Energetic particle transport in NBI plasmas of Heliotron J

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Abstract

In Heliotron J, low magnetic shear configuration, a bursting global Alfvén eigenmode (GAE) has been observed in NBI plasmas under the condition that the energetic particle confinement was fairly good. Recently, a hybrid directional Langmuir probe (HDLP) system has been installed into Heliotron J to investigate the response of fast ion fluxes to the Alfvén eigenmodes. A high coherent response of the ion flux to the GAE bursts has been observed not only by the co-directed probe but also by the counter-directed one. A linear correlation between the response of the co-directed ion flux and the mode amplitude has been found. The radial profile of the response of co-directed ion has decreased with the minor radius and has not been obtained significantly outside last closed flux surface. These results indicate that the fast ion response is considered to be a resonant convective oscillation. The ion flux response of the counter-directed probe has appeared in the growth phase of GAE. Its phase relation has been different from that of co-directed one and magnetic probe located at the Heliotron J vacuum vessel. Two candidates of the detected ion flux of the counter-directed probe have been discussed.

1. Introduction

Energetic particle confinement is one of the most important issues in magnetically confined fusion devices, because burning plasma is mainly heated by the energetic particles produced by fusion reactions. In helical/stellarator magnetic configurations, since the magnetic field has the three-dimensional structure, it is important how to reduce the ripple loss of helically trapped particle. Study of the energetic-particle-driven MHD instability such as Alfvén eigenmode is also important issue since it may affect the transport of energetic particle as an anomalous loss through the consequence of the interaction with the instabilities. Thus the study of fast ion transport in the present experimental devices receives increasing attention. Mechanisms of the energetic ion losses in Alfvén eigenmodes of tokamak plasmas have been discussed from the viewpoint of the dependence of radial transport of the energetic ion on the magnetic fluctuations [1, 2]. To investigate the behavior of the energetic ion losses, lost-fast-ion probe technique has been developed in several torus devices. [3-5]. In Compact Helical Systems (CHS), a directional Langmuir probe method has been applied for fast-ion measurements and fast-ion behavior inside and outside of last closed flux surface (LCFS) [6,7].

In shearless helical/stellarator configurations such as W7-AS and Heliotron J, global Alfvén eighenmodes (GAE) have been a candidate of most unstable modes when fast ion pressure has became fairly high [8], which causes an anomalous transport of energetic ions.

Recently the directional probe system has been installed in Heliotron J in order to investigate the fast ion behavior in NBI heated plasmas [9]. In this study, we investigate the response of fast ion flux to the Alfvén eigenmode and its radial distribution. The characteristics of the ion fluxes by the co- and counter-directed probe are examined.

2. Heliotron J device and hybrid directional Langmuir probe system.

Heliotron J is the medium sized (R_0/a_p = 1.2m/0.17m) helical-axis heliotron device with an L/M = 1/4 helical winding coil, where L and M are the pole number of the helical coil and helical pitch, respectively [10, 11]. Figure 1 shows the bird's-eye view of Heliotron J including the coils and the heating systems. To achieve a flexible configuration control in Heliotron J, five sets of coils are installed, i.e. helical and main vertical (H+V), toroidal A and B (TA and TB) and inner and auxiliary vertical (IV and AV) coils. The TA coils are located at so-called "corner" section where tokamak like magnetic field is formed. On the contrary, the magnetic field in the "straight" section in which the TB coils are set has a local quasi-omnigeneous magnetic field. As shown in Fig. 1, two tangential beamlines of the hydrogen neutral beam injection (NBI) system have been installed in Heliotron J (BL1 and BL2). Each beamline has two bucket-type ion sources and the maximum beam power and acceleration voltage of 0.7 MW and 30 keV, respectively. The mean pitch angle of the beam ions is about 155 (25) degree in the co- (counter-) injection case of the standard configuration of Heliotron J.

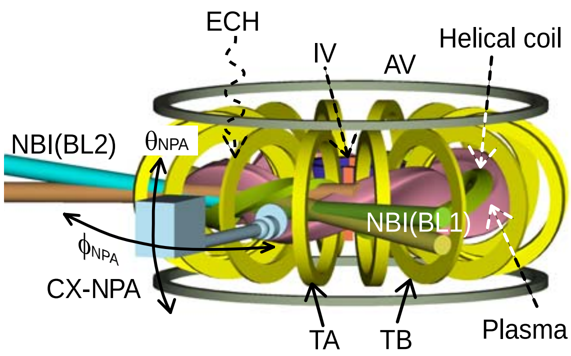

Fig. 1 Schematic view of Heliotron J including coil, heating and diagnostic systems.

The dependence of the energetic particle confinement on the magnetic field configuration in Heliotron J has been discussed from the viewpoint of control of the magnetic Fourier components [11, 12]. Figure 2 shows the operational space of the magnetic configurations under the present experimental conditions. The horizontal and vertical axes are toroidicity ε_t (= B_{10}/B_{00}) and bumpiness ε_b (= B_{04}/B_{00}) normalized by helicity ε_h (= B_{14}/B_{00}), where B_{mn} is the Fourier component of the field strength with m/n mode numbers in the Boozer coordinate system. The radial particle flux in $1/\nu$ regime modeled by Shaing [13] is also shown in the figure. This operational space is limited by (1) the coil current to keep the magnetic field strength at 1.25 T due to the plasma initiation by the 2nd harmonic resonance

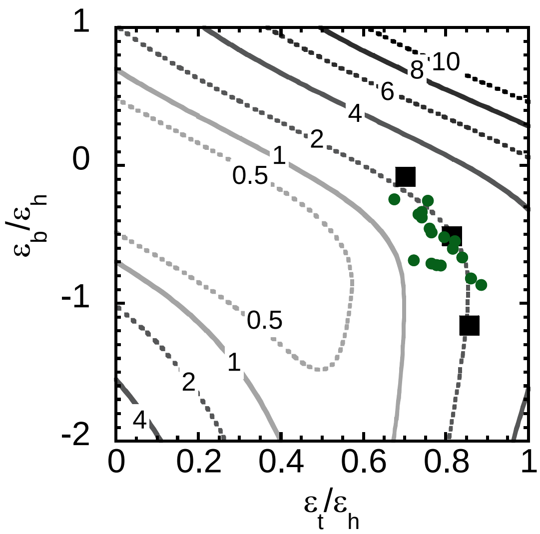

Fig. 2 Operational space of Heliotron J configuration (circle and square) as a function of toroidicity and bumpiness normalized by helicity under the current experimental condition. The dotted and solid lines show the particle flux by Shaing's model.

condition of 70 GHz ECH and (2) the plasma major axis at the ECH injection port R_{ECH} should be setin the range 1.06m < R_{ECH} < 1.08m. The energetic ion confinement has been investigated experimentally in NBI and ICRF heated plasmas by changing the bumpy magnetic field [14-16], which has revealed that the control of bumpiness has had an effect to improve the energetic particle confinement.

The detailed explanation of the hybrid directional Langmuir probe system (HDLP) is described in Refs. [7]. Briefly, as shown in Fig. 3, this system can measure a two dimensional distribution of the co- and counter-directed ion fluxes and heat loads in *R-z* plane as well as the magnetic fluctuations with one Mirnov coil mounted on HDLP. The probe system is also rotatable on its axis to align the pair of probe tips with the magnetic field line. The Poincaré plot of beam ions at the cross section of HDLP calculated using the collisionless orbit calculation [17] is also shown in Fig. 3. The birthpoint of beam ions in the case of the co-injected neutral beam (BL2) are calculated for the standard configuration of Heliotron J using Monte-Carlo method [18]. As shown in the figure, the HDLP system also enables us to estimate the heat flux of the re-entering beam ions [19].

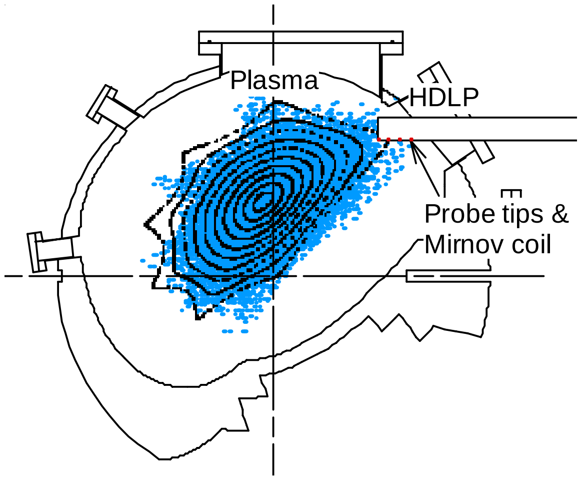

Fig. 3 Schematic view of HDLP and Poincaré plots of flux surface for standard configuration of Heliotron J and beam ions calculated by the collisionless orbit calculation.

3. Experimental results and discussions

In Heliotron J, GAE has been observed in several configurations, and its mode number and amplitude depended on magnetic configurations. Strong bursting GAEs appeared under the condition where the energetic particle confinement was good [8]. Figure 4 shows the typical time evolution of the plasma parameters obtained in the co-injected NBI plasmas under the configuration with the edge rotational transform $\iota(a)/2\pi$ of 0.54 [9]. The hydrogen neutral beam with the accelerate voltage and power of 23kV and 570kW was injected into the deuterium plasmas, respectively, i.e, $v_{b\|}/v_A$ was around 0.5 including impurity (carbon) effect. As shown in the figure, m/n =2/1 GAE appeared after the beam injection.

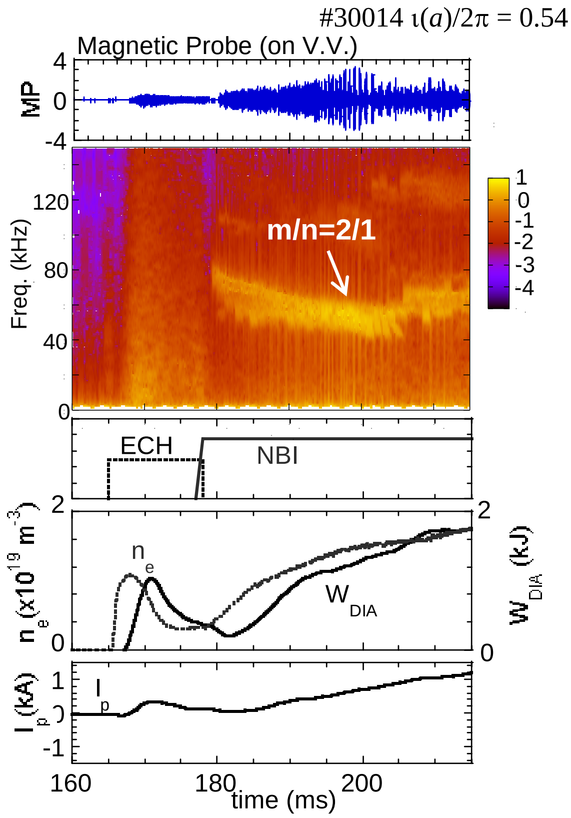

Fig. 4 Temporal evolution of plasma parameters obtained in NBI plasmas of Heliotron J. Strong bursting GAE started from t=194 ms.

The GAE bursts occurred at the electron density of $1.5\times10^{19}m^{-3}$ with a frequency chirping down from 70 to 40 kHz. In that case, the mode propagates in the ion diamagnetic drift direction. The reduction in the plasma stored energy due to one GAE burst was small to detect with diamagnetic loop measurement. From the resonance condition analysis for m/n=2/1 GAE, it would be observed in the condition of $v_{b||}/v_A$ > 0.2 and experimental result indicates observed GAEs are excited through sideband excitation.

Figure 5 shows the wavelet analysis for the magnetic fluctuation, the co-directed and counter-directed ion saturation current by HDLP. In this case, the prove tips were located at *r/a*= 0.84. The magnetic fluctuation was measured with the Mirnov coil located at the Heliotron J vacuum vessel. The Mirnov coil mounted on the HDLP cannot clearly detect the GAE bursts because the Mirnov coil on HDLP has a maximum sensitivity in the r-component (δB_r) in present condition [9]. The observed ion fluxes with both co- and counter-directed probe synchronized with the GAE bursts. In the co-directed probe, a sensitive response to the GAE bursts has been found. The amplitude of the co-directed probe depends on that of GAE bursts and probe position, which is discussed later. This probe has high sensitivity to energetic ions since the secondary electron emission depends on the incident ion energy and the yield rate of the beam energy is more than 5 times higher than that for low energy ions [20]. Then the response obtained by HDLP mainly owes to the energetic ions. Note that no significant oscillation of ion flux outside LCFS was observed. The ion flux of the counter-directed probe also has a small sensitivity in the growth phase of the GAE bursts and disappeared after the peak of magnetic fluctuation. During the bursts, a high coherence between both ion fluxes with co- and counter-directed probes and the GAE bursts were obtained, which indicates the fast ions oscillate with GAE. Under the condition that the coherence was higher than 0.8, the phase relation of co-directed ion fluxes to the magnetic fluctuation was around 90 to 180 degree and that for counter-different probe was 200 and 270 degree. Then the phase relations of the co- and counter-directed probe are different from GAE bursts and each other.

Figure 6 shows the dependence of the amplitude of bursting GAE and the ion flux with the co- and counter-directed

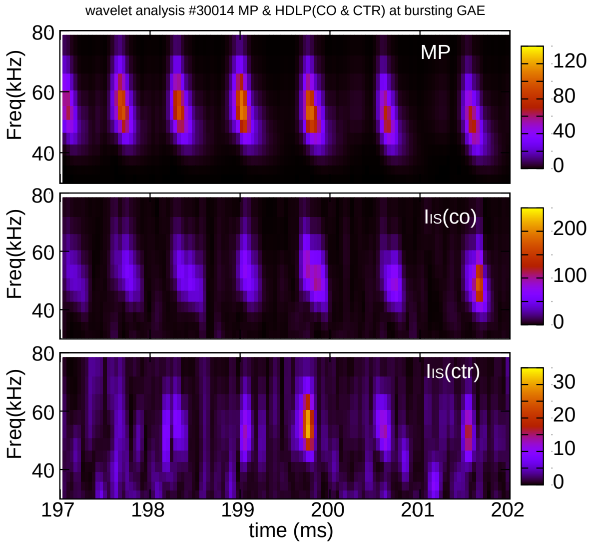

Fig. 5. Power spectrum density using wavelet analysis method for Mirnov coil located at Heliotron J vacuum vessel, fast ion flux of co- and counter-directed probe measured by HDLP.

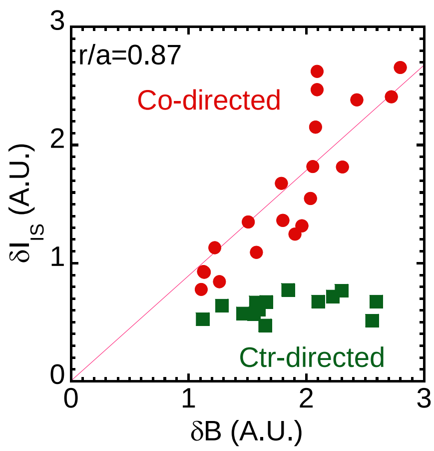

Fig. 6. Ion flux response by the co- and counter-directed probes during GAE bursts as a function of mode amplitude of GAE.

probes. These data are obtained by peak values of each burst. The ion flux has a linear correlation with the GAE amplitude. From the above results, the probable fast ion response with the co-directed probe is considered to be a resonant convective oscillation of fast ion [9]. The fast ions are oscillated by the local oscillation of the GAE magnetic fluctuation. The displacement of the fast ion flux is proportional to the local gradient of the fast ion and the GAE amplitude. The radial profile of the fast ion flux normalized by the amplitude of the magnetic fluctuation is shown in Fig. 7, which is determined by the slope of the relationship between the fast ion flux and the GAE amplitude as shown in Fig. 6. The normalized fast ion flux decreases with the minor radius and is small to identify significant burst outside LCFS, suggesting that the amount of the fast ions lost outside LCFS was small during GAE under the experimental conditions. These results support that the fast ion response is a resonant convective oscillation.

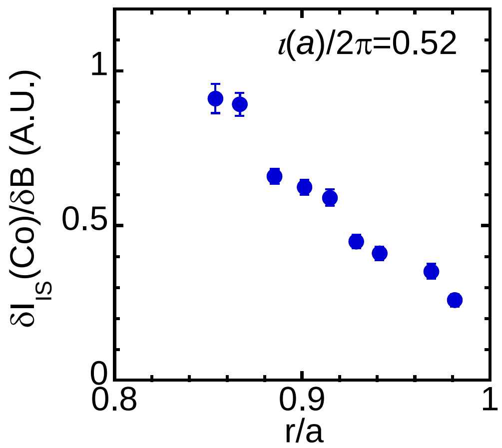

Fig. 7. Radial profile of fast ion response to GAE amplitude for co-directed probe

As mentioned above, the coherent fast ion flux by the counter-directed probe observed in the growth phase of the GAE bursts, which indicates that this phenomenon occurred under the condition where the fast ion pressure was fairly high before the re-distribution of fast ion due to GAE. There are two candidates to interpret it. One is an oscillation of the bulk ion and the other is a pitch angle scattering by GAE. In CHS, the bulk ion response during energetic particle mode (EPM) was measured with HDLP [6]. It was found that the bulk ion oscillated with the same phase relation as EPM by the Mirnov coil mounted on HDLP. The detectable velocity distribution of the counter-directed probe was estimated using a full-orbit calculation code [21]. The counter-directed probe has a small sensitivity to co-directed energetic ions with peculiar pitch angle. For example, 20 % of the 23keV ions with pitch angle of 130 degree have a capability to reach the probe because of the finite-Lamor-radius effect, when the rotating angle of HDLP aligned with the magnetic field line. These high energy particles satisfies the resonant condition of the sideband excitation of m/n = 2/1 GAE. In order to clarify the mechanism, further experiments and measurements are needed to obtain the velocity distribution of energetic ions by rotating the HDLP angle.

Summary

In NBI plasmas of Heliotron J, bursting GAE was observed under the configurations where the energetic particle confinement was fairly good. In the case of the edge rotational transform $\iota(a)/2\pi$ of 0.54, bursting GAE with m/n =2/1 mode number was occurred with frequency chirping down from 70 to 40 kHz. The response of fast ion fluxes to the GAE bursts was measured with the HDLP system. The high coherent responses of the ion flux to the GAE bursts were observed not only by the co-directed probe but also by the counter-directed one. The features of the fast ion flux by the co-directed probe are as follows: (1) the amplitude of the ion flux inside LCFS increases linearly with the GAE amplitude. (2) The fast ion response to the GAE amplitude decreased with the minor radius, (3) and was small outside LCFS. These results indicate that the fast ion response is considered to be a

resonant convective oscillation. The fast ion flux by the counter-directed probe appeared in the growth phase of the GAE bursts, which suggests it would occur under the condition of higher fast-ion beta before the re-distribution of fast ion due to GAE. The phase relation was differed from that of the co-directed probe. There are two candidates for the observed results, one is bulk ion oscillation and the other is pitch angle scattering by the GAE bursts. The counter-directed probe has a small sensitivity to the peculiar pitch angle of the co-directed energetic ions. The velocity distribution measurement by rotating HDLP angle is required to interpret the phenomenon. And furthermore, the wide configuration scan experiments in ε_b- ε_t space are needed to investigate the dependence of the GAE characteristics on the magnetic configuration and the energetic particle confinement.

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