Observation of Fast Ion Response to MHD Activities in Heliotron J

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Fast-ion-driven global Alfven eigenmodes (GAEs) were observed in Heliotron J plasmas heated by high power neutral beams. A hybrid directional probe was installed in outboard side of Heliotron J for fast ion measurement, and fast ion response to bursting GAEs was observed inside the last closed flux surface (LCFS). The fast ion flux oscillates with the GAE frequency, and the amplitude is proportional to the GAE amplitude, indicating the convective oscillation of fast ions. It is implied by the experimental observations that anomalous transport and/or the change of fast ion profile during the GAE burst occur in the core region.

Keywords: global Alfven eigenmode, directional probe method, hybrid directional Langmuir probe, resonant convective oscillation of fast ions, eigen-function of GAE.

1. Introduction

Fast ion confinement is one of the most important issues in magnetically confined fusion experiments, because plasma heating due to high energy particles produced by fusion reactions is the dominant heating process in burning plasmas. In particular, interactions of fast ions with MHD activities such as Alfven eigenmodes are crucial issue, because resultant anomalous transport of fast ions may terminate a burning condition in fusion reactors. Many studies on this topic were performed experimentally and theoretically in tokamak configurations, and it was reported that toroidicity-induced Alfven eigenmode (TAE) and energetic particle mode (EPM) are pointed out the possibility to be unstable in ITER [1-3].

In stellarators, global Alfven eigenmode (GAE) was observed in neutral beam (NB) heated plasmas in Wendelstein7-AS [4] and Heliotron J [5], and the fast ion loss induced by the GAE was also measured by a fast ion loss probe in Wendelstein7-AS [6,7]. Various types of TAEs and EPM were identified in NB heated plasmas in compact helical system (CHS) [8,9] and large helical device (LHD) [10,11], and fast ion loss induced MHD activities have been strongly studied [12,13].

The interaction between fast ions and MHD activities and the resultant anomalous transport of fast ions are common physical issues underlying in tokamaks and stellarators, and have not been fully understood yet.

Recently, a directional probe method was applied to NB heated plasma for fast ion measurement in CHS [14], and the fast ion behaviors during EPM burst were observed in the last closed flux surface (LCFS). The convective oscillation of fast ions and the finite phase between fast ion flux and the EPM indicates the strong resonant interaction between fast ions and the EPM, and the resultant anomalous transport of fast ions was understood by the statistical irreversible transport produced by the phase difference [15,16].

The directional probe was also applied to Heliotron J plasma for fast ion measurement, and the measurement of fast ion behaviors during the GAE has been performed. The advantage of the directional probe is wide scannable area (from outside to inside the LCFS) and simultaneous measurement of fast ions and magnetic fluctuation at the same position. The primal motivation of this experiment is investigation of anomalous transport mechanism of fast ions induced by MHD activities due to direct observation of interaction between fast ions and MHD activities. In this paper, the directional probe system in Heliotron J and first result of fast ion measurements during GAE bursts are presented.

2. Experimental setup

The experiments were performed in Heliotron J device, which is a helical axis heliotron with the toroidal and poloidal periods of n=4 and m=1, respectively [17]. The vacuum rotational transform ($\iota/2\pi$) is 0.3-0.8 with low magnetic shear. The major and minor radii are 1.2m and 0.1-0.2m, respectively, and the magnetic field strength is up to 1.5T on the magnetic axis. The target plasma in present experiment with the electron density of

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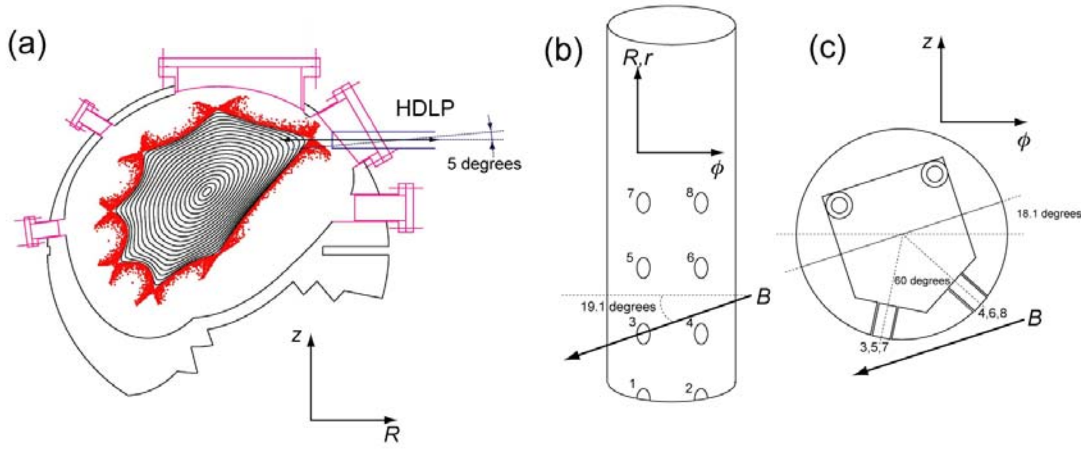

Fig.1 (a) The position of HDLP and the shape of the Heliotron J plasma. The insertion angle of the HDLP can be changed in the vertical direction. (b) The schematic of the HDLP head. The angle between the axis of a set of directional channels and the magnetic field is 19.1 degrees at the LCFS. (c) The schematic of cross section of HDLP body. The direction of the magnetic field at the LCFS is also shown. The rotational angle of the HDLP can be controlled and was fixed at 20 degrees in this experiment.

$0.5\text{-}3\times10^{19}\,\mathrm{m}^{-3}$ were heated and sustained by electron cyclotron resonance heating (ECRH) with the power of 0.5 MW and NB of ~0.6 MW.

A hybrid directional Langmuir probe (HDLP) which had been utilized in compact helical system (CHS) [14] was installed in Heliotron J for fast ion measurement. The linear drive (750mm stroke) inserts the HDLP horizontally from outboard side port and the insertion angle of the HDLP can be slightly changed in the vertical direction (see Fig. 1-(a)). The HDLP position was chosen based on the result of fast ion orbit calculation, and some co-directed fast ions cross the LCFS at the HDLP position. The HDLP has eight channels for measurement on the metal probe body (40 mm in diameter). The conventional Langmuir probes (ch.1 and 2) constitute a directional probe at the end of the probe body, and the hybrid channels (Langmuir probe and calorimeter probe) are mounted on the probe surface with intervals of 20mm in the direction of probe axis and azimuthal direction (see Fig. 1-(b)) [14,16]. A Mirnov coil is also mounted in ch.6 for measurement of magnetic fluctuation at the same position. The magnetic field at the cross point of the LCFS and HDLP has three dimensional components (19.1 degrees in r-ϕ plane and 18.1 degrees in z-ϕ plane), which are shown in Fig. 1-(b) and (c). The z-component of the magnetic field can be eliminated by adjusting the probe angle due to the rotary stage installed on the end of the probe drive. The r-component of the magnetic field produces an error for measurement of small structure such as plasma flow structure in the edge region. For fast ion measurement, however, the deviation of the field line to the pair of probe channels is not so serious problem because the fast ion structure is not so small due to large Larmor radius. Thus, the ch.3 and 4 are utilized as a directional probe for fast ion measurement. Moreover the field direction slightly changes depending on the probe position. In this experiment, the probe angle was fixed at the 20 degrees in z-ϕ plane.

In this experiment, only tangential NB was injected in the co-direction, that is, the fast ions circulate only in the co-direction with small pitch angle. Thus the main target to measure using the HDLP is co-directed passing fast ions. In this situation, the fast ion flux can be estimated by

$$I_{\text{fast ion}} = I_{\text{co}} - I_{\text{ctr}} \qquad (1)$$

where $I_{\text{fast ion}}$, I_{co} and I_{ctr} are fast ion current, co-directed and ctr-directed ion currents measured by the HDLP, respectively. The effect of plasma flow is assumed to be negligibly small, and this can be checked by calorimeter method. In order to obtain the absolute value of fast ion flux, the secondary electron emission was experimentally estimated in CHS as α=5~10 for proton energy of 25-35keV [18].

3. Fast ion transport induced by GAE burst

The bursting GAE was observed in NB heated plasmas [5] and the fast ion measurement was performed using HDLP. The frequency of the GAE quickly chirps downward from 70kHz to 40kHz, which indicates the strong interaction between GAE and fast ions. The signal responding to the GAE bursts was observed in the co-directed ion current measured by HDLP, when the GAE amplitude and the interval of the each bursts become large, which are shown in Fig. 2-(a). The ctr-directed ion current has no response to the GAE, thus the response in co-directed current is identified as fast ion response to the GAE. The magnetic fluctuation shown in Fig. 2 was measured by a Mirnov coil located on the chamber wall. The Mirnov coil mounted on the HDLP can not clearly

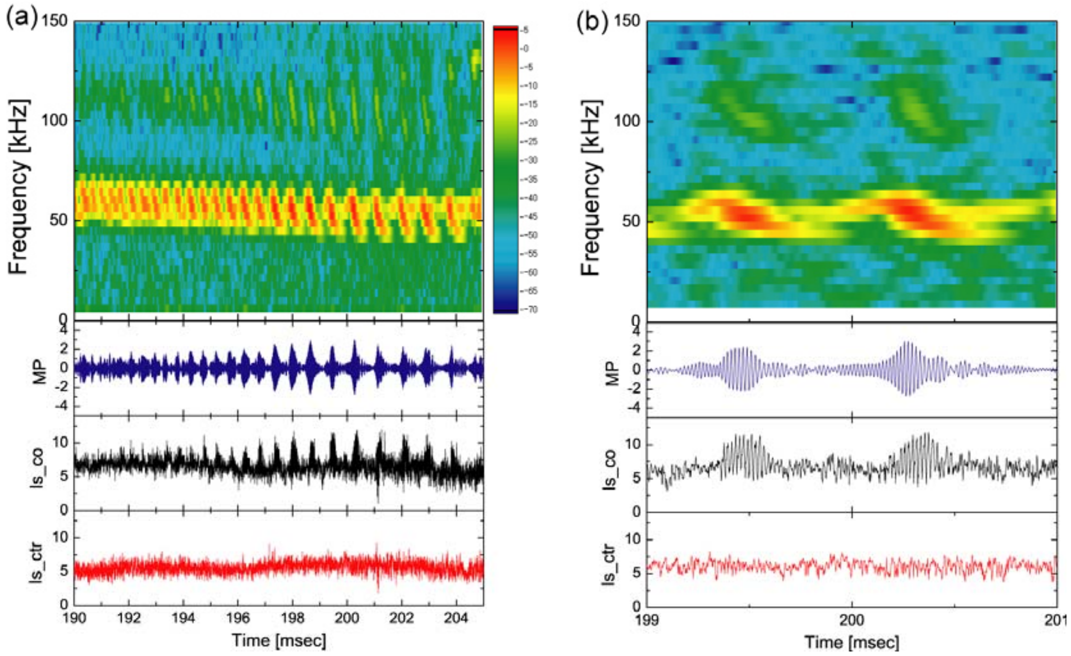

Fig.2 (a) The contour map of the power spectrum of magnetic fluctuation (running FFT with time window of 0.256 msec) and the wave forms of Mirnov signal (MP) located on the chamber wall, co-directed (I_{s_co}) and ctr-directed (I_{s_ctr}) ion currents measured by the HDLP at r/a= 0.9. (Shot No. 30013). (b) The enlarged figure of (a).

detect the GAE bursts because the Mirnov coil on HDLP has a maximum sensitivity in the r-component (δB_r) in present condition.

The fast ion response synchronized with GAE frequency, which indicates that the fast ions oscillate with the GAE. The amplitude of fast ion fluctuation increases with the GAE amplitude. Figure 3 shows the amplitude of fast ion fluctuation as a function of GAE amplitude in the growth phase before the GAE amplitude reaches the maximum value. The fast ion flux tends to have a linear relation to the GAE amplitude (dashed line in Fig. 3) although the each observation point is different.

The spatial structure of fast ion response was investigated on a shot by shot basis. The fast ion response to the GAE burst decreases with minor radius and is slightly detected at just outside of the LCFS. It is considered that the amplitude of eigen-function of GAE and the fast ion density decreases toward outside of the LCFS and they are still finite at just outside of the LCFS at the HDLP position (outboard side).

The probable candidate of observed fast ion response to the GAE burst is a resonant convective oscillation of fast ions, which is a radial oscillation of fast ion flux synchronized with GAE frequency where there is a gradient of fast ion density. The displacement of fast ion flux is proportional to the local GAE amplitude at that position. Thus the oscillating flux observed by HDLP is considered as a oscillation of fast ion flux given by

$$\delta\Gamma_{fast\_ion} \propto \frac{\partial n_{fast\_ion}}{\partial r}\cdot\xi_r \propto \frac{\partial n_{fast\_ion}}{\partial r}\cdot\delta B \qquad (2)$$

where n_{fast_ion} is the density of fast ion and ξ_r is displacement of the fast ion flux. It is noted that the resonant convective oscillation given by Eq.(2) is not a radial transport (anomalous transport) of fast ions, but a

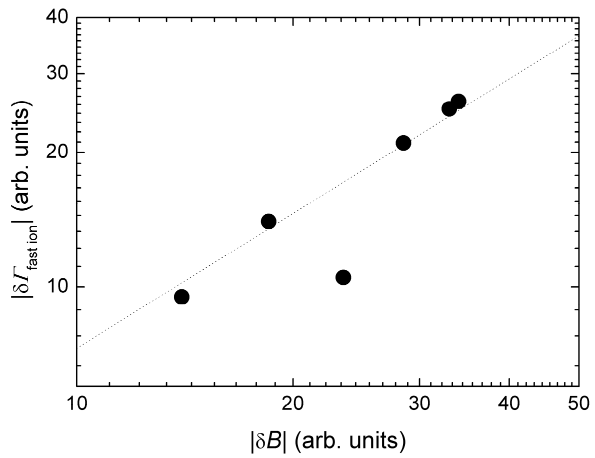

Fig.3 The amplitude of fast ion flux as a function of GAE amplitude measured at the chamber wall. The dashed line indicates the s=1 line in the function of $\delta\Gamma_{fast\_ion} \propto \delta B^s$.

local oscillation at that position.

In CHS experiments, the resonant convective oscillation of fast ion flux in response to EPM bursts was identified by the HDLP at the periphery ($0.9 < r/a < 1.0$) [15,16]. The additional response of fast ions (slow response) proportional to δB^2 was simultaneously observed and it is identified as an anomalous transport produced by the phase difference between resonant convective oscillation of fast ions and the EPM. In comparison with the EPM experiment in CHS, the slow response is not significant in present GAE experiment in Heliotron J. The EPM observed in CHS is located around $r/a = 0.7$ and the anomalous transport and the modification of fast ion density profile induced by the EPM occurs near the edge region where the probe measurement is possible. Thus it is speculated in GAE experiment in Heliotron J that the fast ion profile is mainly modified only in core region and net fast ion transport in edge region is not significant due to small amplitude of the GAE.

The fast ion response has a delay time with the order of 0.1 msec from the peak of GAE amplitude (see Fig. 2-(b)). The Mirnov signal located on the chamber wall is considered to be dominated by the most unstable mode existing near core region. On the other hand, the amplitude of the fast ion oscillation is considered to be determined by the local amplitude of GAE eigen-function at the HDLP position, that is, edge region. Thus the observed time delay between Mirnov and HDLP signals implies that the spatial structure of GAE eigen-function changes in time. The structure of eigen-function is considered to be linked with fast ion profile, therefore it is considered that the anomalous transport of fast ions occur in the core region during the GAE burst.

4. Conclusion

The HDLP was installed to Heliotron J for fast ion measurement and the fast ion response to the GAE bursts was observed inside the LCFS. The co-directed fast ion flux oscillates with GAE, and it is considered as a resonant convective oscillation. In the edge region, the anomalous transport of fast ion was not considered to be so significant in this experiment. The linkage between the delay time of fast ion response and the change of fast ion profile during the burst is discussed. It is implied by the experimental observations that anomalous transport and/or the change of fast ion profile during the GAE burst occur in the core region, however the experimental identification is necessary. The simultaneous measurement of fast ion behavior and the magnetic fluctuation at the same position is necessary to investigate the interaction property and transport characteristics of fast ions induced by GAE, which is left for the future study.

Acknowledgements

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