Edge Plasma Response to Beam-driven MHD Instability in Heliotron J

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Abstract. Nonlinear behavior of broadband fluctuation and dynamical potential change, associated with beam-driven magneto-hydro-dynamic (MHD) phenomenon, are observed around edge region in a medium-sized helical device, Heliotron J. Nonlinear phase relationship between the MHD and broadband fluctuation is demonstrated as a result of bicoherence and envelope analyses applied to floating potential signals measured with multiple Langmuir probes (LPs) in neutral beam injection (NBI) heated plasmas. Structural change of potential profile synchronized with the cyclic MHD burst is also discovered. These experimental observations suggest that such MHD fluctuations may have an influence on the confinement property of bulk plasma through nonlinear process and/or change of electric field structure.

1. Introduction

Energetic particle driven instabilities, represented by Alfvén eigenmodes (AE), have been highlighted since these instabilities cause loss of alpha particles, degradation of fusion plasma performance and damage of vacuum vessel [1-5]. Many kinds of work for physical mechanisms of these instabilities and the influence to the fast ion behavior and plasma performance have been conducted from both experimental and theoretical frameworks.

Furthermore, the possibilities of positive influence of the MHD phenomenon on the bulk plasma confinement have been indicated experimentally and theoretically. For instance, energetic particle driven MHD phenomenon can be a trigger of internal transport barrier to produce negative magnetic central shear plasma and generate poloidal flow shear through redistribution process of energetic particles[5]. In that scenario, the change of fast ion profile due to the redistribution generate an off-axis current drive which can reduce or reverse the central magnetic shear and induce the plasma shear flow, which play essential roles for ITB formation. In addition, shearing electric field oscillation synchronized with beam-driven MHD phenomenon, which is caused by direct loss of fast ion, has found in middle-sized helical device [6]. The feasibility to actively utilize such scenarios or other unexpected phenomena arising from energetic particle driven MHD instabilities have not yet clarified and further experimental study is being required for coming stage of burning plasmas such as ITER and future fusion facilities.

In this study, we discovered two kinds of response to a beam-driven MHD phenomenon around last close flux surface (LCFS) using Langmuir probes (LPs) in Heliotron J device;
One is an influence to broadband fluctuation [7] and the other is an structural change of edge plasma potential responding to cyclic beam-driven MHD burst. The details of experiment and the characteristics of the responses are described and discussed in this paper.

2. Experimental set up

Heliotron J is a medium sized helical device with the plasma major radius R=1.2 m and averaged plasma minor radii of a = 0.1-2 m, respectively [8, 9]. The magnetic field strength is B=1.25 T on axis and the rotational transform \( \nu/2\pi \) is widely controllable from ~ 0.3 to 0.8 with low magnetic shear \( \nu/\nu < 0.04 \). The magnetic field is generated by single helical coil of L/M=1/4, two kinds of toroidal coils located at “straight” and “corner” sections of the device, and three pairs of vertical field coils. The controllability of these coil current realize widely variable magnetic field configurations. In this experiment, plasma was produced by 70 GHz second-harmonic X-mode ECH with power of less than 0.3 MW and sustained by tangential NBI only injected in counter-direction with the energy of 24 kV and the beam power of <0.7 MW.

Four sets of LP have installed to Heliotron J to get the edge profile and fluctuation data, which are located at different toroidal/poloidal locations at #7.5, #8.5, #11.5 and #14.5 sections shown in Fig. 1(a) and (b). All the Probes can be scanned in radial direction and the measurable range of the probes is from inside to outside LCFS. Figure 2 (a-c) show probe head structures at #8.5, #11.5 and 14.5 sections, which are mainly used in this experiment. The probe at #8.5 sections is radially arrayed probe, which is called as “rake probe” in the other studies[10, 11]. Five pins at the probe top are arrayed in poloidal direction along magnetic surface. Note that the scanning lines of the probes are not identical to the normal direction to magnetic surface at #8.5 and #11.5 sections. One pin of the five is located at slightly different radial position, enabling us to measure the radial electric fluctuation and its induced Reynolds stress. Radially arrayed pins are located at the #8.5 probe side. The distances of each pin are 2 mm and 5 mm at the top and side of the probe head, respectively. The probe at #14.5 sections shown in Fig. 2(b) has much simpler structure compared with the other probes, but has magnetic probes (MPs) inside the probe. The 5 pins arrayed in poloidal direction and one pin of the five is located at 5mm different radial position as well as the

![Fig.1](a)Top view of Heliotron J device and location of the four sets of probes. (b) Probe location at #7.5, 8.5, 11.5 and 14.5 sections in the poloidal cross sections.
arrangement of other probes. Three Mirnov coils to detect magnetic fluctuation $\delta B_r$, $\delta B_\theta$ and $\delta B_\phi$ are placed inside the #14.5 probe head, and so simultaneous measurement of local plasma parameters and local magnetic fluctuation is possible. For #11.5 probe these pins are arrayed in poloidal direction along magnetic surface and hence the probe can be utilized to determine the poloidal structure of the modes. Carbon pins with 1mm diameter are used as a probe tips placed at the top of all the probes and are insulated by Boron-Nitride support. The head structures of #8.5 and #11.5 probes are supported by Molybdenum structure. The #14.5 probe is simply supported and covered by Boron-Nitride structure only. We measure ion saturation current $I_s$ and floating potential $V_f$ using single probe pin, otherwise we use three pins as a triple probe or for the evaluation of fluctuation-induced particle flux $\Gamma (\sim I_s \cdot (V_{f1} - V_{f2}))$.

Beam emission spectroscopy (BES) diagnostics has installed to Heliotron J recently. The BES system has radially arrayed 16 sightlines and so can be utilized to clarify internal structure of various MHD instabilities. In the diagnostics, the fluctuation of detected beam current $\delta I_{\text{beam}}/I_{\text{beam}}$ corresponds to density fluctuation $\delta n_e/n_e$. The sightlines are optimized to realize higher spatial resolution in radial extent ($\Delta \rho < 0.1$) although the magnetic configuration of helical devices is quite complicated in Heliotron device. [12]. In addition, Signal-to-noise ratio of the BES is sufficient to measure turbulent fluctuation of which normalized amplitude is typically 0.01.

3. Experimental Results

3-1 Beam driven MHD phenomena in Heliotron J

Typical waveform of line averaged electron density measured with micro-meter interferometer in this experiment is shown in Fig 4(a). The density was kept low to reduce the interaction of probes and plasma. Characteristic MHD fluctuation at ~60 kHz, which is a kind of AE, was observed in low density plasma of $n_e \sim 1 \times 10^{19}$ m$^{-3}$ sustained by NBI only as shown in Fig. 4(b). The mode has poloidal/toroidal mode number of $m/n \sim 1/1$, and is propagating in ion diamagnetic drift direction from the measurement of magnetic probe array located on vacuum vessel of Heliotron J[13]. In Heliotron J, such a mode is frequently observed in NBI sustained plasma, and candidates of the mode are energetic particle mode (EPM) or global Alfvén eigenmode (GAE). [4, 13].
The results of BES measurement shows the mode has a broad structure in radial direction as shown in Fig. 3(c) and (d). There is a broad peak around \( \rho = 0.6 \) in the profile of fluctuation amplitudes, however, significant values of coherence ( >0.4 ), calculated with magnetic fluctuation measured with MP inside #14.5 probe, can be seen in Fig. 5(b) in whole a plasma. Phase differences between BES and MP signals inside #14.5 probe has opposite value at the center and edge of the plasma. Here, the density fluctuation amplitude was obtained by integrating power spectrum density of BES from 55 to 80 kHz and the coherence and phase difference are averaged values in that frequency range.

3-2 Nonlinear influence of beam-driven MHD on broadband fluctuation.

Two kinds of behaviour caused from the MHD phenomenon were observed around LCFS. First, an influence of the MHD fluctuation on broadband fluctuations was observed when the mode appears continuously without intermittency. This was clarified using bicoherence analysis technique. Bicoherence analysis is an useful analysis tool to detect the phase relationship between different frequency components of fluctuations and defined as

\[ b^2(f_1, f_2) = \frac{\langle g_{f_1}^* g_{f_2} g_{f_3} \rangle^2}{\langle |g_{f_1}|^2 \rangle \langle |g_{f_2}|^2 \rangle \langle |g_{f_3}|^2 \rangle} \]  

where \( g_{f_1}, g_{f_2}, \) and \( g_{f_3} \) means complex Fourier components and the frequency and \( \langle \cdots \rangle \) denotes ensemble average[14, 15]. The value of bicoherence takes a value from 0 to 1 at maximum; if the nonlinear phase relationship does not exist among different

Fig. 4 Bicoherence analysis results applied to floating potential signals when (a)the instability was observed steadily and (b) burst phenomena were observed.
frequencies of $f_1$, $f_2$ and $f_3$ the value should converges zero.

Figure 4(a), the result of bicoherence analysis applied to $V_e$ signal at 4mm inside the LCFS ($\rho = 0.93$), shows nonlinear couplings clearly exist between the instability at $\sim 60$ kHz and broadband fluctuation in the frequency range of $\sim 100$-$500$ kHz. This result indicates that the phase relationship between the MHD fluctuation and broadband fluctuation exits significantly, implying the MHD phenomenon affects the broadband fluctuation and its induced transport.

Moreover, the evidence of the influence of the MHD phenomenon on the particle flux induced by broadband fluctuation was demonstrated using envelope analysis. Envelope of the particle flux $\Gamma$ from the frequency range of 300-500 kHz was computed using Hirtbert transform and correlation between the $I_s$ signals and envelope of the high frequency components was investigated in Fig. 5. Clear peak at the spectra and coherence of the envelope can be seen in Fig. 5(b) and (c). This result demonstrates that the MHD phenomena modulate the amplitude of the particle flux in the higher frequency range.

3-2 Potential structural change synchronized with MHD burst

Second, low frequency response less than a couple of kHz, coupled with the MHD fluctuation at $\sim 60$ kHz, was observed as indicated by white arrow in Fig.4 (b). Band-pass filtered signals of the floating potential with different frequency ranges from 0.1 to 20 kHz and from 50 to 100 kHz are shown in Fig. 6(a). The periodic bursts were reproduced every $\sim 1$ ms accompanying rapid chirping up of the frequency. Clearly, slow potential variation synchronized with the burst events can be observed at $\sim 1$ kHz, which is corresponding to the coupling appearing in the low frequency range of fig.4 (b). This characteristic behaviour is observed only when cyclic, intermittent MHD bursts appear. From the measurement of triple probe, this response does not appear in electron temperature, suggesting the response corresponds to the change of space potential. From the multiple probe measurement at

![Fig.5 (a)Time averaged power spectra of ion saturation current and (b) of $\Gamma_{\text{env}}$ envelope for 300-500 kHz fluctuation, and (c) coherence between the $I_s$ signal and $\Gamma_{\text{env}}$ envelope.](image)

![Fig.6 (a)Band-pass filtered signals for 0.1-20kHz and 50-100 kHz of floating potential signal. (b) Amplitude of potential drops on the magnetic fluctuation strength at different radial position of 5mm inside(red), 5 mm outside(blue), and 10 mm outside (green) of LCFS](image)
different toroidal and poloidal sections, it was found that the response is symmetrical change of potential along the torus. This implies that the potential change is not local phenomena such as local electron flux to the probe tips, and the potential profile itself changes symmetrically.

The dependence of potential drops on the MHD fluctuation amplitudes are plotted in figure 6(b). The amplitudes of the MHD fluctuation were derived to evaluate the magnetic fluctuation envelope $|b_0|$ ($b_0 = |b_0|\exp(i\omega(t)t)$) of the mode in the frequency range of $50 – 100$ kHz using Hilbert transform. Clearly the drop is correlated with the MHD fluctuation amplitude. The edge potential drops/recover in growing/decaying phase of each MHD burst. No clear response on microwave interferometer, ECE and BES diagnostic signals to the burst was observed in whole plasma region, and hence the density and temperature profiles do not change so much in each burst.

The radial structural change of potential around LCFS was clarified by using radial multi-channel probe at # 8.5 sections. The typical potential response measured with the probe array and MP signals inside #14.5 probe are compared in Fig. 7. The potential and MP signals are low pass filtered less than $8$ kHz and band-pass filtered from $30-100$ kHz, respectively. Interestingly, the potential drops inside LCFS, on the contrary the potential rises outside LCFS at the same timing. There is no time delay of these responses between potential drops and rises.

Typical structural change of potential on each burst is shown in Fig. 8 (a) and (b), obtained by #8.5 radial array probe. Basically, the floating potential deepens more negatively at the deeper location into the plasma. When the potential drop occurs, the potential become more negative inside LCFS, while becomes more positive outside LCFS. Around LCFS and at the location far from LCFS, the response becomes small.

One of the candidates to explain this potential response is radial current due to anomalous fast ion loss resulted from the MHD bursts because the loss of fast ion should also be correlated with the growth and decay of the MHD behaviour. Indeed, the existence of the fast ion loss linked
with the MHD bursts was confirmed using directional probe measurement in other similar experiments in Heliotron J [16, 17].

4. Summary

Two kinds of response to beam-driven MHD phenomenon were discovered around edge region in Heliotron J, which are measured with multiple Langmuir probes. One is an nonlinear influence of the MHD phenomenon to broadband fluctuation. Bicoherence analysis and envelope analysis clarified the MHD phenomenon have nonlinear coupling with broadband fluctuations and its induced particle flux in higher frequency range from 300 to 500 kHz. The other is a potential response around last closed flux surface, synchronized with the MHD burst. The potential drops/rises as fluctuation amplitude increases/decrease in each burst, which can be attributed to the redistribution process of fast ion on the cyclic MHD burst. Radially arrayed probe demonstrates that the response accompanied with structural change of electric field around LCFS. These experimental results evidenced such a MHD phenomenon can affect the bulk plasma confinement through nonlinear process of fluctuation and/or radial electric field change caused by redistribution process of energetic particles.

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References