Effect of emission spectrum modification on alpha-particle confinement in beam-injected DT fusion plasma

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The effect of fusion emission spectrum modification on prompt alpha-particle loss is evaluated for the ITER-like deuterium-tritium plasma accompanied with neutral-beam-injection (NBI) heating. It is shown that alpha-particle loss increases by several percent from the value when mono-energetic alpha source is assumed in the monotonic magnetic shear equilibrium.

Keywords: alpha particle, prompt loss, ITER, spectrum modification, neutral beam injection

1. Introduction

In magnetic confinement fusion reactors, understanding of fusion alpha-particle behavior is one of the most important issues from the viewpoint of evaluating plasma heating characteristics and heat deposition on the first wall, and hence numerical calculations were made in order to clarify alpha-particle behavior in various reactor systems [1-3]. In these simulations, mono-energetic alpha-particle source was assumed [1]. However, when the fuel-ion has thermal distribution, alpha-particle emission spectrum takes a form of Gaussian. In addition, it is known that fusion emission spectrum spreads from Gaussian owing to the non-Maxwellian tail formation in fuel-ion velocity distribution function by NBI or large-energy-transfer scattering of alpha-particles [4]. Energetic particle has a large Larmor radius and banana width. This makes first-orbit loss and banana-drift diffusion larger [5]. This implies that alpha particle confinement property depends on its birth energy. Hence alpha-particle losses may be affected by the alpha source spectrum.

In this paper, assuming ITER-like fusion reactor, the effect of emission spectrum modification on alpha -particle confinement is evaluated by comparing the alpha-particle loss with the one when delta function (or Gaussian) is assumed for emission spectrum. At first, we calculate fuel-ion distribution function by solving Boltzmann-Fokker-Planck (BFP) equation and derive the alpha-particle emission spectrum. Secondly, we examine energy dependence of alpha-particle loss fraction. The guiding center code ORBIT [6] is used for the calculation. In the current study, we look at only the alpha-particle loss in its first-bounce time, i.e. prompt loss. Finally, we evaluate the effect of spectrum modification on prompt alpha-particle loss using derived alpha-particle emission spectrum and energy dependence of alpha-particle loss fraction.

2. α-particle Emission Spectrum

The fuel-ion velocity distribution function in burning plasma accompanied with NBI heating is obtained by solving the following BFP equation for ion species i (i = D, T, and alpha-particle),

$$\sum_j \left(\frac{\partial f_i(v)}{\partial t} \right)_j^C + \sum_k \left(\frac{\partial f_i(v)}{\partial t} \right)_k^{NES} + \frac{1}{v^2} \frac{\partial}{\partial v} \left(\frac{v^3 f_i(v)}{2\tau_C^*(v)} \right) + S_i(v) - L_i(v) = 0 \quad (1)$$

where $f_i(v)$ is the velocity distribution function of ion species i. The first term in left-hand side of Eq (1) is Fokker-Planck term, which represents Coulomb interaction between ion species i and background spacies j (j = D, T, alpha, and electron). The second term represents nuclear elastic scattering (NES) of species i by background ion k, $(i,k) = (D,\alpha),(T,\alpha),(\alpha,D)$ and (α,T). The third term represents the diffusion in velocity space due to thermal conduction. The fourth term is source term, and the fifth term is loss term. Figure 1 shows the deuteron distribution function obtained by solving BFP equation (solid line). In this calculation, the ion densities $n_D = n_T = 2\times10^{19}\,\mathrm{m}^{-3}$, electron and ion temperature $T_e = T_i = 20\mathrm{keV}$, energy confinement times $\tau_E = 3.0\,\mathrm{sec}$, NBI energy $E_{NBI} = 1\mathrm{MeV}$, and NBI power $P_{NBI} = 40\mathrm{MW}$ are assumed. The dotted line in Fig.1 is

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Maxwellian at the same temperature.

The alpha-particle emission spectrum is described as

$$\frac{dN_\alpha}{dE}(E) = \iiint f_D(|\vec{v}_D|) f_T(|\vec{v}_T|) \frac{d\sigma}{d\Omega} \delta(E-E_a) v_r d\vec{v}_D d\vec{v}_T d\Omega \ , \quad (2)$$

where $d\sigma / d\Omega$ is the differential cross section of $\mathrm{T}(d,n)^4\mathrm{He}$ reaction. The 17.6MeV energy produced by T(d,n)α reaction is divided between alpha-particle and neutron. The fraction of the energy provided for alpha-particle depends on velocities of both deuteron and triton before the reaction. E_α represents the alpha-particle energy in the laboratory system; which is written as

$$E_\alpha = \frac{1}{2} m_\alpha V_c^2 + \frac{m_n}{m_\alpha + m_n}(Q+E_r) + V_c \cos\theta_c \sqrt{\frac{2m_\alpha m_n}{m_\alpha + m_n}(Q+E_r)} \ , \quad (3)$$

where $m_{\alpha(n)}$ is the alpha-particle (or neutron) mass, V_c is the center-of-mass velocity of the colliding particles, θ_c is the angle between the center-of-mass velocity and the alpha-particle velocity in the center-of-mass frame, Q is the reaction Q-value, and E_r represents the relative energy. Figure 2 shows the calculated alpha-emission spectrum. The calculation conditions are the same as those in Fig.1. The dotted line is Gaussian at the same parameters. Here, these two spectra in Fig.2 are normalized so that $\int \left(dN_\alpha / dE \right) dE = 1$. The alpha emission spectrum is broadened toward both low and high energy regions. The fraction of emission rate above 3.52MeV energy is larger than that below 3.52MeV. This is because the kinetic energy carried by deuteron and triton before the T(d,n)α reaction is transferred to the kinetic energy of fusion-produced alpha-particle (and neutron).

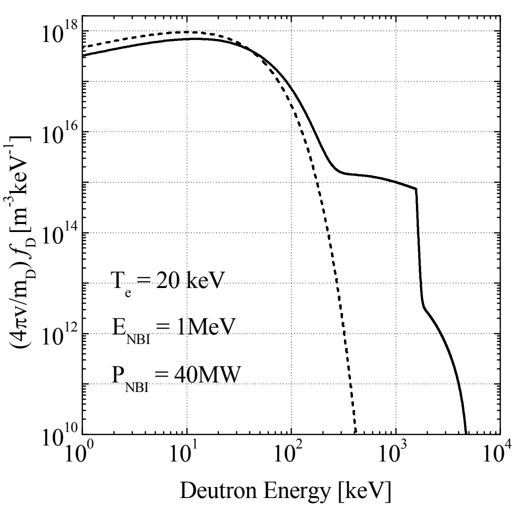

Fig.1 Deuteron distribution function for electron temperature $T_e = 20\mathrm{keV}$, energy confinement time $\tau_E = 3.0\sec$, and beam-injection energy $E_{NBI} = 1\mathrm{MeV}$.

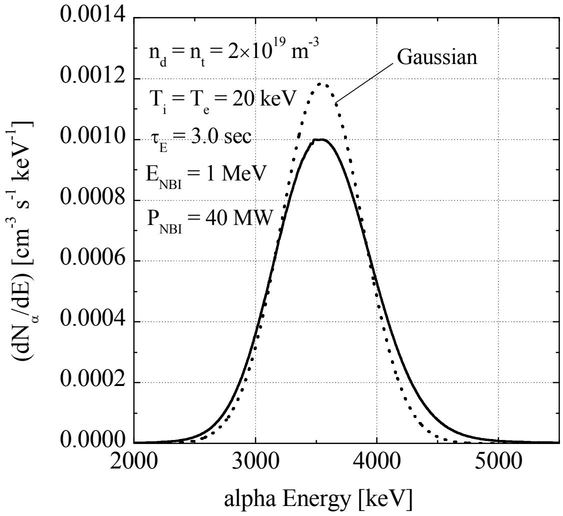

Fig.2 Alpha-particle emission spectrum as a function of alpha-particle in the laboratory system. The electron temperature $T_e = 20\mathrm{keV}$, energy confinement time $\tau_E = 3.0\sec$, and beam-injection energy $E_{NBI} = 1\mathrm{MeV}$ are assumed.

Table I Plasma parameters

	MS	RS
B_T [T]	5.3	5.3
I_P [MA]	11.6	15.4
R_{axis} [cm]	634	634
a [cm]	198	198

3. Energy Dependency of α-particle Loss

For the purpose of computing test-particle orbit, ITER-like profiles of magnetic field, plasma pressure and current density is determined from safety factor profile, flux surface and TF ripple profile which are taken from previous works [7-10]. The major plasma parameters used in the calculation are given in Table I.

The equilibrium flux surfaces are geometrically determined using the parametric dependence of the cylindrical coordinates, $R = R(r,\theta)$ and $Z = Z(r,\theta)$ [7]. Here, R and Z represent the spatial variables of the cylindrical coordinate system [R, Z, ϕ] (ϕ is the toroidal angle), r is the flux surface radius in the equatorial plane containing the magnetic axis and θ is the poloidal angle. The parametric dependences of R and Z are described as

$$R(r,\theta) = R^0 + \varDelta R \ , \quad (4)$$

$$Z(r,\theta) = \kappa r \sin\theta \quad (5)$$

with

$$R^0 = R_{maj} + \Delta(r) + r\cos\theta \ , \quad (6)$$

$$\varDelta R = -r\varLambda(r)\sin^2\theta \ , \quad (7)$$

$$\varLambda(r) = \delta_{tri}(r/a)^2 \ , \quad (8)$$

where δ_{tri} is triangularity, κ is ellipticity and $\Delta(r) = \Delta_0(1-(r/a)^2)$ is Shafranov-shift. The triangularity and ellipticity are taken as $\delta_{tri} = 0.54$ and $\kappa = 1.94$ [8].

The analytic form for TF ripple is written as [2]

$$\delta(R,Z) = \delta_0 \exp[((R - R_{\min}(Z))^2 + b_r Z^2)^{0.5} / \omega_r] \ . \ (9)$$

Here b_r is the ellipticity of ripple contours, ω_r is the scale length of the ripples, δ_0 is the minimum value of ripple field, and $R_{\min}$ is the radius at which value of ripple field equal δ_0. The ripple data field is determined by referring to the consulting previous work [9], $b_r = 0.09$, $\omega_r = 0.384$ m, $\delta_0 = 5.0\times10^{-6}$, $R_{\min} = 5.22 - 0.0443Z^2$. The number of toroidal field coils is taken as 18. Figure 3 shows the equilibrium (doted lines) and maximum TF ripple (solid lines) contours.

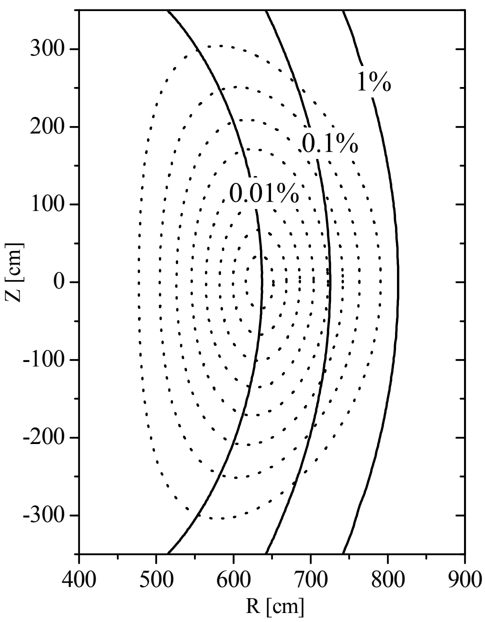

Fig.3 TF ripple contours (solid lines) and flux surfaces (dotted lines).

The safety factor profile is an important factor that affects ripple loss. In this study, we assume two cases of operation. First case; safety factor has monotonic radial profile, i.e., monotonic shear (MS). Second case; q has high central value and non-monotonic radial profile, i.e., reversed shear (RS). Figure 4 shows the safety factor profiles used in this study. The data was taken from Ref.[10].

For the purpose of calculating alpha-particle loss, we use the guiding-center code ORBIT. As a first step, we calculate only the prompt alpha-particle loss. The calculation follows 15000 alpha-particle orbit for 20 toroidal transit time, i.e. $\approx 1.6\times10^{-4}$ msec. The alpha-particle which reaches the last flux surface is regarded as lost one. In this paper we define the

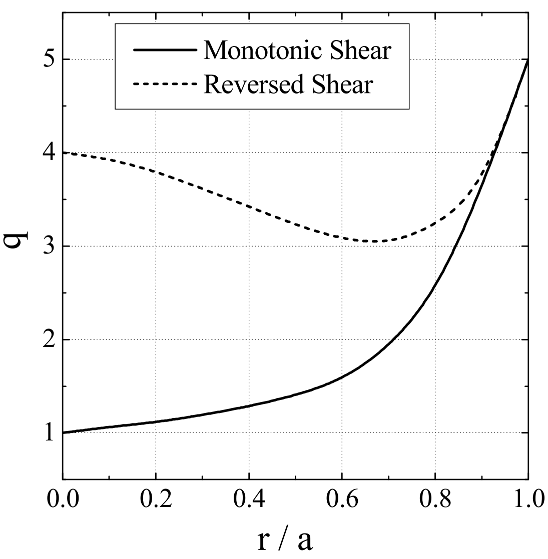

Fig.4 Safety factor profile used in the calculation.

alpha-particle loss $F(E)$ as

$$F(E) = \frac{\text{(the number of lost test-alpha-particle)}}{\text{(total number of test-alpha-particle)}} \times 100 \ [\%] \ . \quad (10)$$

Background ion (D and T) density $n_D = n_T = 2\times10^{19}\,\mathrm{m}^{-3}$ has been assumed to be radially constant. The temperature profiles of ion and electron was assumed to be

$$T_e(\psi) = T_i(\psi) = 20.0(0.9(1-\psi)+0.1) \ . \quad (11)$$

The radial profile of alpha-particle generation rate was given by temperature and density profiles.

Figure 5 shows the $F(E)$ as a function of alpha-particle energy for two cases: (a) monotonic shear, (b) reversed shear. It is shown that $F(E)$ depends strongly on alpha-particle energy. Alpha-particle emission spectrum is shown in the same energy scale as a comparison. The solid lines in Figs.5 (a) and (b) are fitting curves of $F(E)$ obtained by means of the least-square method. In Fig.5 (a), exponent is 1.46 and in Fig.5 (b), exponent is 1.95. The alpha-particle loss fraction is larger in RS. In the RS mode, safety-factor is larger than MS mode, and this implies that poloidal magnetic field is smaller than the toroidal magnetic field. This makes banana-width of trapped alpha-particle larger. As the result, the confinement region will be smaller and alpha-particle loss will be larger.

4. Effect of Spectrum Modification on prompt α-particle loss

To evaluate the effect of spectrum modification on the alpha-particle loss, alpha-particle loss fraction ξ which

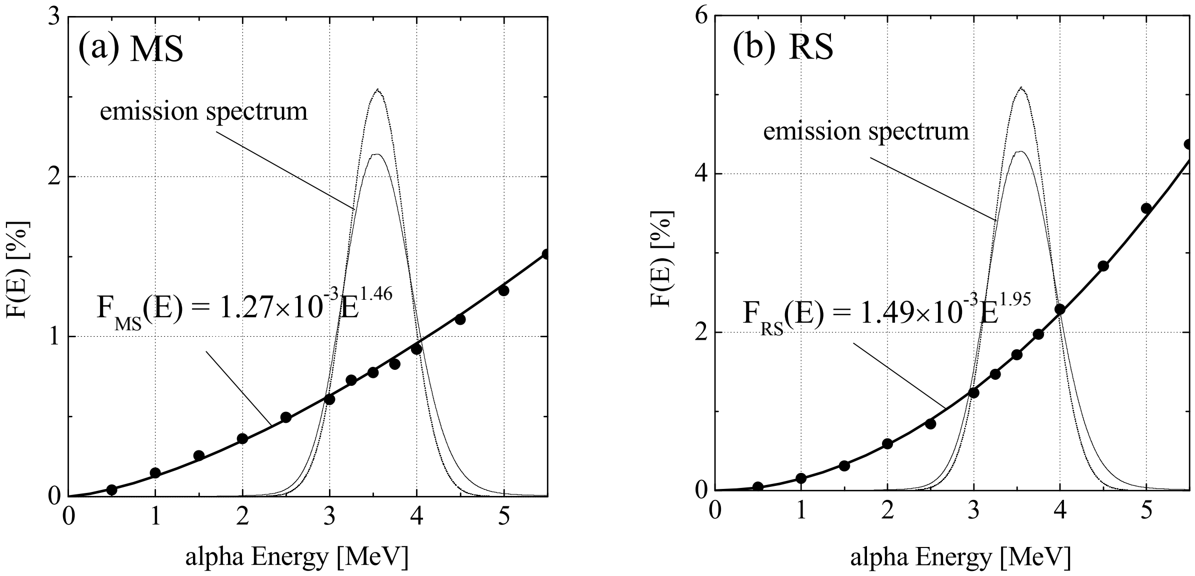

Fig.5 Prompt loss fraction of alpha-particle $F(E)$ vs alpha energy for two cases: (a) monotonic shear, (b) reversed shear. The solid lines are fitting curves of $F(E)$ obtained by means of the least-square method.

takes into account the spreading of alpha-particle emission spectrum is defined. The ξ is written as follows.

$$\xi = \frac{\int \frac{dN_\alpha}{dE}(E)F(E)dE}{\int \frac{dN_\alpha}{dE}(E)dE} . \qquad (12)$$

We evaluate the ξ for the following three conditions. First case; the calculated emission spectrum is used. Second case; Gaussian distribution is assumed for emission spectrum. Third case; delta-function is assumed for emission spectrum. In Table II, we show the ξ for three conditions of calculation. The ξ values for Gaussian and calculated spectra are larger than that for delta-function spectrum. This is due to the fact that $F(E)$ shape is not liner but exponentially increasing with alpha-particle energy. In addition, when the calculated spectrum is used, fraction of alpha-particle which is born with the energy above 3.52 MeV is larger than that with the energy lower than 3.52 MeV.
When monotonic shear is assumed, the ξ when the calculated spectrum is used reaches 0.81%, which is roughly 3.5% larger than the value when delta-function is assumed for the alpha-particle emission spectrum, 0.78%.

Table II The ξ parameters

spectrum	MS	RS
calculated	0.81 %	1.87 %
Gauss distribution	0.79 %	1.83 %
delta function	0.78 %	1.77 %

When reversed shear is assumed, the ξ when the calculated spectrum is used reaches 1.87%, which is roughly 5.8% larger than the value when delta-function is assumed for the alpha-particle emission spectrum, 1.77%.

5. Concluding Remark

The effect of alpha-particle emission spectrum modification on prompt alpha-particle loss has been evaluated. It is shown that prompt alpha-particle loss increases several percent from the value when mono-energetic alpha source is assumed. For this calculation, we used Eq.(11) to express the ion temperature profile. The alpha-particle loss depends on radial profile of alpha-particle source which determined by the ion temperature profile. Alpha-particle generation rate and temperature profile is changed by intermittent transport or transient MHD phenomena. If ion temperature profile was more flat, the ξ parameter would further increases. In this study, we have considered alpha-particle loss only in the first bounce time. In the next step, the calculation for full slowing-down time is necessary for more detailed analysis. In such a calculation, since pitch angle scattering frequency is in inverse proportion to alpha energy, the effect of alpha-particle emission spectrum modification on alpha-particle loss may be weakened to some extent. Throughout the calculations isotropic beam injection has been assumed (ion velocity distribution functions, alpha-particle emission spectrum have been treated in one-dimensional velocity space). In the actual case, however, external beam is injected in a specific direction, so the emission spectrum of alpha-particle would have anisotropic distribution. In such a case, the fraction of energetic alpha-particle which is emitted toward beam injected direction increases. The alpha-particle loss fraction depends on its emission angle relative to the direction of toroidal magnetic field. Hence the alpha-particle loss property would be affected by beam injected direction. Further detailed studies for the effect of emission spectrum modification on alpha -particle loss would be required.

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