Observation of nonlinear coupling in azimuthal wavenumber space in a cylindrical magnetized plasma

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Many theoretical and experimental works have shown the importance of good understanding of plasma turbulence to reduce turbulent transport in thermonuclear fusion reactors [1]. Nonlinear interactions of fluctuating components can produce strong turbulence states of plasmas. Recently, bispectral analysis is widely used to measure strength of nonlinear interaction between three modes that satisfy the matching condition. In particular, strong turbulence state has been observed in low temperature cylindrical plasmas [2], where mutual nonlinear interactions among coherent fluctuating components and broadband turbulence are significant. In such a state, it is necessary to analysis the nonlinear interaction from various aspects to distinguish the different processes and the complex interplay they can form. The present contribution shows the spatiotemporal distribution of nonlinear coupling strength of a nonlinear plasma wave, the waveform of which shows large deviation from a trigonometric function. Wavelet bispectral analysis with conditional average is used to compute the strength of nonlinear coupling. The analysis results demonstrate that there is an inhomogeneity bicoherence in azimuthal direction that rotates rigidly in electron diamagnetic direction.

The experimental observation is carried out on a cylindrical magnetized plasma device, the Plasma Assembly for Nonlinear Turbulence Analysis (PANTA) [3]. The PANTA has a length of 3740 mm and a diameter of 450 mm. Field coils surrounding the device can generate a homogeneous axial magnetic field. An argon plasma is produced at one side of the device with a rf heating of 3 kW. The experimental conditions for this study are a magnetic field strength of 0.09 T and a neutral gas pressure of 3.0 mTorr (relatively high pressure condition). Under these

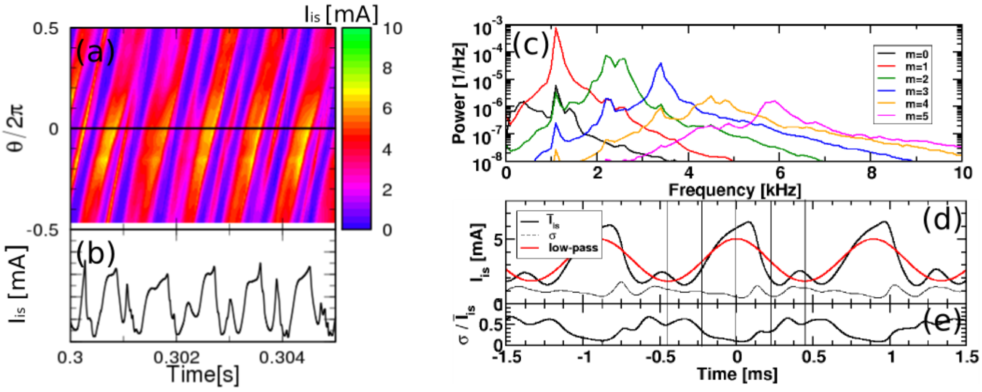

Figure 1: (a) Spatiotemporal evolution of ion saturation current fluctuation. (b) Time evolution of ion saturation current measured at $\theta/2\pi = 0$. (c) Mode decomposed auto power spectrum of ion saturation current fluctuation. (d) Conditional average of the ion saturation current signal, standard deviation from the averaged signal, and the averaged signal filtered with a 1.5kHz low-pass filter. (e) Deviation from the averaged signal. Five vertical lines indicate $\varphi_i/\pi = -1.0, -0.5, 0, 0.5, 1.0$, respectively.

conditions, the plasma has a peaked electron temperature T_e and electron density n_e profile of typically $T_e \sim 3$ eV and $n_e \sim 1 \times 10^{19}$ m^{-3}, respectively. The 64-channel azimuthal Langmuir probe array is installed at $r = 40$mm, where the gradient of the electron density profile is the largest. The ion saturation current fluctuation profile is measured with 32 probe tips. The ion saturation current fluctuation normalized by its mean value is used an index of the electron density fluctuation profile. It has been found that several waves in the frequency range of resistive drift wave are excited.

Wavelet bicoherence [4] with conditional average [5] is defined as

$$\hat{b}_i^2(f_3) = \frac{|\langle W(t,f_1)W(t,f_2)W^*(t,f_3)\rangle_i|^2}{\langle|W(t,f_1)W(t,f_2)|^2\rangle_i\langle|W(t,f_3)|^2\rangle_i}, \quad (1)$$

where $W(t,f)$ is a discrete wavelet component and the asterisk represents the complex conjugate. The matching condition $f_3 = f_1 \pm f_2$ has to be satisfied. In the present contribution, the conditional average, represented by bracket in Eq. (1), is constructed by using the phase of the dominant fluctuating component $\varphi(t)$, where $\varphi(t) = \tan^{-1} W(t, f = f_{\mathrm{dominant}})$. The phase of the dominant fluctuating component is divided into regular intervals using the value φ. The conditional average is then defined as $\langle\psi(t)\rangle_i = \sum_{\varphi_i<\varphi(t)<\varphi_{i+1}} \psi(t)$, where $\psi(t)$ is an arbitrary function of t and $\varphi_i = -\pi + 2(i-1)\pi/n$.

Spatiotemporal evolution of the ion saturation current fluctuations is shown in Figs. 1 (a) and (b). The positive direction of vertical axis indicates electron diamagnetic direction. A non-

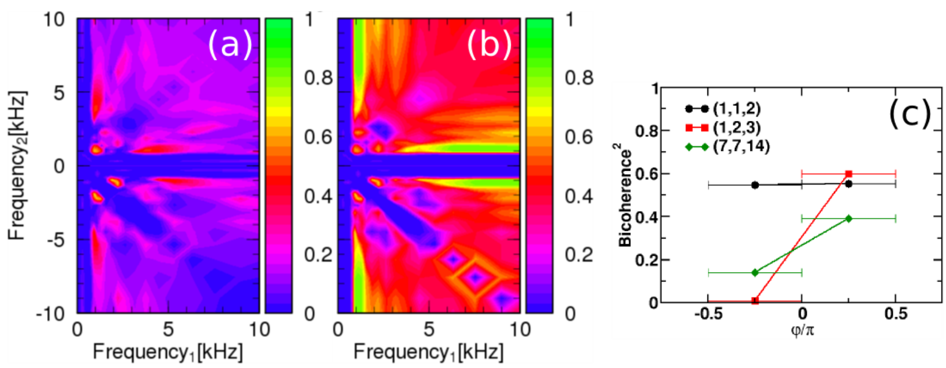

Figure 2: Squared wavelet bicoherences for the cases of (a) $-0.5 < \varphi/\pi < 0$ and (b) $0 < \varphi/\pi < 0.5$. (c) Evolution of the squared wavelet bicoherence for three specific combinations of fluctuating components. Legend indicates the combination as (m_1, m_2, m_3).

trigonometric waveform traveling in the positive azimuthal direction is observed. Figure 1 (c) shows mode-decomposed Fourier power spectrum of the normalized ion saturation current fluctuations for the lower frequencies and mode numbers. The power spectrum is characterized by coherent components: a fundamental mode ($f = 1.1$ kHz, $m = 1$) and its higher harmonics ($m = 2, 3, ...$), all of which have the same phase velocity. There is one-to-one correspondence between the frequency and mode number for all of these modes, so that spectral analysis in the mode number domain can be directly linked to that in the frequency domain. The conditional average of the raw signal is calculated to emphasize the periodic properties of the signal. It is computed as $\bar{I}_{\mathrm{is}}(\tau) = 1/N\sum_{i=1}^{N} I_{\mathrm{is}}(t_i - T/2 < t < t_i + T/2)$, where T is a specific time width. The value t_i indicates the i-th time $\varphi(t)$ becomes zero and N is the total number of periods. The standard deviation of the conditional averaged signal is also defined as $\sigma(\tau) = \sqrt{1/N\sum_{i=1}^{N}[I_{\mathrm{is}}(t_i - T/2 < t < t_i + T/2) - \bar{I}_{\mathrm{is}}(\tau)]^2}$. Figure 1 (d) shows the conditional average of the raw signal, the standard deviation from the averaged signal, and the $f = 1.1$ kHz component (the fundamental mode) extracted by a digital low-pass filter with $f_{\mathrm{filt}} = 1.5$ kHz. Figure 1 (e) shows the deviation ratio from the averaged signal, $\sigma/\bar{I}_{\mathrm{is}}$. In the conditional averaged raw signal there are two distinct peaks in one period of the fundamental mode: a first large distorted peak followed by a smaller peak. The small peak has a large standard deviation (more than 50 %). A detailed investigation has been done for this small peak and was presented in elsewhere [6]. Four time intervals are shown by the vertical lines in Fig. 1 (d). The large peak is located at $-0.5 < \varphi/\pi < 0.5$ and the small peak is located at $-1.0 < \varphi/\pi < -0.5$ and $0.5 < \varphi/\pi < 1.0$.

Figures 2 (a) and (b) show squared wavelet bicoherences for the large peak of the conditional averaged signal. For two different phase intervals, the figures show a clear change in the bicoherence. Figure 2 (c) shows changes of the squared bicoherence for three specific combinations of fluctuating components. The squared wavelet bicoherence of (m_1, m_2, m_3)=$(1, 1, 2)$ is almost constant in both time intervals. In contrast, the squared wavelet bicoherence of (m_1, m_2, m_3)=$(1, 2, 3)$ changes considerably. In the case of $-0.5 < \varphi/\pi < 0$, the squared wavelet bicoherence of (m_1, m_2, m_3)=$(1, 2, 3)$ is almost zero, so that the nonlinear phase relation among these three modes is estimated to be random. The squared wavelet bicoherence of (m_1, m_2, m_3)=$(1, 2, 3)$ becomes high (almost 0.6) in the phase $0 < \varphi/\pi < 0.5$. The squared wavelet bicoherence of (m_1, m_2, m_3)=$(7, 7, 14)$ also change largely (it becomes twice larger). These tendency about changes in bicoherence can be seen in calculation results from different azimuthal locations. Therefore we can estimate the existence of an inhomogeneity of the bicoherence strength in the azimuthal direction rotating rigidly with the fundamental mode.

In summary, a non-trigonometric ion saturation current wave traveling in positive azimuthal direction was observed in the PANTA device. Wavelet bicoherence with conditional average revealed a rigidly rotating inhomogeneity in the bicoherence strength.

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