Effect of nuclear elastic scattering on slowing down of ICRF resonated ions and plasma heating characteristics

Atsushi Fujimaru, Hideaki Matsuura, Yasuyuki Nakao
Department of Applied Quantum Physics and Nuclear Engineering, Kyushu University,
744 Motooka, Fukuoka 819-0395, Japan

In scattering collisions between light nuclei, effect of nuclear force becomes appreciable when the colliding particle energy is higher than ~ several 100keV. A deuterium-tritium (DT) plasma accompanied with ion-cyclotron range of frequencies (ICRF) heating at the second harmonic of deuteron is considered, and the nuclear elastic scattering (NES) effect on the energy deposition of resonated deuteron is examined on the basis of the two-dimensional Boltzmann-Fokker-Planck (BFP) equation for a resonated deuteron. It is shown that the fraction of resonated deuteron energy deposited to ions increases by about 10 % owing to the NES effect.

Keyword: nuclear elastic scattering, the fraction of resonated deuteron energy deposited to ions, DT plasma, ICRF heating

1. Inroduction

In scattering collisions between light ions, main interaction is Coulomb scattering. When the colliding particle energy is higher than ~ several 100keV, however, the effect of nuclear force on scattering process of light ion becomes appreciable. The cross section obtained by subtracting purely Coulomic component from the measured scattering cross section is defined as nuclear elastic scattering (NES) cross section [1,2]. It is necessary to evaluate the NES effect on slowing down process of high energy ions for comprehension of a characteristic of nuclear burn plasma.

In recent ICRF heating experiments on Large Helical Device (LHD), highly-energetic trapped ions (≥~1MeV) were observed [3]. In the presence of neutral beam injection (NBI) heating, it was found that the fraction of beam-ion energy deposited to ions increases owing to the effect of NES [4,5]. The NES effect can appear also in plasma under ICRF heating because the highly-energetic resonated ion loses its energy via collisional process. It is important to grasp the NES effect on ICRF plasma heating.

In this paper, we consider a deuterium-tritium (DT) plasma accompanied with ICRF heating at the second harmonic of deuteron, and examine the NES effect on the energy deposition of resonated deuteron. The two-dimensional Boltzmann-Fokker-Planck (BFP) equation is solved to obtain the velocity distribution function of resonated deuteron. Using the obtained distribution function, the fraction of resonated deuteron energy deposited to bulk ions is evaluated.

2. Analysis Model

In this paper to facilitate the analysis triton- and electron-distribution functions are assumed to be Maxwellian at the same temperature. We solve the following BFP equation [4-8] for deuteron:

$$\sum_j \left(\frac{\partial f_D}{\partial t}\right)_j^{Col} + \sum_i \left(\frac{\partial f_D}{\partial t}\right)_i^{NES} + \left(\frac{\partial f_D}{\partial t}\right)^{RF} - \frac{1}{v^2}\frac{\partial}{\partial v}\left\{\frac{v^3}{2\tau_C^*(v)} f_D\right\} - \frac{f_D}{\tau_P^*(v)} - \left(\frac{\partial f_D}{\partial t}\right)_R^{loss} + S(v) = 0, \quad (1)$$

where $f_D(v, \mu)$ is the velocity distribution function of deuteron (μ is the direction cosine between the velocity of deuteron and the external magnetic field). The $\tau_C^*(v)$ and $\tau_P^*(v)$ stand for the typical energy-loss time due to thermal conduction and particle-loss time due to particle transport respectively [5]. It is assumed that they are followed Bittoni's treatment [9].

The first term in Eq. (1) represents the effect of the Coulomb collisions with bulk charged particles, i.e., j = D, T, α-particle and electron [10,11].

The second term accounts for the NES with bulk deuteron and triton, i.e., i= D, T [4-8]. In this paper, the NES cross sections are taken from Cullen and Perkins [2].

The third term in Eq. (1) represents the effect of RF diffusion. The quasi-linear diffusion in velocity space owing to ICRF injection [12] can be written as

author's e-mail:fujisin @nucl.kyushu-u.ac.jp

$$\left(\frac{\partial f_D}{\partial t}\right)^{RF} = \frac{1}{v_\perp}\frac{\partial}{\partial v_\perp}\left(v_\perp D \frac{\partial f_D}{\partial v_\perp}\right). \tag{2}$$

Here $v_\perp$ represents vertical velocity component to the external magnetic field and, D represents diffusion coefficient due to ICRF second harmonics [12-15], and can be written as

$$D = \frac{C_D}{v_{th}^2}\left| J_1\left(\frac{k_\perp v_\perp}{\omega_{cD}}\right) + \frac{E_-}{E_+} J_3\left(\frac{k_\perp v_\perp}{\omega_{cD}}\right)\right|^2. \tag{3}$$

Here E_-/E_+ can be shown as following form [11].

$$\frac{E_-}{E_+} \approx -\frac{L}{R}. \tag{4}$$

From the equation of dispersion relation of cold plasmas, the parameter of Bessel function can be written as

$$\frac{k_\perp v_\perp}{\omega_{cD}} = \frac{\sqrt{2}}{c}\left[\frac{RL}{R+L}\right]^{1/2} v\sqrt{1-\mu^2}, \tag{5}$$

where c represents the speed of light, and ω_{cD} denotes the cyclotron frequency of deuteron. The coefficient C_D is determined from the ICRF absorbed power, P_{ICRF}, which is described as

$$P_{ICRF} = -2\pi m_D \iint D v_{th}^2 v\left[v^2\left(1-\mu^2\right)\frac{\partial f_D}{\partial v} - v\mu\frac{\partial f_D}{\partial \mu}\right] dv d\mu. \tag{6}$$

The forth and fifth term in Eq. (1) represent the diffusion in velocity space due to thermal conduction and particle transport respectively.

The sixth term in Eq. (1) denotes the effect of particle loss due to $T(d,n)^4He$ reaction.

$$\left(\frac{\partial f_D}{\partial t}\right)_R^{loss} = \frac{n_T f_D}{\sqrt{2\pi}}\left(\frac{2m_T}{m_D}\right)^{3/2} \times \frac{1}{v}\int_0^\infty dv_T v_T \exp\left(-\frac{m_T}{m_D}v_T^2\right) \times \int_{|v-v_T|}^{v+v_T} dv_r v_r^2 \sigma_{DT}(v_r). \tag{7}$$

Here v_T and v_r represent the velocity of triton and the relative velocity between deuteron and triton respectively. In addition, $\sigma_{DT}(v_r)$ denotes the cross section of $T(d,n)^4He$ reaction, and is provided by Duane [16].

The seventh term in Eq. (1) represents particle source. The particle losses due to fusion reaction and particle transport are compensated by some appropriate fueling method. The source term $S(v)$ can be written as following form.

$$S(v) = \frac{S_0}{4\pi v^2}\delta(v - v_{fuel}), \tag{8}$$

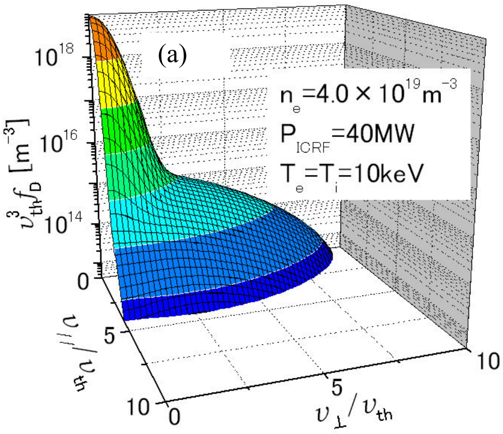
where, S_0 can be written as

$$S_0 = n_D n_T < \sigma v >_{DT} + \frac{n_D}{\tau_P}, \tag{9}$$

and v_{fuel} is the speed of the fueled particle, which is much smaller than the thermal velocity (nearly zero).

3. Results and Discussion

In Fig. 1(a) the velocity distribution function of deuteron, and (b) the Maxwellian at the same temperature



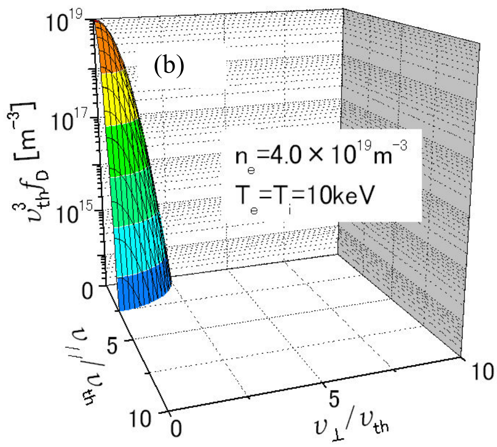


Fig. 1(a) The velocity distribution function of deuteron, and (b) Maxwellian.

are shown. In this calculation the bulk temperature T_i=T_e=10keV, ion and electron densities n_e = $2n_D$=$2n_T$=4×10^{19}m^{-3}, energy and particle confinement time τ_E=(1/2) τ_P =3sec , and ICRF power absorbed by deuteron 40MW are assumed. Here v_{th} represents the thermal velocity of deuteron, and $v_\perp$ ($v_{//}$) denotes the vertical (parallel) velocity component to the external magnetic field. As a result of the ICRF heating, a non-Maxwellian tail is formed in high energy region, because of the vertical velocity component increased due to the ion-cyclotron resonance. From the obtained deuteron distribution function, the transferred energy from high-energy resonated deuteron to bulk ions via NES is estimated as

$$P_{D\to i}^{NES} = -\sum_{i=D,T} \int \frac{1}{2} m_D v^2 \left(\frac{\partial f_D}{\partial t} \right)_i^{NES} d\mathbf{v} \times V_p . \qquad (10)$$

Where V_p represents plasma volume, and throughout the calculations V_p =800m^3 is assumed.

The integrand in Eq. (10) is shown in Fig. 2. In this case the bulk temperature T_i=T_e=10keV, ion and electron

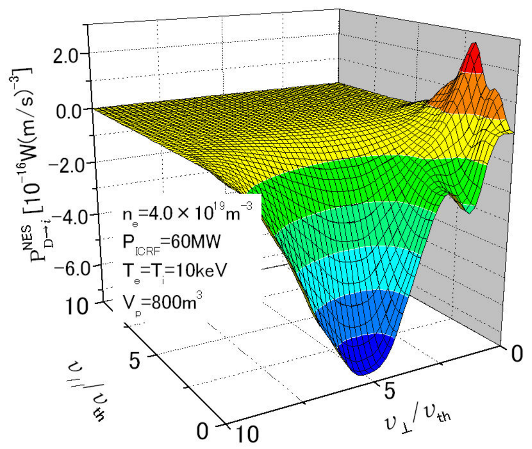


Fig. 2 The deposited energy to bulk ions via NES.

densities n_e = $2n_D$=$2n_T$=4×10^{19}m^{-3}, energy and particle confinement time τ_E=(1/2)τ_P =3sec , and ICRF power absorbed by deuteron 40MW are assumed. It is found that deuterons which have the large vertical velocity component lose their energy due to NES. In consequence, the deposited energy from high energy resonated deuteron to bulk ions increases relatively compared with the case that only Coulomb scattering is considered.

In Table. 1 the transferred powers from deuteron (a) to bulk ions and electrons via Coulomb scattering, and (b) to bulk ions via NES, the loss powers from plasma due to (c) T(d,n)^{4}He reaction, and (d) Transport and Conduction, (e) the ICRF absorbed power, (f) the transferred power from alpha particle to deuteron via Coulomb scattering are shown. In this case the bulk temperature T_i=T_e=10keV, ion and electron densities n_e=$2n_D$=$2n_T$=4×10^{19}m^{-3}, energy and particle confinement time τ_E=(1/2)τ_P =3sec , and ICRF power absorbed by deuteron 40MW are assumed. About 70% of resonated deuteron energy is deposited to plasma, and about 30% is lost from plasma. Besides, it is found that the transferred power to bulk ions via NES is smaller than that via Coulomb scattering relatively. By using the plasma heating powers due to Coulomb scattering and NES, the fraction of plasma heating power deposited to ions is calculated. The plasma heating power due to Coulomb scattering and NES are written respectively as $P^C_{D\to j}$ (i.e., j= D, T, e) and $P^{NES}_{D\to i}$(i.e., i= D, T), the fractional power deposition to ions can be written as

$$F_{ion}^{Coulomb+NES} = \frac{\sum\limits_{i=D,T} P_{D\to i}^{NES} + \sum\limits_{i=D,T} P_{D\to i}^{C}}{\sum\limits_{i=D,T} P_{D\to i}^{NES} + \sum\limits_{j=D,T,e} P_{D\to j}^{C}} . \qquad (11)$$

If NES is not included, the fraction is written as

$$F_{ion}^{Coulomb} = \frac{\sum\limits_{i=D,T} P_{D\to i}^{C}}{\sum\limits_{j=D,T,e} P_{D\to j}^{C}} . \qquad (12)$$

To express numerically the NES effect on the fractional power deposition to ions, we introduce the following enhancement parameters:

$$\xi = \left(\frac{F_{ion}^{Coulomb+NES}}{F_{ion}^{Coulomb}} - 1 \right) \times 100[\%]. \qquad (13)$$

By using this parameter, the NES effect on the fractional power deposition to ions is evaluated. In the case shown in Table. 1, for example, the fractional power deposition to ions is calculated from Eq. (11) and (12) as $F_{ion}^{Coulomb+NES} = 0.30$, and $F_{ion}^{Coulomb} = 0.29$, so, the enhancement parameter ξ is estimated as $\xi = 3.4[\%]$.

In Fig. 3 the ξ value is plotted as a function of plasma temperature. In this case the ion and electron densities n_e=$2n_D$=$2n_T$=4×10^{19}m^{-3}, energy and particle confinement time τ_E=(1/2)τ_P =3sec, and ICRF power absorbed by deuteron 40MW (solid line), and 60MW (dotted line) are assumed. For T=15keV temperature, the ξ value reaches 12% and 5% for ICRF power absorbed by deuteron 60, 40 MW, respectively. It is found that the enhancement parameter ξ increases with increasing P_{ICRF}. This is because the high-energy component in deuteron distribution function becomes relatively large

Table. 1 The transferred, heat and loss power.

(τ_E=3.0sec, T_e=T_i=10keV, n_e=$2n_{D(T)}$=4.0×10^{19}m^{-3}, B=5.0T, V_p=800m^3)

(a)			(b)		(c)	(d)
D→D	**D→T**	**D→e**	**D→D**	**D→T**	**0.36**	**12.3**
5.7	**2.9**	**21.0**	**0.43**	**0.08**		

(e)	(f)
40.0	**2.3**

(e)+(f)	(a)+(b)+(c)+(d)	error
42.3	**42.9**	**1.4%**

[MW]

and the transferred energy from resonated deuteron to bulk ions via NES increases for high $P_{\rm ICRF}$. It should be noted that the ξ value decreases at the low- and high-temperature range. The reason would be that in low-temperature plasmas the slowing down of energetic ions due to Coulomb scattering (mainly) by electrons is intensified; thus the high-energy component in deuterium velocity distribution function becomes relatively small, which causes a reduction in the transferred power from resonated deuteron to ions via NES. On the other hand at the high-temperature range, relative velocity between energetic resonated deuteron and bulk ions becomes small, and the contribution of NES is reduced compared with that of Coulomb scattering.

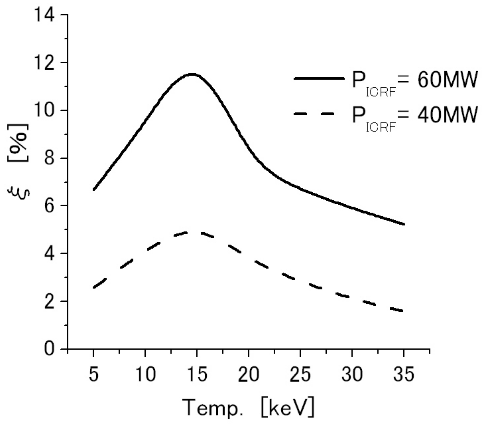


Fig. 3 The ξ value as a function of plasma temperature

4. Conclusion

It is revealed that the fraction of ICRF heating power deposited to bulk ions increases owing to the NES effect. In the case of the bulk temperature T_i=T_e=15keV, ion and electron densities $n_{\rm e}$=2$n_{\rm D}$=2$n_{\rm T}$=4×10^{19}m^{-3}, energy and particle confinement time $\tau_{\rm E}$=(1/2)$\tau_{\rm P}$ =3sec**,** and ICRF power absorbed by deuteron 60MW (40MW), the enhancement parameter ξ reaches almost 12% (5%).

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