Effect of Nuclear Elastic Scattering on Energy Transfer Process of ICRF Resonated Ions in DT Plasmas

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The nuclear elastic scattering (NES) effect on energy transfer process of resonated-deuteron is examined by solving two-dimensional Boltzmann-Fokker-Planck (BFP) equation for deuteron in ion-cyclotron-resonance-frequency (ICRF) heated deuterium-tritium (DT) plasmas. It is found that the fraction of resonated-deuteron energy transferred to bulk ions increases by about 10 % owing to the NES effect.

Keywords: nuclear elastic scattering, the fraction of resonated-deuteron energy transferred to bulk ions, ICRF heating, DT plasma, Boltzmann-Fokker-Planck equation.

1. Introduction

In thermonuclear plasmas Coulomb interactions are the dominant energy-transfer mechanism between light ions. For suprathermal ions, it is also well known that the contribution of nuclear force on the slowing down process becomes appreciable. The cross section obtained by subtracting purely Coulombic component from the measured scattering cross section is defined as nuclear elastic scattering (NES) cross section [1,2]. It is necessary to investigate the NES effect on slowing down process of high energy ions for understanding of plasma heating characteristics.

Previously we have studied the NES effect on the fractional beam-energy deposition to bulk ions [3,4] and T(d,n)^{4}He reaction rate coefficient [5] in NBI heated plasmas. In recent ion-cyclotron resonance frequency (ICRF) heating experiments on Large Helical Device (LHD), energetic (>2MeV) trapped ions were observed [6]. Because the ICRF-resonated-ion also loses its energy via collisional process, the NES effect can appear in the plasma accompanied with ICRF heating. The knock-on tail formation in deuteron distribution function due to NES by ICRF-resonated-energetic helium-3 (^{3}He) was investigated by Zaitsev, et al [7] without considering the NES effect on the ICRF tail-formation process in resonated-ion (^{3}He) distribution function.

In this paper, we consider a ITER-like deuterium-tritium (DT) plasma accompanied with ICRF heating at the second harmonic of deuteron. The two-dimensional Boltzmann- Fokker-Planck (BFP) equation is developed, and solved to evaluate the non-Maxwellian tail in resonated-ion distribution function considering the competition between acceleration due to the ICRF resonance and slowing-down due to both Coulomb and nuclear elastic scattering processes. By using the obtained distribution function, the energy transferred from resonated-deuteron to bulk particles is evaluated. It is shown that fraction of the energy transferred from resonated-deuteron to bulk ions increases by about 10 % owing to the NES effect.

2. Analysis Model

In this paper to simplify the analysis the velocity distribution functions of triton and electron are assumed to be Maxwellian. We solve the following BFP equation [3-5,8,9] 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 $\tau_P^*(v)$ account for the typical energy-loss time due to thermal conduction and particle-loss time due to particle transport respectively [4]. It is assumed that they are followed Bittoni's treatment [10].

The first term in Eq.(1) represents the effect of the Coulomb scattering by bulk charged particles, i.e., j = D, T, α-particle and electron [11,12].

The second term in Eq.(1) represents the NES with

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bulk ions, i.e., i = D, T. We quote the NES cross sections from the paper of Cullen and Parkins [2].

The third term in Eq.(1) accounts for the effect of RF diffusion. The quasi-linear diffusion in velocity space owing to ICRF injection [13] can be written as

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

Here $v_\perp$ represents vertical velocity component to the external magnetic field and, D represents diffusion coefficient due to ICRF second harmonics [13-16], and can be written as

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

J_1 and J_3 represent first and third order Bessel function of the first kind respectively. And $k_\perp$ accounts for the wave number in vertical direction to external magnetic field. v_{th} represents the velocity of deuteron at 20keV, and E_-/E_+ can be shown as following form [12].

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

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 accounts for 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)^{4}He reaction, and can be written as

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

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)^{4}He reaction, and is provided by Duane [17].

The seventh term in Eq.(1) represents particle source. In this paper the particle losses 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 is determined to balance a total of particle losses, 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 obtained by solving the BFP equation, and (b) the Maxwellian at the same temperature are shown.

In this calculation the electron temperature T_e=10keV, ion and electron densities $n_e=n_D+n_T+2n_\alpha=4.2\times10^{19}$m^{-3}, energy and particle confinement time $\tau_E=(1/2)\tau_P$ =3sec , and ICRF power absorbed by deuteron 60MW are assumed[18]. As a result of ICRF injection, non-Maxwellian tail is formed in high energy region

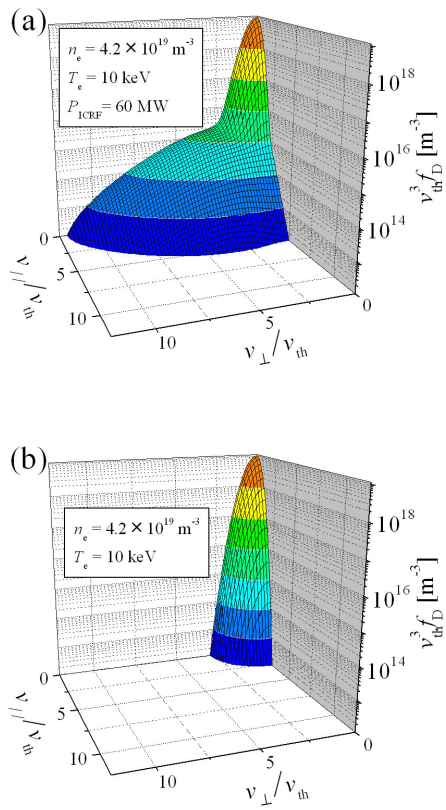

Fig.1 (a) The velocity distribution function of deuteron obtained by solving the BFP equation, and (b) the Maxwellian at the same temperature.

because of the vertical velocity component of deuteron increased due to ion-cyclotron resonance. From the obtained velocity distribution function of deuteron, the transferred energy from resonated-deuteron to bulk ions via NES is evaluated as

$$E_{D\to i}^{NES} = -\sum_{i=D,T} \frac{1}{2} m_D v^2 \left(\frac{\partial f_D}{\partial t} \right)_i^{NES} \tag{9}$$

$$P_{D\to i}^{NES} = \int E_{D\to i}^{NES} d^3 v \times V_p \tag{10}$$

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

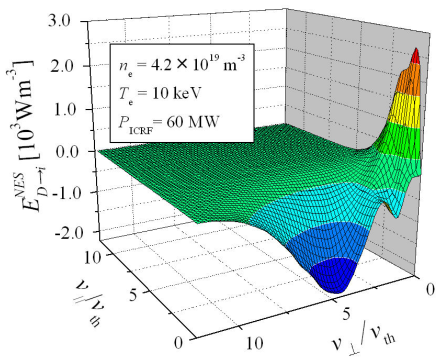

Fig.2 The transferred power via NES

The integrand in Eq.(10) is shown in Fig.2. In this case the electron temperature T_e=10keV, and electron densities n_e=n_D+n_T+2n_α=4.2×10^{19}m^{-3}, energy and particle confinement time τ_E=(1/2)τ_P =3sec , and ICRF power absorbed by deuteron 60MW are assumed.

In Fig.2, the resonant deuterons lost their energy due to NES flow into the thermal energy region, and a small peak is formed in low energy region. Although NES is assumed isotropic in the centre of mass system, the small peak formation is not isotropic (a small hollow is formed in vertical direction to magnetic field only). This is because that there is the energy transfer from the hollow to thermal-energy region via NES due to the presence of a large number of deuterons in vertical direction. As a result, the transferred energy from 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 to bulk particles via Coulomb scattering, and NES, and the loss powers due to T(d,n)^{4}He reaction, Transport and Conduction are shown. Here ‘Coulomb’ and ‘NES’ represent the transferred power from resonated-deuteron to bulk particles via Coulomb scattering and NES respectively. ‘Loss powers’ accounts for the total of loss powers due to T(d,n)^{4}He reaction, and Transport and Conduction. ‘ICRF’ represents the ICRF power absorbed by deuteron, and ‘alpha’ represents the transferred power from alpha particle to deuteron via Coulomb scattering. ‘HEAT’ accounts for the total of ‘ICRF’ and ‘alpha’, and ‘LOSS’ represents the total of ‘Coulomb’, ‘NES’ and ‘Loss powers’. In this case the electron temperature T_e=20keV, and electron densities n_e=n_D+n_T+2n_α=4.2×10^{19}m^{-3}, energy and particle confinement time τ_E=(1/2)τ_P =3sec , and ICRF power absorbed by deuteron 60MW are assumed. About 75% of resonated-deuteron energy is deposited to plasma, and about 25% is lost from plasma. In addition, it is found that the transferred power to bulk ions via NES is smaller than that via Coulomb scattering relatively. By using the transferred power from deuteron to bulk charged particles via Coulomb scattering and NES, the fraction of deposited deuteron energy to ions is estimated. The transferred power via Coulomb scattering and NES are written respectively as $P_{D\to j}^{C}$ (i.e., j= D, T, e) and $P_{D\to i}^{NES}$(i.e., i= D, T), the fractional power given to ions can be written as

$$F_{ion}^{Coulomb+NES} = \frac{\sum_{i=D,T} P_{D\to i}^{NES} + \sum_{i=D,T} P_{D\to i}^{C}}{\sum_{i=D,T} P_{D\to i}^{NES} + \sum_{j=D,T,e} P_{D\to j}^{C}}. \tag{11}$$

On the other hands, if NES is not included, the fraction is written as

$$F_{ion}^{Coulomb} = \frac{\sum_{i=D,T} P_{D\to i}^{C}}{\sum_{j=D,T,e} P_{D\to j}^{C}}. \tag{12}$$

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

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

By using this parameter, the NES effect on fraction of the energy transferred from resonated-deuteron to bulk ions is evaluated.

In the case shown in Table.1, for example, the fraction of the energy transferred from resonated-deuteron to bulk ions is calculated from Eq.(11) and Eq.(12) as $F_{ion}^{Coulomb+NES} = 0.4856$, and $F_{ion}^{Coulomb} = 0.4450$, so, the enhancement parameter ξ is estimated as $\xi = 9.2\%$.

In Fig. 3 the ξ value is plotted as a function of electron temperature. In this case the electron densities

Table.1 The transferred and loss power.

(τ_E=3.0sec, T_e=20keV, n_e=2$n_{D(T)}$+2n_α=4.2×10^{19}m^{-3}, B=5.0T, plasma volume 800m^3)

Coulomb			NES		*Loss powers
D→D	D→T	D→e	D→D	D→T	
12.1	10.5	27.7	3.2	0.8	16.5

[MW]

ICRF	alpha	HEAT	LOSS	error
60.0	9.5	69.5	70.8	1.8%

(*) The total of loss powers due to T(d,n)^{4}He reaction, Transport and Conduction.

$n_e=n_D+n_T+2n_\alpha=4.2\times10^{19}\text{m}^{-3}$, energy and particle confinement time $\tau_E=(1/2)\tau_P=3\text{sec}$, and ICRF power absorbed by deuteron 40MW (black line), and 60MW (red line) are assumed. At T_e=25keV temperature, the ξ

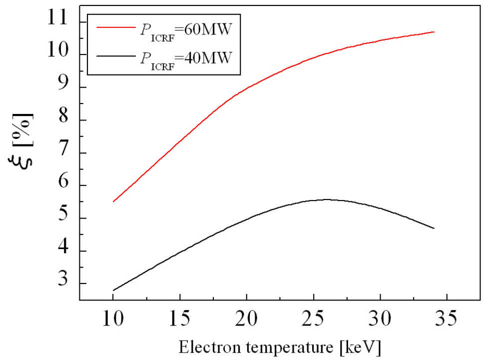

Fig.3 The ξ value as a function of electron temperature.

value reaches 10% and 5.5% for ICRF power absorbed by deuteron 60, 40 MW, respectively. Thus, it is found that the enhancement parameter ξ increases with increasing ICRF power. This is because the energetic component in deuteron distribution function i.e., non-Maxwellian tail becomes relatively large and the transferred energy from resonated-deuteron to bulk ions via NES increases for high ICRF power. Besides, it should be noted that the ξ value decreases at the low-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 non-Maxwellian tail in deuteron velocity distribution function becomes relatively small, which causes a reduction in the transferred energy from resonated-deuteron to ions via NES. On the other hand at the high-temperature range, the degree of the increase in the ξ parameter becomes smaller. Because relative velocity between energetic resonated-deuteron and bulk ions becomes small, thus the contribution of NES is reduced compared with that of Coulomb scattering.

4. Concluding Remarks

It is revealed that the fraction of the energy transferred from resonated-deuteron to bulk ions increases owing to the NES effect. In the case of that the electron temperature T_e=25keV, and electron densities $n_e=n_D+n_T+2n_\alpha=4.2\times10^{19}\text{m}^{-3}$, energy and particle confinement times $\tau_E=(1/2)\tau_P=3\text{sec}$, and ICRF power absorbed by deuteron 60MW (40MW), the enhancement parameter ξ reaches almost 10% (5.5%).

In our previous calculation for NBI heating, it was revealed that the NES effect is not changed so much when $n_e > 4\times10^{19}\text{m}^{-3}$ [2]. In the ICRF heating, however, the wave number in vertical direction to external magnetic field is proportional to the square root of the electron density, and as electron density increases, the energy range where the non-Maxwellian tail is formed tends to be small. In high density region, i.e. $n_e > 4\times10^{19}\text{m}^{-3}$, the NES effect on the fractional energy deposition to ions may decrease to some extent. At this pont, the relative error for the calculation is several percent (as shown in Table 1). The further improvement of the calculation accuracy should be necessary as well as the benchmark calculation using other reliable code opened to the public. Throughout the calculations an uniform plasma has been considered. In actual devices, however, the spatial distribution of the magnetic field should be considered. To examine the NES effect more accurately, the bounce-averaged calculation, would be required.

5. References

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