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Measurement of the Energetic Particle in NBI Plasmas of Heliotron J

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Abstract

The behavior of energetic particles is investigated with a charge-exchange neutral particle energy analyzer (CX-NPA) system in Heliotron J. In the tangential neutral beam injection (NBI) experiments, the high energy tail component up to 20 keV is observed in proton energy spectrum. The dependence of the energetic particle confinement on the magnetic configuration is studied with regard to one of the Fourier spectrum of the magnetic field, bumpiness. The decay time of CX-flux after the termination of NBI decreases with increasing the bumpiness component.

Keywords:

Heliotron J, particle confinement, neutral beam injection, charge-exchange neutral particle measurement, configuration effect

1. Introduction

In magnetized fusion plasmas, study of the energetic particle confinement and the ripple transport is important subject not only for the production of high performance plasma but also for the reduction in damage to the wall materials through plasma-wall interactions. From the viewpoint of the wave-plasma interactions, the energetic particle transport is closely related to the magnetohydrodynamic (MHD) instabilities [1].

The energetic ion behavior in helical systems strongly depends on the magnetic configuration due to its asymmetry. In the planar axis heliotron configuration, such as Heliotron E, particle confinement can be improved when the magnetic axis is shifted inwardly. However, this magnetic configuration has a rather magnetic hill and clear MHD instabilities are observed [2]. In a helical-axis heliotron configuration device, Heliotron J, a high level compatibility between the good particle confinement and the MHD stability has been studied to explore the concept of helical-axis heliotron configuration [3]. The MHD stability in low shear helical systems is mainly provided by a magnetic well. In Heliotron J, a vacuum magnetic well is formed in the entire plasma region. On the other hand, the theoretical analysis predicts that the variety of the magnetic field strength along the toroidal direction (toroidal mirror ratio), bumpiness component in Boozer coordinates [4], plays an important role in the energetic particle transport in the helical-axis heliotron configuration [5]. In Heliotron J, the bumpiness component is comparable to main helical field component but with the opposite sign, which is considered to be effective in suppressing neoclassical ripple transport. Then, the investigation of the effect of the magnetic field configuration, in particular bumpiness, on the energetic particle transport is an important subject. In this paper, we report the experimental results on the behavior of energetic particles produced by neutral beam injection (NBI) in Heliotron J plasmas [6]. The confinement of the energetic particles is discussed in the bumpiness control experiments in conjunction with numerical calculation.

2. Experimental set-up

Heliotron J is a medium sized plasma experimental device with an $L/M = 1/4$ helical coil ($R_0/a = 1.2\,\mathrm{m}/0.17\,\mathrm{m}$, $B_0 < 1.5$ T). The magnetic configuration can be controlled over a wide range by changing the current ratios in the coil system of the device. Two sets of toroidal field coils with different coil currents are equipped to control the bumpiness component.

The experimental set-up of the neutral beam injection (NBI) and charge exchange neutral particle analyzer (CX-NPA) systems is shown in Fig. 1. Hydrogen

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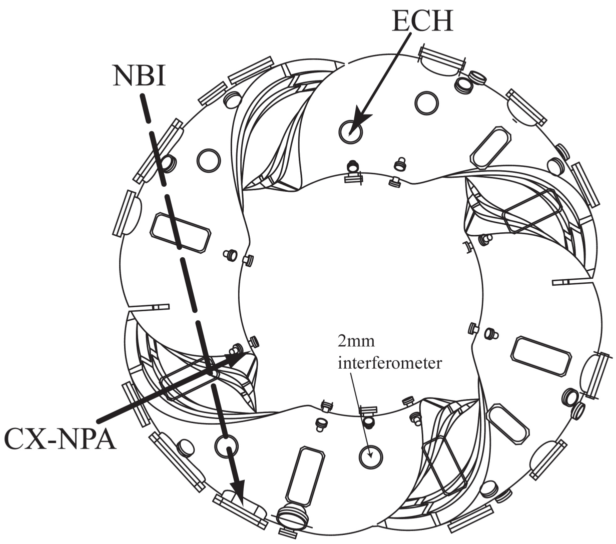

Fig. 1 Experimental set-up of NBI and CX-NPA systems.

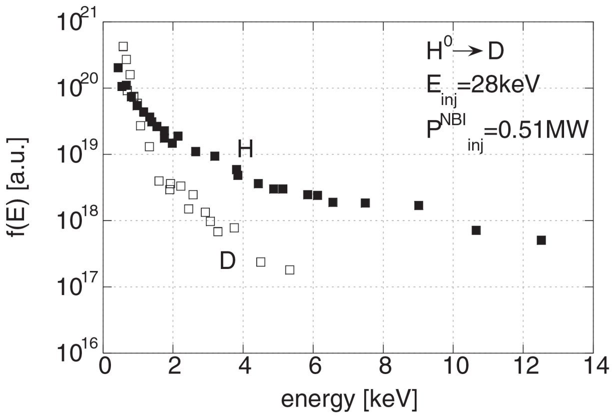

Fig. 2 Energy spectra measured with CX-NPA in NB injection into deuterium plasma.

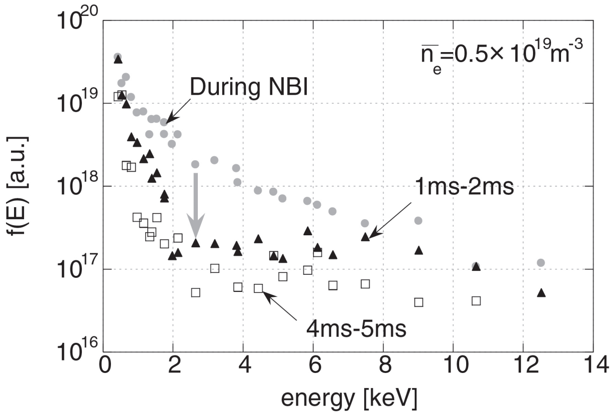

Fig. 3 The energy spectra at 1 – 2 ms, 4 – 5 ms after termination of NBI. The energy spectra during NBI are also shown.

beams are injected in the tangential direction with the maximum acceleration voltage of 30 kV and the maximum power of 0.7 MW. The ion energy distribution functions are measured with a CX-NPA system [7]. The CX-NPA system is an $E//B$ type one which can measure the hydrogen and deuterium neutral atoms separately and has energy ranges from 0.4 to 80 keV (hydrogen) and from 0.2 to 40 keV (deuterium), respectively. In the standard configuration of Heliotron J (rotational transform $l/2\pi = 0.56$ at last closed flux surface), the chord of CX-NPA crosses the plasma center. The pitch angle of detective particle on the magnetic axis is 68 degree that corresponds to a passing particle in the standard configuration of Heliotron J.

3. Experimental results

3.1 NBI heating experiment

The injection experiment of the hydrogen neutral beam into deuterium plasmas has been carried out. Figure 2 shows the ion energy spectrum measured with the CX-NPA system in the case that the beam energy and injected power are 28 keV and 0.51 MW, respectively. In the hydrogen spectrum, a clear high energy tail component up to 20 keV is observed. In the deuterium spectrum, energetic particles up to 5 keV are observed and the bulk ion temperature is estimated to be 0.3 keV. Since the present CX-NPA system can not detect the CX-flux having the same pitch angle as the injected neutral beam, the full and one half energy components of the injected beam are not observed clearly. However a small ”shoulder” in the hydrogen spectrum in 7 to 9 keV. This ”shoulder” may be attributed to one third energy (9.3 keV) component.

Figure 3 shows the energy spectra from 1 to 2 ms, and from 4 to 5 ms after the NBI turned off. The line averaged electron density is 0.5×10^{19} m^{-3}. The decay of CX-flux in energy range from 2 to 6 keV is faster than in the other energy ranges. In this energy range, the 1/e decay times of CX-flux are about 1 ms. On the other hand the decay time of CX-flux at 7 keV is about 2.5 ms. However, the non-collisional orbit calculation of guiding center predicts that the loss time of the ions in energy range from 2 to 6 keV is longer than that of higher (> 7 keV) energy ranges. For example, the loss times averaged in detection area of CX-NPA are 1.8 and 0.8 ms for ions having energy of 5 keV and 7 keV, respectively. The calculation result is not consistent with the experimental result. The detail explanation of the calculation is described in the next subsection. One candidate of the mechanism of faster decay in energy range from 2 to 6 keV is the effect of radial electric field. In helical systems, radial electric field plays an important role in the particle confinement in this energy range. If a radial electric field exist and poloidal drift due to the $E_r \times B$ drift cancel the poloidal motion of the passing particles due to the rotational transform, passing particles will drift vertically out of the plasma because of the toroidal curvature drift. This effect is called "toroidal resonance" [8]. For instance, for toroidal resonance of 2 keV ions with pitch angle of 70 degree, a potential of about 0.8 kV at the plasma center is required. The measurement of the radial electric field experimentally and further analysis with regard to the numerical calculation for the energetic particles taking account of the effect on the radial electric field are needed for the future work.

3.2 Bumpiness control experiment

In order to investigate the dependence of the energetic ion confinement on the strength of the bumpiness component, the behavior of the CX-flux has been studied by changing the bumpiness component, B_{04}/B_{00} from 0.04 to 0.15. Here B_{mn} is the Fourier component of magnetic field strength in the Boozer coordinates where the subscript m/n denotes poloidal/toroidal mode numbers. In these configurations, the magnetic axis position ($\langle R \rangle = 1.2$ m), plasma volume ($V_p = 0.7\,\mathrm{m}^3$) and rotational transform ($l/2\pi = 0.56$) at LCFS are almost fixed. Figure 4 shows (a) energy spectra during NBI and (b) the time evolution of CX-flux with energy of 7.5 keV for several configurations with different bumpiness component. The electron density is almost kept constant in these discharges, then the ion collisionality is considered to be almost the same. In the case of $B_{04}/B_{00} > 0.08$, clear changes are observed in both the energy spectra and behavior of the CX-flux. In the energy spectra, high energy tail components decrease with increase the bumpiness component. The 1/e decay time of CX-flux after the NBI turned-off decreases with increase the bumpiness component. In the case of $B_{04}/B_{00} < 0.08$, no clear differences can be seen in the energy spectra and behavior of the CX-flux. To understand the experimental result, the non-collisional orbit calculation for ion guiding center is carried out. In this code, the drift orbit equation is solved in real coordinate. Figure 5 shows the loss time of the test particles launched along the chord of CX-NPA as functions of major radius and pitch angle, where the loss time is defined by the flight duration of the test particle to wall. At $B_{04}/B_{00} = 0.15$, the main part of the detection area of CX-NPA is dominated by the direct loss particles which have the loss time less than 0.5 ms, while at $B_{04}/B_{00} = 0.04$ and 0.08 CX-NPA observes the passing particles which have the loss time more than 10 ms. Then the decrease in the decay time with bumpiness component can be considered to be attributed to the change in the loss cone. However further analysis is needed with regard to the numerical calculation for the

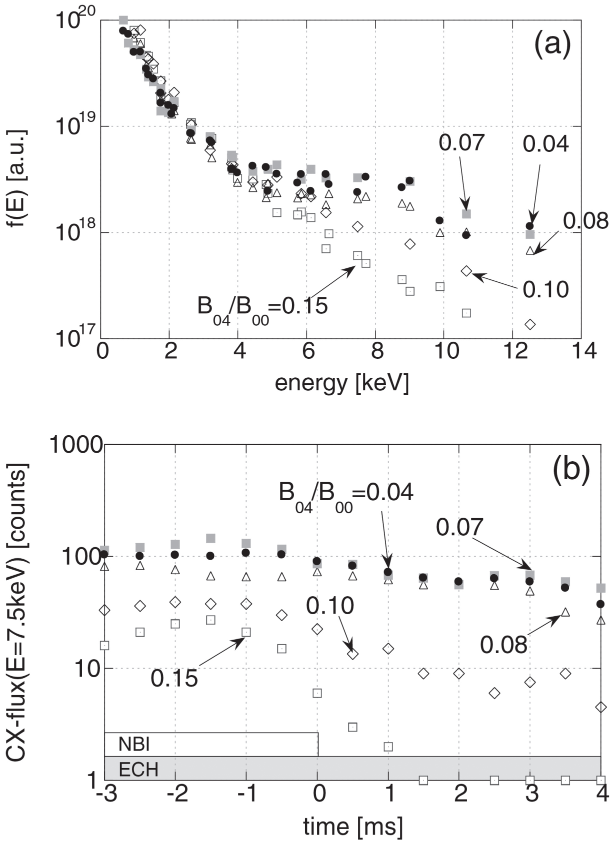

Fig. 4 (a) energy spectra during NBI and (b) the time evolution of CX-flux with energy of 7.5 keV measured in the bumpiness control experiment.

high energy particles taking account of the pitch angle scattering for the future work.

4. Summary

The behavior of the energetic particle is investigated in Heliotron J.

When the hydrogen NB is injected into deuterium plasmas, high energy protons up to 20 keV and deuterium up to 5 keV are observed, while the bulk (D) ion temperature is estimated to be 0.3 keV. The decay of CX-flux having energy ranges from 2 to 6 keV after the termination of NBI is faster than in the other energy ranges. The faster decay may be due to the radial electric field. The dependence of the energetic particle confinement on the bumpiness component is examined in the range of B_{04}/B_{00} from 0.04 to 0.15. The high energy tail components ($E > 5$ keV) in the energy spectra decrease and the 1/e decay time of CX-flux after the NBI turn-off decreases with increasing the bumpiness component. The non-collisional orbit calculation for ion guiding center predicts that the main part of the detection area of CX-NPA is dominated by the direct loss particles in the high bumpiness case, while CX-NPA can observe the passing particles in the low bumpiness case. Since the behavior of the energetic particles

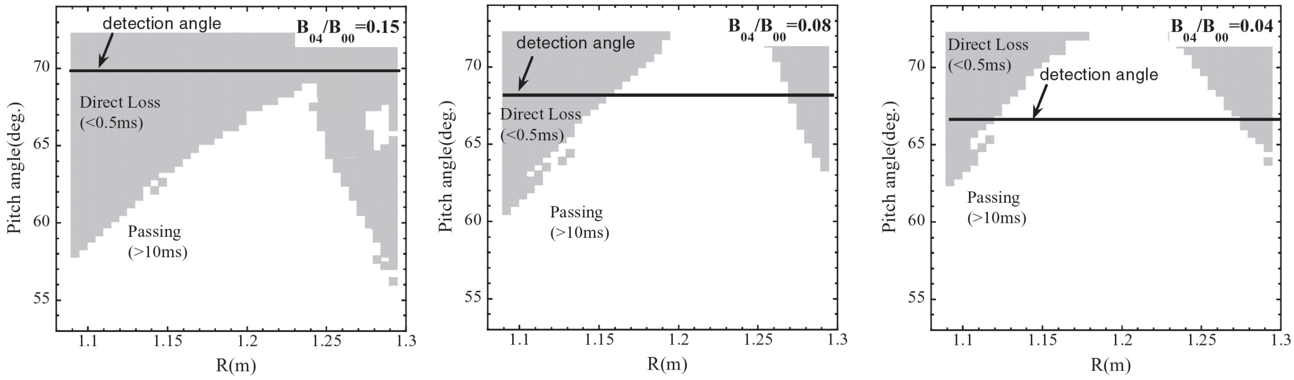

Fig. 5 Result of non-collisional orbit calculation for proton having energy of 7.5 keV in the case of B_{04}/B_{00} = 0.04, 0.08, and 0.15. Detection angle of CX-NPA is also shown.

has strong dependence on the pitch angle, observation of the pitch angle distribution is necessary for more detailed discussion.

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