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

Fumiyoshi KIN, Takuma YAMADA1,2), Shigeru INAGAKI2,3), Hiroyuki ARAKAWA4), Yoshihiko NAGASHIMA2,3), Naohiro KASUYA2,5), Akihide FUJISAWA2,3), Kousuke NAKANISHI, Hikaru KONO, Takaaki MIZOKAMI, Makoto SASAKI2,3), Yusuke KOSUGA3,5), Kimitaka ITOH2,6) and Sanae-I. ITOH2,3)

Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, 6-1 Kasuga-koen, Kasuga 816-8580, Japan
1)Faculty of Arts and Science, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan
2)Research Center for Plasma Turbulence, Kyushu University, 6-1 Kasuga-koen, Kasuga 816-8580, Japan
3)Research Institute for Applied Mechanics, Kyushu University, 6-1 Kasuga-koen, Kasuga 816-8580, Japan
4)Teikyo University, 6-22 Misakimachi, Otama 836-8505, Japan
5)Institute for Advanced Study, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan
6)National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan
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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.

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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 × 1019 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, negative parallel to the plasma current [10].

An ion saturation current is measured with a 64-channel azimuthal probe array [4]. 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 alternately-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.
the B2-mode. On the other hand, density at 10 mm (inside the end plate region) increased in the B1-mode, and further increased in the B2-mode. Fluctuation was reduced in B1-mode and profile of density became steep in the B1-mode and steeper (outside the end plate region) decreased. Thus, the radial array. Electron density at 10 mm (inside the end plate region) increased. In particular, at (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, the mediator frequency is also 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 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 bi-coherence. There is a pronounced line at 6.5 kHz and the rest of modes. For example, f1 = 6.5 kHz couples with f2 = ±1.5 kHz and produces f = 5 kHz and 8 kHz drift waves. In particular, at (f1, f2) = (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 f1

\[ B = \langle X(f_1)X(f_2)X^*(f_3) \rangle, \]

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

\[ \hat{b}^2(f_1, f_2) = \frac{\langle \hat{b}(f_1, f_2) \rangle^2 }{ \langle |X(f_1)X(f_2)|^2 \rangle^2}. \]

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

\[ \sum_{f_1 + f_2 = f_3, \text{const.}} \hat{b}^2(f_1, f_2). \]

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 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 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.

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
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 \((f = 1.5 \sim 2.5 \text{kHz})\) and that with \(m = 2\) drift wave is decreased \((f = 6.5 \sim 7.5 \text{kHz})\).

\(= 1.5 \text{kHz}\) 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 \(f_1 = 7 \text{kHz}\) are unclear compared to those at \(f_1 = 6.5 \text{kHz}\) in S-mode. In particular, the \((f_1, f_2) = (7 \text{kHz}, 7 \text{kHz})\) self-coupling is reduced compared to that in S-mode. On the other hand, the coupling with mediator, \(f_1 = 2 \text{kHz}\) 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 \(f_1 = 7.5 \text{kHz}\) are even fainter. In particular, the \((f_1, f_2) = (7.5 \text{kHz}, 7.5 \text{kHz})\) self-coupling is considerably reduced.

A pronounced line at \(f_1 = 2.5 \text{kHz}\), indicates coupling with mediators. Especially, the self-couplings of the mediator in B2-mode (i.e., \(f_1 = 2.5 \text{kHz}\) and \(f_2 = 2.5 \text{kHz}, 5.0 \text{kHz}\) and \(7.5 \text{kHz}\)) 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 \((7.5 \text{kHz})\) in this B2-mode, so that it is difficult to separate the contributions from these two different types of nonlinear couplings at \((f_1, f_2) = (2.5 \text{kHz}, 7.5 \text{kHz})\). 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 \(f = 6.5 \text{kHz}\) 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 \((f = 7 \text{kHz}\) for B1-mode and \(7.5 \text{kHz}\) 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
modes (\(>20\,\text{kHz}\)) 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 \(\sim\) 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 \(\sim\) 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 \(\sim\) 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 \(\sim\) 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 \(\sim\) 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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