The Role of Fast Electrons for the Performance Characteristics of Hydrogen Ion Sources

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Abstract

The influence of fast primary electrons on the ion species ratios in a hydrogen plasma is discussed numerically. The optimum condition for plasma production with high proton ratio is to eliminate the presence of fast electrons, whereas the production of H^- ions is enhanced anomalously by the presence of fast electrons.

1. Introduction

One of the most powerful and effective methods for the additional heating of a fusion plasma is neutral beam injection (NBI). For this purpose, it requires a plasma source capable of generating high current density and high-power beams of energetic particles over large areas. Several kinds of plasma generators are being used in NBI heating.[1)]

In a positive ion source, one of other properties highly desirable for the plasma generator is the ability to provide a beam with high atomic component. Typically, hydrogen ion sources produce multimomentum beams cosisting of atomic ions (H_1^+) and molecular ions (H_2^+ and H_3^+). In a NBI system, the molecular ions pass through a charge-exchange gas cell and break up into atoms with one-half (from H_2^+) or one-third (from H_3^+) of their accelerated energy. These lower energy components do not penetrate deeply into a plasma and may be unwanted because the heating of the outside plasma yields an adverse effect. Therefore, the problem of the hydrogen ion species ratio in positive ion sources is of great importance in the fusion area.

There have been many experimental[2−8)] and numerical[9−12)] studies concerning the improvement of the proton ratio. Among them, Ehlers and Leung[3,4)] investigated the hydrogen ion species ratios in a multicusp ion source (bucket source). They found that the presence of fast primary ionizing electrons in the vicinity of the extraction grid increased the percentage of molecular ions. By using a permanent magnetic filter, they could eliminate the presence of the fast electrons in the front region of the source and improve the atomic species.

On the other hand, the development of powerful negative ion sources is essential to the NBI system, beam energies considerably in excess of 150 keV, for the next generation of fusion reactors. Because, the neutralization efficiency of the ions is a

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function of the ion energy,[13] and the practicality of the positive ion source begins to fail when the required neutral beam energy exceeds about 150 keV.

Some experiments with low-pressure-hydrogen discharges have observed unexpectedly high negative ion densities. Namely, more than 30% of the ions may be H^-.[14,15] Theoretical studies indicate that anomalous H^- ions are formed from vibrationally excited hydrogen molecules.[16] Besides, vibrational excitation rates are predicted to be large for electron energies in excess of 30 eV.[17] Although these results have not been extended to very high plasma density conditions, such discharges are currently being studied for the development of negative ion sources.[18,19]

As described above, fast primary electrons play an important role for the performance characteristics of both positive and negative ion sources. In the present paper, we report the details of the numerical results on the effects of fast elections for the positive ion species ratio in the hydrogen plasma. Moreover, the role of fast electrons in H^- production[20] and wall effects on the ion species ratios[8,12] are also discussed briefly.

2. Computational Model

The ratios of the ion species can be obtained from the equations of particle balance in production and loss for each species of neutral particles and ions in the source plasma, i. e. atomic hydrogen H_1, molecular hydrogen H_2, atomic ion H_1^+ and molecular ions H_2^+ and H_3^+. In the previous model,[8,12] we assume that a partially–ionized Maxwellian plasma is produced at a constant gas pressure and that these Maxwellian electrons, e, play a dominant role in ionizing or breaking up hydrogen species. However, when high energy monoenergetic electrons (corresponding to the primary current carrying electrons) are present and are assumed to be responsible for ionization, reaction processes due to these fast primary electrons, e_f, must be taken into account

The reaction processes considered in the present model and its notation for the corresponding rate coefficients are as follows :

$$H_2 + e \rightarrow H_2^+ + 2e, \quad \langle \sigma_1 v_e \rangle \equiv \alpha_1, \quad (1-a)$$

$$H_2 + e_f \rightarrow H_2^+ + e_f + e, \quad \sigma_1 v_f \equiv \alpha_{f1}, \quad (1-b)$$

$$H_2 + e \rightarrow 2H_1 + e, \quad \langle \sigma_2 v_e \rangle \equiv \alpha_2, \quad (2-a)$$

$$H_2 + e_f \rightarrow 2H_1 + e_f, \quad \sigma_2 v_f \equiv \alpha_{f2}, \quad (2-b)$$

$$H_2^+ + e \rightarrow H_1^+ + H_1 + e, \quad \langle \sigma_3 v_e \rangle \equiv \alpha_3, \quad (3-a)$$

$$H_2^+ + e_f \rightarrow H_1^+ + H_1 + e_f, \quad \sigma_3 v_f \equiv \alpha_{f3}, \quad (3-b)$$

$$H_2^+ + H_2 \rightarrow H_3^+ + H_1, \quad \langle \sigma_4 v_+ \rangle \equiv \alpha_4, \quad (4)$$

$$H_1 + e \rightarrow H_1^+ + 2e, \quad \langle \sigma_5 v_e \rangle \equiv \alpha_5, \quad (5-a)$$

$$H_1 + e_f \rightarrow H_1^+ + e_f + e, \quad \sigma_5 v_f \equiv \alpha_{f5}, \quad (5-b)$$

$$H_3^+ + e \rightarrow H_1 + H_2, \quad \langle \sigma_6 v_e \rangle \equiv \alpha_6, \quad (6)$$

$$H_3^+ + e \rightarrow H_1^+ + 2H_1 + e, \quad \langle \sigma_7 v_e \rangle \equiv \alpha_7, \quad (7)$$

$$H_3^+ + e_f \rightarrow H_2^+ + H_1 + e_f, \quad \sigma_8 v_f \equiv \alpha_{f8}, \quad (8)$$

where v_e, v_f and v_+ are the thermal electron, the fast electron and the ion velocities; σ_j and α_j are the cross-section and the rate coefficient for the reaction of the j-th process described above; $\langle\ \rangle$ denotes the average over the distribution function.

The reaction rates for the Maxwellian electron collision processes can be calculated for various electron temperatures T_e using the established values for the cross-sections.[9,10,21] The variation of these rates with T_e is represented in Fig. 1, and

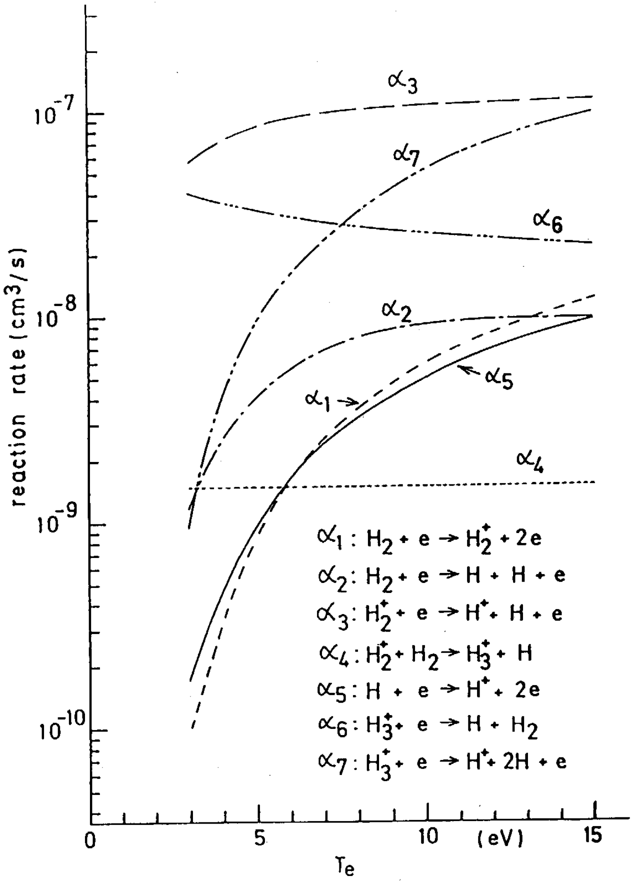

Fig. 1 The ionization and dissociation rates $\langle \sigma v_e \rangle$ averaged with a Maxwellian velocity distribution function as a function of T_e.

these values are used in the present calculations. For reference α_4 is also shown, although it is independent of T_e. According to the experimental data,[22] the cross-section σ_4 for H_3^+ ion formation decreases with relative $H_2^+ - H_2$ energy. In the present analysis, the value of α_4 has been assumed to be constant and equal to $1.5 \times 10^{-9} cm^3/sec$.[12] Rate coefficients for primary electrons are taken from Ref. 9, and the values are shown as a function of fast electron energy E_{fe} in Fig. 2.

From the view point of experimental conditions, we consider the ion species ratios in a steady state plasma. In this case, the particle balance equations for H_1, H_1^+, H_2^+ and H_3^+ are written as follows:

$$2N_2(n_e\alpha_2+n_{fe}\alpha_{f2})+n_2(n_e\alpha_3+n_{fe}\alpha_{f3})+n_2N_2\alpha_4+n_3n_e(\alpha_6+2\alpha_7)$$
$$+n_3n_{fe}\alpha_{f8}-N_1(n_e\alpha_5+n_{fe}\alpha_{f5})-\gamma\frac{N_1}{T_1}=0, \quad (9)$$

$$N_1(n_e\alpha_5+n_{fe}\alpha_{f5})+n_2(n_e\alpha_3+n_{fe}\alpha_{f3})+n_3n_e\alpha_7-\frac{n_1}{\tau_1}=0, \quad (10)$$

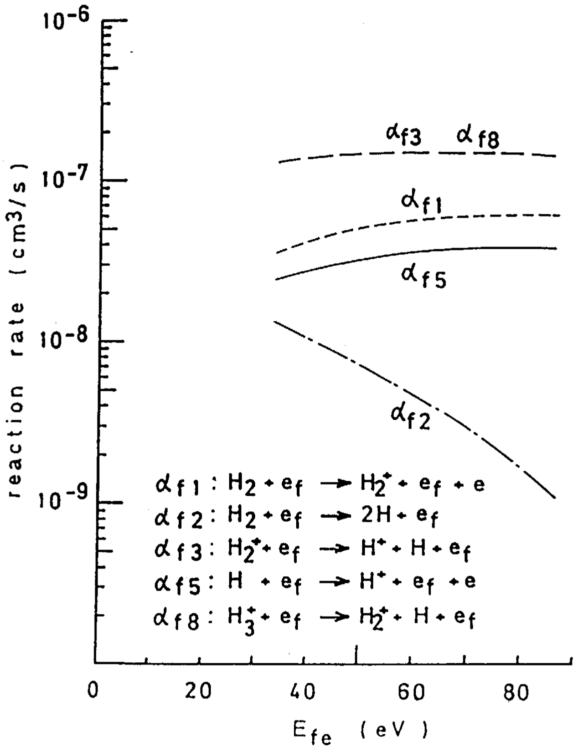

Fig. 2 The ionization and dissociation rates for fast electrons as a function of E_{fe}.

$$N_2(n_e\alpha_1+n_{fe}\alpha_{f1})+n_3n_{fe}\alpha_{f8}-n_2(n_e\alpha_3+n_{fe}\alpha_{f3})-n_2N_2\alpha_4-\frac{n_2}{\tau_2}=0, \quad (11)$$

$$n_2N_2\alpha_4-n_3n_e(\alpha_6+\alpha_7)-n_3n_{fe}\alpha_{f8}-\frac{n_3}{\tau_3}=0. \quad (12)$$

Charge and particle number conservation give

$$n_1+n_2+n_3=n_e+n_{fe}, \quad (13)$$

$$N_2+\frac{N_1}{2}+\frac{n_1}{2}+n_2+\frac{3}{2}n_3=N_0, \quad (14)$$

where N_1, N_2, n_1, n_2, n_3, n_e, and n_{fe} are the densities of H_1 atoms, H_2 molecules, H_1^+ ions, H_2^+ and H_3^+ molecular ions, thermal and fast electrons, respectively ; τ_1, τ_2 and τ_3 are the containment times of H_1^+ ions, H_2^+ and H_3^+ molecular ions, respectively ; T_1 is the transit time of H_1 atoms across the chamber, and the containment time of H_1 would be T_1/γ ; γ is either the recombination or the sticking factor for H_1 atoms at the wall ; N_0 $(=p/(\kappa T_0)$; p : hydrogen gas pressure, κ : Boltzmann's constant, T_0 :

room temperature) is the density of hydrogen molecules before discharge on.

In the above model, all the species of ions recombine at the wall to produce molecules. However, the H_1 atoms recombine only partially when γ is smaller than unity. Because, the loss rate equals $\gamma N_1/T_1$. The value of T_1 is estimated from the relation $T_1 = 4V/(v_0A)$, where V is the volume of the source chamber, A the area of the wall surface and v_0 the mean velocity of the H_1 atoms. We assume that the ratio of τ_1, τ_2 and τ_3 is the the ratio of the square root of the respective ion masses, and we treat τ_1 as one of the unknown values.

The unknown values of N_1, N_2, n_1, n_2, n_3 and τ_1 can be obtained from eqs. (9)—(14) when n_e, n_{fe}/n_e, T_e, p and V/A are given. For example, if we want to discuss n_e dependence of ion species ratios, calculation procedure is to vary n_e as an independent variable on the assumption that T_e, p, n_{fe}/n_e and V/A are constant parameters.

3. Results of Numerical Calculations and Discussion

In the present calculation, the ion species ratios are obtained as a function of n_e, T_e and p, respectively. According to the experimental results by Wood and Wise,[23,24] the interaction of hydrogen atoms with the wall can vary in a wide range. Therefore, in order to study the wall effects, we treat γ as another numerical parameter[8,12] and the value of γ is varied from 0.01 to unity.

Calculations have been done for two situations, i. e. Case I fitted to a low density plasma source and Case II fitted to usual high current ion sources. In the former case, plasma parameters are chosen typically as follows: $n_e = 1\times10^{11}cm^{-3}$, T_e = 5eV, $p = 5\times10^{-4}$ Torr and V/A = 2cm. In the latter case, typical plasma parameters are as follows: $n_e = 5\times10^{12}cm^{-3}$, T_e = 5 eV, $p = 5\times10^{-3}$ Torr and V/A = 2cm.

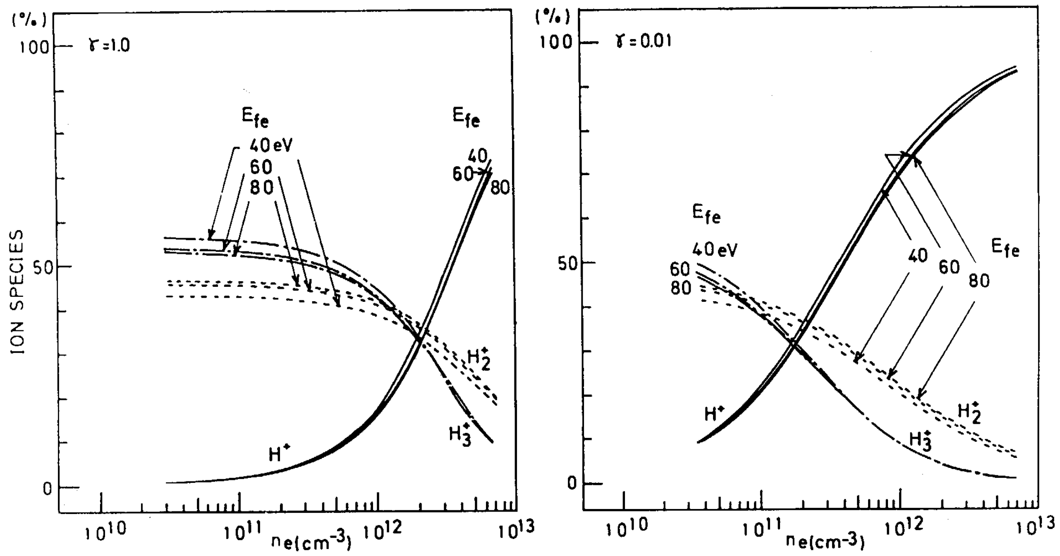

Fig. 3 Ion species ratios as a function of n_e with E_{fe} as a parameter. Other parameters are: T_e = 5 eV, $p = 5\times10^{-3}$ Torr, n_{fe}/n_e = 0.01 and V/A = 2cm.

3.1 Effects of fast electrons on ion species ratios in positive ion sources

First of all, we consider the effect of fast electron energy E_{fe} on ion species ratios. Figure 3 shows the ion species ratios as a function of n_e. The value of E_{fe} is taken as a parameter. Varying E_{fe} from 40 eV to 80 eV makes little change in ion species ratios. Therefore, in the following calculations, E_{fe} is kept constant at 40 eV.

On the other hand, varying γ makes the marked change in the ion species ratio[8,12]. For example, at the point (in Fig. 3) where $n_e = 1 \times 10^{12} cm^{-3}$, the proton ratio is about 17% when γ is 1.0. Decreasing γ to 0.01, the proton ratio rises up to about 70%.

Figures 4 and 5 show the ion species ratios as a function of n_e for Case I and Case II, respectively. The density ratio n_{fe}/n_e is taken as a parameter. In both cases,

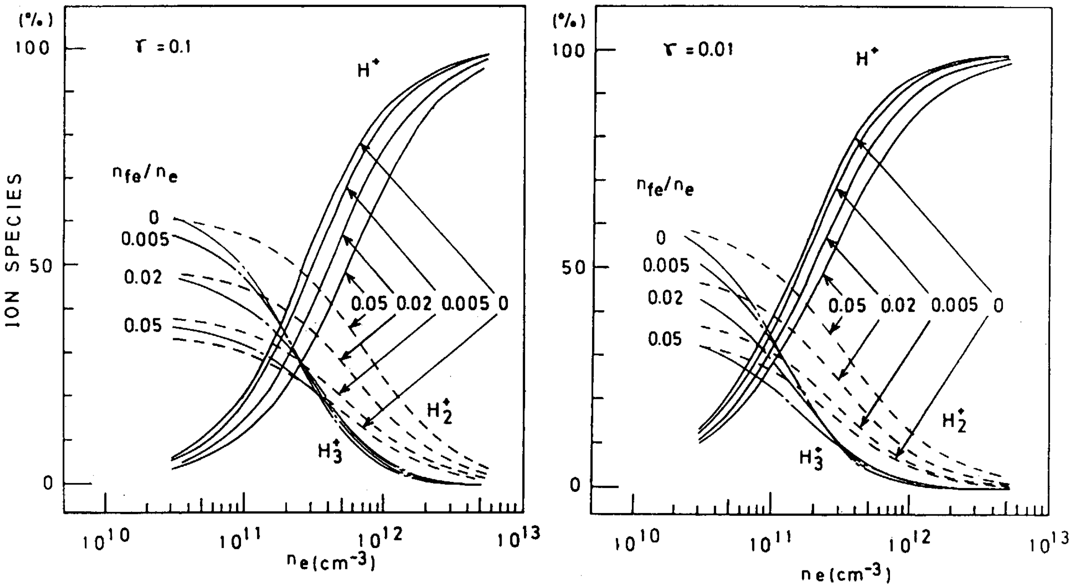

Fig. 4 Ion species ratios as a function of n_e, for T_e = 5 eV, p = 5 $\times 10^{-4}$ Torr and V/A = 2 cm. The value n_{fe}/n_e is a parameter.

the proton ratio depends strongly on n_e and increases sharply with n_e for constant T_e and p. With increasing primary electrons, however, H_1^+ and H_3^+ decrease, and H_2^+ increases.

In Ref. 3, to increase the H_1^+ fraction in a bucket source, the ionizing fast electrons which produce H_2^+ in the front region of the source are eliminated with a permanent magnetic filter. This experimental result is well explained qualitatively by the numerical results shown in Figs. 4 and 5.

As described above, the proton ratio also becomes high with decreasing γ. However, the effect of varying γ does not become remarkable until γ becomes smaller than 0.1. So, numerical results are shown when the values of γ are 0.1 and 0.01.

Figures 6 and 7 show the ion species ratios as a function of T_e for Case I and Case II, respectively. In both cases, the proton ratio decreases with increasing T_e for constant n_e and p. This tendency derives from a weakly ionized plasma considered here. According to T_e dependence of the rate coefficients for dissociation processes, i. e. α_2 and α_3, the proton ratio is expected to become high with increasing T_e. However, for a low-ionization degree plasma, increase in T_e is considered to cause a

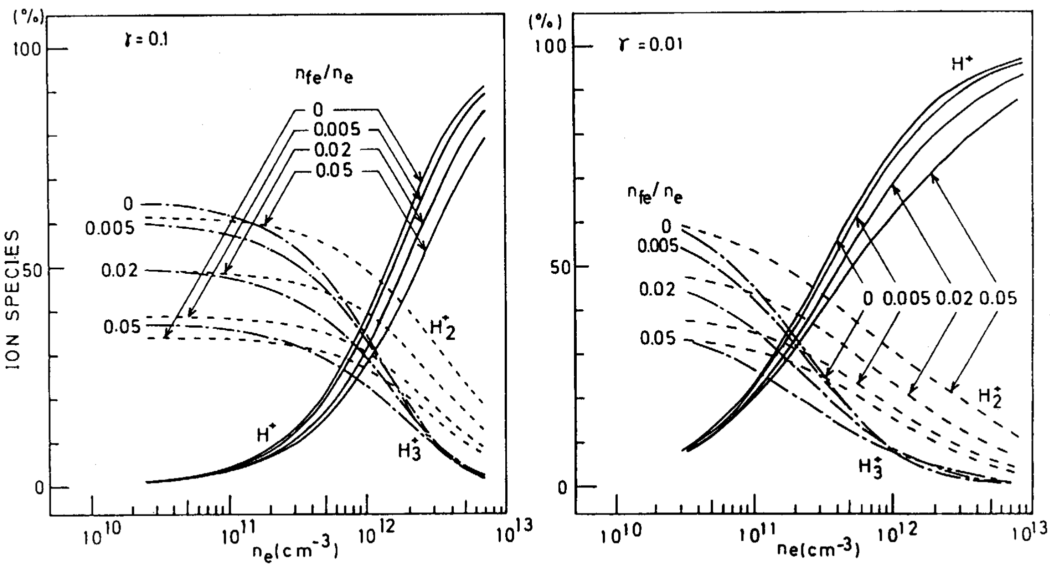

Fig. 5 Ion species ratios as a function of n_e, for T_e = 5 eV, p = 5 $\times 10^{-3}$ Torr and V/A = 2 cm.

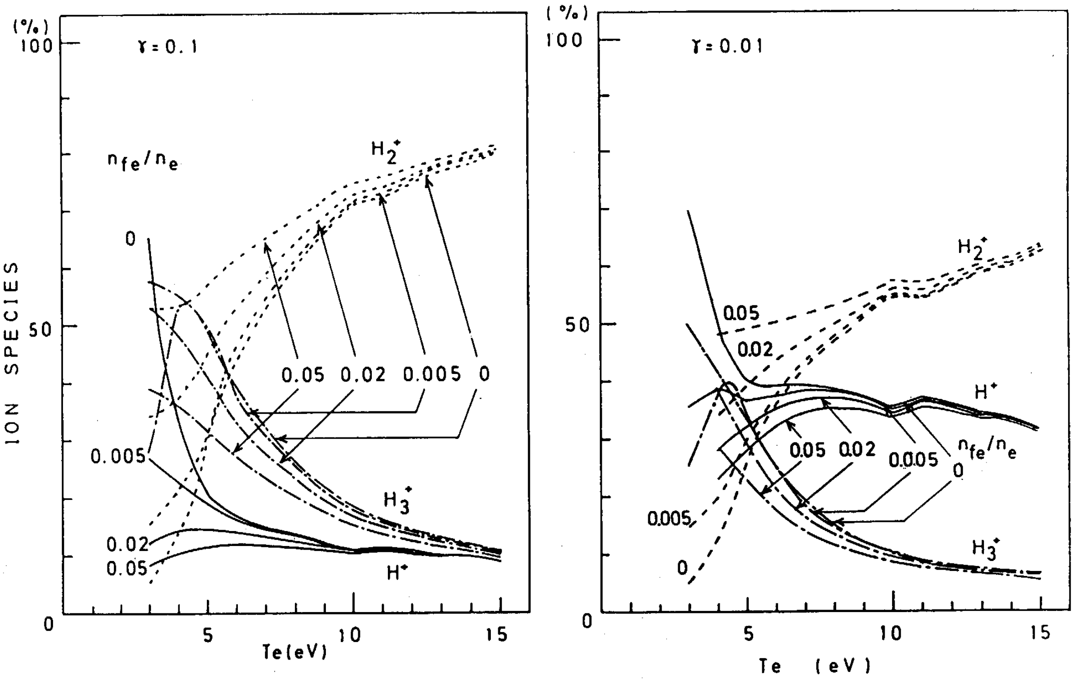

Fig. 6 Ion species ratios as a function of T_e, for n_e = 1 $\times$ $10^{11}cm^{-3}$, p = 5×10^{-4} Torr and V/A = 2cm.

depression of dissociation reaction for H_2 while enhancing H_2^+–formation reaction. This process leads to a decrease in the H_1^+–formation probability.

In low T_e, the presence of fast electrons enhances the H_2^+–formation reaction remarkably. With increasing T_e, however, the effects of fast electrons in H_2^+–formation would be masked by the effects of plasma electrons. Therefore, with increasing fast electrons, the proton ratio decreases sharply in the region of low T_e.

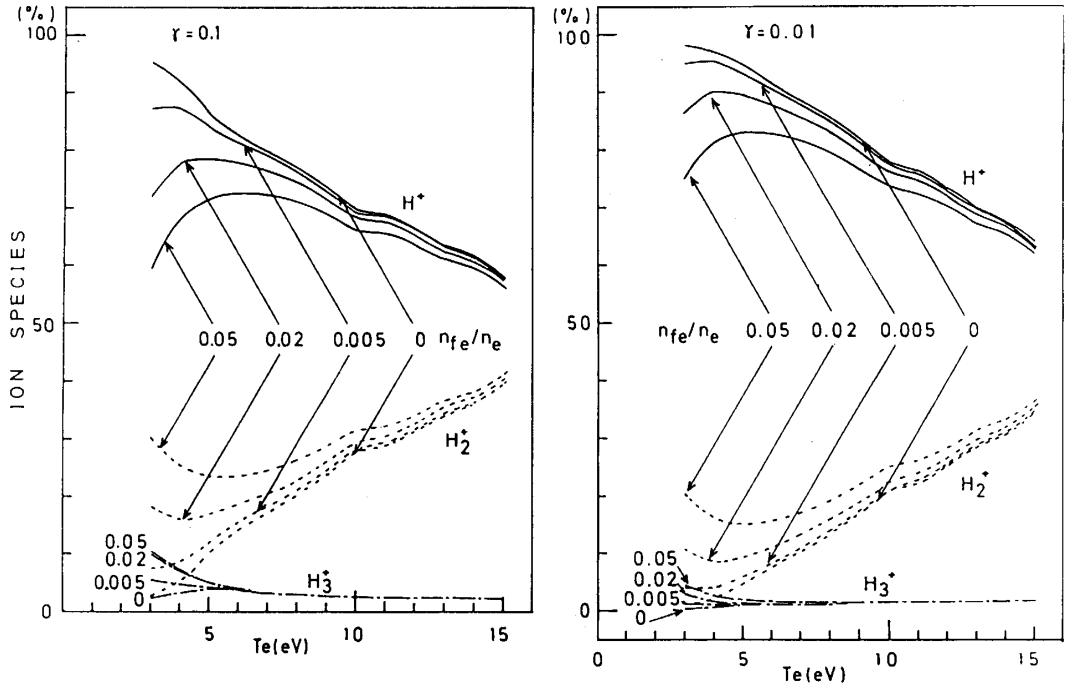

Fig. 7 Ion species ratios as a function of T_e, for $n_e = 5 \times 10^{12} cm^{-3}$, $p = 5 \times 10^{-3}$ Torr and V/A = 2cm.

Figures 8 and 9 show the ion species ratios as a function of the gas pressure for Case I and Case II, respectively. The proton ratio decreases with increasing p for constant T_e and n_e. Besides, with increasing fast electrons, H_2^+ increases and H_1^+ decreases, respectively.

3.2 The role of fast electrons for negative ion production

Concerning the volume production of H^- in a plasma, a working hypothesis has been proposed.[25] The negative ions are generated by dissociative electron attachment to vibrationally excited hydrogen molecules. Vibrational excitation rates are predicted to be large for electron energies in excess of 30 eV.[17]

In order to clarify the mechanism of volume production of H^- and to investigate the dependence of H^- production on plasma parameters, both H^- and positive ion species ratios in hydrogen plasmas are calculated numerically as a function of plasma parameters by using the partile balance model.[20] This model, where we distinguish between the vibrationally excited hydrogen molecules H_2^* and the ground state mole-

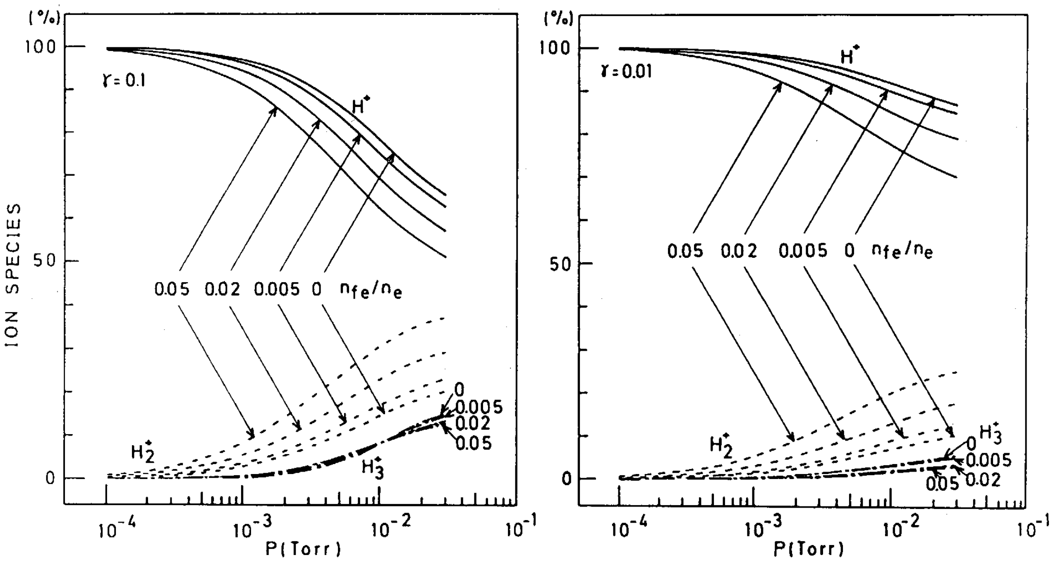

Fig. 8 Ion species ratios as a function of p, for $n_e = 1\times10^{11}cm^{-3}$, T_e = 5 eV and V/A = 2cm.

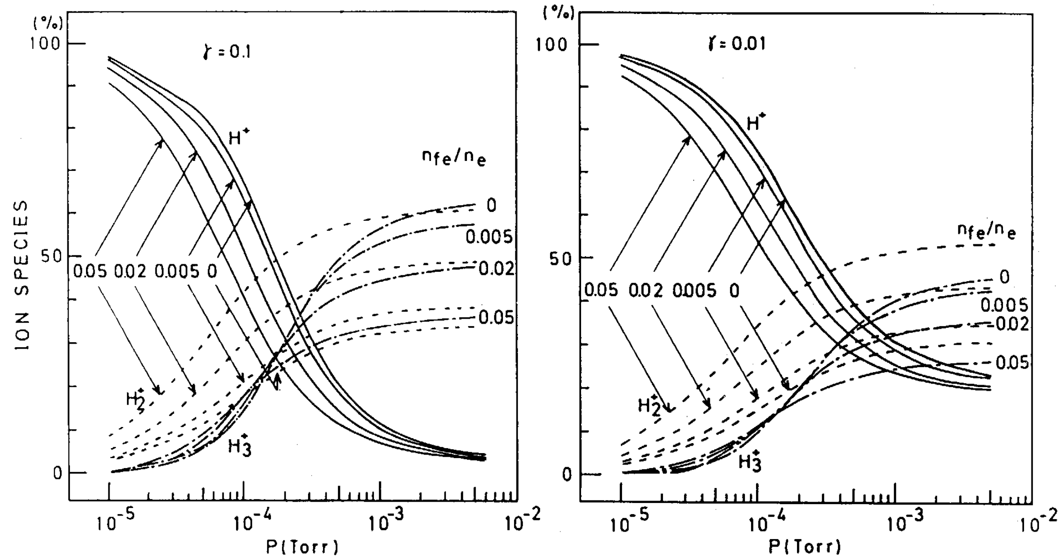

Fig. 9 Ion species ratios as a function of p, for $n_e = 5\times10^{12}cm^{-3}$, T_e = 5 eV and V/A = 2cm.

cules H_2, is the extension of the model in Chap. 2. We make the six equations for the balance in production and loss for H_1, H_2^*, H_1^+, H_2^+, H_3^+ and H^-, and two boundary conditions, i. e. charge neutrality and particle number conservation.

Figure 10 shows the effect of fast electrons on the production of H^- ions. Calculation procedure is to vary n_e as an independent variable on the assumption that T_e = 2eV, P = 5×10^{-3} Torr, V/A = 2cm, E_{fe} = 40 eV, the ratio of the containment time of H^-, τ_-, to the transit time of H_1, T_1, τ_-/T_1 = 10, γ is 1.0, and the wall parameter of H_2^* due to de–excitation collisions, γ_W, is 0.1. When n_{fe}/n_e is zero, H^- ratio becomes very small, i. e. about 5×10^{-2} %. With increasing n_{fe}/n_e, H^- ratio becomes high and has some optimum n_e. In this model, the production of H_2^* due to the neutralization of molecular ions is also included. However, it is apparent from Fig. 10 that, concerning the production of H_2^*, the process($H_2+e_f \rightarrow H_2^*+e_f$)is essential.

In order to elucidate the role of H_2^* in the H^- production, we use another numerical model from which H_2^* is omitted. The calculated H^- ratios, i. e. about 5×10^{-2} %, are smaller by about two orders of magnitude than those in the presence of H_2^*(see Fig. 10). Therefore, H^- ions are generated mostly by dissociative attachment to vibrationally excited molecules which are produced by fast electrons.

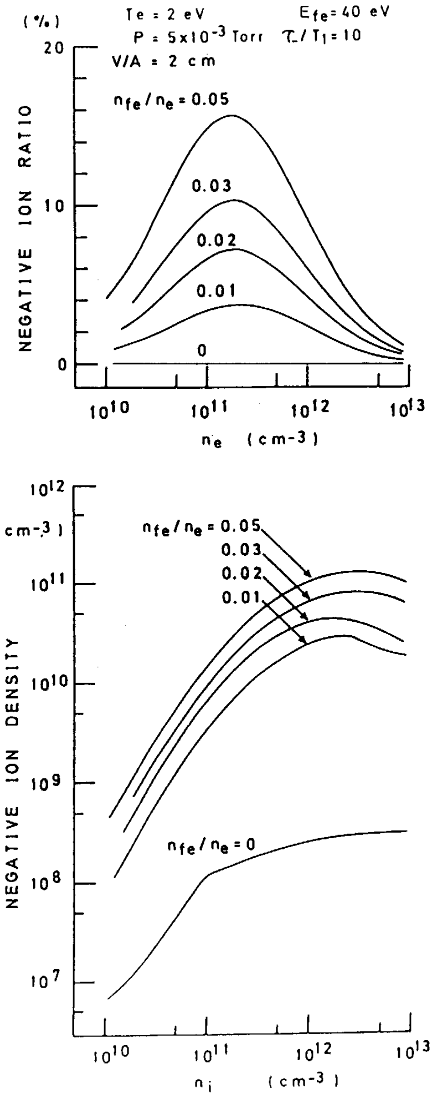

Fig. 10 Variation of negative ion ratio, $H^-/(H_1^++H_2^++H_3^+)$, vs n_e(upper), and variation of negative ion density vs total density of positive ions n_i(lower). The value n_{fe}/n_e is a parameter.

3.3 Effects of the wall

The H_1 density in the discharge is very important to the proton ratio. In the present model, the loss rate of H_1 eguals $\gamma N_1/T_1$. Therefore, when γ is smaller than unity, H_1 density becomes high due to increase in the effective containment time of H_1, i. e. T_1/γ. Corresponding to this, the proton rises because of the increased probability of the ionization process (5).[12]

The quantity γ is treated as numerical parameter and varied from unity to 0.01 in the present calculation. Experimentally, the values of γ can be reduced by selecting wall materials where the recombination coefficient is smaller than unity.[23,24] Besides, there can be some wall condition which causes the effective recombination coefficient to decrease.[6-8,12] However, until more complete information appropriate to the basic processes of particle-wall interaction becomes available, γ must be treated as an exploratory parameter.

Recently, there are some papers pointing out the wall effects on the performance characteristics of both the negative[20,25,26] and positive[8,11,12] ion sources. In particular, the optimum wall condition for producing high negative ions due to volume processes in hydrogen plasma is not compatible with the wall condition for producing the plasma with high proton ratio.[20,26] With decreasing γ, H_1 and H_1^+ becomes large. Then, H^- ratio decreases sharply because of the attenuation of vibrationally excited molecules and the enhanced ion-ion neutralization process, $H^- + H_1^+ \rightarrow 2H_1$. Therefore, γ must be chosen to be nearly equal to unity in the negative ion source.

4. Conclusion

By using the particle balance model, we have investigated systematically the role of fast primary electrons in hydrogen plasmas.

The most marked point is that ion species ratios depend strongly on the presence of fast electrons as well as plasma parameters(n_e, T_e, p and the recombination factor γ). The presence of fast electrons causes the proton ratio to decrease. Therefore, with decreasing fast electrons, the performance characteristics of the positive ion source is improved.

On the contrary, in the negative ion source, the presence of fast electrons is essential to the production of H^- ions. We have also confirmed numerically that an optimum condition of H^- prodution is not compatible with the condition of plasma production with high proton ratio.

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