Effect of Nuclear Plus Interference Scattering on Fast α-Particle Orbit and Confinement in Magnetic Field Configuration*)

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Assuming a deuterium-tritium (DT) burning plasma, effect of the nuclear plus interference (NI) scattering is newly incorporated into the alpha-particle orbit simulation. The effect of the NI scattering on the energetic alpha-particles orbit and confinement in a magnetic fusion device is examined. It is shown that due to transition of the alpha-particle orbit by NI scattering, the fraction of the alpha-particles lost from the plasma during their slowing-down process to the initial generation decreases to a certain extent.

Keywords: nuclear plus interference scattering, guiding-center orbit simulation, trapped particle

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1. Introduction

In magnetic confined fusion plasma, it is important to understand the fast-ion behavior from the viewpoint of plasma heating and heat load on the first wall. Particle orbit analysis is useful to understand the fast-ion behavior in thermonuclear plasmas, and has been used to examine, for example, the diffusion of fast ions in a magnetic field [1]. Stringer incorporated Coulomb scattering effect into the particle orbit analysis and indicated that confinement of bulk ions are stabilized by the scattering [2]. It is well known that for fast-ions, Coulomb and non-Coulombic, i.e. nuclear plus interference (NI) [3], scattering† contribute to the fast-ion slowing down process. NI scattering is caused by nuclear force plus nuclear Coulomb interference when ions are close enough. The Coulomb scattering process is characterized by many small-energy-transfer events. The NI scattering is a large-angle scattering process, and a large fraction of the fast-ion energy is transferred in a single event. So far in the previous particle orbit analyses, the effect of the NI scattering has not been considered.

NI scattering changes direction of the particles motion and the number of particles scattered into the loss cone. Assuming the magnetic mirror device, Kantrowitz and Conn noted that particle loss is increased by NI scattering [4]. On the other hand, NI scattering accelerate the fast-ion slowing-down. If we neglect the NI scattering effect, slowing-down time of the fast-ion is overestimated [5]. The influence on the fast-ion distribution function, i.e. decrement in energetic component in the slowing-down distribution function, has been evaluated [6, 7]. However, these analyses were made on the basis of the Boltzmann-Fokker-Planck (BFP) simulation, i.e., particle orbit in the magnetic field configuration was not considered. In the magnetic field, it is also well known that collisions change the particle orbit pattern and affect the particles confinement properties [8]. The NI scattering could also be influential on the particle orbit and the confinement properties. Fast ions lost from a particular orbit may be concentrated on a spot on the first wall. It is important to grasp the NI-scattering effect on the fast-ion loss process in fusion devices.

The purpose of this study is to incorporate the effect of NI scattering effect into the charged-particle orbit analysis simulation and to evaluate the effect of the NI scattering on the fast alpha-particles behaviors. In particular, we reveal the transition of the alpha-particle orbit caused by NI scattering and its effect to energetic alpha-particles loss process.

2. Equations and Figures

The NI-scattering effect was incorporated into the charged-particle orbit analysis code, i.e. guiding center orbit code ORBIT [9] developed at PPPL.

The probability $p(v)$ that a test particle moving with velocity v occurs NI scattering during a small time step Δt is

$$p(v) = n_b v \sigma_{NI} \Delta t, \qquad (1)$$

where n_b is the number density of background ions, and σ_{NI} is the cross section of the NI scattering. As a first step, the effect of thermal motion of target particles, i.e. deuteron and triton, was neglected. This is because the cross section of the NI scattering is small in the low energy region (< 1 MeV). Scattering in the center-of-mass system

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† The NI scattering is defined by subtracting Coulomb contributions from experimental data. It is also referred to as "nuclear elastic scattering (NES)".

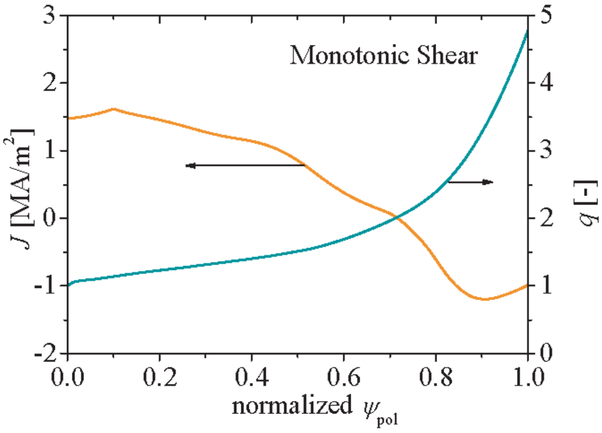

Fig. 1 Radial profiles of safety factor and current density assumed in the present calculations [11].

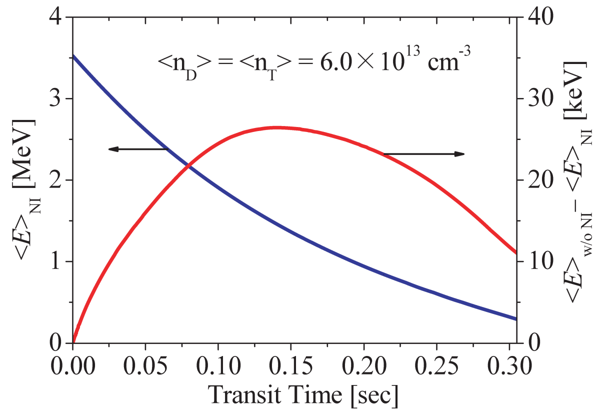

Fig. 2 Temporal behavior of averaged alpha-particle energy when NI scattering is considered, and its relative difference from the value when NI scattering is neglected.

was assumed to be isotropic. Transferred energy in a single scattering event ΔE can be written as

$$\Delta E = \frac{E}{2}(1-\alpha)(1-\cos\varphi), \quad (2)$$

where E is kinetic energy of the test particle before scattering and ϕ is the scattering angle in the center-of-mass system. Here $\alpha = \{(m_t - m_b)/(m_t + m_b)\}^2$, m_t and m_b are mass of test particle and background ion. In this paper, the NI scattering cross sections are taken from the work of Perkins and Cullen [10].

We assumed ITER-like plasma. As a test particle 3.52 MeV alpha-particle is chosen. Toroidal magnetic field $B_T = 5.3$ T, and radial profile of bulk ions and electrons densities $n_i = n_e = 1.0\times10^{14}\times(1-\psi^2_{pol,n})^{1.5}$ is assumed, where $\psi_{pol,n}$ represents the normalized poloidal magnetic flux function ψ_{pol}. Radial profiles of the safety factor and current density assumed in the present simulations are referred from the Ref. [11] and shown in Fig. 1. Throughout the calculations, 30000 test particles and 100000 toroidal transit calculation time are assumed.

3. Result and Discussion

3.1 Acceleration of slowing down by NI scattering

In Fig. 2, temporal behaviors of the averaged alpha-particle energy when NI scattering is considered, i.e., $\langle E\rangle_{NI}$, and the relative decrement of the averaged energy due to NI scattering, i.e., $\Delta E \equiv \langle E\rangle_{w/o\,NI} - \langle E\rangle_{NI}$, are shown. Here $\langle E\rangle_{w/o\,NI}$ represents the averaged alpha-particle energy when NI scattering is neglected. In the calculation the space-averaged ion and electron temperatures are assumed as 10.5 keV.

We can see the ΔE has positive values during the slowing-down process, which implies that the slowing-down of the alpha-particle is underestimated when the NI scattering is neglected. This effect has already been reported previously as the enhancement of energy deposition to bulk ions by the NI scattering (e.g. [5–7]). We can also ascertain the effect in the present simulation. The slowing-down of alpha-particles are accelerated by NI scattering, and initially, i.e., $< \sim 0.15$ sec, $|\Delta E|$ is increased. As alpha-particles slow down, i.e. $> \sim 0.15$ sec, the fraction of energetic component in alpha-particle distribution function decreases and relative intensity of the NI to Coulomb scattering become small, i.e., $|\Delta E|$ is decreased.

3.2 Orbit transition due to NI scattering

Alpha-particle orbit can be divided into two patterns, i.e. trapped and untrapped orbit. These orbits projected on the poloidal plane are shown in Fig. 3. Alpha-particles moving on the trapped orbit satisfy the following requirement [8]

$$\frac{v_{//0}}{v_{\perp 0}} = \frac{1}{|\tan\theta_0|} < \left(2\frac{r_0}{R_m}\right)^{1/2}, \quad (3)$$

where $v_{//0}$ and $v_{\perp 0}$ are parallel and vertical components of the particle velocity to the magnetic field lines at the minimum-magnetic-field point on its orbit. θ_0 and r_0 are the position of the alpha-particle, i.e., pitch angle and the distance from the plasma center when the particle passes a point $Z = 0$ and $R > R_m$. R_m is the major radius.

A few percent of alpha particles lose their energy by NI scattering during their slowing down process (The mean NI collision time of 3.52 MeV alpha particle τ_{NI} is evaluated as almost 6 sec, and typical slowing-down time that 3.52 MeV alpha particle loses its energy to 1.0 MeV is estimated as 0.1~0.5 sec). When $v_{//0}$, $v_{\perp 0}$ or r_0 are changed by the NI scattering, trapped particles may go out from the trapped region, or untrapped particles may come into the trapped region. Schematic view of the typical transition process, i.e., a trapped alpha-particle changes its orbit to untrapped one, is exhibited in Fig. 4.

In Fig. 5 (a), fraction of the number of ions, i.e. on trapped (red rectangle) and untrapped (green rectangle) orbit, to total ions confined in the device is plotted as a function of r_0. Where r_0 is a same parameter as equation (3). In the calculation the space-averaged ion and electron tem-

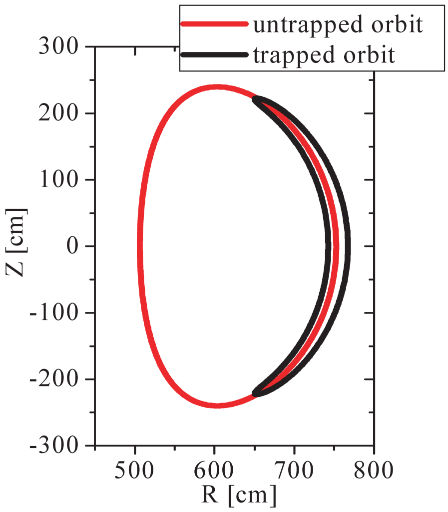

Fig. 3 An example of trapped and untrapped orbit projected on poloidal plane.

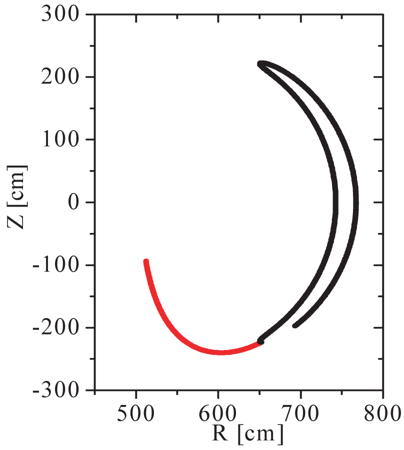

Fig. 4 Typical calculation for the alpha-particle orbit transition from trapped to untrapped orbit due to NI scattering.

peratures are assumed as 20 keV and calculation time is taken as 12 toroidal transit time. In the device the number of ions moving on the trapped orbit is smaller than that moving on the untrapped orbit. The fraction of the ions in the $r_0 \geq 150$ cm region is enlarged and shown in Fig. 5 (b) again. It is found that at the outer region of the poloidal plane $r_0 \geq 150$ cm, number of particles moving on the trapped orbit are greater than that moving on the untrapped orbit. We next show the fractions shown in Fig. 5 (b), i.e., fraction of the number of ions with $r_0 \geq 150$, as a function of pitch angle in Fig. 6. The calculation condition is the same as those in Fig. 5. The ions moving toward opposite direction to the magnetic field, i.e., $\theta > 90°$, on the untrapped orbit tend to be shifted inside region, i.e. $r_0 < 150$ cm, in the poloidal plane by curvature and ∇B drift, and disappear from the Fig. 6. Because the NI scattering probability does not depend on the type of the particle orbit, in the region $r_0 \geq 150$, the number of ions moving on the trapped orbit tend to be decreased due to the NI scattering.

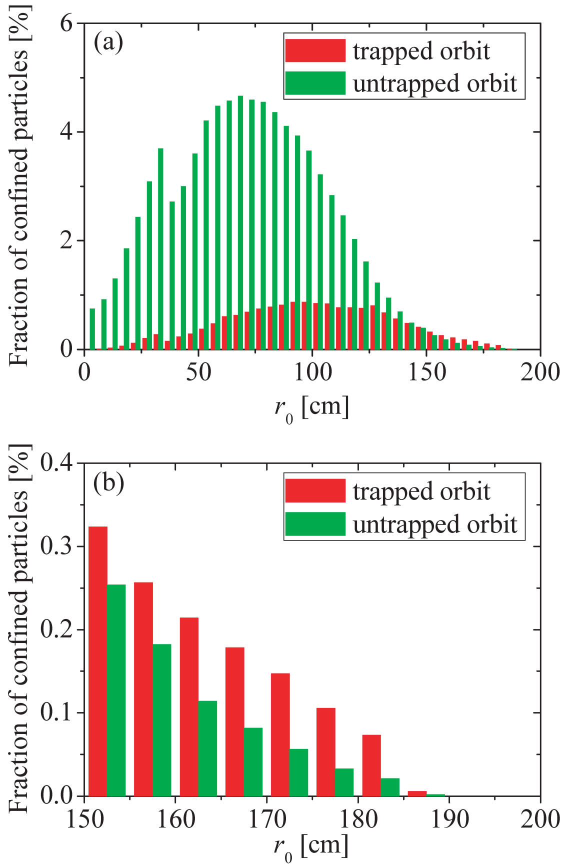

Fig. 5 Fraction of the number of alpha-particles to total particles as function of r_0 (a) in region of all r_0, (b) in region $r_0 \geq$ 150.

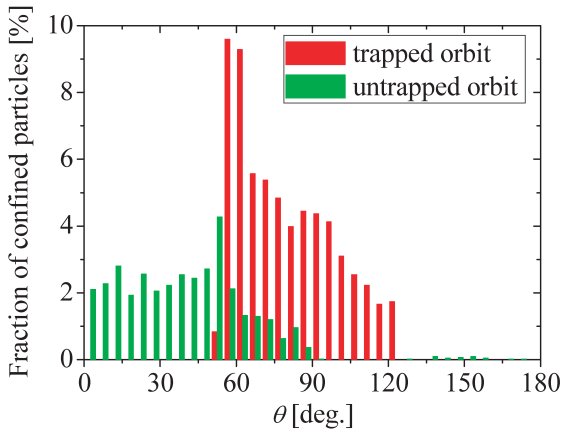

Fig. 6 Fraction of the number of alpha-particles to number of total particles as a function of pitch angle in region $r_0 \geq$ 150.

In Fig. 7, we next show the fraction of the number of lost ions as a function of r_0. The fraction of ions lost from the trapped orbit is indicated by red rectangles and ones lost from the untrapped orbit is shown by green rectangles. In this calculations, the First-Orbit (FO) loss ions, i.e., ions lost within the one troidal-periodic motion, is neglected. This is because that the FO loss is independent of the particles orbit. It is found that most of the alpha-particles are

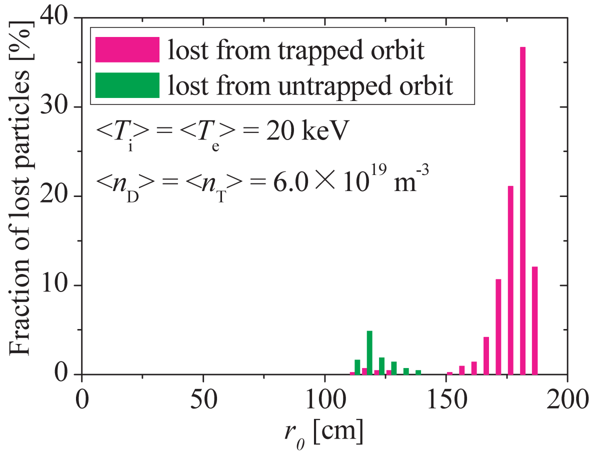

Fig. 7 Fraction of the number of lost particles to total lost particles as a function of r_0 (except FO loss).

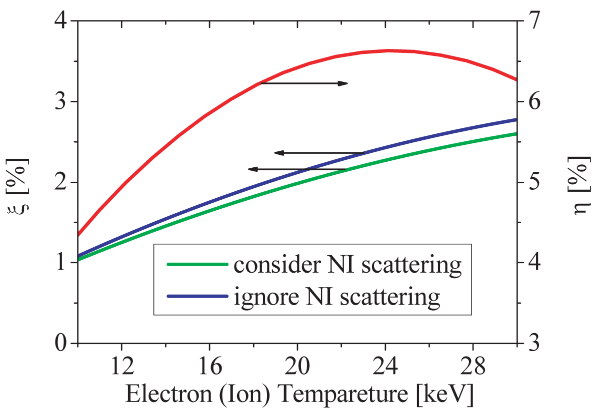

Fig. 8 Fraction ξ of energy lost from the plasma to initially generated and degree of decreasing η from the value when NI scattering ignored as function of temperature.

lost from the trapped orbit at outer region in the poloidal plane. This is because that particles moving on the trapped orbit are strongly affected by the toroidal field ripple [12]. For example, at 20 keV temperature, the fraction of ions lost from the trapped orbit except FO loss is evaluated as 91%.

From the above discussion, we can say that most of the ions are lost from the trapped orbit, and the NI scattering tend to reduce the fraction of ions moving on the trapped orbit.

3.3 Reduction of energy loss due to NI scattering

In Fig. 8, (a) fraction of the energy lost from the plasma to the one initially generated, i.e., ξ, and (b) the degree of the increment of ξ from the value when NI scattering is ignored ξ_0, i.e., $\eta = (\xi_0\text{-}\xi)/\xi$, are shown. Because the slowing-down effect via Coulomb scattering is weakened at the high temperature range, magnitude of the energetic alpha-particle component is relatively increased at the high temperature range. The energetic alpha-particles are more difficult to confine in the magnetic field compared with the low energy ones. Thus the ξ value increases in high temperature range. When NI scattering is ignored, slowing-down effect of energetic ions is underestimated, and energetic component in alpha-particles distribution is overestimated compared with the case when NI scattering is considered. When NI scattering is ignored, hence the ξ value tends to have large values over all the temperature range compared with when NI scattering is considered. When T = 24 keV temperature, energy loss from the plasma is overestimated by about 6.5% when the NI scattering is neglected.

The degree of the overestimation of the energetic component in the slowing-down distribution function when NI scattering is ignored was evaluated on the basis of the BFP model [7]. In the previous study, however, the overestimation is caused by the reduced energetic distribution function due to the accelerated slowing-down by NI scattering. In the BFP simulation, the effect of the orbit transition caused by the NI scattering (discussed in Figs. 6 and 7) has not been considered. The degree of the overestimation shown in the present study, i.e., η value in Fig. 8, reaches almost twice compared with the previous result obtained by the BFP simulation [6]. The difference in the evaluation would be caused by the orbit transition due to the NI scattering.

4. Conclusion

The NI scattering effect has been incorporated into the alpha-particle orbit simulation. We have newly pointed out that the NI scattering changes the pattern of the alpha-particle orbit in the magnetic confinement plasma and as a result of the orbit transition the loss energy during the slowing-down process is reduced. In the subsequent step, effect of the NI scattering on other plasma properties, e.g., bootstrap current, should be examine.

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