31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-5.104 (2004)

Experimental study of high energy particle confinement in Heliotron J

M. Kaneko[1],S. Kobayashi[2], Y. Suzuki[1], T. Mizuuchi[2], K. Nagasaki[2], H. Okada[2], Y. Nakamura[1], K. Hanatani[2], S.Murakami[3], K. Kondo[1], and F. Sano[2]

[1]*Graduate School of Energy Science, Kyoto University, Gokasho, Uji 611-0011, Japan*
[2]*Institute of Advanced Energy, Kyoto University, Gokasho, Uji 611-0011, Japan*
[3]*Graduate School of Engineering, Kyoto University, Kyoto 606-8501, Japan*

1. Introduction

The confinement of high energy ions is a issue for the prospect to steady state helical reactor. In the planar axis configuration, such as Heliotron E, particle confinement can be improved for a magnetic configuration with the magnetic axis shifted inward. However, this magnetic configuration has a rather magnetic hill and clear MHD instabilities are typically observed[1].

In Heliotron J[2], to overcome the limitation of the planar axis configuration, helical-axis heliotron configuration is adopted, and the high level compatibility of the good particle confinement and MHD stability has been studied to explore the concept of optimization of helical-axis heliotron configuration. From the theoretical calculation, it has been pointed out that controlling Fourier components of magnetic field plays a key role in the particle confinement[3]. In this paper, we report the experimental results on the behavior of high energy particles in Heliotron J plasmas. The confinement of the high energy particles is discussed with regard to a Fourier component of the magnetic field, toroidal mirror ratio (bumpiness component).

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 m / 0.2 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. In particular, the bumpiness component can even change its sign by controlling the currents in the toroidal coils A and B separately, so that its role on confinement properties can be investigated over a wide range.

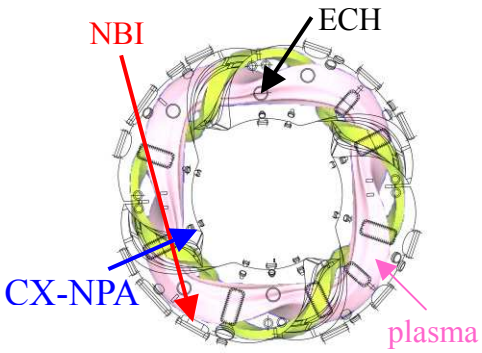

Fig.1 Experimental set-up in Heliotron J

For the purpose of plasma heating and study of

the high energy particle confinement, an NBI system has been installed in Heliotron J[4]. Hydrogen beams are injected in the tangential direction with the maximum acceleration voltage of 30kV and maximum power of 0.7 MW. In order to measure the ion energy distribution, a charge exchange neutral particle analyzer (CX-NPA) system has been installed[5]. The CX-NPA system is an E//B type one which has the detective energy ranges of 0.4-80keV for hydrogen and 0.2-40keV for deuterium. In the standard configuration of Heliotron J ($\iota/2\pi$ = 0.55 at LCFS), the chord of CX-NPA crosses the plasma center. The experimental set-up of the NBI and CX-NPA system is shown in Fig.1.

3. Experimental Results

3. 1 NBI heating experiment

The injection experiment of the 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, high energy 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 bean components (E, E/2, E/3) are not observed clearly. Figure 3 shows the energy spectra from 0 to 1ms (light blue), from 4 to 5 (blue), and from 7 to 8 ms (green) after the NBI turned off. The decay of the CX-flux having energy range of 2-3 keV is much faster than the other energy ranges. The non-collisional orbit calculation predicts that the loss time of the ion at 2 keV is longer than that of 5 keV. The calculation result is not consistent with the experimental result. The detail explanation of the calculation is described in the next subsection. Although the mechanism of this phenomenon is under investigation, it is considered that some loss mechanism might exist. One candidate for the loss mechanism is "toroidal resonance" [6], which occurs when the E×B drift cancels the poloidal motion of passing particles. For instance, for toroidal resonance of 2 keV ions with pitch angle of 70 degree, a potential of about 0.8 kV is required.

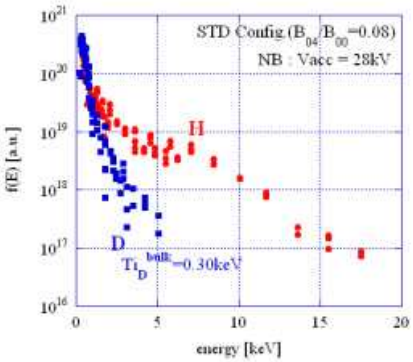

Fig.2 Energy spectra measured with CX-NPA in injection experiment of NB into deuterium plasma

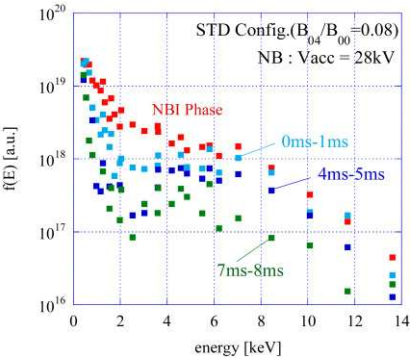

Fig.3 The energy spectrum at 0-1, 4-5, and 7-8 ms after NBI turned off. The energy spectrum in NBI phase is also shown.

3. 2 Bumpiness control experiment

In order to investigate the dependence of the high energy particle confinement on the bumpiness component, the behavior of the charge exchange neutral particle was studied by changing the bumpiness component, B_{04}/B_{00}, where B_{nm} is the Fourier harmonics of magnetic field strength in the Boozer coordinate having poloidal/toroidal mode numbers m/n, 0.04 to 0.15. In these configurations, the magnetic axis position (<R> =1.2 m), plasma volume (V_p = 0.7 m^3) and rotational transform ($\iota/2\pi$ = 0.55) at LCFS are almost fixed. Figure 4 shows the time evolution of CX-flux with energy of 7 keV. The horizontal axis shows the time from the NBI turned-off. In this scan, the electron density is almost kept constant, then the ion collisionality is considered to be almost the same. In the case of $B_{04}/B_{00} < 0.08$, difference in the behavior of CX-flux is not observed, while the 1/e decay time of CX-flux after the NBI turned-off decreases with increasing the bumpiness component in the case of $B_{04}/B_{00} > 0.08$. To understand the experimental result, the non-collisional orbit calculation for ion guiding center has been carried out. Figure 5 shows the loss time of the test particles launched on 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 CX-NPA observes the passing particles. At B_{04}/B_{00} = 0.08, CX-NPA observes the direct loss region. However, under this condition, passing particle can be deflected into detection area of CX-NPA ($\Delta\theta$ = 2.5 deg.) in 0.1 ms by the pitch angle scattering, which is less than the loss time, where $\Delta\theta$ is scattering angle in which the passing particle deflects to the detection area of CX-NPA. Then it is expected that

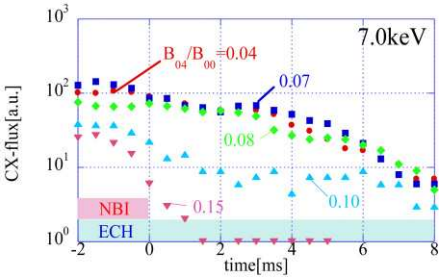

Fig.4 Time evolution of CX-flux having energy of 7 keV in the bumpiness control experiment.

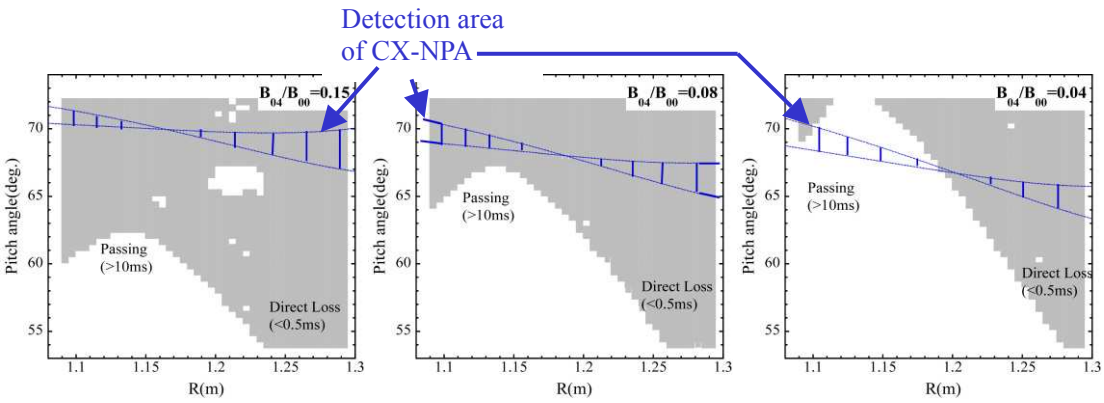

Fig.5 Result of non-collisional orbit calculation for proton having energy of 7 keV in the case of B_{04}/B_{00} = 0.04, 0.08, and 0.15. Detection area of CX-NPA is also shown.

CX-NPA can also observe the passing particles. On the other hand, at B_{04}/B_{00} = 0.15, CX-NPA can never observe the passing particles, since the deflection of passing particles toward the detection area of CX-NPA requires the scattering time of 1.5 ms. Then the decrease in the decay time with bumpiness component may be attributed to the change in the loss cone.

The dependence of the high energy particle confinement on the bulk plasma density is examined. Figure 6 shows time evolution of CX-flux (3.6 keV and 7.0 keV) for two density cases (0.8×10^{19}m^{-3} and 0.5×10^{19}m^{-3}). It was found that the decay time in the higher density case is longer than that in the lower density case. The mechanism of the dependence of decay time on density has not been clarified yet, further analysis is needed with regard to the numerical calculation for the high energy particles taking account of the pitch angle scattering for the future work.

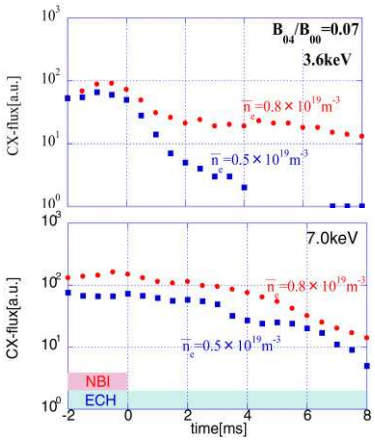

Fig.6 Time evolution of CX-flux (3.6 keV and 7.0 keV) for two density cases (0.8×10^{19}m^{-3} and 0.5×10^{19}m^{-3}).

3. Summary

The behavior of the high energy particle in Heliotron J, has been investigated. When the hydrogen NB is injected into deuterium plasmas, high energy protons up to 20 keV and deuterium up to 5keV are observed, while the bulk (D) ion temperature is estimated to be 0.3keV. The dependence of the high energy particle confinement on the bumpiness component (B_{04}/B_{00}) is examined in the B_{04}/B_{00} from 0.04 to 0.15. The 1/e decay time of CX-flux after the NBI turned-off decreases with increasing the bumpiness. 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 in the high bumpiness case, while CX-NPA observes the passing particles in the low bumpiness case. The present CX-NPA system cannot observe the trapped particles. Therefore, in order to investigate the effect of controlling the bumpiness component on the confinement of the trapped particles, the system is being upgraded for the pitch angle scan.

References

[1] T. Obiki, *et al*. Plasma Physics and Controlled Nuclear Fusion Research (1990) Vol.2 425
[2] T. Obiki, *et al*. Nuclear Fusion **41** (2001) 833
[3] M. Yokoyama, *et al*. Nuclear Fusion **40** (2000) 261
[4] S.Kobayashi, *et al.*, *Proc.14th Int. Stellarator Workshop*. (Greifswald,2003) **P.Tu12**
[5] M.Kaneko, *et al*., *Proc. 30th EPS Conf. Contl. Fusion Plas. Phys*. (St.Petersburg 2003) **27A**, 328
[6] K.Hanatani *et al*., *Proc. 14th EPS Conf. Contl. Fusion Plas. Phys*. (Madrid 1987) Part I, 396