Identification of cesium effects on enhancement of H^- production in a volume negative ion source

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Effects of cesium vapor injection on H^- production in a tandem source are studied theoretically and parametrically as a function of different surface processes. Model calculation is done by solving a set of particle balance equations in steady-state hydrogen discharge plasmas. By including H^- surface production processes caused by H atoms or positive hydrogen ions, enhancement of H^- production observed experimentally is reproduced in the model.

I. INTRODUCTION

Sources of H^- or D^- ions are required to generate efficient neutral beams with energies in excess of 150 keV. The magnetically filtered multicusp ion sources have been shown to be a promising source of high quality, multiampere H^- ion sources. According to our simulation results,[1,2] in pure hydrogen discharge plasmas most of the H^- ions are produced by the two-step process,[3] which involves dissociative attachment of slow plasma electrons e (with electron temperature $\kappa\, T_e \sim 1$ eV) to highly vibrationally excited molecules H_2 (v''). Different techniques, i.e., optimization of the magnetic filter and the plasma grid potential, to enhance H^- yield in the multicusp source have been studied by many authors. Furthermore, it has been confirmed that the performance of this volume source is highly improved by adding cesium to the hydrogen discharge.[4–7]

Previously, we studied theoretically cesium effects on enhancement of H^- yield.[8] Although only surface production of H^- ions due to H atoms are included, preliminary results have shown that surface effects play an important role, and enhance H^- yield remarkably. Surface effects of the second chamber mainly contribute to enhancement of the H^- yield. In this paper, to further study the cesium effects, we will discuss enhancement of the H^- yield as a function of different surface processes, i.e., the processes caused by H atoms and positive hydrogen ions.

II. SIMULATION MODEL

To study H^- and $H_2(v'')$ production in a tandem two-chamber system, we divide the single chamber of volume $L\times L\times L$ into two parts.[2] 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 the magnetic filter. We assume that fast electrons e_f are present only in the first chamber because the magnetic filter impedes e_f from coming into 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 except e and e_f are assumed to move freely between two chambers without being influenced by the filter. The number of particles passing through the filter is treated in the form of flux nv, where n and v are the particle density and velocity, respectively.

The present model is an extended version of the previous one.[9,10] Main modification caused by cesium injection is H^- surface production.[8] The following four processes are considered:[11]

$$H_n^+ + \text{wall} \rightarrow H^- + \cdots \quad (n=1,2,3),$$

$$H + \text{wall} \rightarrow H^-.$$

In modeling, surface production rates of negative ions are evaluated as follows: For example, the term representing the loss term of H atoms to the wall surface is expressed as $-\gamma_1 N_H/T_H$, where γ_1 is a wall loss parameter (usually known as a wall recombination coefficient), N_H is H density, and T_H is a confinement time of H.[1] Therefore, the production rate is expressed as $P_{cs}\gamma_1 N_H/T_H$, where P_{cs} indicates the probability of H^- formation at the wall and is treated as a numerical parameter. In the same way, production rates of H^- ions from positive ions are also evaluated.

In each chamber, 19 rate equations for H, $H_2(v''=1\text{–}14)$, H^-, H^+, H_2^+, and H_3^+ are derived by taking into account the above-mentioned reaction processes and other collisional reaction processes in hydrogen plasmas,[1,9,10] and the interaction between two chambers. Besides these, there are two constraints, i.e., the charge neutrality and the particle number conservation. Then, 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

Calculations are done by varying electron density in the first chamber $n_e(1)$ on the assumption that other plasma parameters are kept constant, i.e., the electron density ratio between two chambers $n_e(2)/n_e(1)=0.2$, density of e_f in the first chamber $n_{fe}(1)/n_e(1)=0.05$, hydrogen gas pressure $p=5$ mTorr, electron temperature in the first chamber $\kappa T_e(1)=5$ eV, and electron temperature in the second chamber $\kappa T_e(2)=1$ eV, and the filter position $L_1{:}L_2=28{:}2$ cm. According to the previous results,[1,2] those plasma conditions are chosen to optimize H^- production in the second chamber.

A. Effect of H atoms

Figure 1 shows the H^- densities in the second chambers $H^-(2)$ for two different values of γ_1. In this case,

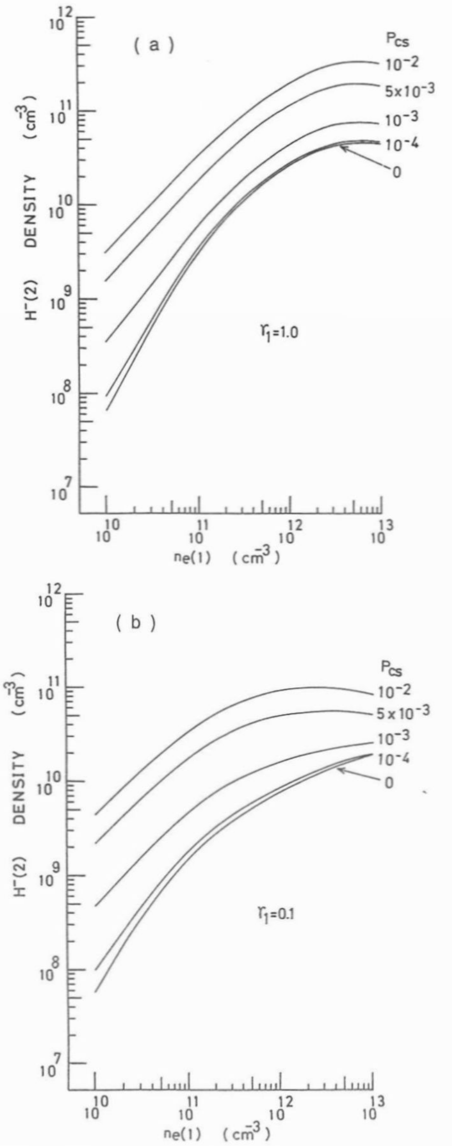

FIG. 1. Effects of the surface production due to H atoms on enhancement of H^- production: H^- density, $H^-(2)$, in the second chamber vs electron density in the first chamber $n_e(1)$, (a) wall loss parameter $\gamma_1=1.0$, and (b) $\gamma_1=0.1$. Parameter is a probability of H^- formation at the wall, P_{cs}.

only the surface production process due to H atoms is included. Effects of surface processes are considered in both two chambers and P_{cs} is varied as a parameter. When $P_{cs}=0$, H^- ions are produced by the so-called two-step volume production. With increasing P_{cs}, $H^-(2)$ increases remarkably, although its enhancement depends on γ_1 in the high density region.

For reference, corresponding to the variations of H^- ions in Fig. 1, densities of H, H_2, and positive ions vs $n_e(1)$ are shown in Fig. 2. The calculated density of H is sensitive to γ_1.[1] The value of γ_1 depends not only on wall materials but also wall conditions.[12] The numerical results shown in Fig. 2 are obtained under the condition $\gamma_1=0.1$ and 1.0. Wall effects considered here are strongly affected by H atoms colliding with wall surfaces, i.e., $P_{cs}\gamma_1 N_H/T_H$. It is clear that, with increasing γ_1, wall loss of H atoms increases, and then enhancement of H^- yield caused by surface production is remarkable in high density region.

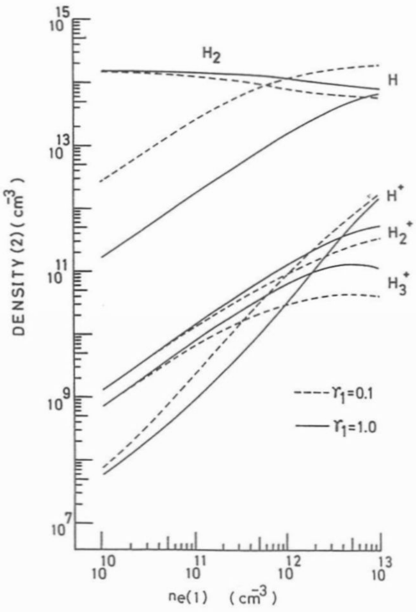

FIG. 2. Densities of positive ions, H_2 molecules, and H atoms in the second chamber vs $n_e(1)$. They correspond to $H^-(2)$ in Fig. 1 when $P_{cs}=0$.

Previously, we discussed the mechanism of wall effects.[8] Namely, where is the most effective region for surface H^- production. Both the effect of the second chamber surface and that of the first chamber surface are examined numerically. According to those results, enhancement of $H^-(2)$ caused by surface effects remarkably appears only when surface effects in the second chamber are included. Physical meaning is as follows: In the tandem source, to optimize the two-step H^- production, e_f is present only in the first chamber and $\kappa T_e(1)$ is higher than $\kappa T_e(2)$. Then, produced H^- ions in the first chamber are easily lost via electron collisional detachment due to e_f and e, and surface effects in the first chamber hardly contribute to enhancement of $H^-(2)$. The effect of this loss process appears more clearly in the high density region.

As the magnetic filter is close to the end plate (i.e., L_1: $L_2=28$:2 cm), surface effects in the second chamber are mainly due to this end plate. Experimentally, it is confirmed that cesium effects are mainly due to surface production of H^- ions on the plasma grid,[13] i.e., the end plate in our notation. The numerical results are qualitatively well in agreement with the experimental results.

B. Effect of positive ions

To discuss the effect of positive ions, the same calculation as the ones show in Fig. 1 has been done. In this case, surface production due to only positive ions is included, i.e., $H_n^+ + \text{wall} \rightarrow nH \rightarrow nH^-$ $(n=1,2,3)$.

Numerical results are shown in Fig. 3. With increasing P_{cs}, as a whole, enhancement of $H^-(2)$ is nearly the same as the ones in Fig. 1. According to the positive ion species

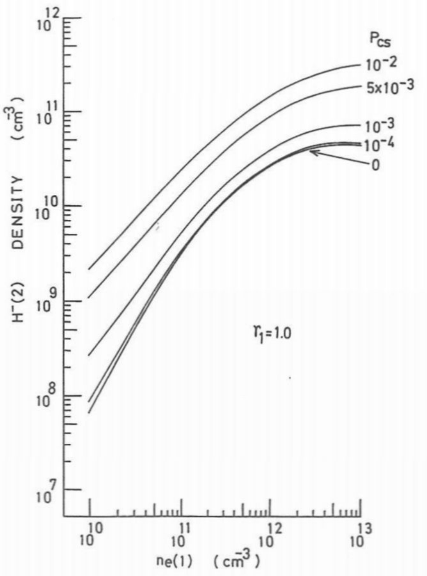

FIG. 3. Effects of the surface production due to positive ions on enhancement of H^- production: $H^-(2)$ vs $n_e(1)$.

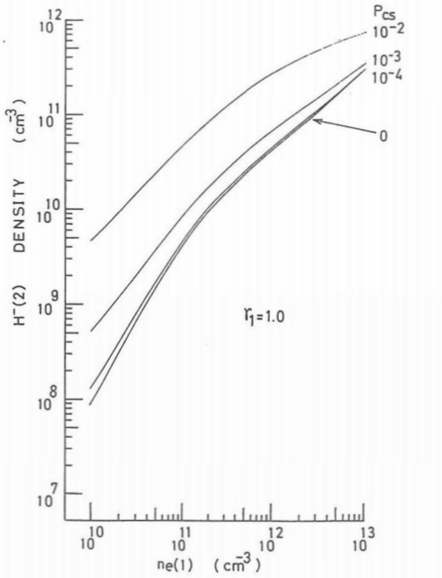

FIG. 4. Effects of the surface production due to both H atoms and positive ions on enhancement of H^- production: $H^-(2)$ vs $n_e(1)$.

ratio in Fig. 2, surface production due to H^+ is essential to H^- enhancement in a high density region. On the other hand, molecular ions predominate in a rather low density region ($n_e \leqslant 5\times10^{11}$ cm^{-3}). In this case, surface production due to molecular ions would play an important role in H^- enhancement.[14]

C. Hybrid effect of both H atoms and positive ions

So far, we show the numerical results where $H^-(2)$ strongly depends on surface effects. In those cases, however, the probability of producing $H_2(v'')$ on the wall is neglected. According to our previous simulation,[9,10] the effects of $H_2(v'')$ production processes due to neutralization of positive ions at the wall[15] have a large influence on the vibrational spectrum. In this section, we present the results on wall effects of both H atoms and positive ions where processes of H^- and $H_2(v'')$ surface productions for positive ions are included.

Figure 4 shows $H^-(2)$ as a function of $n_e(1)$. When $P_{cs}=0$, H^- ions are produced only by the volume process, i.e., the dissociative attachment of e to $H_2(v'')$. $H^-(2)$ increases remarkably with $n_e(1)$, particularly in a high density region. This is quite different from the results shown in Figs. 1 and 3. A increase in $H_2(v'')$ density due to positive ions at the wall is essential to enhancement of H^- ions. With increasing P_{cs}, $H^-(2)$ increases, although its enhancement decreases gradually with the increase of $n_e(1)$. Therefore, also in the present case, surface production processes play an important role on enhancement of H^- yield.

Probability of incoming H atoms changing into H^- ions on the wall is given as $\beta=(2/\pi)\exp[-(\phi-A)/av]$,[16] where ϕ is the work function, A is the electron affinity, a is the decay constant, and v is the normal velocity of the incident particle. Effect of cesium is expressed through the value of the work function. In the future, we will study further cesium effects quantitatively. To this end, we must discuss the relationship between P_{cs} in our code and probability β.

In summary, we have theoretically studied cesium effects on the enhancement of H^- yield. In modeling surface effects, for example, the production rate of H^- ions due to H atoms is estimated by $P_{cs}\gamma_1 N_H/T_H$. Numerical results show that surface effects in the second chamber play an important role, and enhance the H^- yield remarkably. H atoms have the most dominant contribution to H^- enhancement and H^+ ions have the next dominant one.

[1] O. Fukumasa, J. Phys. D **22**, 1668 (1989).
[2] O. Fukumasa and S. Ohashi, J. Phys. D **22**, 1931 (1989).
[3] J. R. Hiskes and A. M. Karo, J. Appl. Phys. **56**, 1927 (1984).
[4] S. R. Walther, K. N. Leung, and W. B. Kunkel, J. Appl. Phys. **64**, 3424 (1988).
[5] K. N. Leung, C. A. Hauck, and W. B. Kunkel, and S. R. Walther, Rev. Sci. Instrum. **60**, 531 (1989).
[6] Y. Okumura, M. Hanada, T. Inoue, H. Kojima, Y. Matsuda, Y. Ohara, M. Seki, and K. Watanabe, 5th International Symposium on Production and Neutralization of Negative Ions and Beams, Brookhaven, 30 October–3 November 1989 (unpublished).
[7] H. Kojima, M. Hanada, T. Inoue, Y. Matsuda, Y. Ohara, Y. Okumura, H. Oohara, M. Seki, and K. Watanabe, Proceedings of the 13th Symposium on Ion Sources and Ion-Assisted Technology, Tokyo, 1990 (unpublished), p. 145.
[8] O. Fukumasa, H. Naitou, and T. Tanebe, 6th International Symposium on the Production and Neutralization of Negative Ions and Beams, Brookhaven, 9–13 November 1992 (unpublished).
[9] O. Fukumasa, K. Mutou, and H. Naitou, Rev. Sci. Instrum. **63**, 2693 (1992).
[10] O. Fukumasa, J. Appl. Phys. **71**, 3193 (1992).
[11] P. Berlemont, D. A. Skinner, and M. Bacal, Chem. Phys. Lett. **183**, 397 (1991).
[12] O. Fukumasa, R. Itatani, and S. Saeki, J. Phys. D **18**, 2433 (1985).
[13] Y. Okumura, M. Hanada, T. Inoue, H. Kojima, and K. Watanabe, in Ref. 7, p. 149.
[14] K. N. Leung, C. F. A. van Os, and W. B. Kunkel, Appl. Phys. Lett. **58**, 1467 (1991).
[15] J. R. Hiskes and A. M. Karo, J. Appl. Phys. **67**, 6621 (1990).
[16] B. Rasser, J. N. M. Van Wunnik, and J. Los, Surf. Sci. **118**, 697 (1982).