a function of hydrogen gas pressure p. Calculations are performed for varying p on the assumption that other plasma parameters are kept constant: The electron density in the first chamber $n_e(1)=2\times10^{12}\,\text{cm}^{-3}$ in (a) and $5\times10^{12}\,\text{cm}^{-3}$ in (b), the electron density ratio between two chambers $n_e(2)/n_e(1)=0.2$, density of e_f in the first chamber $n_{fe}(1)/n_e(1)=0.05$, T_e in the first chamber $T_e(1)=5$ eV and T_e in the second chamber $T_e(2)=1$ eV, and the filter position $L_1:L_2=28:2$ cm. Wall conditions are as follows. For positive ions, $P_{CS_1}=P_{CS_2}=P_{CS_3}=P_{CS}(+)$, and $P_{CS}(+)=20P_{CSH}$, where $P_{CSH}=5\times10^{-3}$. $P_0=P_1=0.01$, and $P_2=P_3=0.3$.

In Fig. 2, dashed line (without Cs) shows the H^- (2) produced by the so-called two-step pure volume process. With Cs ($P_{CSH}=5\times10^{-3}$), as shown previously,[8,9,13] H^- (2) increases markedly. According to the production rate and destruction probability of H^- (2) corresponding to the result in Fig. 2, the predominant production process is surface production due to H. For destruction of H^- ions, electron detachments caused by H and H_2 are predominant when $p>1$ Pa. In the low-pressure region ($p\leqq1$ Pa), however, both electron detachments caused by H^+ and loss flux of negative ions $\Gamma_{2\rightarrow1}$, i.e., flow of H^- (2) across the filter to the first chamber, are predominant. As γ_1 is a wall parameter for controlling H density, H density increases with decreasing γ_1. Therefore, with decreasing γ_1, H^- (2) is enhanced caused by H^- surface production due to H.

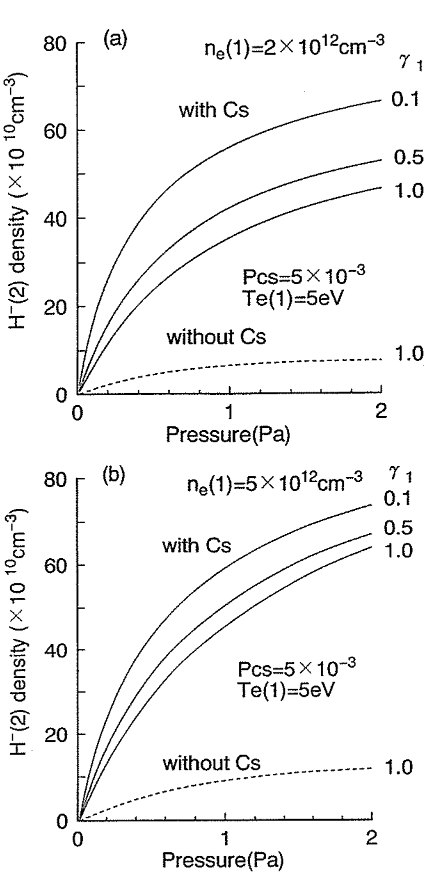

FIG. 2. Effects of hydrogen gas pressure on H^- production: H^- (2) vs gas pressure p with and without Cs, (a) electron density in the first chamber $n_e(1)=2\times10^{12}\,\text{cm}^{-3}$ and (b) $n_e(1)=5\times10^{12}\,\text{cm}^{-3}$. Parameter γ_1 is a wall recombination coefficient of H. For cesium seeded case, γ_1 is varied from 1.0 to 0.1.

Usually, experimental results show the extracted H^- current as a function of p. In Refs. 6 and 7, the H^- current is enhanced severalfold, and p_{opt} is reduced to 0.5–0.8 Pa and is almost constant irrespective of I_a or arc power P_{arc}. Figure 2, however, shows not the extracted H^- current but the H^- density in the second chamber. Therefore, strictly speaking, we could not directly compare the numerical results shown in Fig. 2 with the experimental ones. Because, the pressure dependence of H^- current depends strongly on stripping loss of H^- ions along the beam axis.[7,15]

In order to discuss pressure dependence of the extracted H^- current, we derive the extracted H^- ions from H^- (2) by taking into account stripping loss of H^- ions in the acceleration grid region. According to gas pressure distribution along the beam axis estimated by the Monte Carlo simulation,[15] we calculate the survival factor F against the stripping loss of H^- ions, i.e., $H^-+H_2\rightarrow H+H_2+e$ and $H^-+H\rightarrow 2H+e$. F is a decreasing function of pressure.

Figure 3 shows the extracted H^- ions, corresponding to the results in Fig. 2(a), as a function of p. They are the product of H^- (2) in Fig. 2 with F. In the absence of Cs, p_{opt} is observed for each $n_e(1)$, and the value of p_{opt} increases with $n_e(1)$ not shown here. Experimentally, this is a typical tendency in a multicusp volume source where the parameter is not n_e but arc current I_a. With Cs injection, H^- density increases by several times. Furthermore, in the present case,

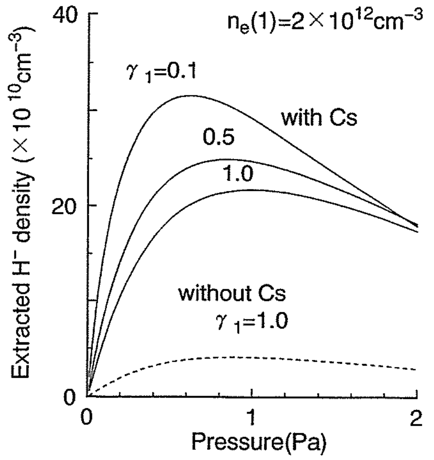

FIG. 3. Pressure dependence of the extracted H^- ions: H^- density vs p, corresponding to the results shown in Fig. 2(a), where stripping loss of H^- ions in the acceleration grid region is included.

p_{opt} also appears clearly. This comes from the pressure dependence of F. Namely, F decreases sharply with pressure. However, when $\gamma_1 = 1.0$, p_{opt} does not shift to a low-pressure region as observed in some experiments.[6,7] When the value of γ_1 with Cs is reduced to 0.1, however, p_{opt} shifts to a lower-pressure region compared with the results without Cs. This tendency agrees with experiments. As γ_1 is a parameter for controlling H density, this suggests that H density plays an important role in H^- production with Cs. H density increases with decreasing γ_1. Therefore, we speculate that H density(or H ratio) in hydrogen discharge with Cs becomes higher compared with that in pure hydrogen discharge although no experimental data are reported concerning this point. Details are now under study.

Electron cooling comes from the Cs-ionization energy loss of the electrons and the ionization may occurs mainly in the first chamber. Therefore, the cooling effect appears as the lowering of the electron temperature $T_e(1)$ in the first chamber. For reference, in Fig. 4, we also plot the numerical results of the extracted H^- ions obtained under $T_e(1)=3$ eV

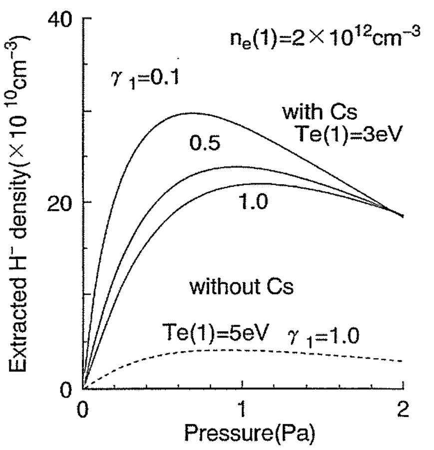

FIG. 4. Pressure dependence of the extracted H^- ions: H^- density vs p. In this simulation, to show the effect of electron cooling, $T_e(1)$ with Cs is reduced to 3 eV.

with Cs, corresponding to the same P_{CSH} for the results in Fig. 3. As a whole, H^- densities are reduced compared with the results shown in Fig. 3. Although P_{CSH} is kept constant corresponding to the variation of $T_e(1), T_e$ dependence of H^- ions keeps the same tendency.[13] Therefore, at least for plasma conditions discussed here, electron cooling effects not enhancement of H^- ions but reduction of H^- ions. Details are discussed in a separate article.[13]

In the present simulation study where only surface process of Cs effects is included, model calculation reproduces the characteristic features of H^- enhancement in the Cs seeded ion sources. Recently, volume effects of Cs related reactions have been studied.[16] They suggest that H^- density decreases with increasing Cs density. In the future, we will discuss Cs effects on H^- production including those volume effects.

IV. CONCLUSIONS

We have theoretically studied cesium effects on enhancement of H^- yield and plasma parameter dependence of H^- density in negative-ion volume sources. Considering H^- surface production, enhancement of H^- production and pressure dependence of H^- production observed experimentally are qualitatively well reproduced in the model calculation, where stripping losses in the extraction and acceleration regions are taken into account. H^- surface production due to H and positive ions (H^+ and H_3^+) contribute predominantly to H^- enhancement. For destruction of H^-, H, and H_2 contribute predominantly in high pressure region. Therefore, H density determines the pressure dependence of H^- production in cesium seeded hydrogen plasmas. For plasma conditions discussed here, electron cooling reduces H^- production.

ACKNOWLEDGMENT

This work was supported by a Grant-in-Aid for Scientific Research from the Japanese Ministry of Education, Science, Sports and Culture.

[1] J. R. Hiskes and A. M. Karo, J. Appl. Phys. **56**, 1927 (1984).
[2] O. Fukumasa, J. Phys. D **22**, 1668 (1989).
[3] O. Fukumasa and S. Ohashi, J. Phys. D **22**, 1931 (1989).
[4] S. R. Walther, K. N. Leung, and W. B. Kunkel, J. Appl. Phys. **64**, 3424 (1988).
[5] K. N. Leung, C. A. Hauck, W. B. Kunkel, and S. R. Walther, Rev. Sci. Instrum. **60**, 53 (1989).
[6] Y. Okumura, N. Hanada, T. Inoue, H. Kojima, Y. Matsuda, Y. Ohara, M. Seki, and K. Watanabe, *Proceedings of the 5th International Symposium Production and Neutralization of Negative Ions and Beams* (AIP, New York, 1990), p. 169.
[7] A. Ando *et al.*, Phys. Plasmas **1**, 2813 (1994).
[8] O. Fukumasa, T. Tanebe, and H. Naitou, Rev. Sci. Instrum. **65**, 1213 (1994).
[9] O. Fukumasa and E. Niitani, Jpn. J. Appl. Phys., Part 2 **35**, L1528 (1996).
[10] O. Fukumasa and K. Yoshino, Rev. Sci. Instrum. **69**, 941 (1989).
[11] Y. Okumura, Y. Fujiwara, T. Inoue, K. Miyamoto, N. Miyamoto, A. Nagase, Y. Ohara, and K. Watanabe, Rev. Sci. Instrum. **67**, 1092 (1996).
[12] K. N. Leung, C. F. A. van Os, and W. B. Kunkel, Appl. Phys. Lett. **58**, 1467 (1991).
[13] O. Fukumasa (unpublished).
[14] O. Fukumasa, J. Appl. Phys. **71**, 3193 (1992).
[15] Y. Takeiri *et al.*, Rev. Sci. Instrum. **66**, 2541 (1995).
[16] M. Ogasawara, T. Morishita, M. Miura, N. Shibayama, and A. Hatayama, Rev. Sci. Instrum. **69**, 1132 (1998).