24E08

Nuclear plus interference scattering and energetic-ion slowing-down distribution function in reactor-grade plasmas

炉心プラズマにおける高速イオンの核弾性散乱と減速分布関数

Hideaki Matsuura, Daisuke Sawada and Yasuyuki Nakao
松浦 秀明、澤田 大輔、中尾 安幸

Applied Quantum Physics and Nuclear Engineering, Kyushu University
744 Motooka, Fukuoka 819-0395, Japan
九州大学、エネルギー量子工学部門 〒819-0395 福岡市西区元岡744

Effect of the nuclear plus interference (NI) scattering on slowing-down distribution functions of energetic-ions, e.g., protons produced by ^{3}He(d,p)^{4}He reactions, alpha-particles produced by T(d,n)^{4}He reactions and deuterium beam injected into DT plasmas, are examined on the basis of the Boltzmann-Fokker-Planck (BFP) model. As a result of the acceleration of the slowing-down process of energetic ions due to NI scattering, the magnitude of the energetic component is relatively reduced compared with the case when NI scattering is ignored. The degree of the reduction and its energy range are quantitatively evaluated for various plasma conditions.

1. Introduction

It is well known that fast ions slow down via Coulomb and non-Coulombic, i.e. nuclear plus interference (NI) [1], scattering and create knock-on tails in fuel-ion distribution functions. Effect of the knock-on tail formation on plasma burning characteristics [2] and its application to plasma diagnostics [3,4] have been examined. The NI scattering accelerates slowing-down process of fast ions and enhances the fractional energy deposition from fast to bulk ions [5]. So far, many studies concerning to the NI-scattering effect on plasma burning characteristics have been made, however, the most of the previous discussions have been focused on the effect on distortion of the “bulk” component in fuel-ion distribution functions and also on the transferred energy from fast to bulk ions. When the bulk ions are knocked up to the high-energy region, the fast ions also ought to lose large fraction of their energy. When NI scattering is ignored, the transferred energy per unit time from fast to bulk ions is underestimated (slowing-down time is overestimated) and the relative magnitude of the suprathermal to bulk distribution components must be overestimated compared with the case when NI-scattering effect is considered.

Recently we examined the correlation between the slowing-down time and the magnitude of the equilibrium slowing-down distribution function of fast alpha-particles in deuterium-tritium (DT) plasmas [6]. It was shown that in high-density, low-temperature range, the slowing-down time becomes shorter and energetic component of the alpha-particle distribution function relatively decreases, which may reduce the instability excitation probability caused by the fast alpha-particles in the Alfvén velocity range.

The slowing-down time of the fast ions also decreases owing to the NI scattering. In such a case the loss fraction of fast ions during slowing-down process may also be reduced. It is important to grasp the reduction of the fast-ion slowing-down distribution function due to NI scattering. In this paper, on the basis of the Boltzmann-Fokker-Planck (BFP) simulation [7], effect of the NI scattering on fast-ion slowing-down distribution function is evaluated. As fast ions, alpha-particles produced by the T(d,n)^{4}He reactions, protons by the ^{3}He(d,p)^{4}He reactions or deuterium beam injected into plasma is considered. A noticeable reduction in the fast ion population in confined plasma is shown. The effect of the reduction on fast-ion loss process is discussed.

2. Analysis Model

The Boltzmann–Fokker–Planck (BFP) equation for fast ions, i.e., protons produced by ^{3}He(d,p)^{4}He reactions, alpha-particles produced by T(d,n)^{4}He reactions and deuterium beam injected into DT plasmas. As background-particle species, main fuel ions and electrons, i.e., deuterons, ^{3}He (triton), and electrons in D^{3}He (DT) plasma, are considered. In this study, for simplicity, the background ions and electrons are assumed to be Maxwellian with the same temperature. We consider the NI scattering [8] of fast ions only by background main-fuel ions. The NI cross sections are taken from the work of Perkins and Cullen [8].

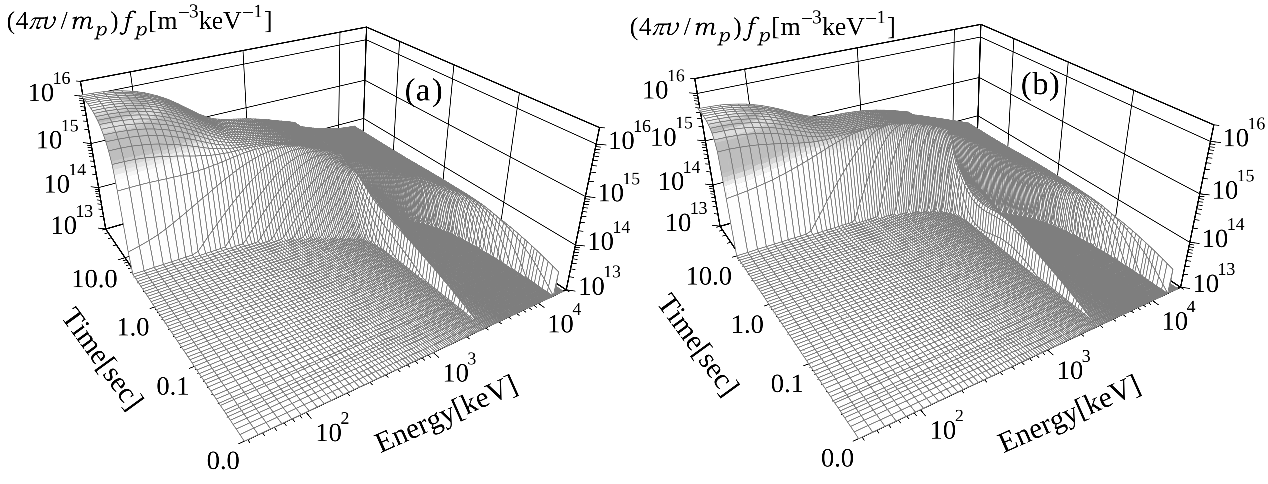

Fig.1 Time evolution of proton distribution functions when (a) NI scattering is considered and (b) ignored. In the calculations, $T_i = T_e = 80\,\mathrm{keV}$, $n_D = 2n_{3He} = 10^{20}\,\mathrm{m}^{-3}$ and $\tau_E = (1/2)\tau_p = 3\,\mathrm{s}$ are assumed.

3. Results and Discussion

In Fig.1 (a) and (b) temporal behaviors of the proton distribution functions in a typical D^3He plasma, i.e., $T_i = T_e = 80\,\mathrm{keV}$, $n_D = 2n_{3He} = 10^{20}\,\mathrm{m}^{-3}$ and $\tau_E = (1/2)\tau_p = 3\,\mathrm{s}$, when (a) NI scattering is considered and (b) ignored are shown. We assume that proton generation by ^{3}He(d,p)^{4}He and D(d,p)T fusion reactions begins at t = 0. During the simulations, the fuel-ion densities, electron temperature and energy (particle) confinement time are kept constant. The slowing-down distribution is formed gradually and at 50 s after the beginning of the simulation, it reaches a near equilibrium state. When NI scattering is ignored, the proton distribution function changes its shape more slowly toward the equilibrium state. Note that in the equilibrium state, the relative magnitude of the bulk and suprathermal distribution components are influenced by the NI scattering significantly. In Fig.2 the equilibrium distribution functions when (a) NI scattering is considered and (b) ignored are shown. When the NI scattering is ignored, the magnitude of the distribution function is 50 ~ 70 % larger in the energy range from 2 to 8 MeV. The fast-ion loss fraction during the slowing-down process and Alfvén instability excitation probability would be predicted to depend on the magnitude of the slowing-down distribution function. By considering the NI-scattering effect adequately, the fast-ion loss and instability excitation may be reduced. Further detailed analysis is required. At the presentation, we also discuss the NI scattering effect on the slowing-down distribution function of alpha-particles and injected deuterium beam in DT plasmas.

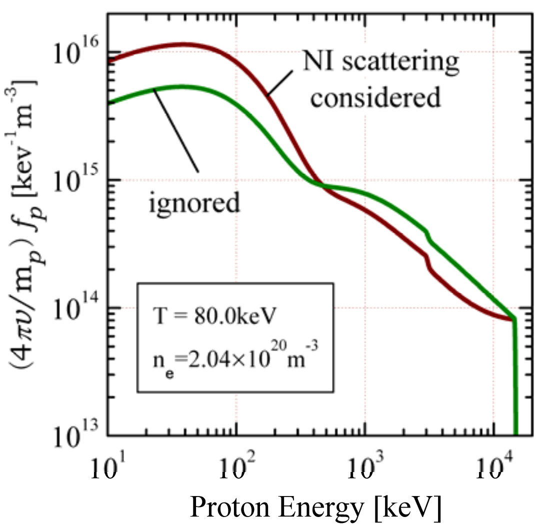

Fig.2 Equilibrium proton distribution functions when (a) NI scattering is considered and (b) ignored.

References

[1] J.J. Devaney and M.L.Stein, Nucl. Sci. Eng. **46** (1971) 323.

[2] H.Matsuura, et al., Plasma Phys. Controlled Fusion, **53** (2011) 035023.

[3] R.K.Fishier, et al., Nucl. Fusion **34** (1994) 1291.

[4] L.Ballabio, G. Gorini, J. Källne, Phys. Rev. E **55**, (1997) 3358.

[5] Y. Nakao, et al., Nucl. Fusion **28** (1988) 1029.

[6] H.Matsuura, et al., Plasma Fusion Res. **6** (2011) 2405086.

[7] H.Matsuura, et al., Phys. Plasmas **13** (2006) 62507.

[8] S.T.Perkins, D.E.Cullen, Nucl. Sci. Eng. **77** (1981) 20.