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Energy Distribution Function of Fast Neutral Atoms and Neutron Production Rate in Inertial Electrostatic Confinement Device

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Abstract

Fast-neutral energy distribution function in inertial electrostatic confinement (IEC) plasmas is studied by solving the Boltzmann equation for fast neutral, which is produced by several kinds of charge-exchange reactions, for various presumed ion distribution functions. From the obtained fast-neutral distribution functions, the Doppler-shift spectrum (energy spectrum) of fast-neutral in IEC devices is evaluated. By comparing the spectra between the present calculation and previous experiment [1,2], the broadness of the ion distribution function in the energy space is estimated.

Keywords:

IEC, charge-exchange, fast-neutral, energy distribution function, Doppler shift spectrum

1. Introduction

The inertial electrostatic confinement (IEC) is a concept for electrostatically confining high-energy fuel ions in potential well [3-7]. In ideal IEC plasmas, the ions converge toward the center of the device. The IEC fusion system has intrinsic potential for earlier practical use of fusion as a compact and economical neutrons/protons source. So far, neutrons/protons more than 10^8 ns^{-1} produced by D(d,n)^{3}He (^{3}He(d,p)^{4}He) fusion reactions have been observed on several devices. To improve further the device performance, it is important to understand the physics of the IEC plasmas.

In the device several kinds of ion-neutral collisions occur, *e.g.* elastic-scattering, ionization, charge exchange in parallel with the fusion reaction. Especially, the charge exchange reaction (CX) changes accelerated ions to fast-neutrals which can cause fusion reaction with background gas. In previous researches, it has been shown that fusion reaction between the fast-neutral and background gas is comparable with those between ion and back ground gas [8,9].

We have examined correlation between the ion energy distribution function and neutron production rate in spherical IEC devices [10-12], and have shown that neutron production rate between ion and background gas is sensitively affected by the shape of ion energy distribution function itself. In order to identify the shape of the energy distribution function of fast neutral in typical IEC devices, the Doppler-shift wavelength of the hydrogen specific H_α line has also been measured [1,2]. The fast-neutral distribution function is strongly influenced by the shape of the ion distribution function. In this paper, we solve the Boltzmann equation for excited fast-neutral for various presumed ion distribution functions, and using the obtained fast-neutral distribution function we evaluate the Doppler-shift spectrum (energy spectrum) in the IEC devices. By comparing the spectra between the present calculation and previous experiment [1,2], we estimate the broadness of the ion distribution function in the energy space.

2. Analysis model

2.1 Collisional processes

We consider the following collisional processes.

$$\mathrm{H}^+(E) + \mathrm{H}_2 \rightarrow \mathrm{H}^*(E) + \mathrm{H}_2^+ \tag{1}$$

$$\mathrm{H}_2^+(E) + \mathrm{H}_2 \rightarrow \mathrm{H}^*(E/2) + \mathrm{H}(E/2) + \mathrm{H}_2^+ \tag{2}$$

$$\mathrm{H}_3^+(E) + \mathrm{H}_2 \rightarrow \mathrm{H}^*(E/3) + \mathrm{H}_2(2E/3) + \mathrm{H}_2^+, \tag{3}$$

$$\mathrm{H}^* + \mathrm{H}_2 \rightarrow \mathrm{H}^+ + \mathrm{H}_2 + \mathrm{e}, \tag{4}$$

$$\mathrm{H}^* + \mathrm{H}_2 \rightarrow \mathrm{H}^* + \mathrm{H}_2 \tag{5}$$

where H^* is fast excited neutrals and H_2 is background gas. The eqs. (1)-(3) represent the CX reactions in which the fast H^* neutrals are produced. Here E is kinetic energy of the particles. We assume that the fast neutral which is produced by CX reaction has the same velocity as the ion before the reaction. Reaction (4) is the ionization reaction, which has high cross-sections in $1 - 100$ keV energy range. The eq. (5) indicates the elastic-scattering.

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2.2 Ion distribution function

In order to investigate the fast-neutral energy distribution function for various shapes of ion energy distribution functions, we introduce the following model function.

$$f_a(E,L) = c_a \exp\left[-\left(\frac{E-\xi_a|q_a\phi_0|}{\alpha_a q_a \phi_0}\right)^2 - \left(\frac{L}{\beta_a L_0^a}\right)^2\right] \quad (6)$$

where q_a is charge of the particles of species a , total energy $E = 1/2mav^2 + q\phi$ and angular momentum $L = marv_\perp$ respectively. Here rcat is the cathode radius. The subscript a represents particle species (i.e. H^+, $H_2{}^+$), ϕ_0 the grid voltage and $L_0^a = r_{cat}\sqrt{m_a q_a \phi_0}$. By adjusting the α_a, β_a and ξ_a, we can simulate the broadness of the distributions in the energy, angular momentum direction, and the position of energy peak. The coefficient c_a is determined so that the density at the cathode n_a is equal to ${n_a}^{cat}$. Following Thorsons's treatment [9,13], we relate ${n_a}^{cat}$ to the measured cathode current $I_a\, meas$ by

$$ {n_a}^{cat} = \frac{1}{1-\gamma^2}\frac{1}{1+\delta}\frac{I_a^{meas}}{4\pi q_a r_{cat}^2\sqrt{2q_a\phi_0/m_a}}, \quad (7)$$

where γ represents the transparency factor of the inner grid [4], δ is the number of secondary electrons emitted from the grid due to ion impact [13]. Throughout the calculation $\gamma = 0.95$, $\delta = 1$ are assumed.

2.3 Boltzmann equation

The fast excited neutral energy distribution function f_{H^*} is determined by solving the Boltzmann equation.

$$\frac{\partial f_{H^*}}{\partial t} + \mu\frac{\partial f_{H^*}}{\partial r} = \left(\frac{\partial f_{H^*}}{\partial t}\right)_a^{CX} - \left(\frac{\partial f_{H^*}}{\partial t}\right)^{Ionization} + \left(\frac{\partial f_{H^*}}{\partial t}\right)^{Elastic}. \quad (8)$$

Most of ions can be considered moving along the direction $\mu = \pm 1$ (μ is direction cosine). So, we assume high convergence of the ions towards the center of sphere (i.e. $\beta_a = 0.05$), and only consider the particle of $\mu \approx \pm 1$, i.e. partial differential term about μ is ignored. The second term on the left side in eq. (8) is the streaming term for f_{H^*}.

The first term on the right side in eq. (8) represents the effect of H^* generation by CX between ${H_a}^+$ ion and H_2 gas (eqs. (1-3)).

$$\left(\frac{\partial f_{H^*}}{\partial t}\right)_a^{CX} = \sum_a \frac{2\pi}{v_{H^*}} f_{H_a^+}(v_{H^*}) \int_0^\infty v_{H_2} f_{H_2}(v_{H_2}) \int_{|v_{H^*}-v_{H_2}|}^{v_{H^*}+v_{H_2}} v_r^2 {\sigma_a}^{CX}(v_r)\mathrm{d}v_r \mathrm{d}v_{H_2}, \quad (9)$$

where v_r is the relative velocity between the fast excited neutral velocity v_{H^*} and background gas velocity v_{H_2} . The background gas distribution function f_{H_2} is assumed to be Maxwellian at 0.1 eV temperature. An ion which has velocity v_{H^*} changed to the fast excited neutral which has velocity v_{H^*} . The second term on the right side in eq. (8) represents the effect of the fast excited H^* neutral loss by ionization reaction with background gas (eq. (4)).

$$\left(\frac{\partial f_{H^*}}{\partial t}\right)_{Loss}^{Ionization} = -\frac{2\pi}{v_{H^*}} f_{H^*}(v_{H^*}) \int_0^\infty v_{H_2} f_{H_2}(v_{H_2}) \int_{|v_{H^*}-v_{H_2}|}^{v_{H^*}+v_{H_2}} v_r^2 \sigma^{Ionization}(v_r)\mathrm{d}v_r \mathrm{d}v_{H_2}. \quad (10)$$

The third term on the right side in eq. (8) is the Boltzmann collision integral (eq. (5)),

$$\left(\frac{\partial f_{H^*}}{\partial t}\right)^{Elastic} = \frac{2\pi}{v_{H^*}^2} \int_0^\infty v'_{H^*} f_{H^*}(v'_{H^*}) \int_0^\infty v_{H_2} f_{H_2}(v_{H_2}) P(v'_{H^*} \to v_{H^*}|v_{H_2}) \int_{|v_{H^*}-v_{H_2}|}^{v'_{H^*}-v_{H_2}} v'^2_r \sigma^{Elastic}(v'_r)\mathrm{d}v'_r \mathrm{d}_{v_{H_2}} \mathrm{d}v'_{H^*} - \frac{2\pi}{v_{H^*}} f_{H^*}(v_{H^*}) \int_0^\infty v_{H_2} f_{H_2}(v_{H_2}) \int_{|v_{H^*}-v_{H_2}|}^{v_{H^*}+v_{H_2}} v_r^2 \sigma^{Elastic}(v_r) \mathrm{d}v_r \mathrm{d}v_{H_2}, \quad (11)$$

where $P(v'_{H^*} \to v_{H^*}|v_{H_2})$ is the probability function that the H^* which has the speed v'_H is scattered into the speed region $v_H + \Delta v_H$ due to the elastic scattering with the H_2 which has speed v_{H_2}. If we assume that elastic-scattering is isotropic in the center of mass system,

$$P(v'_{H^*} \to v'_{H^*}|v_{H_2}) = \begin{cases} \frac{2v_{H^*}}{v'^2_{H^*}+v^2_{H_2}} \left(0 \le v_{H^*} \le \sqrt{v'^2_{H^*}+v^2_{H_2}}\right). \\ 0 \qquad (otherwise) \end{cases} \quad (12)$$

Cross-sections of CX (${\sigma_a}^{CX}$), ionization ($\sigma^{Ionization}$)and elastic-scattering($\sigma^{Elastic}$) are taken from the work of Tabata and Shirai [14]. We substitute the ion energy distribution function into eq. (9) and solve the Boltzmann equation to obtain the fast neutral energy distribution function. In the region within the spherical cathode, the potential structure is assumed to be zero, while outside of the spherical cathode, Child-Langmuir radial potential is assumed.

3. Results and discussion

The radial profile of the fast-neutral energy distribution function is presented in Fig. 1. In this calculation, grid voltage $\phi_0 = 10$ kV, total cathode current $I^{meas} = 30$ mA, cathode radius $r_{cat} = 0.05$ m, anode radius $r_{ano} = 0.25$ m, background gas pressure = 0.67 Pa, ${\alpha_a}^+ = 0.1$ and $\xi_a = 0.2$ are assumed. It is found that fast-neutrals are distributed all over the device almost uniformly. This is because the mean free path of

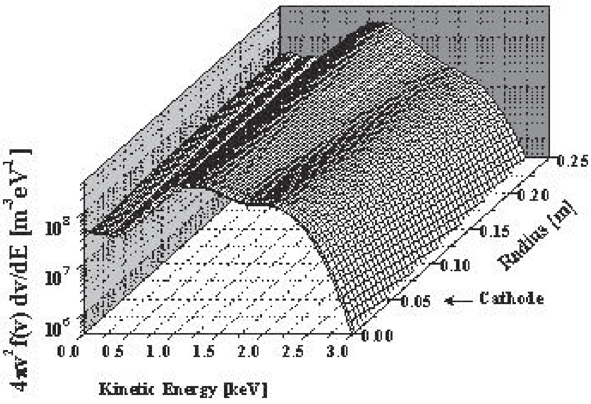

Fig. 1 Radial profile of fast-neutral distribution function.

the fast-neutrals is longer than that of ions. There are high energy peaks in the fast neutral energy distribution function, which is caused by CX of background gas with the high-energy and the high-concentration ions in the cathode region.

In previous experiment [1], single light channel ($\mu \approx \pm 1$) Doppler-shift spectrum was measured in IEC devices of grid voltage $\phi_0 = 10$ kV and background gas pressure = 0.67 Pa. The accelerated ion in the device consist of three kinds of hydrogen molecules, i.e. H^+(20 %), $H_2{}^+$(60 %), and $H_3{}^+$(20 %), and the maximum energy is considered as ∼ 2 keV. The Doppler-shift spectrum [1] is shown by white circles in Fig. 2. In the same condition with the experiment [1], we evaluate the Doppler shift spectrum (energy spectrum) from the obtained fast-neutral distribution function, and the result is shown by solid line in Fig. 2. In this case, we choose the same broadness of the distribution function in the energy space as previous calculations [11-13], i.e. $\alpha_H{}^+ = \alpha_{H_2}{}^+ = \alpha_{H_3}{}^+ = 0.1$, $\xi_a = 0.2$. In Fig. 2 it is difficult to distinguish the three peaks of the intensity. In Fig. 3 we next show the calculation when $\alpha_H{}^+ = 0.1$, $\alpha H_2^+ = 0.075$ and $\alpha H_3^+ = 0.05$ are assumed. In this calculation, the effect of the mass on the broadness of the ion distribution function in the energy space is included. It is found that three peaks produced by the CX reactions (eqs. (1)-(3)) appear in almost the same energy range compared with the experiments [1]. (We changed $\xi_{H2}{}^+ = 0.225$, $\xi_{H_3}{}^+ = 0.25$ respectively to adjust energy peaks.) The highest peak around 0.9 nm (0.8 keV) energy range appear owing to the CX reaction caused by H_3^+ (eq. (3)). Since the cross section of the ionization reaction eq. (4) increases with increasing energy of fast excited neutral H^*, the excited neutral easily disappear from the device via ionization reaction. This is the reason why the highest peak in Fig. 3 is sustained by the CX reaction caused by $H_3{}^+$, even though 60 % of ions are occupied by $H_2{}^+$.

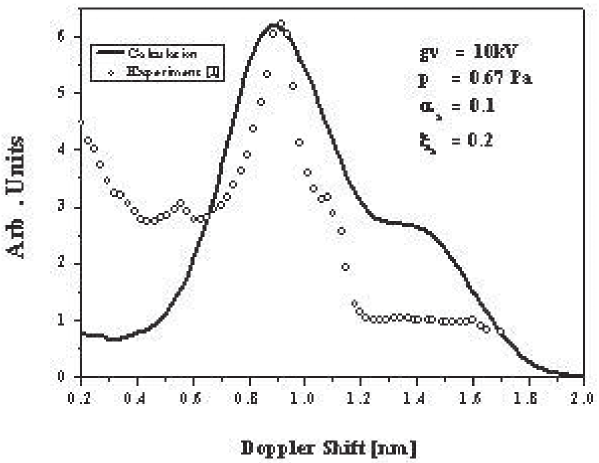

Fig. 2 Doppler-shift spectrum of fast excited neutral, $\alpha_H^+ = \alpha_{H_2}{}^+ = \alpha_{H_3}{}^+ = 0.1$ and $\xi_a = 0.2$.

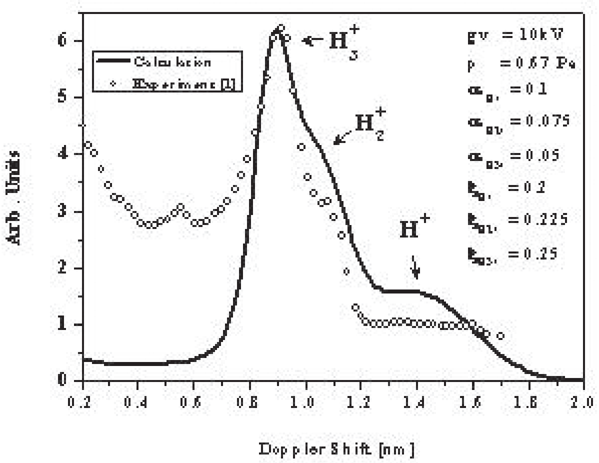

Fig. 3 Doppler-shift spectrum of fast excited neutral, $\alpha_H^+ = 0.1$, $\alpha_{H_2}{}^+ = 0.075$, $\alpha_{H_3}{}^+ = 0.05$ and $\xi_H^+ = 0.2$, $\xi_{H_2}{}^+ = 0.225$, $\xi_{H_3}{}^+ = 0.25$.

4. Concluding remarks

The energy distribution function of fast excited neutral has been derived by solving the Boltzmann equation. It has been shown that the experimentally-obtained Doppler-shift spectrum (energy spectrum) of fast-neutral can be reproduced by our model using the $\alpha_H{}^+ = 0.1$, $\alpha_{H_2}{}^+ = 0.075$ and $\alpha_{H_3}{}^+ = 0.05$ parameters. In this paper, we assumed that potential structure is zero within the spherical cathode. In actual devices, however, virtual anode may appear by the space charge of high-concentrated ions within the spherical cathode [13]. To incorporate this effect into the analysis, the Boltzmann equation must be solved simultaneously with the Poisson equation.

Acknowledgements

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References

[1] J. Khachan *et al*., Phys. Plasmas. **10**, 596 (2003).
[2] J. Khachan *et al*., Phys. Plasmas. **8**, 1299 (2001).
[3] G.L. Kulucinski, Fusion Technol. **34**, 477 (1998).
[4] R.L. Hirsh, Phys. Fluids **11**, 2468 (1968).
[5] G.H. Miley *et al*., Fusion Technol. **19**, 840 (1991).
[6] Y. Gu and G.H. Miley, IEEE Trans. Plasma Sci. **28**, 331 (2000).
[7] R.P. Ashley *et al*., Fusion Technol. **39**, 546 (2001).
[8] J.F. Santarius *et al*., presented at the 5th U.S.-Japan Workshop on IEC Fusion, October 2002, Madison WI.
[9] T.A. Thorson *et al*., Nucl. Fusion **38**, 495(1998).
[10] H. Matsuura *et al*., Nucl. Fusion **43**, 989 (2003).
[11] H. Matsuura *et al*., Nucl. Fusion **40**, 1951 (2000).
[12] H. Matsuura *et al*., Fusion Technol. **39**, 1167 (2001).
[13] T.A. Thorson *et al*., Phys. Plasmas **4**, 4 (1997).
[14] T. Tabata and T. Shirai, Atomic Data and Nuclear Data Tables, **76**, 1 (2000).