Evaluation of Non-Linear Mode Coupling During End-Plate Biasing Experiment in PANTA*)

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To understand turbulent transport in magnetized plasmas, an end-plate biasing experiment was performed in a linear magnetized plasma device, PANTA. Here we report the change of bi-coherence among fluctuations during biasing. During biasing, coupling with drift waves is decrease, and that with the mediator is increase.

Keywords: plasma turbulence, streamer, bias experiment, bi-spectrum, nonlinear

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1. Introduction

Turbulence in magnetized plasmas creates meso-scale structures, such as zonal flows and streamers, through nonlinear interactions [1, 2]. These structures play a crucial role in magnetic confinement of plasmas. Zonal flows, well studied structures, are radially localized, poloidally elongated structures that regulate turbulent transports. On the other hand, streamers, poloidally localized and radially elongated structures, enhance radial transports [3]. Streamers were first identified in linear plasma device by using two azimuthal probe arrays [4]. Bi-spectral analysis [5,6] revealed that a mediator, a fluctuation propagating in the ion diamagnetic direction, nonlinearly couples with drift waves.

The research of control knobs of plasma turbulence is the most relevant issue. An electrode biasing is one of the techniques to control plasma turbulence through plasma current flow [7, 8]. In the linear magnetized plasma device, PANTA, the end-plate biasing experiment has been performed to control the streamers [9]. The streamer structure was broken during biasing. In this case, a decrease in turbulence and steepening of density profile have also been observed. In addition, further changes in turbulence and profiles during biasing were discovered. There are at least two modes in the biased plasmas. In this paper, we calculated bi-coherence before and during biasing and discuss the changes in nonlinear coupling. We also discuss temporal evolution of fluctuations during biasing.

2. End Plate Biasing in PANTA

The PANTA is a linear magnetized plasma created by helicon wave (3 kW/7 MHz). The cylindrical vacuum vessel has a diameter of 450 mm and a length of 4 m. Plasma diameter is about 100 mm ~ 120 mm. Axial magnetic field is 0 ~ 0.15 T, and argon pressure is 0 ~ 3 mTorr. Typical central density and electron temperature are 1×10^{19} m^{-3} and 3 eV, respectively. The electron density gradient is steep in the region of $r = 30$ - 40 mm, and excites drift wave instabilities. Drift waves propagate in the electron diamagnetic direction (positive azimuthal direction in this paper). An ion saturation current is measured with a 64-channel azimuthal plobe array. The array is located at 2115 mm away from the end plate, and its radial position is 40 mm. Each probe consists of a tungsten tip with a diameter of 0.8 mm and a length of 3 mm. The alternatingly-arranged 32 probes of the array measure ion saturation current, and the other 32 probes measure floating potential. We also measure ion saturation current at different radii (r = 10, 20, 30, 40 and 50 mm) with a 5-channel radial probe array. The array is located at 2375 mm away from the end plate. The diameter of the end-plate electrode is 50 mm.

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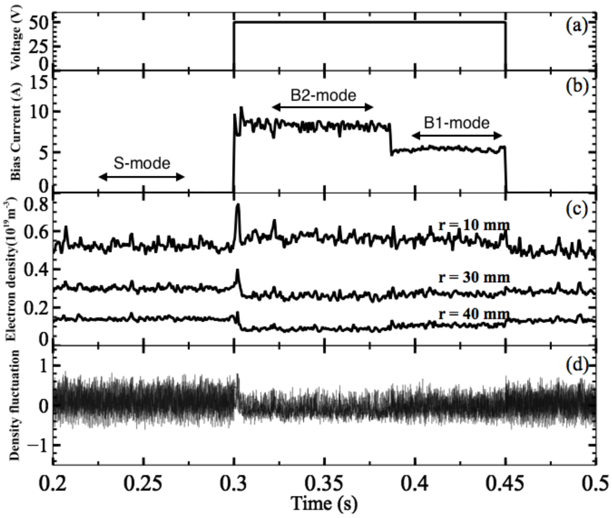

Fig. 1 (a) Bias voltage. (b) Time evolution of bias current. Biasless S-mode yields the streamer region, B2-mode suppresses fluctuations more than B1-mode. (c) Averaged electron density at three different radii (r = 10, 30 and 40 mm). (d) Fluctuation component of ion saturation current at r = 30 mm.

In PANTA, streamer appears when the axial magnetic field of 0.09 T and the argon pressure of 0.8 mTorr. Positive biasing was applied from 0.3 to 0.45 s as shown in Fig. 1. The biasing voltage was scanned from 10 V to 50 V. When the voltage was up to 40 V, the bias current saturated once around 5.5 A. If the voltage reached 50 V, however, the bias current took two values and jumped from one to the other several times. The current jump is an index of transition. Figure 1 (b) shows one current jump during a discharge. The presence of current jump indicates different states in PANTA plasma. Here we define three states; The first state is S-mode (Streamer mode), which is a state without the biasing. The other two states occurr during biasing with 50 V. A state in which bias current takes lower value, 5.5 A, is called as B1-mode (Biased 1 mode), and higher current (8 A) phase is called as B2-mode (Biased 2 mode). Figure 1 (c) shows averaged electron density at r = 10, 30 and 40 mm measured with a 5-channel radial probe array. Electron density at r = 10 mm (inside the end plate region) increased in the B1-mode, and further increased in the B2-mode. On the other hand, density at r = 40 mm (outside the end plate region) decreased. Thus, the radial profile of density became steep in the B1-mode and steeper in the B2-mode. Fluctuation was reduced in B1-mode and further reduced in B2-mode as shown in Fig. 1 (d).

3. Spectral Analysis

Auto-bi-spectrum shows the degree of coupling between three waves with frequencies f_1, f_2 and f_3, which satisfy a matching condition, $f_1 + f_2 = f_3$ [10]. Auto-bi-spectrum is defined as

$$\hat{B} = \langle X(f_1)X(f_2)X^*(f_3)\rangle,$$

where $X(f)$ is the Fourier transform of a time series $x(t)$. Auto-bi-coherence $\hat{b}$ is a normalized bi-spectrum, and is defined as

$$\hat{b}^2(f_1, f_2) = \frac{|\hat{B}(f_1, f_2)|^2}{\langle|X(f_1)X(f_2)|^2\rangle\langle|X(f_1 + f_2)|^2\rangle}.$$

The total bi-coherence is useful for analyzing the contribution of many mode couplings to a certain mode f_3. It is defined as

$$\sum \hat{b}^2 = \sum_{f_3=f_1+f_2=const.} \hat{b}^2(f_1, f_2).$$

The 2D power spectra and auto-bi-coherence of the ion saturation current fluctuation in the three different modes are shown in Fig. 2. Each 2D power spectrum was averaged over 26 ensembles (10 ms time window). Auto-bi-coherence was obtained from 179 ensemble averaging (2 ms time window). To increase the number of ensemble, the 32 probe signals are used. Thus, in total, 5728 ensembles were averaged to evaluate the bi-coherence. The confidence level of the squared bi-coherence is $1/5728 = 0.00017$.

First, we discuss the change of the 2D power spectrum. Figure 2 (a) represents a typical spectrum of streamer. The mode at $(m, f) = (1, -1.5\,\text{kHz})$ is the mediator of the streamer structure, which rotates in the ion diamagnetic direction. Here , "m" is the azimuthal mode number. Strong drift wave fluctuations exist at (m, f) = (2, 6.5 kHz) and (3, 5 kHz), which rotate in the electron diamagnetic direction. The mediator strongly couples with these drift waves and this is one of the characters of streamer [11]. In B1-mode, Fig. 2 (b) shows that the m = 2 drift wave frequency is changed from 6.5 kHz (S-mode) to 7 kHz. The mediator frequency is also changed from −1.5 kHz (S-mode) to −2 kHz. The power spectra of the drift wave fluctuations ($m > 0$) is decreased. In contrast, the power spectrum of the mediator is increased and harmonics of the mediator appear as $(m, f) = (2, -4.5\,\text{kHz})$. In B2-mode, Fig. 2 (c) shows that the m = 2 drift wave frequency is changed from 6.5 kHz (S-mode) to 7.5 kHz. The mediator frequency is also changed from −1.5 kHz (S-mode) to −2.5 kHz. The power of the drift wave fluctuations ($m > 0$) is further decreased compared to the B1-mode. In addition, the power of the mediator and its harmonics are further increased compared to the B1-mode.

Next, we discuss the change of bi-coherence. Figure 2 (d) shows the squared auto-bi-coherence of the streamer. There is a pronounced line at f_1 = 6.5 kHz, which indicates the coupling between f_1 = 6.5 kHz and the rest of the modes. For example, f_1 = 6.5 kHz couples with f_2 = ±1.5 kHz and produces f = 5 kHz and 8 kHz drift waves. In particular, at (f_1, f_2) = (6.5 kHz, 6.5 kHz), there is a strong self-coupling, which appears in the 2D power spectrum as (m, f) = (4, 13 kHz). Meanwhile, a line at f_1

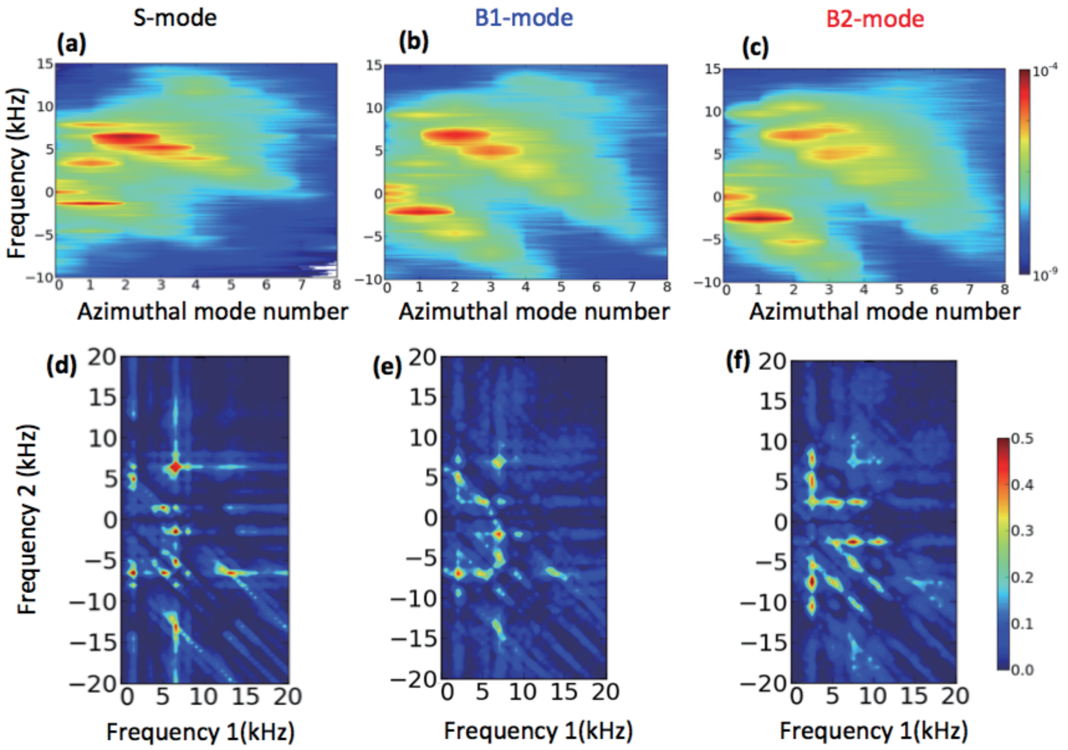

Fig. 2 Power spectra in S-mode (a), B1-mode (b) and B2-mode (c). The power spectra of drift waves ($m > 0$) is lower during biasing. Squared auto-bi-coherence in S-mode (d), B1-mode (e) and B2-mode (f). Auto-bi-coherence was also changed during biasing.

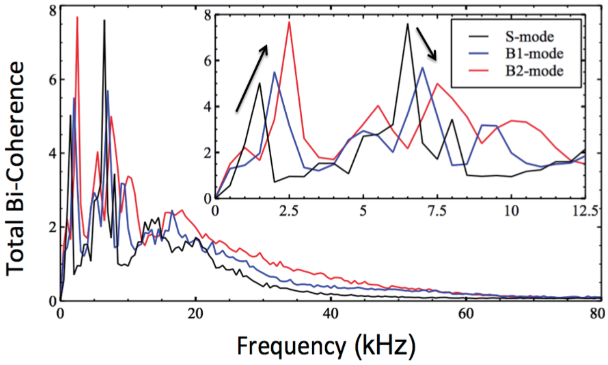

Fig. 3 Total bi-coherence of S-mode (black line), B1-mode (blue line) and B2-mode (red line). During biasing, coupling with mediator is increased (f = 1.5 ~ 2.5 kHz) and that with m = 2 drift wave is decreased (f = 6.5 ~ 7.5 kHz).

= 1.5 kHz indicates the coupling with mediators. In B1-mode, Fig. 2 (e) shows that the nonlinear coupling with the $m = 2$ drift wave is reduced, since the lines at f_1 = 7 kHz are unclear compared to those at f_1 = 6.5 kHz in S-mode. In particular, the (f_1, f_2) = (7 kHz, 7 kHz) self-coupling is reduced compared to that in S-mode. On the other hand, the coupling with mediator, f_1 = 2 kHz line is more pronounced than in S-mode. Further changes appeared in B2-mode. Figure 2 (f) indicates that the nonlinear coupling with the $m = 2$ drift wave is further reduced, since the lines at f_1 = 7.5 kHz are even fainter. In particular, the (f_1, f_2) = (7.5 kHz, 7.5 kHz) self-coupling is considerably reduced. A pronounced line at f_1 = 2.5 kHz, indicates coupling with mediators. Especially, the self-couplings of the mediator in B2-mode (i.e., f_1 = 2.5 kHz and f_2 = 2.5 kHz, 5.0 kHz and 7.5 kHz) are clearly shown. These self-couplings do not contribute to the streamer formation but to the formation of a solitary structure. In contrast, the couplings between the mediator and drift waves contribute to the streamer formation. Unfortunately, the frequencies of the $m = 2$ drift wave and third harmonic of the mediator are too similar (7.5 kHz) in this B2-mode, so that it is difficult to separate the contributions from these two different types of nonlinear couplings at (f_1, f_2) = (2.5 kHz, 7.5 kHz). Therefore, mode decomposition of the bi-coherence analysis is required. This is left for future work.

As explained above, auto-bi-coherence of drift waves and their power spectra are decreased during biasing, while power spectrum of mediators and its harmonics is increased and auto-bi-coherence of mediator is increased during biasing. This fact is supported by the total bi-coherence in each mode.

Figure 3 shows that the total bi-coherence is large at f = 6.5 kHz in S-mode and thus the $m = 2$ drift wave is strongly coupled with other fluctuations. With biasing, the coupling with the $m = 2$ drift wave (f = 7 kHz for B1-mode and 7.5 kHz for B2-mode) is decreased. On the other hand, mediator's coupling is increased during biasing. This result is consistent with the above bi-coherence analysis. In addition, coupling with respect to broad-band turbulence

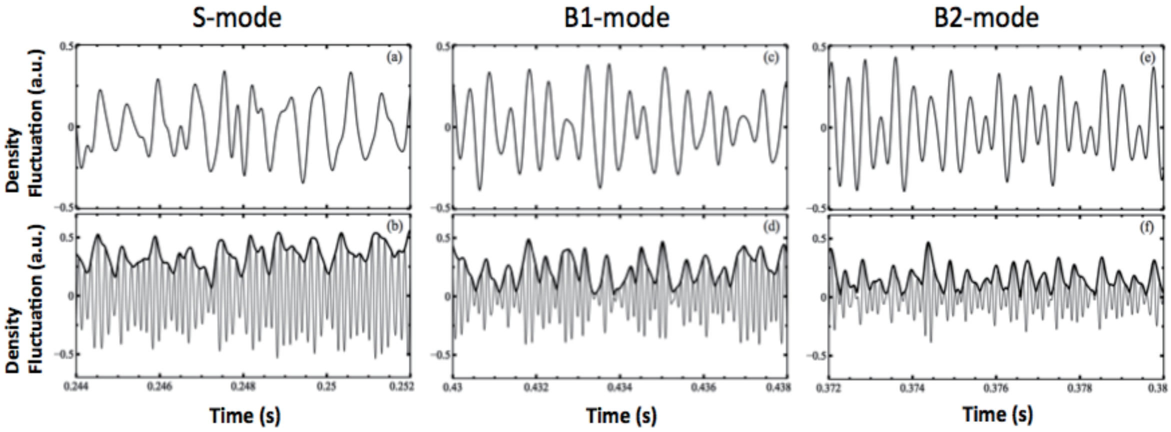

Fig. 4 Fluctuations in the 0.8 ∼ 3 kHz range (mediator frequency) in S-mode (a), B1-mode (c) and B2-mode (e). Fluctuations and its envelope (bold line) in the 4.8 ∼ 9.0 kHz range in S-mode (b), B1-mode (d) and B2-mode (e).

modes (> 20 kHz) is increased during biasing. Energy may be transferred from the low frequency quasi-coherent modes to the high frequency ambient turbulence. Identification of such energy transfer between fluctuations is left for future work.

4. Temporal Evolution of Fluctuations

Figure 4 shows the time evolution of density fluctuations in each mode. Figures 4 (a), (c) and (e) show the density fluctuations, filtered in the 0.8 ∼ 3.0 kHz frequency range, which includes the mediator. Figures 4 (b), (d) and (f) show density fluctuations and its envelope (bold line), filtered in the 4.8 ∼ 9.0 kHz frequency range, which includes the drift waves ($m = 2$ and 3) and mediator harmonics in B1-mode and B2-mode. Here the envelope of fluctuations was derived from Hilbert conversion. These figures indicate that the drift waves were modulated by the mediator fluctuations that form an envelope in every modes, i.e., S-mode, B1-mode and B2-mode. For example, in B1-mode, Fig. 4 (c) shows about 10 periods of wave in 0.43 ∼ 0.435 s, which corresponds to a frequency of 2.0 kHz, while envelope in (d), there are also about 10 times modulation during 0.43 ∼ 0.435 s. This observation further supports the coupling of mediator and drift waves or that of mediator and its harmonics during biasing.

Approximately 20 ∼ 30 V/m of radial electric field change is required to generate the frequency shift of 1.0 kHz. The resolution of the radial electric field measurement with probes [9] is insufficient to resolve such a change of electric field.

5. Summary

To control the streamer and drift waves, end-plate biasing has been investigated in PANTA. The streamer structure is suppressed during the biasing. Experimental observations include; (1) The 2D power spectrum of density fluctuations show that the drift waves are decreased and mediators and its harmonics are increased during biasing. (2) Nonlinear coupling with the mediator is increased, while that with $m = 2$ drift wave is decreased during biasing. Understanding of the dynamical change in streamer is a key issues to increase the predictive capability of turbulence transport.

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