Modification of α-particle emission spectrum and its effect on plasma heating characteristics in non-Maxwellian deuterium-tritium plasmas

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The α-particle emission spectrum in a tail-created (non-Maxwellian) deuterium-tritium (DT) burning plasma is examined by solving the Boltzmann-Fokker-Planck (BFP) equations for deuteron, triton and α-particle simultaneously. It is shown that owing to the existence of energetic component in fuel-ion energy distribution functions due to neutral-beam injection (NBI) and/or nuclear elastic scattering (NES), the generation rate of the high-energy (>3.52MeV) α-particle increases significantly compared with the case of Gaussian distribution. The influence of the broadened energy spectrum on the α-heating characteristics is discussed.

Keywords: neutral beam injection heating, knock-on tail formation, α-particle emission spectrum, nuclear elastic scattering, Boltzmann-Fokker-Planck equation

1. Inroduction

Energetic ions in burning plasma have important roles in various stages of fusion-reactor operations. The energetic deuterons produced by neutral-beam-injection (NBI) heating and/or ion-cyclotron resonance frequency (ICRF) heating[1,2] create a non-Maxwellian tail in deuteron and triton velocity distribution functions. The nuclear elastic scattering[3,4] (NES) of injected-beam and/or energetic α-particle by thermal ion also causes a knock-on tail formation in fuel-ion distribution functions[5-8]. In magnetically-confined deuterium-tritium (DT) plasmas, the resulting modification of the neutron emission spectrum was computed, and its application to the plasma diagnostics was proposed[9]. By observing the deviation of the neutron emission spectrum from Gaussian distribution, the knock-on tail formation in fuel-ion velocity distribution functions was experimentally ascertained[10,11]. A similar modification of the emission spectrum would also be observed for fusion-produced α-particle. This modification may influence the plasma confinement condition via α-heating power, the fractional energy deposition to ions and turbulent transport process of energetic α-particle, and/or α-particle diagnostics. It is hence important to grasp accurately the modification of α-particle spectrum in reactor plasmas.

In this paper, we consider a DT plasma accompanied with injection of a mono-energetic deuterium beam. On the basis of the Boltzmann-Fokker-Planck (BFP) model[12,13], the modification of the α-particle emission spectrum is evaluated simultaneously considering the distortion of deuteron, triton and α-particle distribution functions. It is shown that the modification is significantly influenced by the tail formations in both deuteron and triton distribution functions due to beam injection and NES. The effect of the modification on plasma heating characteristics (fractional energy deposition to ions) is discussed.

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2. Analysis Model

2.1 Boltzmann-Fokker-Planck model

The BFP equation for ion species a (a= D, T and α-particle) is written as

$$\sum_j \left(\frac{\partial f_a}{\partial t}\right)^{\mathrm{C}} + \sum_i \left(\frac{\partial f_a}{\partial t}\right)_i^{\mathrm{NES}} + \frac{1}{\upsilon^2}\frac{\partial}{\partial \upsilon}\left(\frac{\upsilon^3 f_a}{2\tau_c^*(\upsilon)}\right) + S_a(\upsilon) - L_a(\upsilon) = 0\,, \qquad (1)$$

where $f_a(\upsilon)$ is the velocity distribution function of the species a. The first term in the left-hand side of Eq.(1) represents the effect of the Coulomb collision[14]. The summation is taken over all background species, i.e. j= D, T, α-particle and electron. The collision term is hence non-linear, retaining collisions between ions of the same species. The second term accounts for the NES of species a by background ions. We consider NES between 1) α-particle and D and 2) α and T, i.e., (a,i) = (D,α), (T,α), (α,D) and (α,T) . The NES cross-sections are taken from the work of Cullen and Perkins[4].

The third term in the left-hand side of Eq.(1) represents the diffusion in velocity space due to thermal conduction. To incorporate the unknown loss mechanism of energetic ions into the analysis, we simulate the velocity-dependence of the energy-loss due to thermal conduction and the particle-loss time (see Ref.5-7).

The source ($S_a(\upsilon)$) and loss ($L_a(\upsilon)$) terms take different form for every ion species. For deuteron, the source and loss terms are described so that the fueling, beam-injection, transport loss and the loss due to T(d,n)^{4}He reaction are balancing [5-7];

$$S_D(\upsilon) - L_D(\upsilon) = \frac{S_{\mathrm{D}}}{4\pi\upsilon^2}\delta(\upsilon - \upsilon_D^{fueling}) + \frac{S_{\mathrm{NBI}}}{4\pi\upsilon^2}\delta(\upsilon - \upsilon_D^{NBI}) - \varsigma_D f_D - \frac{f_D(\upsilon)}{\tau_p^*(\upsilon)} . \quad (2)$$

Here $\upsilon_D^{fueling}$ indicates the speed of the fueled deuteron, which is much smaller than the thermal speed, i.e. nearly equal to zero. The fueling rate S_D is determined so that the deuteron density is kept constant, i.e. $S_D = n_D/\tau_p + n_D n_T \langle\sigma\upsilon\rangle_{DT} - S_{NBI}$. The S_{NBI} is the NBI rate per unit volume and υ_D^{NBI} is the speed corresponding to injected beam energy E_{NBI}. We express the injection rate S_{NBI} using the beam energy E_{NBI} and injection power P_{NBI}, i.e. $S_{NBI} = P_{NBI}/(E_{NBI}V)$. Here V represents the plasma volume. Referring to the design parameter for ITER[15], we assume $V = 800\mathrm{m}^3$. The T(d,n)^{4}He reaction rate coefficient is written as

$$\langle\sigma\upsilon\rangle_{\mathrm{DT}} = \frac{4\pi}{n_D n_T}\int \upsilon^2_{D(T)}\varsigma_{D(T)}(\upsilon_{D(T)}) \times f_{D(T)}(\upsilon_{D(T)})d\upsilon_{D(T)} , \quad (3)$$

with

$$\varsigma_{\mathrm{D(T)}} = \frac{2\pi}{\upsilon_{D(T)}}\int \upsilon_{\mathrm{T(D)}} f_{T(D)}(\upsilon_{\mathrm{T(D)}}) \times \left[\int_{|\upsilon_{\mathrm{D}}-\upsilon_{\mathrm{T}}|}^{\upsilon_{\mathrm{D}}+\upsilon_{\mathrm{T}}} d\upsilon_r \upsilon_r^2 \sigma_{DT}(\upsilon_r)\right] d\upsilon_{\mathrm{T(D)}} . \quad (4)$$

The T(d,n)^{4}He fusion cross has been taken from the work of Bosch[16].

For triton the NBI injection term has not been included in Eq.(2), and the source and loss terms are described so that the fueling rate, transport loss and the loss due to T(d,n)^{4}He reaction are balancing [5-7].

For α-particle, the source and loss terms are written as

$$S_\alpha(\upsilon) - L_\alpha(\upsilon) = S_\alpha(\upsilon) - \frac{f_\alpha(\upsilon)}{\tau_p^*(\upsilon)} , \quad (5)$$

where NBI and fueling rate in Eq.(2) are replaced by the α-particle generation rate due to T(d,n)^{4}He reaction,

$$S_\alpha(\upsilon) = \frac{(dE/d\upsilon)}{4\pi\upsilon^2}\frac{dN_\alpha}{dE} , \quad (6)$$

where $N_\alpha(E)$ represents the α-particle generation rate, which is described in the next section.

2.2 neutron and α-particle emission spectrums

The α-particle (neutron) emission energy spectrums are written as

$$\frac{dN_{\alpha(n)}}{dE}(E) = \iiint f_D(\vec{\upsilon}_D) f_T(\vec{\upsilon}_T) \times \frac{d\sigma}{d\Omega}\delta(E - E_{\alpha(n)})\upsilon_r d\vec{\upsilon}_D d\vec{\upsilon}_D d\Omega , \quad (7)$$

where $E_{\alpha(n)}$ is the α-particle (neutron) energy in the laboratory system;

$$E_{\alpha(n)} = \frac{1}{2}m_{n(\alpha)}V^2 + \frac{m_{\alpha(n)}}{m_\alpha + m_n}(Q+K) + V\cos\varphi\sqrt{\frac{2m_n m_\alpha}{m_n + m_\alpha}(Q+K)} , \quad (8)$$

where $m_{\alpha(n)}$ is the α-particle (neutron) mass, V is the centre-of-mass velocity of the colliding particles, φ is the angle between the centre-of-mass velocity and the α-particle (neutron) velocity in the centre-of-mass frame and K represents the relative energy given by

$$K = \frac{1}{2}\frac{m_n m_\alpha}{m_n + m_\alpha}\left|\vec{\upsilon}_D - \vec{\upsilon}_T\right|^2 . \quad (9)$$

Using the α-particle emission spectrum, the source term of BFP equation for α-particle, i.e. Eq.(6), is determined. By means of the computational iterative method, both the energy spectrum and the deuteron, triton and α-particle velocity distribution functions are consistently obtained. The differential cross sections of the T(d,n)^{4}He reaction are taken from the work of Drosg [17].

3. Results and Discussion

In Figure 1 we first show the (a) deuteron and (b) triton distribution functions as a function of deuteron or triton energy when 10, 40 and 100 MW NBI heating are made. In the calculations, the ion and electron densities $n_e = 2n_D = 2n_T = 4\times10^{19}\,\mathrm{m}^{-3}$, electron temperature $T_e = 20\mathrm{keV}$, energy and particle confinement times $\tau_E = (1/2)\tau_p = 3\,\mathrm{sec}$ and beam-injection energy $E_{NBI} = 1\mathrm{MeV}$ are assumed. The dotted lines in both

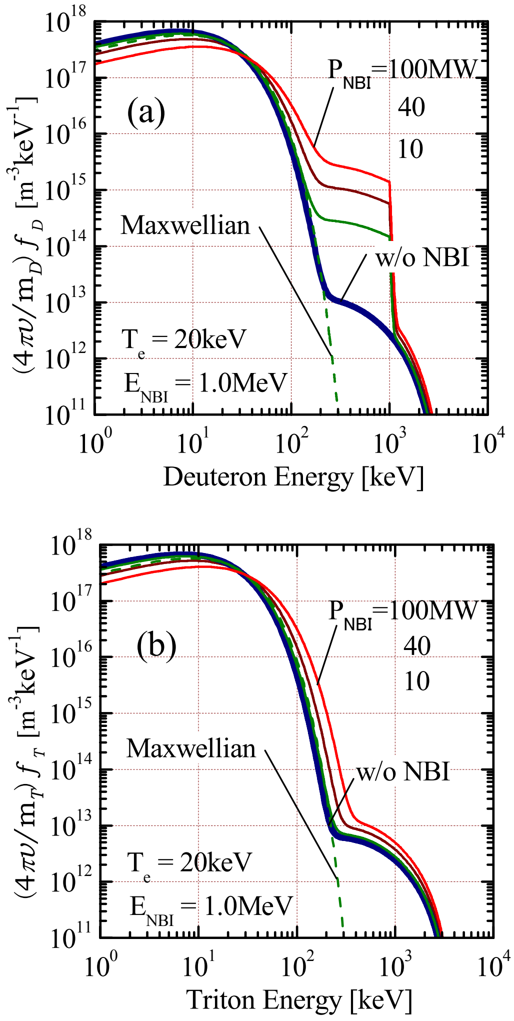

Fig.1 (a) Deuteron and (b) triton distribution functions when 10, 40 and 100 MW NBI heatings are made. The dotted lines denote Maxwellian when no NBI heating is made.

deuteron and triton distribution functions denote Maxwellian at 20keV temperature. The bold lines represent the distribution functions when no NBI heating is made. It is found that the non-Maxwellian tails due to NBI are formed less than 1-MeV energy range in the deuteron distribution function. The relative intensity of the tail is increased by NBI with increasing beam-injection powers. The knock-on tails due to NES of injected beam and α-particle are also observed in the triton distribution function and in the energy range above 1-MeV in the deuteron distribution function. We also find that the bulk temperature increases due to large NBI powers.

In Figure 2 the normalized neutron emission spectrum in deuterium-tritium plasmas is exhibited as a function of neutron energy in the laboratory system. The calculation conditions are the same as the ones in Fig.1. The bold line expresses the neutron spectrum when no NBI heating is applied, which is well agreed with the previous calculation[9] and experiment[11]. The dotted line denotes a Gaussian distribution corresponding to the case when no NBI heating is made. It is found that the neutron emission spectrum is broadened toward both low and high energy directions, and fraction of the neutron with both more and less than 14MeV energy increases with increasing NBI powers. We next show the normalized α-particle emission spectrum in Fig.3 as a function of the α-particle energy. The calculation conditions are the same as the ones in Fig.1 and 2. As was seen in Fig.2, the broadness of the α-particle emission spectrum also tends to be conspicuous for large NBI heating powers. For example, when 40-MW NBI heating is made, the fraction of the generation rate of α-particle with 5-MeV birth energy is almost 50 times larger than the case when no NBI injection is made and is almost 10^4 times larger than the value for Gaussian distribution.

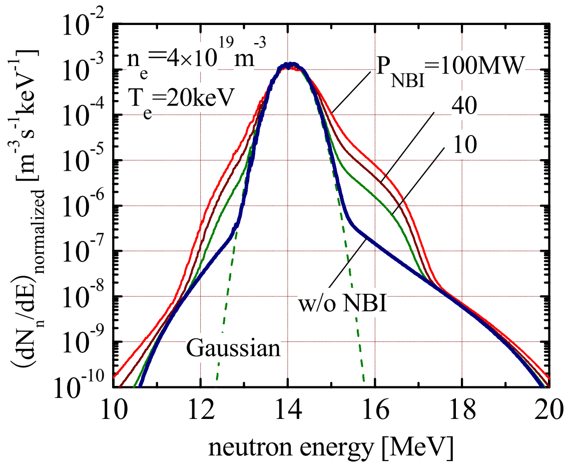

Fig.2 The neutron emission spectrum as a function of neutron energy in the laboratory system.

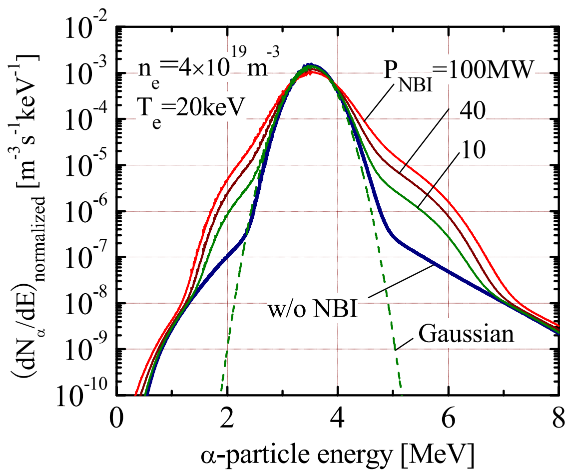

Fig.3 The α-particle emission spectrum as a function of α-particle energy in the laboratory system.

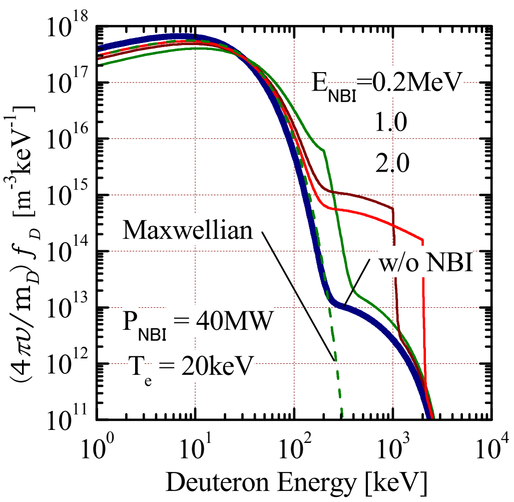

Fig.4 The deuteron distribution function when NBI heating is made with 0.2, 1.0 and 2.0-MeV beam-injection energies.

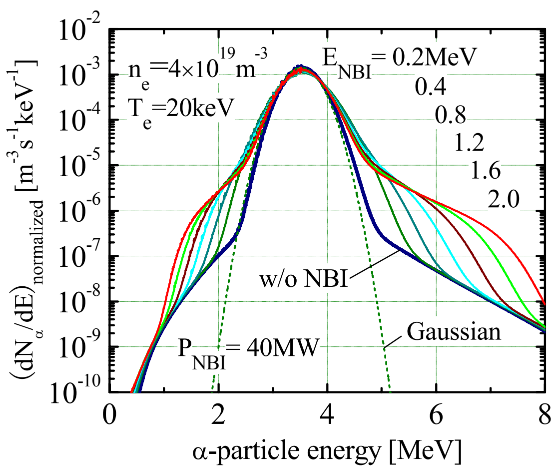

Fig.5 The α-particle emission spectrum as a function of α-particle energy in the laboratory system.

In Fig.4 we next show the deuteron distribution function for 0.2, 1.0 and 2.0 MeV beam-injection energies. In this case, the NBI heating power is taken as 40MW, and other plasma parameters are the same as the ones in Fig.1-3. It is shown that the fraction of the energetic deuteron increases with increasing beam-injection energy. In Fig.5 the normalized α-particle emission spectrum is shown. The calculation conditions are the same as the ones in Fig.4. As a result of the increment in the energetic component of deuteron distribution function (as shown in Fig.4), the fraction of the energetic (>4MeV) α-particle to total generation rate also increases.

The α-particle emission spectrum in the presence of NBI heating has been evaluated. When electron densities $n_e = 4\times10^{19}\,\mathrm{m}^{-3}$, electron temperature $T_e = 20\mathrm{keV}$, NBI power $P_{NBI} = 40(60)\mathrm{MW}$ and energy $E_{NBI} = 1\mathrm{MeV}$ are assumed, the fraction of the power carried by α-particle with energy above 4MeV to total α-heating power almost reaches to 13.3 (15.2)%, which is roughly 1.5 times larger than the value when Gaussian distribution is assumed for the spectrum, i.e. 8.7 (10.0) %.

The transport processes of α-particle in the fusion devices, e.g. ripple and orbit losses[18,19], tend to be influenced by α-particle's energy. The increment in the fraction of the energetic (≥3.5MeV) α-particle may cause the enhancement of the α-particle loss[18]. On the contrary, the initial kinetic energy of fuel ions (before the $T(d,n)^4He$ reaction occurs) must be transformed into a part of the emitted α-particle and neutron energies. Thus if the correct α-particle spectrum is not adopted into a calculation, we may underestimate the α-heating power to some extent.

In the fusion devices, the α-particle diagnostics using γ-ray generating nuclear reaction, e.g. $^9Be(\alpha,n\gamma)^{12}C$ reaction, has been developed[20]. The influence of the broadened emission spectrum on the diagnostics method should be examined. Further detailed investigation for the correlation between the α-particle spectrum and burning plasma characteristics would be required.

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