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Study of pitch-angle-scattering spectrum of high-energy ions in the Large Helical Device

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Abstract

The perpendicular spectrum of high-energy particles originally injected tangentially was measured using a neutral particle analyzer (NPA) based on a natural diamond detector (NDD) in the Large Helical Device (LHD). The steady state spectrum showed the dependence on the magnetic configuration, indicating the effect of the orbit loss. An analytical asymptotic solution of the Fokker-Planck equation, taking into account collision terms of coulomb interaction, the fast-ion source term and the orbit loss of the helically trapped and transition particles, is proposed.

Introduction

As neutral beam injection (NBI) heating is one of the main methods of plasma heating, it is important to investigate the characteristics of high-energy ions confined in a magnetic configuration. In helical systems, ion orbits are classified into five orbits judging from trajectory patterns of drift motions (passing orbit, helically trapped orbit, transition orbit, locally trapped orbit and lost orbit). Passing ions have been shown to be well confined in a heliotron configuration and tangential NBIs were employed in the Large Helical Device (LHD) [1]. The perpendicular energetic ions have also been studied extensively by spectrum measurement of energetic neutrals, which were originally accelerated perpendicularly by Ion Cyclotron Radio Frequency waves [2]. It was concluded that the helically trapped ions were also stable for about 100 ms when their drift surface matched a magnetic flux surface R_{ax}= 3.6 m [3,4]. Using a neutral particle analyzer (NPA) based on a natural diamond detector (NDD), we measured the perpendicular flux and spectrum of high-energy particles originally injected tangentially. In the

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present paper, the dependence of defected flux and spectrum on the position of magnetic axis (R_{ax}) are discussed to investigate the effects of transition orbit lying between the passing and helically trapped orbits on a χ (pitch angle) – ρ plane.

Experimental Results

Since the first application of ICRF-heating on LHD in 2000, a natural diamond detector installed on a perpendicular port with major radius, R = 3.676m, nearly viewing the magnetic axis, has been used to measure energetic neutral particles. In the present study, however, only tangential hydrogen neutral beams of 180 keV were injected from two injectors—one in the counter and one in the co-direction. The typical injected power was about 1 MW for each. The co- and counter beams were injected over 0.3–2 s and over 1.3–3.3 s, respectively. The NDD spectrum was sent to the histogram memory every 10 ms, but they were summed for three time durations (co-beam beam region, balanced beam region and counter beam region) when they were stable during each shot. Gas puffing was controlled so that wide ranges of density and collisionality were possible.

Fig. 1 shows a typical example of the NDD spectrum. The spectrum was corrected with a factor of $<\sigma_{cx} v>$, where σ_{cx} is the charge exchange cross-section between H^+ and H^0, to convert it to an ion spectrum. As reported in our previous paper [6], the neutral particle density $n^0(r)$, which is responsible for neutralisation, attenuates steeply when diffused into the central region, while the deposition profile of beam particles, $n^B(r)$, peaks at the core, and the profile of the product, $n^B(r)* n^0(r)$, shows a rather flat distribution, and weak dependence on the density at $\rho <$ 0.8 a. The measured ion spectra were compared with a stationary solution of the Fokker-Planck equation, $f_{FP}(v) = \frac{S_0}{4\pi}\frac{\tau_s}{v^3 + v_c^3}$, where $\tau_s = \frac{53.6\varepsilon_0^2 m_i^{3/2} T_i^{3/2}}{n_i Z_i^4 e^4 \ln\Lambda}$, $v_c = \frac{3\sqrt{2\pi} T_e^{3/2} Z^b}{2 m_i m_e^{1/2}}$ and S_0 is the source rate of beam particles. The normalisation factor of measured neutral flux to the latter at 31.6 keV, shown as A in Fig. 1, is plotted in Fig. 2 as a function of τ_d for three magnetic configurations of R_{ax} at 3.6, 3.75 and 3.53 m. Here, τ_d is the deflection time, $\tau_d = \frac{2\pi\varepsilon_0^2 m_i V^3}{n_i e^4 Z_i^4 \ln\Lambda}$, estimated at 180 keV. This factor represents the survival probability of energetic ion if the neutral particle density does not vary shot to shot. As shown in Fig. 2, the survival probability decreases steeply as τ_d increases, indicating that energetic ions suffer from loss during the deflection. The spectrum shown in Fig. 1 shows much faster decay than the stationary solution of the Fokker-Planck equation, $f_{FP}(v)$. In Fig. 3 were plotted a ratio of measured counts at 82 keV to $A*f_{FP}(v)$. The ratio is ranging between 0.01 and 0.1, depending on the magnetic configuration. The results of R_{ax} = 3.75 m decayed faster than the others, indicating that the loss during defection was the most severe.

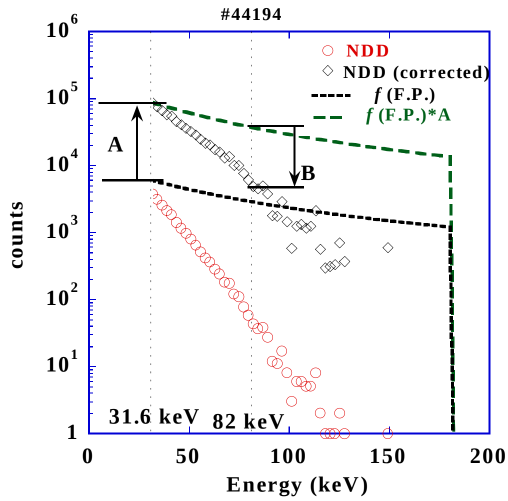

Fig. 1 Typical example of NDD spectrum and that of stationary solution of Fokker-Planck equation.

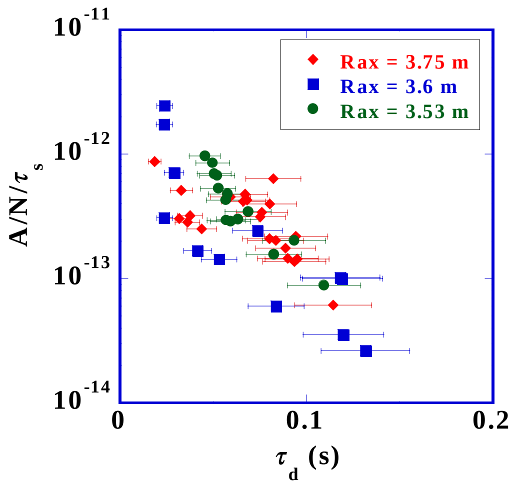

Fig.2 The dependence of survival probability (A/N/τ_s) of ions on deflection time. Survival probability decays steeply with the increase of deflection time. The difference of magnetic configurations is not observed.

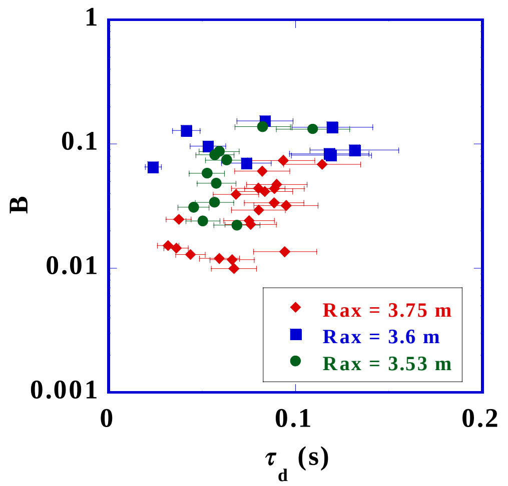

Fig. 3 The dependence of on deflection time. The value B of R_{ax} = 3.75 m is lower than those of R_{ax} = 3.6, 3.53 m.

Theoretical Considerations

The velocity distribution function of ions can be obtained with a Fokker-Planck equation,

$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\nabla f + \frac{e}{m}\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)\cdot\frac{\partial f}{\partial \mathbf{v}} = \left(\frac{\partial f}{\partial t}\right)_C + \left(\frac{\partial f}{\partial t}\right)_S + \left(\frac{\partial f}{\partial t}\right)_L$$

where, the first, the second, and the third term of the right are the collisional, the source, and the loss terms. In the present work, the loss term was assumed to originate from the loss boundary of the trapped particle and transition particle [6,7]. The Fokker-Planck equation can be expressed as follows [8,9];

$$\tau_s \frac{\partial f}{\partial t} = \frac{1}{v^2}\frac{\partial}{\partial v}\left(v^3 + v_c^3\right)f + \frac{Z_{eff} v_c^3}{2v^3}\frac{\partial}{\partial \xi}\left(1-\xi^2\right)\frac{\partial f}{\partial \xi} + \tau_s S_0 \delta(v - v_b)\delta(\xi - \xi_b)H(t)$$
$$-\frac{\tau_s}{\tau_{cx}(v)} f - H(\lambda_a - \lambda_0)H\left(1-k_0^2\right)f - H(\lambda_0 - \lambda_b)H\left(k_0^2 - 1\right)f \, .$$

Expanding the velocity distribution function in a series of Legendre polynominals in ξ,

$f(v,\xi,t) = \sum_{l=0}^{\infty} f_l(v,t)P_l(\xi)$, and $S(v,\xi,t) = \sum_{l=0}^{\infty} S_l(v,t)P_l(\xi)$, then the solution is expressed as

$$f(v,\xi,t) = \frac{S_0\tau_s}{v^3 + v_c^3} H\left[t - \frac{1}{3}\tau_s \ln\left(\frac{v_b^3 + v_c^3}{v^3 + v_c^3}\right)\right]$$
$$\times \exp\left[-\tau_s \int_v^{v_b} \frac{v^2}{v^3 + v_c^3}\left(\frac{1}{\tau_{cx}} + H(\lambda_a - \lambda_0)H\left(1-k_0^2\right) + H(\lambda_0 - \lambda_b)H\left(k_0^2 - 1\right)\right)dv\right].$$
$$\times \sum_{l=0}^{\infty} \frac{1}{2}(2l+1)P_l(\xi)P(\xi_b) \times \left[\frac{v^3}{v_c^3}\left(\frac{v_b^3 + v_c^3}{v^3 + v_c^3}\right)\right]^{\frac{1}{6}l(l+1)Z_{eff}} H(v_b - v)$$

The numerical calculation is currently in progress, and the results will be compared with the observed spectra.

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