Edge turbulence study in neutral beam heated plasma of Heliotron J

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1. Introduction

Recent advances of plasma turbulence study are based on progress of diagnostics and analysis techniques. Multi-channel diagnostics, such as multi-channel Langmuir probes (LPs) or beam probes, has been successful in characterizing the structure of turbulence and demonstrating the existence of meso-scale structures, namely, zonal flow, geodesic acoustic mode and streamer [1-8]. Moreover, new analysis tools useful to investigate nonlinear and unsteady phenomena, for example, wavelet and bispectral analysis, have been developed [6,9,10]. These techniques have been applied to turbulence fluctuation data, and thereby several works have clarified and quantified the temporal behavior of the turbulence and nonlinear coupling between the turbulence and the meso-scale structures in detail [6, 7, 8].

Multiple LP systems for edge plasma studies have recently been installed in Heliotron J [11]. The first results of the measurement around last closed flux surface (LCFS) in neutral beam injection (NBI) heated plasmas are described and discussed in this paper.

II. Experimental set up and results

The experiment was carried out in a helical-axis helitoron, Heliotron J [12,13]. The averaged major and minor plasma radii are R = 1.2 m and a = 0.17 m with an L/M =1/4 helical coil and the magnetic field strength of B < 1.5 T. The magnetic field configuration is generated by five sets of coils (a helical coil, two types of toroidal coils, main vertical, internal vertical and auxiliary vertical coils), enabling a variety of magnetic configurations by controlling each coil current. The device is equipped with a couple of NBI systems and co and/or counter injection of the NBI are possible.

Figures 1 schematically shows the probe locations from the top view of Heliotron J and the scanning lines of the LP systems in the poloidal cross sections. These probe systems are located at different toroidal/poloidal sections in Heliotron J, and #8.5 and #11.5 probes separated about 70 degrees in the toroidal direction each other were mainly used in this study. The location of the systems corresponds to the O-point/X-point near the LCFS, which is useful to investigate the difference of turbulence characteristics at the different toroidal/poloidal locations. The probe located at #11.5 section has multi-electrodes arrayed in poloidal and radial directions, which measure ion saturation current (I_s), floating potential (V_f),

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radial and poloidal electric fields (E_r and E_θ), and fluctuation driven particle flux Γ ($=<\Gamma_{fluc}> = <\delta n \cdot \delta v_r> \propto <\delta I_s \cdot \delta E_\theta>$). The probe can also be used as a triple probe to evaluate electron density, temperature, and space potential. The data of all the LP systems were digitized with 1 MS/s analog-to-digital converters through isolation amplifiers with 1MHz bandwidth.

Figure 2(a) shows a typical time trace of line averaged density measured with a microwave interferometer in this experiment. The plasma was generated by electron cyclotron resonance heating and sustained by co-NBI only. The density was kept low (less than 1 x 10^{19}m^{-3}) to avoid significant heat load damage to the probe tips.

Under this experimental condition, several coherent modes in V_f and I_s signals measured with the

Fig.1, Top view of Heliotron J and the probe location and cross sectional view of #8.5 and #11.5 sections.

LPs were observed, as shown in Fig. 2(b). This spectrogram was calculated with fast Fourier transform (FFT) and the time interval and frequency resolution are approximately 500 μs and 1kHz, respectively. Two kinds of modes were observed, one is an energetic-particle-driven instability accompanying higher harmonics (~90, ~180, ~270…. kHz) and the other is a lower frequency mode about ~20 kHz. Here we call the former and the latter as high frequency modes (HF modes) and low frequency mode (LF mode), respectively. From the measurement of magnetic probe array, the HF mode at 90 kHz has a structure with poloidal/toroidal mode number of m/n=2/1, rotating in the ion diamagnetic drift direction. By contrast, since the magnetic signal of the LF mode was not so strong compared with those of the HF modes, several magnetic probes cannot detect the mode, resulting that the structure of LF mode has not been identified.

In the shear-less machine, Heliotron J, a global Alfven eigenmode and/or an energetic particle mode (EPM) can be considered as a candidate for the HF modes, which are often observed in NBI heated discharges. The HF modes are likely to be EPM because the mode frequency does not clearly show density dependence in comparison between Fig. 2 (a) and (b).
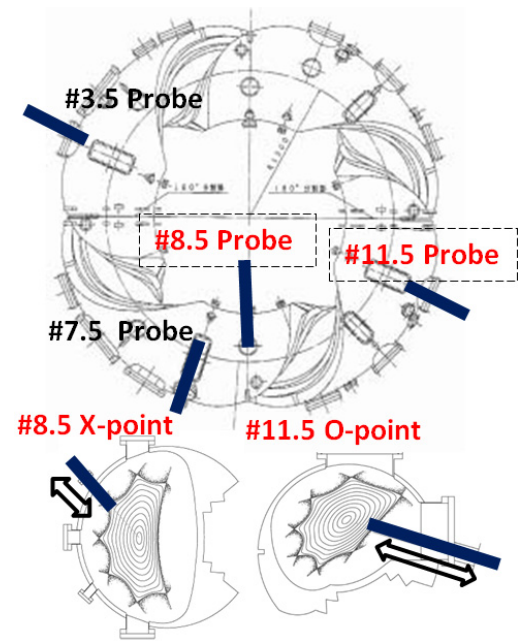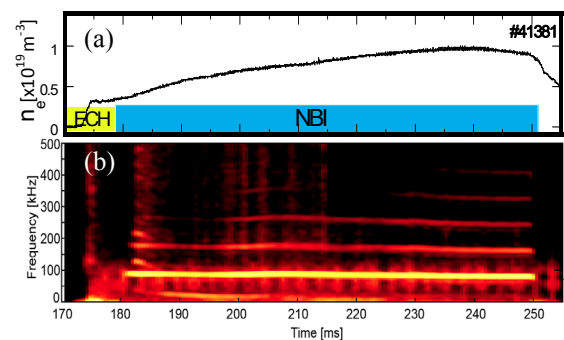
Nonlinear characteristics of the LF and HF

Fig.2 (a)Time trace of line averaged density. (b)Spectrogram of potential fluctuation at 4mm inside LCFS

modes were investigated by applying bicoherence analysis to the LP signals. Squared bicoherence is defined as $b^2(f_1, f_2) = |<X(f_1) \cdot X(f_2) \cdot X^*(f_3)>|^2 / <|X(f_1) \cdot X(f_2)|^2> <|X(f_3)|^2>$, where $X(f)$ is a complex Fourier component obtained from FFT applied to the raw signals, frequency f_3 should be $f_1 \pm f_2$, and, $<\cdots>$ denotes the ensemble average. If some phase coupling exists amongst three waves having different frequency components of f_1, f_2 and f_3, it should be close to unity, while it should be zero if there is no coupling. Figure 3 shows the result of bicoherence analysis applied to I_s fluctuation measured with the #11.5 probe located at 4mm inside the LCFS ($\rho = 0.93$). Nonlinear couplings were clearly observed between the LF mode and broad-band fluctuation in the frequency range of ~ 100-500 kHz, and also between the HF mode and broad-band fluctuation in the similar frequency range.

Fig.3 Result of bicoherence analysis applied to the Ion saturation current fluctuation.

Moreover, envelope analysis was used to investigate the influence of these modes on the transport caused by broad-band turbulence [5,7]. Figure 4 shows (a) a time-averaged power spectrum density for I_s fluctuation, (b) that of envelope for Γ_{fluc} and (c) the coherence between them when probe located at LCFS. The Γ_{fluc} envelope is obtained by evaluating instantaneous amplitude of band-pass filtered signal for 300-500kHz fluctuations using Hilbert transform. In such high frequency range, the Γ_{fluc} fluctuation was not correlated with magnetic probe signals. Obviously, high correlation we have seen around 90kHz, corresponding to the fundamental harmonic of HF modes, indicating that the HF mode actually affects the fluctuation induced particle flux caused by the broad-band (300-500 kHz) fluctuation, and modulates the envelope of the fluctuation. On the contrary, for LF mode, such a modulation was not observed at that frequency range. A simple hypothesis of the interplay between the mode and turbulence is that the modulation results from the density or temperature profile variations due to strong MHD fluctuation of the HF mode. Driving force of turbulence may be affected through the change of the profile gradient. Further analysis of the
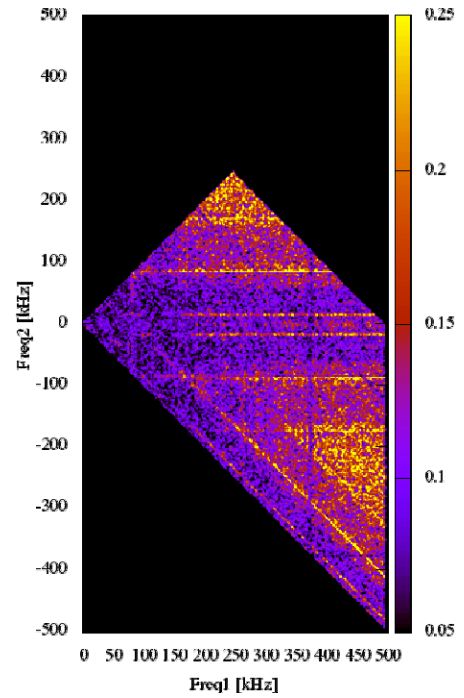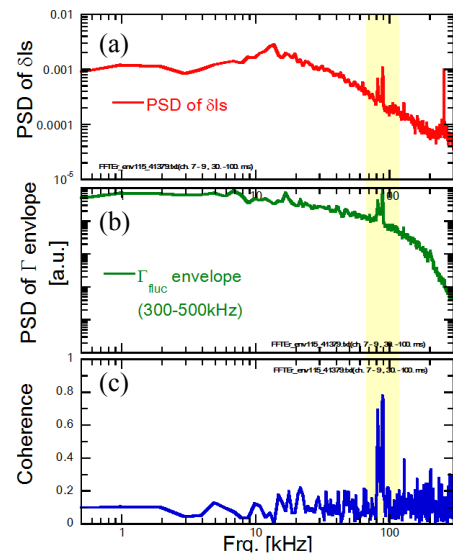

Fig.4 (a)Time averaged power spectrum density of ion saturation current and (b) of Γ_{fluc} envelope for 300-500 kHz fluctuation, and (c) coherence between the Is signal and Γ_{fluc} envelope.

interaction mechanism should be needed.

Radial structure and long range correlation were investigated for the LF mode using different LP signals located at different toroidal sections (#8.5 and #11.5 probes). The radial position of the probe at #11.5 was fixed at $\rho = 0.93$, and the other probe at #8.5 was scanned in radial direction. The correlation and phase difference between these probe signals were evaluated. Figure 5 shows the profile of coherence (closed red circles) and phase differences (black open squares) between the V_f fluctuations from these two probes. The figure shows that the LF mode is localized and the phase is reversed in narrow radial distance of $\delta\rho \sim 0.07$ ($\delta r \sim 1.5$ cm). It indicates that the LF mode has a small scale structure in radial direction although the LF mode has long range correlation along the torus, suggesting the LF mode may have a kind of meso-scale structures.
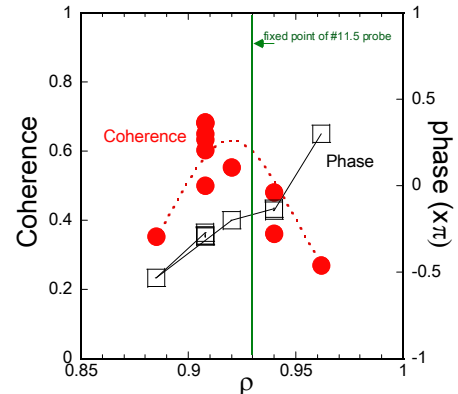
Fig.5 Radical structure of coherence and phase difference for LF mode between Vf signals measured with two probes located at different toroidal positions.

3. Summary

Edge fluctuation measurement was made in NBI heated plasmas of Heliotron J. Two distinct modes were observed, and one mode is a high frequency mode at ~90 kHz which is caused by an energetic ion driven MHD phenomenon accompanying higher harmonics. The other mode is a low frequency mode at ~20 kHz. The bicoherence analysis clarified these modes on I_s fluctuations have nonlinear coupling with broad-band fluctuations (100-500 kHz). Moreover, the result of envelope analysis shows the fluctuation induced particle flux in higher frequency range (300-500 kHz) was affected by the HF mode at 90 kHz. The LF mode seems to be localized inside LCFS in radial direction but has a long distance correlation along the torus, suggesting a kind of meso-scale structures.

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