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Observation of nonlinear coupling of plasma turbulence in linear cylindrical plasma
直線磁化プラズマにおける乱流の非線形結合の観察

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Density fluctuations propagating in the azimutal direction are observed in the Plasma Assembly for Nonlinear Turbulence Analysis (PANTA), under various neutral gas pressure conditions. Nonlinear waveform and their frequency-mode number Fourier power spectrum entirely change depending on the neutral gas pressure. Nonlinear causal relation is estimated by using bispectral analysis and the Amplitude Correlation Technique (ACT). Finally we discuss about relation between magnitude of amplitude and strength of nonlinear coupling.

1. Introduction

Understanding of plasma turbulence is one of the important issues to realize thermonuclear fusion reactors. Many theoretical and experimental works have contributed to reveal that turbulent transport can be a serious obstacle to achieve good confinement state of magnetized plasmas [1]. It is well known that turbulence can form structures (e.g., zonal flows) through nonlinear wave-wave coupling process, which strongly influence plasma confinement ability. Recently, some theoretical works have reported impact of neutral gas pressure on the turbulent structure formation [1,2]. Neutral-ion and/or neutral-electron collisions were possible candidates for a damping force in turbulent structure formation. Neutral gas pressure dependence on the structure formation was discussed. Here, we focus on the impact of neutrals in low temperature linear magnetized plasma. Characteristic features of nonlinear coupling are precisely investigated in different neutral gas pressure regimes, and mechanisms that determine the turbulent-state are discussed.

Bispectral analysis has been widely used to experimentally observe nonlinear interactions [3,4]. The squared bicoherence, i.e., the squared normalized third-order spectral correlation, shows strength of nonlinear correlation among three modes, which satisfy the matching condition, $f_3=f_1 \pm f_2$, with a value from zero to unity. Even if one uses bispectrum analysis, causal relation, such as direction of energy transfer among modes, cannot be determined. For this purpose, we apply the ACT [5], which is defined as,

$$C_{AB}(\tau) = \overline{\tilde{A}(t)\tilde{B}(t-\tau)} \Big/ \sqrt{\overline{\tilde{A}^2(t)}\,\overline{\tilde{B}^2(t)}}\,, \qquad (2)$$

where $\tilde{A}(t)$ [$\tilde{B}(t)$] is amplitude modulation, calculated by running FFT and $\bar{A}(t)$ [$\bar{B}(t)$]

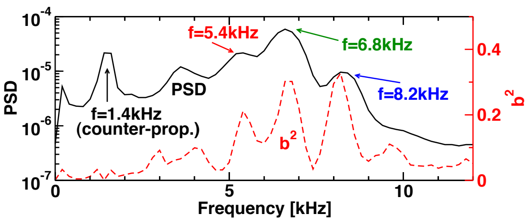

Fig.1. Observed power spectrum density (black curve) and squared bicoherence with respect to a mode at f_3~*1.4* [kHz] (red curve).

indicates long-time average of $A(t)$ [$B(t)$]. Directions of energy flows are estimated from correlation and time lag in the time evolution of amplitude modulation.

Experiments are performed in the PANTA, a linear device with a rf helicon discharge of 3 kW. Excited plasma has a typical electron density of $n_e \sim 1\times10^{19}$ m^{-3} and electron temperature of $T_e \sim 3$ eV. Neutral gas pressure is measured with an ion gauge and controlled by a mass flow controller just before each discharge. A multichannel (64ch) azimuthal Langmuir probe array measures spatiotemporal evolution of density fluctuation. We define the electron diamagnetic direction as the positive direction.

2. Results

We briefly overview observed fluctuation power spectrum density, as an example. We show power spectrum density and squared bicoherence with respect to a mode at $f_3=1.4$ [kHz] for the case P_n = 1 mTorr in Fig. 1. Rather large amplitude peaks are observed in low frequency range, f < 17 [kHz]. In relatively low neutral gas pressure cases (P_n < 2 mTorr), somewhat broad peaks exist at f~4-10 [kHz]. A counter-propagating (ion diamagnetic direction) mode is also observed at f=1.4 [kHz]. Bicoherence between the broad spectral peaks and counter-propagating mode is significant.

To clarify direction of energy flow, we apply the ACT. Figure 2 (a) shows time evolutions of normalized mode amplitude of distinguishable spectral peaks shown in Fig. 1. They are calculated with a time-window of 5 ms and the time-window is shifted by steps of 0.5 ms. Figure 2 (b) shows cross correlation function of mode amplitude at three different frequencies with that of the reference mode at f=1.4 [kHz]. The mode at f=6.8 [kHz] has opposite correlation to the counter-propagating mode with zero time lag. This might indicate the counter-propagating mode and the mode at f=6.8 [kHz] are coupled (or in predator-prey relation). Fluctuations at f=5.4, 8.2 [kHz] have positive correlation with the reference mode. Taking into account the time lag, primary modes which are linearly unstable can be identified as the mode at f=6.8 [kHz] and the mode at f=8.2 [kHz] and/or the counter-propagating mode. Same analyses are also applied in high neutral cases. In addition, recently endplate-biasing experiment is running in the PANTA. We externally give perturbation to mode amplitudes and observe the time lag of responses in fluctuating modes to obtain another evidence for detection of the direction of energy flow.

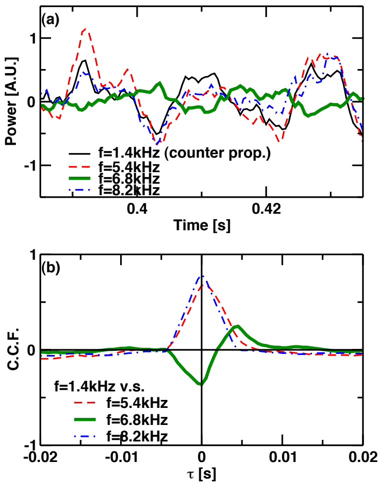

Fig.2. (a) Time evolution of fluctuation mode amplitude (normalized by its long-time average), (b) amplitude correlation with respect to counter propagating mode.

3. Conclusion

We calculate integrated fluctuation power, which is almost complementally determined by linear mode power, and total squared bicoherence in a low frequency region for various P_n conditions. Similarity of these shapes is found, clearly indicating that the nonlinear coupling process is quite essential to determine turbulent states.

Acknowledgments

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