Two-Dimensional Spatial Structure of Plasma Turbulence in LMD-U

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Introduction

Recent progress in theoretical and experimental works on plasma turbulence has indicated that the micro turbulence tends to form spatiotemporal structures, which can either enhance or suppress the turbulent transport[1]. The structure formation in turbulent plasma, thus, is considered to be one of the most important issues to be clarified in the study of turbulence transport. The weak to strong turbulence transition is produced in the LMD-U device by controlling the strength and shape of the magnetic field and/or neutral pressure[2, 3]. To clarify the turbulence transition mechanism, an understanding of each state, i.e. the weak and strong turbulent state, is essential. For this purpose, this paper presents 2-dimensional structures of the electrostatic fluctuations observed in the weak turbulent plasmas.

Experimental Setup and Observation of Fluctuations in LMD-U

Drift wave excitation experiments were performed in the Large Mirror Device Upgrade (LMD-U)[4]. A cylindrical plasma with a diameter of approximately 10cm and an axial length of 3.74m is produced by the helicon wave system (with a wave frequency of 7MHz and a power of 3kW) and radially confined in the linear magnetic configuration (the magnetic field is 900G). Neutral gas (Ar) is injected by a mass flow controller. Ion-neutral collisions stabilize the dissipative drift waves[5], thus, plasma is produced under high neutral pressure (6 mTorr) to achieve the weak turbulent state (similarly, reduction of neutral pressure is required to achieve the strong turbulence state). In this experiment, the reflected power is kept stationary during the discharge except for the initial break down phase. To study the non-linear interaction of the waves, the observation of the spatiotemporal structure of the fluctuations is essential. For the low electron temperatures typical of LMD-U plasmas ($\sim$3eV), Langmuir probe diagnostics are most suitable to measure the fluctuations at a high temporal and spatial resolution. Figure 1 shows typical fluctuations observed with the 2-dimensional movable probe (2-D probe). The 2-D probe has three colinear tungsten tips as shown in Fig. 1(d). The center tip measures the ion saturation current fluctuation, I_{is} and the other tips measure the floating potential fluctuations, $V_{f,up/down}$,

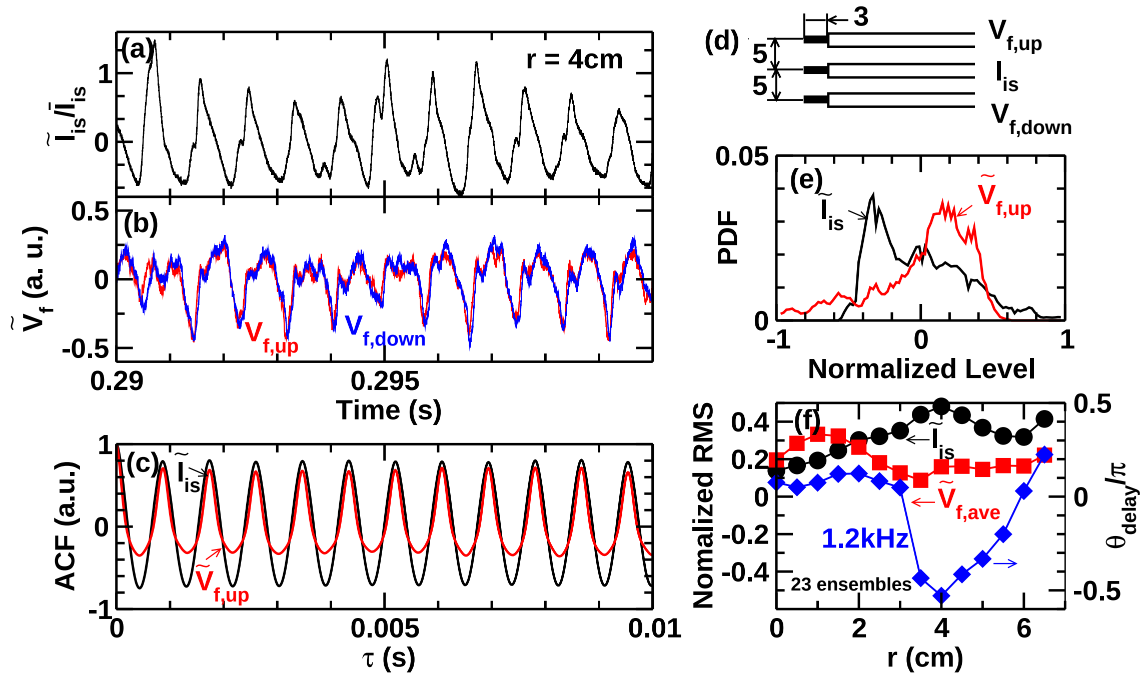

Figure 1: Typical time evolutions of (a) the $\tilde{I}_{\rm is}$ and (b) the $\tilde{V}_{\rm f,up/down}$ and (c) their auto-correlation functions. (d): The schematic view of 2-D movable probe tips. (e): Probability density functions corresponding to time series of (a) and (b). (f): Radial profile of normalized amplitude of the $\tilde{I}_{\rm is}$ and the $\tilde{V}_{\rm f,ave}$ and phase delay between $\tilde{I}_{\rm is}$ and the $\tilde{V}_{\rm f,ave}$ at 1.2kHz.

simultaneously. Typical time evolutions of $\tilde{I}_{\rm is}$ and $\tilde{V}_{\rm f,up/down}$ are shown in Fig. 1(a) and (b). Here $\tilde{f} = f - \langle f \rangle$ and $\langle f \rangle = (T)^{-1}\int_0^T f(t)dt$ indicates temporal averaging. The frequency of the dominant component of both is 1.2kHz (the frequency resolution is 60Hz). The waveforms, however, are non-trigonometric functions similar to sawtooth waves. The auto-correlation functions indicate that the fluctuations are coherent with long correlation times as shown in Fig. 1(c). In the auto-correlation function of $\tilde{V}_{\rm f,up/down}$, the asymmetric features of sawtooth waves appear prominently. The probability density functions (PDFs) of both $I_{\rm is}$ and $V_{\rm f,up}$ are strongly skewed as shown in Fig. 1(e). Here, the fluctuation amplitudes are independently normalized by their respective maximum values. Positive and negative tails appear in the PDFs. These observations indicate that the waves are strongly deformed by the non-linear effects. A distinct phase delay between $\tilde{I}_{\rm is}$ and $\tilde{V}_{\rm f,up/down}$ is observed in Fig. 1(a)(b). The value of $\tilde{V}_{\rm f}$ at the center probe tip is estimated from $\tilde{V}_{\rm f,ave} = (\tilde{V}_{\rm f,up} + \tilde{V}_{\rm f,down})/2$ and the phase delay with respect to $\tilde{I}_{\rm is}$ is calculated. The radial profile of the phase delay indicates that a delay of approximately $\pi/2$ exists in the region of $r = 3.5 - 5$cm, where the normalized $\tilde{I}_{\rm is}$ amplitude (the root mean square) has an peak and $\tilde{V}_{\rm f,up/down}$ is small. On the other hand, $\tilde{I}_{\rm is}$ and $\tilde{V}_{\rm f,up/down}$ become in-phase in the core region

($r < 3$cm). A sharp boundary between the two regions is observed at $r = 3 - 3.5$cm

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Figure 2(a) shows the power spectrum in frequency-wave number (azimuthal direction) space. Azimuthal structure of the ion saturation current fluctuations were measured with a 64-channel azimuthal probe array[6]. The probe tips in this array are arranged in a circle with $r = 4$cm. The power spectrum has some peaks, which lie along a straight line on the frequency-wave number space and satisfy a condition of $rk =$m (m is the azimuthal mode number and $r = 4$cm). An m = 1 wave at $f \sim 1.2$kHz is strong and excites higher harmonic waves. Both even as well as odd harmonic components are included as is the case with the sawtooth waves. These waves are considered to be produced by nonlinear wave coupling effects (e.g. frequency doubling).

Two-point correlation between the 2-D probe and a reference probe is obtained by changing the position of the 2-D probe, shot by shot, under an identical external discharge condition. The 2-D probe and a reference probe are separated by 25cm in the magnetic field direction and the reference probe is located at $r = 4$cm. By using the correlation technique, two-dimensional spatial profiles of coherence and the cross-sectrum of $\tilde{I}_{\rm is}$ are obtained. The coherence structure of the $f = 1.2$kHz component are long both in the azimuthal and radial directions as shown in Fig. 2(b). Although the phase delay relation between $\tilde{I}_{\rm is}$ and $\tilde{V}_{\rm f,up/down}$ changes drastically across the boundary located at $r = 3 - 3.5$cm, strong coherence between $\tilde{I}_{\rm is}$ at $r = 4$cm and in the core region ($r < 3$cm) exists over this boundary. The cross-spectrum gives information about the wave amplitude and phase relation. The imaginary part of the cross-spectrum, $\xi \sin(\Delta\theta)$, indicates the shape of wave front. The 2-dimensional probe usually scans on half the cross section of the LMD-U. The cross-spectrum of the whole 2-dimensional area, therefore, is reconstructed by assuming azimuthal symmetry. The obtained cross-spectrum structure (see Fig. 2(c)) shows that there is a wave which has with an m = 1 helically distorted structure rotating in the electron diamagnetic direction. The mode number obtained from two different probe systems is in good agreement with each other. The 2-D structure of $\tilde{V}_{\rm f}$ will be reported in a forthcoming paper.

Summary

A non-trigonometric wave is excited in the LMD-U device. Transition to a turbulent wave from the non-linear wave is made by controlling the strength and the shape of magnetic field and/or neutral pressure. To clarify the turbulence transition mechanism, the two-dimensional structure of the non-linear wave is observed by using the two-point correlation technique. Obtained results under this experimental condition are as follows: 1) The waveforms of $\tilde{I}_{\rm is}$ and $\tilde{V}_{\rm f,up/down}$ are similar to sawtooth waves and the PDFs are skewed. 2) The largest spectral peak

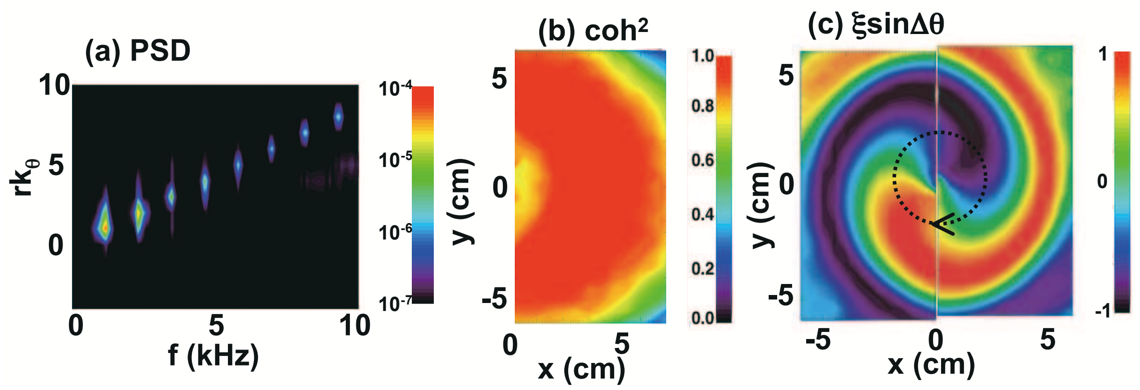

Figure 2: (a): Power spectrum in frequency-wave number space at $r = 4$cm. Two dimensional structures of (b) squared coherence and (c) imaginary part of cross-spectrum for the coherent mode at 1.2kHz. The arrow denote the direction of propagation (the electron diamagnetic drift direction).

is excited at 1.2kHz and the even and odd higher harmonic waves are also excited. 3) The coherence structure at 1.2kHz is broad both in the azimuthal and the radial directions. 4) A spiral-shaped (m = 1) wave is formed.

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