Coexistence of the drift wave spectrum and low-frequency zonal flow potential in cylindrical laboratory plasmas

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Introduction

Physics of zonal flows and their interaction with turbulence is one of the most attractive research fields in fusion plasma confinement and its control [1]. The zonal flow is considered to be exclusively driven by nonlinearity of micro-scale turbulence, and to affect turbulence transport. However, many experimental research tasks for understanding the zonal flow physics are left; How does the zonal flow distribute radially, where is the zonal flow excited and damped, and how is turbulence affected by the zonal flow?

In the Large Mirror Device of Kyushu University [2], a low-frequency zonal $E \times B$ velocity ($ZV_{E\times B}$) is observed as well as the drift wave spectrum (DW), and details of coexistence of the $ZV_{E\times B}$ and the DW has been investigated. The Large Mirror Device (LMD) is a basic plasma experiment device shown in Fig. 1(a), which has a cylindrical vacuum vessel made of stainless steel with a linear magnetic field configuration up to 0.12 T. Helicon plasmas are produced by an RF source (2 kW) at one end of the vacuum vessel. Fluctuations are mainly measured with a Reynolds stress probe (RSP) shown in Fig. 1(b), located at 60 cm far from the source region where axial density profile is stable. Three electrodes in the RSP are used for the floating potential fluctuation $\tilde{\Phi}_f$ measurement and Reynolds stress term $\langle \tilde{v}_r \tilde{v}_\theta \rangle$ assuming that $E \times B$ velocity is dominant as the plasma velocity. In this paper, we show detail features of the $ZV_{E\times B}$ and the DW, and nonlinear interactions between them in the LMD.

Quadratic spectra of the zonal $E \times B$ velocity and the drift wave
The coexistence of the ZVE\textsubscript{E×B} and the DW is observed in the vicinity of a phase transition in which the fluctuation behaviors change from combination of coherent spectral peaks to the broadband spectrum. The phase transition occurs spontaneously as the magnetic field strength $B$ increases with the filling Ar gas pressure $P_{\text{Ar}}$ fixed and/or as $P_{\text{Ar}}$ reduces with $B$ fixed. In this operation, $B=0.12$ [T] and $P_{\text{Ar}} \sim 3.5$ [mTorr].

Figure 2 shows a comparison of spectrum between the normalized ion saturation current fluctuation $\tilde{I}_i/\tilde{I}_{i,\text{sat}}$ and the normalized floating potential fluctuation $\tilde{\Phi}_f/\bar{T}_e$, where $\bar{T}_e$ is the equilibrium electron temperature. Two distinctive spectral peaks are observed at $\sim 0.4$ and 7-8 kHz. We abbreviate the former and the latter fluctuations as the ZVE\textsubscript{E×B} and the DW, respectively. Confirmations are described in following sentences.

The ZVE\textsubscript{E×B} has larger potential amplitude than density. The two-point cross-phase analysis shows that the poloidal and the axial cross-phases of the ZVE\textsubscript{E×B} is within $\pm 0.2$ [rad/2$\pi$], consistent with the poloidal/axial mode numbers $m/n = 0/0$. The DW has features different from the ZVE\textsubscript{E×B}. The DW normalized amplitude of potential is similar with that of density, and wave numbers of the DW are finite ($m/n=3-5/2-3$). These features does not contradict that the DW is the drift wave. Figure 3(a) shows radial profile of the radial wave number $k_r$ of the ZVE\textsubscript{E×B}. The ZVE\textsubscript{E×B} has finite radial wave numbers at the radial location $r=\sim 2$ and 4 cm. However, we also observe inversion of polarity in the ZVE\textsubscript{E×B} $k_r$ relative to the location of maximal DW amplitude. On the other hand, Figure 3(b) shows radial profile of $k_r$ of the DW. Signs of the
Figure 4: Information of poloidal velocity fluctuation associated with the ZV$_{E \times B}$ oscillation. (a) $\tilde{V}_\theta(t)$ measured by the TDE analysis, (b) $\tilde{\Phi}(t)$ for ZV$_{E \times B}$. (c) power spectrum of $\tilde{V}_\theta(t)$ and (d) the cross-coherence and the cross-phase between $\tilde{V}_\theta(t)$ and $\tilde{\Phi}(t)$. A time window $\tau_{TDE}$ for the TDE analysis is 512 [\mu sec] ($\tau_{ZV} > \tau_{TDE} > \tau_{DW}$), and results from quadratic spectra is valid for $f < \sim 2$ kHz.

$k_r$ polarity change radially, indicating that $k_r$ of the DW is modulated spatially (a vortex tilting). Linear dispersion relation of the DW is calculated. Using observed parameters at the radial location where the DW amplitude has a maximum, we evaluate the drift wave frequency $\omega_{DW}=\omega^*/(1+k^2_\perp \rho_s^2)=6$-$8$ kHz, where $\omega^*=k_\theta T_e/(eB\lambda_n)$, $k_\perp$ is the wave number perpendicular to the magnetic field, $\rho_s$ is the ion Larmor radius at the electron temperature, $k_\theta$ is the poloidal wave number, and $\lambda_n$ is the density scale length. The calculation of frequency is consistent with the spectral peak frequency of the DW 7-8 kHz.

**Details of the zonal E × B velocity**

Potential analysis is not enough for identifying the zonal flow. Definition of the zonal flow is an poloidal ion flow velocity, therefore, other poloidal flow measurements can test whether the ZV$_{E \times B}$ is the zonal flow or not. Supported by the Time Delay Estimation analysis [3], the poloidal flow oscillation of turbulent fluctuations associated with the ZV$_{E \times B}$ is evaluated. Figure 4 shows results of the poloidal velocity fluctuation $\tilde{V}_\theta(t)$ derived from the TDE analysis and their relationship with the potential fluctuation for the ZV$_{E \times B}$. Two plots of $\tilde{V}_\theta(t)$ and $\tilde{\Phi}(t)$
demonstrate a synchronization of $\tilde{V}_\theta(t)$ and $\tilde{\Phi}_f(t)$ at the ZV$_{E\times B}$ frequency, shown in Fig. 4. Testing significance of the synchronization by cross-correlation analysis, we observe a significant spectral peak of the squared coherence between $\tilde{V}_\theta(t)$ and $\tilde{\Phi}_f(t)$ at the ZV$_{E\times B}$ frequency. We confirm that the synchronization is statistically admissible. The cross-phase between potential and $\tilde{V}_\theta(t)$ is different in radius.

**Nonlinear interaction between the ZV$_{E\times B}$ and the DW**

The bispectral analysis [4] can also demonstrate significance of nonlinear three-wave interaction, and is applied to nonlinear interaction between the zonal flow and turbulence. Figure 5 shows auto-bicoherence plot of the floating potential fluctuations, normalized $\langle \tilde{\Phi}_f(f_1)\tilde{\Phi}_f(f_3-f_1)\tilde{\Phi}_f^*(f_3) \rangle$, at frequency $3 = 0.366$ kHz (frequency of the ZV$_{E\times B}$). A significant spectral peak at $f_1 \sim 7$-8 kHz confirms that the ZV$_{E\times B}$ is nonlinearly coupled to the DW.

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**References**


