Evaluation of Fast-ion Confinement with Three dimensional Magnetic Field Configurations on LHD

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The fast-ion confinement properties with the three dimensional magnetic field components are investigated by using the FICXS-diagnostics on LHD. The dependence of fast-ion confinement properties on the Fourier-components of magnetic fields are evaluated by changing the axes of magnetic configuration. The experimental observation qualitatively agrees with the theoretical prediction by GNET. This implies tPhe improvement of fast-ion confinement with the reduction of the sideband components. On the other hand, the improvement of fast-ion confinement with the toroidal mirror components was not observed clearly by the experiment although this might be due to the limitation of observation area with the observation geometry.

I. Introduction

Confinement of fast-ions is one of the most important issues in the magnetically confined fusion devices. Recently, it is recognized that non-axis symmetric ripple components of magnetic fields might affect the confinement properties of fast-ions in tokamak devices since the installations of the Test Blancket Modules (TBM) [1] and Resonant Magnetic Perturbation (RMP)-coils[2] break the axis symmetry of the configuration in ITER. The three dimensional (3D) ripple effect on fast-ion confinement is also a common problem in helical devices. Since the 3D component of magnetic field can be changed more drastically in helical devices than in tokamaks, the 3D-effects on fast-ion confinement properties can be more clearly investigated in helical devices.

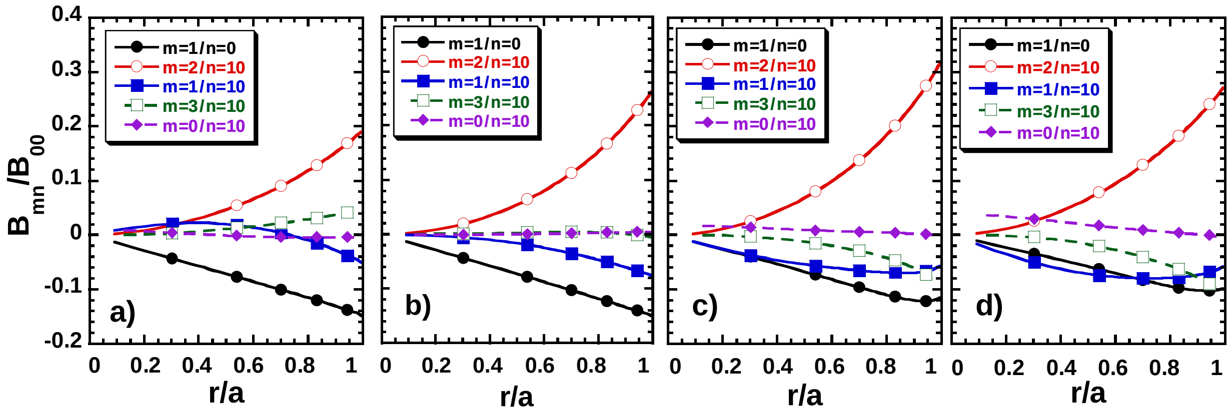

Fig.1 Fourier components of magnetic field strength of four different LHD-configurations are shown. The magnetic axes of the configurations are (a)Rax=3.9m (outwardly-shifted configuration), (b) 3.75m(standard configuration), (c) 3.6m (σ-optimized configuration) and (d) 3.53m(Neo-Classical: optimized configuration), respectively.

On the Large Helical Device (LHD), the magnetic field ripple components can be varied by changing the magnetic axis location of its configuration from inboard side to out board side. The change of their ripple components with the variation of magnetic axis location are shown in Fig.1. As shown in. Fig.1, LHD has two major Fourier components of magnetic field strengths. The one has the poloidal mode number (m) of 1 and the toroidal mode number (n) of 0. This component is often called as toroidicity. The other is the m=2/n=10 component. This is the main helical component of LHD since it consists of *l*=2 and M=10 helical coils. In addition to these components, two other components of m=1/n=10 and m=3/n=10, which are often called as "side bands" of the main helical components, have relatively large amplitudes. One of the most important change of its Fourier components is the decrease of the side bands with the shift of magnetic axes locations from the outboard side (R_{ax}=3.9m) to the inboard side (R_{ax}=3.6m). On the other hand, the toroidal mirror component (m=0/n=10) starts to increase as the magnetic axis shifts to father inboard side to Rax=3.53m. In Helitron-type devices, it is theoretically pointed out that the good confinement property of fast-ions can be achieved by changing its magnetic-axis from the outboard-side to the inboard-side [3]. The configuration of R_{ax}=3.6m corresponds to the σ-optimized configuration [4], where the neoclassical transport is significantly improved compared to the standard Heliotron configuration (Rax=3.75m in LHD). The configuration of Rax=3.53m is called as Neo-Classically (NC) optimized configuration where the neoclassical transport is optimized in LHD [5]. It was pointed out that the increased toroidal mirror component plays an important role in the reduction of transport at NC-optimized configuration [6]. To clarify the role of those ripple components on fast-ion confinement, it is necessary to investigate the confinement properties of fast-ions experimentally on each magnetic configuration of LHD.

2. Measuement of perpendicular fast-ions by fast-ion charge exchange spectroscopy

To evaluate the fast-ion confinement properties on LHD, the Fast-Ion Charge eXchange Spectroscopy (FICXS) was recently applied [7]. The Doppler shifted Hydrogen Balmer-alpha(H_α) lights are measured by using a radially injected neutral beam (NB) as an active neutral source of the diagnostics as similar to the Fast-Ion D-Alpha (FIDA) measurements on DIIID[8]. One of the advantages of this diagnostic is that it can obtain energy resolved spatial distribution of fast-ions. The radial-NB is also used as a source of fast-ions to evaluate their confinement properties on LHD. They have their kinetic energies mostly perpendicular to the magnetic field lines and are more sensitive to the magnetic ripples than parallel ones. Moreover, their normalized Larmour radii (r_L/a) in the LHD 2-3T operations are in the range of 1.6-2.4%, which are almost comparable to the radii of alpha particles in reactor relevant machines, such as ITER and FFHR[9]., where the symbol ‘a’ denotes the minor radius of the torus. Therefore, they can be used as test particles in bench-marking fast-ion simulation-codes.

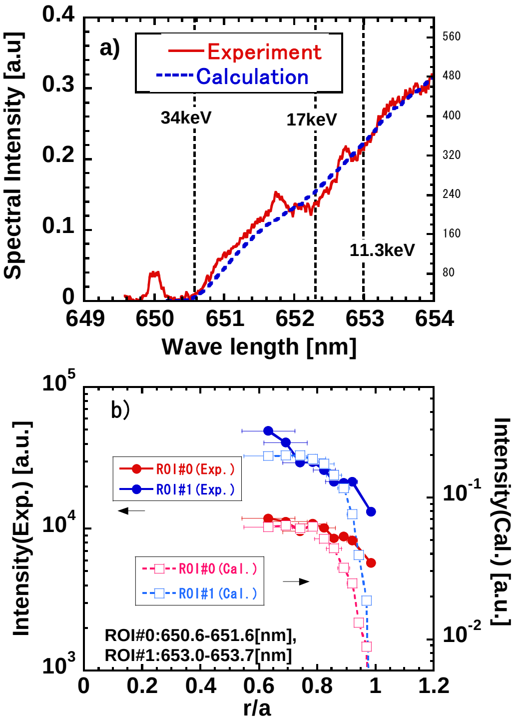

Fig.2 (a) Typical blue shifted H_α-spectra. solid curves are for the experiment and dashed curves are evaluated by calculations based on GNET simulation[6]. (b)Spatial distribution of blue shifted H_α-lights for two regions of interest in wave length (ROI#1 and #2).

In Fig.2(a), typical blue-shifted H_α spectra are shown for the σ-optimized configuration of LHD. In the figure, the vertical dashed lines indicate the expected wave lengths of Doppler shifted H_α for the full, the half, and the one third-component of Neutral Beam (NB) injection energy. The calculated spectrum well reconstructs the observed one. The spatial distributions for two wavelength regions of the spectra are shown in Fig.2(b). They correspond to the fast-ion distributions in two energy ranges. The experimental data are shown by circles and the calculated ones based on GNET simulations are shown in squares, where GNET is a Monte-Carlo simulation code which solves a drift kinetic equation in five-dimensional(5D) phase space (three dimensional in real-space and two dimensional in velocity space) in Boozer-coordinate[10]. Both distributions in two energy ranges agree fairly well. This indicates the good accuracy of GNET simulation in Fast-ion distribution calculation. The deviations of the calculation data points from the experimental ones are significant at the edge region. This is considered to be due to the too strict boundary conditions for the edge region in the simulation, where the boundary is set at r/a=1 since GNET is based on the Boozer-coordinate system.

3. Dependence of Fast-Ion confinement magnetic axis location.

The FICXS spectra for different magnetic configurations are shown in Fig.3. As shown in Fig.3, the spectra for both the NC-optimized configurations and the σ-optimized configuration configurations have steeper slope than the standard configurations both in experiment and simulation, while the spectra for outwardly-shifted configuration shows gentle slope than the standard one. The dependence of the spectral shape on the axes locations of the configurations agrees qualitatively between the experiment and the calculation. On the other hand, the intensity of the FICXS spectra for the standard configuration and the outwardly shifted configuration are much smaller in the simulation than in the experiment. Again, these differences in the intensities are also considered to be due to the Boozer coordinate since the drift surfaces of perpendicular particles are well agrees with the flux surface of LHD-plasmas for the σ-optimized configuration and the NC-optimized

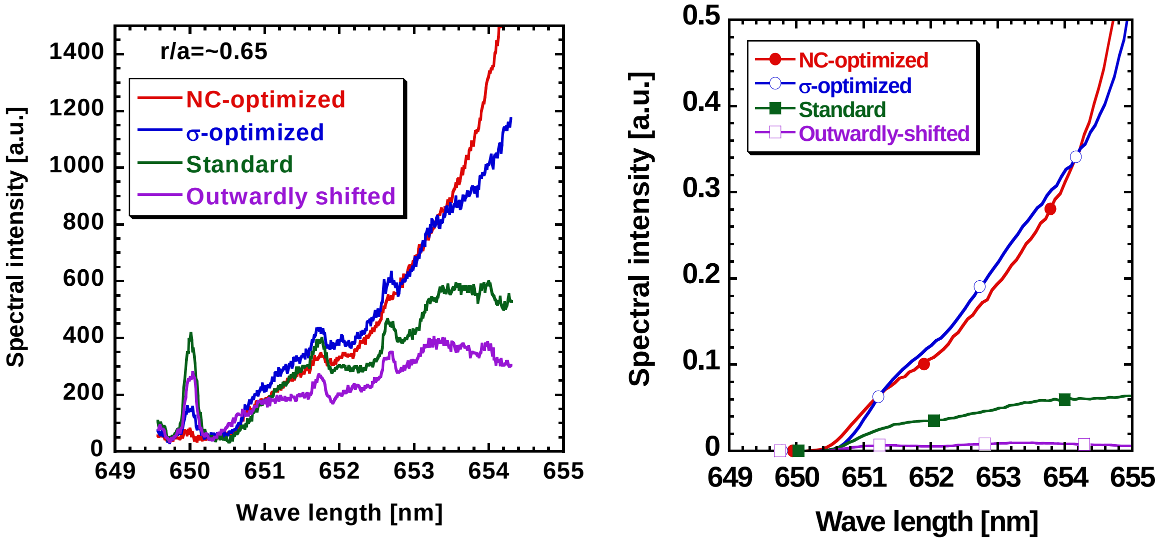

Fig.3 Magnetic configuration dependence of FICX spectra obtained by (a) experiment and (b) GNET-simulation

configuration, while the radial excursion of these particles from flux surfaces are significant for standard-configurations and outwardly shifted configurations [5]. The use of the Last Closed Flux Surface (LCFS) as a boundary of fast-ion orbit calculation seems to be too strict.

To verify the assumption, we have adopted the result of MORH (Monte-Carlo code based on Orbit following in the Real coordinate for Helical system[11]) was adopted for the analysis of FICXS. A basic concept of the MORH-code is similar to the OFMC-code [12]. One of the advantages of this code is that it can use the magnetic fields provided by the HINT-code[13,14]. Thus, MORH-code can handle various 3-dimensional magnetic configurations including the magnetic islands. In the code, the calculation boundary is set at the surface of the vacuum vessel, it can handle the particles which go out from the LCFS and re-enter to the LCFS. Figure 4 shows the evaluated FICX-spectra using the result of MORH-code. As shown in the figure, the intensity of the FICX-spectra for the outwardly-shifted configuration becomes about the half of the spectra for the σ-optimized configurations, which is comparable to the experimental results. This supports the idea that the calculation based on Boozer-coordinates system overestimates the loss of fast-ions. From the comparison of the estimated spectra, the numbers of the survived ions evaluated by the real-coordinate systems are about 2times larger for the standard-configuration and 10-20 times larger for outwardly shifted configuration than in the code based on the Boozer-coordinate. From the observed FICX spectra, it can be seen that the reduction of the side band helical-ripple component improves the confinement of fast-ions. On the other hand, the effect of mirror ripple components on the fast-ion confinement on LHD is not clear. This might be problems of the observation sight lines since the difference between NC-optimized configuration and s-optimized configuration is not clear both in GNET and MORH code.

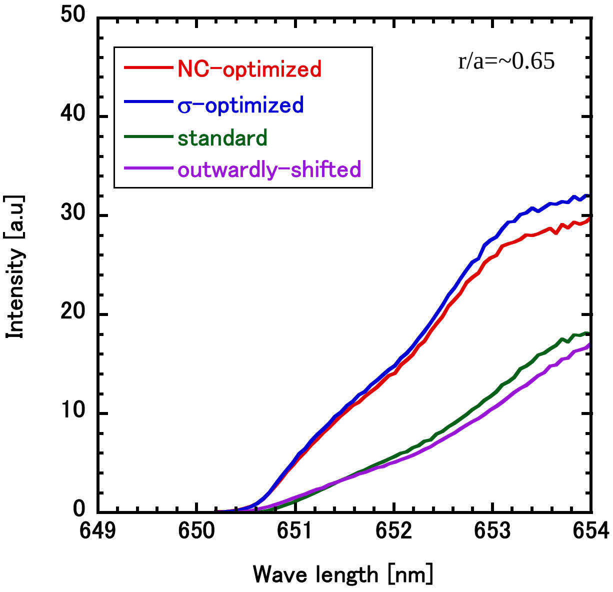

Fig.4 Eavluated FICX-spectra using the result of MORH-code.

4. Conclusion

The fast-ion confinement properties

with the three dimensional magnetic field components are investigated by using the FICXS-diagnostics on LHD. The dependence of fast-ion confinement properties on the Fourier-components of magnetic fields are evaluated by changing the axes of magnetic configuration. The experimental observation qualitatively agrees with the theoretical prediction by GNET. It is turned out that the GNET-code over estimates the fast-ion loss amount with the comparison of observed FICX-spectra to the evaluated spectra based on GNET-code. This is due to the too strict boundary condition of fast-ions by the Boozer-coordinate. The evaluation of FICX-spectra based on MORH-code confirms this fact. Qualitative agreement of the observed FICX-spectra to the theoretical prediction indicates the improvement of fast-ion confinement with the reduction of the sideband components. On the other hand, the improvement of fast-ion confinement with the toroidal mirror components was not observed clearly by the experiment although this might be due to the limitation of observation area with the observation geometry.

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