Modification of Alpha-Particle Emission Spectrum and Its Effect on Plasma Heating Characteristics in Beam-Injected DT Plasmas

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(Received: 2 September 2008 / Accepted: 24 November 2008)

The alpha-particle emission spectrum in beam-injected (non-Maxwellian) deuterium-tritium (DT) burning plasma is examined by solving the Boltzmann-Fokker-Planck (BFP) equations for deuteron, triton and alpha-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) alpha-particle increases significantly compared with the case for Gaussian distribution. The influence of the broadened energy spectrum on the alpha-heating characteristics is discussed.

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

1. Introduction

It is well known that in burning deuterium-tritium (DT) plasmas, knock-on tail[1] is created in fuel-ion velocity distribution functions due to nuclear elastic scattering (NES)[2,3] of bulk ion by energetic alpha(α)-particles. The knock-on tail formation and the resulting modification of the neutron emission spectrum was computed[1], and the knock-on tail formation in fuel-ion velocity distribution functions was experimentally ascertained[4,5] by observing the deviation of the neutron emission spectrum from Gaussian distribution. The plasma diagnostics using the knock-on tail have also been proposed and developed[6-8]. We have shown that when neutral-beam-injection (NBI) heating is applied, more significant knock-on tail is formed[9], and NES effect on fractional beam-energy deposition to ions[9,10] and T(d,n)^{4}He reaction rate coefficient[11] are enhanced. In such a case the modification of the emission spectrum would be further conspicuous and a similar modification of the emission spectrum would also be observed for fusion-produced alpha-particle. This modification may influence the alpha-particle confinement condition and the alpha-heating characteristics. It is hence important to grasp accurately the modification of alpha-particle spectrum in reactor plasmas in addition to that in neutron.

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 [9,11-12], the modification of the alpha-particle emission spectrum is evaluated simultaneously considering the distortion of deuteron, triton and alpha-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, and the fraction of energetic (> 3.52MeV) alpha-particle significantly increases due to the modification of the emission spectrum. The effect of the modification on plasma heating characteristics is discussed.

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

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

where $f_a(v)$ 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[13]. The summation is taken over all background species, i.e. j= D, T, alpha-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[9,11]. 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 Perkins and Cullen[3].

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.9,11-12).

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The source ($S_a(v)$) and loss ($L_a(v)$) 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 each other[9,11];

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

Here $v_D^{fueling}$ 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. $S_D = n_D/\tau_p + n_D n_T\langle\sigma v\rangle_{DT} - S_{NBI}$. The S_{NBI} is the NBI rate per unit volume and v_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[14], we assume $V = 800\mathrm{m}^3$. The T(d,n)^{4}He reaction rate coefficient is written as

$$\langle\sigma v\rangle_{DT} = \frac{4\pi}{n_D n_T}\int v_D^2 \varsigma_D(v_D) \times f_D(v_D)dv_D \ , \quad (3)$$

with

$$\varsigma_D = \frac{2\pi}{v_D}\int v_T f_T(v_T) \times\left[\int_{|v_D-v_T|}^{v_D+v_T} dv_r v_r^2 \sigma_{DT}(v_r)\right]dv_T . \quad (4)$$

The T(d,n)^{4}He fusion cross has been taken from the work of Bosch[15].

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 [7,9-10].

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

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

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

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

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

2.2 neutron and alpha-particle emission spectra

The alpha-particle (neutron) emission energy spectrum is written as

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

where $E_{\alpha(n)}$ is the α-particle (neutron) energy in the laboratory system[16];

$$E_{\alpha(n)} = \frac{1}{2}m_{\alpha(n)}V_c^2 + \frac{m_{n(\alpha)}}{m_\alpha+m_n}(Q+E_r) + V_c\cos\theta_c\sqrt{\frac{2m_n m_\alpha}{m_n+m_\alpha}(Q+E_r)} , \quad (8)$$

where $m_{\alpha(n)}$ is the α-particle (neutron) mass, V_c is the centre-of-mass velocity of the colliding particles, θ_c is the angle between the centre-of-mass velocity and the α-particle (neutron) velocity in the centre-of-mass frame, Q is the reaction Q-value, and E_r represents the relative energy given by

$$E_r = \frac{1}{2}\frac{m_D m_T}{m_D+m_T}|\vec{v}_D-\vec{v}_T|^2 . \quad (9)$$

Using the alpha-particle emission spectrum, the source term of BFP equation for alpha-particle, i.e. Eq.(6), is determined. By means of the computational iterative method, both the energy spectrum and the deuteron, triton and alpha-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 Fig.1 we first show the deuteron distribution functions as a function of deuteron energy when 10, 40 and 100 MW NBI heating are made. In the calculations, electron temperature $T_e = 20\mathrm{keV}$, the ion densities $n_D = n_T = 3\times10^{19}\mathrm{m}^{-3}$, energy and particle confinement times $\tau_E = (1/2)\tau_p = 3\sec$ and beam-injection energy $E_{NBI} = 1\mathrm{MeV}$ are assumed. The electron density has different values according to the NBI heating power as $6.6-7.0\times10^{19}\mathrm{m}^{-3}$. The dotted line in deuteron distribution function denotes Maxwellian distribution at 20keV temperature. The bold line represents the distribution functions when no NBI heating is made. It is found that the non-Maxwellian tail due to NBI is formed in the energy range below 1MeV in the distribution function. The relative intensity of the tail is increased by NBI with increasing beam-injection powers. The knock-on tail due to NES of alpha-particle is also observed in the energy range above 1-MeV in the distribution function. We also find that the bulk temperature slightly increases due to the NBI powers.

In Fig.2 the normalized neutron emission spectrum in deuterium-tritium plasmas is exhibited as a function of neutron energy in the laboratory system. The calculation parameters are the same as those in Fig.1. The bold line

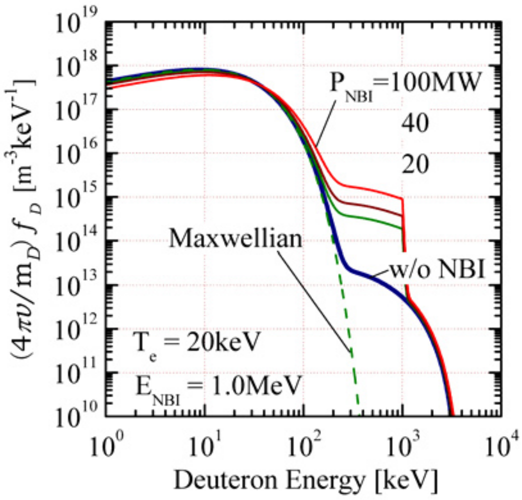

Fig.1 Deuteron distribution functions when 20, 40 and 100 MW NBI heatings are made. The dotted line denotes Maxwellian when no NBI heating is made.

expresses the neutron spectrum when no NBI heating is applied. We can look at almost the same neutron emission spectrum with the previous calculation[1] and experiment [4]. 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 alpha-particle emission spectrum in Fig.3 as a function of the alpha-particle energy. The calculation parameters are the same as those in Fig.1 and 2. As was seen in Fig.2, the broadness of the alpha-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 alpha-particle with 5-MeV birth energy is almost 50~100 times larger than in the case when no NBI injection is made and is almost 100~200 times larger than the value for Gaussian distribution.

In Fig.4 and Fig.5 the deuteron distribution function and the resulting modification in the alpha-particle emission spectrum are shown for several beam-injection energies. In this case, the NBI heating power is taken as 40MW, and other plasma parameters are the same as those in Fig.1-3. It is shown that the fraction of the energetic deuteron increases with increasing beam-injection energy, which causes the increment in the fraction of the power carried by energetic alpha-particles. To quantitatively estimate the increment, we introduce the following parameter;

$$F_{>4MeV} = \frac{\int_{4MeV}^{\infty} E\left(\frac{dN_\alpha}{dE}\right)dE}{\int_{0}^{\infty} E\left(\frac{dN_\alpha}{dE}\right)dE} , \qquad (10)$$

which implies the fraction of the power carried by energetic (>4MeV) alpha-particles to total generation power. The power fraction when the modification is considered $F_{>4MeV}$ and the one when Gauss distribution is assumed $F_{>4MeV}^{Gauss}$ are evaluated, and the increment in the fraction due to the modification, $F_{>4MeV}/F_{>4MeV}^{Gauss}$, is

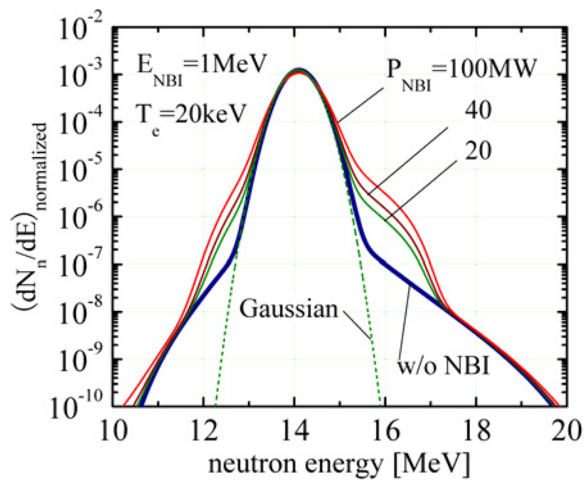

Fig.2 The neutron emission spectra as a function of neutron energy in the laboratory system.

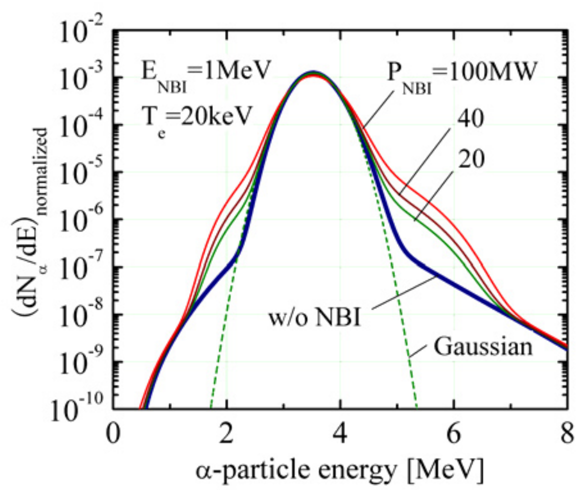

Fig.3 The alpha-particle emission spectra as a function of alpha-particle energy in the laboratory system.

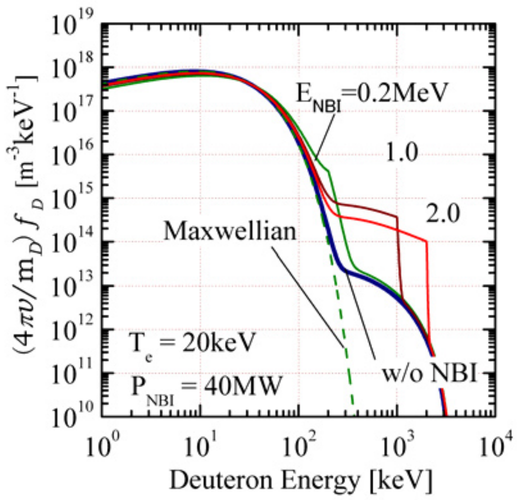

Fig.4 The deuteron distribution function when NBI heating is made with 0.2, 1.0 and 2.0-MeV beam-injection energies.

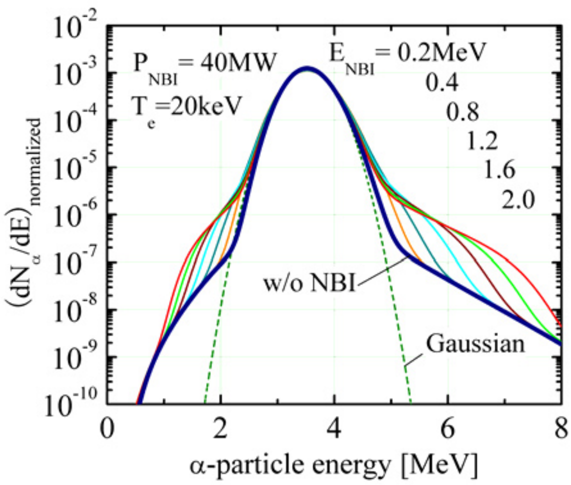

Fig.5 The alpha-particle emission spectra as a function of alpha-particle energy in the laboratory system.

presented in Fig.6 for several electron temperatures as a function of the NBI heating power. It is found that the increment becomes significant with decreasing electron temperature. This is because in low-temperature range, the half width of the Gaussian distribution decreases, thus the modification of the emission spectrum from the Gaussian distribution becomes further conspicuous. The absolute values for the fraction of the power carried by energetic (>4MeV) alpha-particles when the modification is considered $F_{>4MeV}$ and neglected $F^{Gauss}_{>4MeV}$, and the ratio, i.e. $F_{>4MeV}/F^{Gauss}_{>4MeV}$, are exhibited in Fig.7 when electron temperature is 10keV.

The alpha-particle emission spectrum in the presence of NBI heating has been evaluated and it has been shown that the fraction of energetic (>4.0MeV) alpha-particle increases due to the modification of the emission spectrum. When electron temperature $T_e = 20(10)$keV, electron density $n_e = 6.7(6.2)\times10^{19}$ m^{-3}, NBI power P_{NBI} = 40MW and energy E_{NBI} = 1MeV are assumed, the fraction of the power carried by alpha-particle with energy above 4MeV to total alpha-heating power reaches to 11.7 (5.1)%, which is roughly 1.3 (2.4) times larger than the value when Gaussian distribution is assumed for the alpha-particle emission spectrum, i.e. 9.1 (2.1) %.

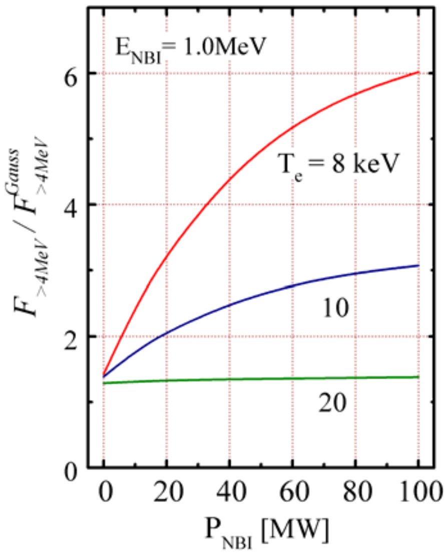

Fig.6 Increment in the fraction of power carried by energetic (>4MeV) alpha-particle due to the modification of the emission spectrum.

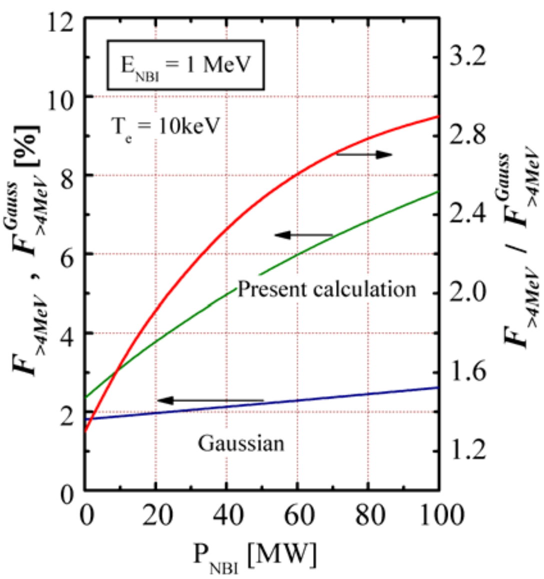

Fig.7 The fraction of power carried by energetic (>4MeV) alpha-particle to the total alpha-heating power as a function of the NBI heating power.

The transport processes (confinement) of alpha-particle in the fusion devices tend to be influenced by alpha-particle's energy. The increment in the fraction of the energetic (≥3.5MeV) alpha-particle may influence the alpha-heating performance. The initial kinetic energy of D and T (before the $T(d,n)^4He$ reaction occurs) must be exactly converted into a part of the emitted alpha-particle and neutron energies. Thus if the correct alpha-particle spectrum is not adopted into a calculation, we may underestimate the alpha-heating power to some extent.

In the fusion devices, the alpha-particle diagnostics using the γ-ray generating nuclear reaction, e.g. $^9Be(\alpha,n\gamma)^{12}C$ reaction, has been developed[18,19]. The influence of the broadened alpha-particle emission spectrum on the diagnostics should be examined. A new approach to diagnose the energetic-ion velocity distribution function by utilizing the modification of the emission spectrum due to beam injection may be considered. Further detailed investigation for the correlation between the alpha-particle spectrum and burning plasma characteristics would be required.

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