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Observation of nonlinear processes between coherent fluctuations and turbulent fluctuations in the edge regions of JFT-2M and CHS

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Introduction

A study of nonlinear self-regulation processes in plasma turbulence has crucial importance for clarifying the mechanism of anomalous transport in magnetically confined plasmas. Resent theoretical progress has highlighted the importance of nonlinear couplings between meso-scale structures and micro-scale turbulent fluctuations. For example, zonal flows [1] are nonlinearly driven by drift wave turbulence, and also regulate the turbulence and turbulent transport. Experimental identification of zonal flows was confirmed [2], and by a bicoherence analysis [3], experimental tests for the nonlinear theory in the drift wave-zonal flow systems has been performed. Other target of the studies is a nonlinear relationship between coherent magnetohydrodynamics (MHD) oscillations and turbulent fluctuations. These nonlinear processes can be observed as the bispectral functions. Thus, the bispectral analysis provides a fundamental technique for clarifying these nonlinear processes. In this paper, we present experimental observations of nonlinear processes between coherent fluctuations and turbulent fluctuations in toroidal plasmas. In the JFT-2M tokamak edge, the significant auto-bicoherence and biphase in potential fluctuations were measured between the geodesic acoustic mode (GAM), which is a sideband mode of zonal flow, and broadband turbulence. Under a model equation of the drift wave-zonal flow systems [4], a semi-quantitative study has been performed. In the H-mode edge plasmas of the CHS device, the significant nonlinear couplings between low frequency coherent fluctuations around 4 kHz [5] and turbulent fluctuations (at few hundreds kHz) were observed.

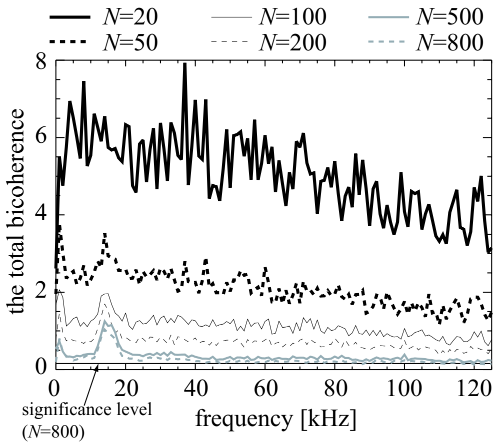

Figure 1: Evaluated total bicoherence for various numbers of realizations up to 800.

The contribution of the nonlinear process to radial particle transport will be discussed.

Results from the JFT-2M tokamak: Nonlinear couplings between zonal flows and turbulence

In the JFT-2M tokamak, geodesic acoustic modes (GAM) were observed in ohmically heated plasmas and in *L*-mode plasmas by a reciprocating Langmuir probe (RLP) [3] and by a heavy ion beam probe [6]. The GAM frequency range is 10-15 kHz. Nonlinear processes of potential fluctuations between GAM and turbulent fluctuations was observed as squared bicoherence. Figure 1 shows the total bicoherence$\sum \hat{b}^2(f_1, f_2) = \sum \frac{|\langle \phi(f_1)\phi(f_2)\phi^*(f_1 \pm f_2)\rangle|^2}{(\langle|\phi(f_1)\phi(f_2)|^2\rangle\langle|\phi(f_1 \pm f_2)|^2\rangle)}$, illustrating the convergence properties (i.e., dependence on the realization number of statistical ensemble). We have obtained the total bicoherence at the GAM frequency well above the significance level. Convergence curves of the total bicoherence depending on the realization number N have a form $C_1 + \frac{C_2}{N}$, where C_1 is the converged total bicoherence (in the limit of large N), and $\frac{C_2}{N}$ is a noise level. The quantitative study of the nonlinear coupling needs converged bispectral coherence C_1. Figure 2 shows convergence curve of the total bicoherences at GAM and turbulence frequency range. For the nonlinear couplings between GAM and turbulence, we have C_1 of ~ 0.88, and for the nonlinear couplings among turbulence, C_1 of ~ 0.052 is obtained. The nonlinear theory of the drift wave-zonal flow systems predicted the total bicoherence in a following expression, $\sum \hat{b}^2 = 4M(\frac{1}{h(k_{\perp \rho_s})}\frac{q_x k_\perp^2 \rho_s^3}{1+k_\perp^2 \rho_s^2})^2 \frac{\phi_Z^2}{\phi_d^2} + 3(\frac{1}{h(k_\perp \rho_s)}\frac{k_x k_\perp^2 \rho_s^3}{1+k_\perp^2 \rho_s^2})$ [4]. For the nonlinear coupling between GAM and turbulence, the theoretical estimate for total bicoherence is around 0.9, and for the nonlinear couplings among turbulence is around 0.05. (Experimental parameters used here are number of frequency segments $M = 125$, ion Larmour radius at the electron temperature $\rho_s \sim 0.2\,[\mathrm{cm}]$, poloidal wavenumber of turbulence $k_\theta \sim 1.5\,[\mathrm{cm}^{-1}]$, radial wavenumber of zonal flow $q_x \sim 0.5\,[\mathrm{cm}^{-1}]$, perpendicular wavenumber of turbulence $k_\perp \sim \sqrt{2}k_\theta$, normalized nonlinear turbulence decorrelation rate $h(k_\perp \rho_s) = \tau^{-1}\omega_*^{-1}\phi^{-1} \sim 0.4$, and squared amplitude ratio of zonal flow potential to turbulence potential $\phi_Z^2/\phi_d^2 \sim 1.0$.) Theoretical predictions are consistent with experimental observations. The theoretical formula has second and/or third

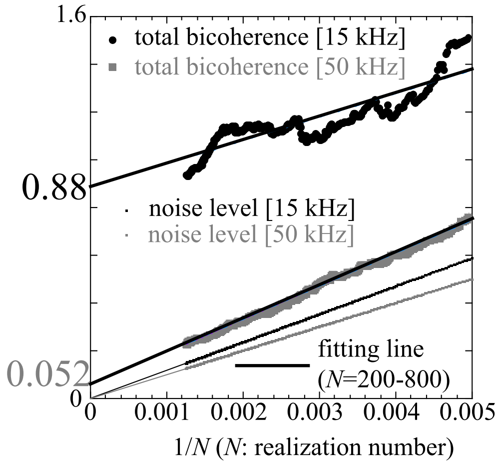

Figure 2: Convergence curves of the total bicoherence. Black and gray plots indicate the total bicoherence at GAM frequency and turbulence frequency, respectively. Converged values by extrapolation in the limit of $N = \infty$ are also shown.

order terms of wavenumbers, therefore, we need precise measurements of wavenumbers for the future detail comparison.

Results from the CHS device: Contribution of a coherent MHD fluctuation to particle transport via nonlinear process

In *H*-mode plasmas of the CHS device, a coherent magnetic fluctuation has been observed and has been intensively studied by a beam emission spectroscopy [5]. We have performed edge fluctuation measurements by the hybrid probe (HP) [7] for investigating edge nonlinear processes and contribution of the coherent fluctuations to transport. The HP has 4 electrodes. One electrode was used for $\tilde{I}_{\mathrm{i,\ sat}}$ and other three electrodes were used for $\tilde{\phi}_{\mathrm{float}}$ measurements. Cross correlation is measured transport process. For instance, particle flux can be estimated from a summation of quadratic spectra, $\Gamma_r = \mathrm{Re}\sum \frac{\langle \tilde{n}_\mathrm{e}(f)(-ik_\theta \tilde{\phi}(f))\rangle}{B_0}$, where $\tilde{n}_\mathrm{e}(f)$ is the density fluctuation at frequency f, and $-ik_\theta \tilde{\phi}(f)$ is the poloidal electric field, respectively. Cross-biphase is useful in measuring nonlinear processes in convection. In the case that a (coherent) fluctuation has a density fluctuation and modulates other higher frequency density and poloidal electric field fluctuations (forward interaction), radial particle fluxes driven by the modulation $n_\mathrm{e}(f_1)E_\theta(f_2)$ is synchronized with the modulating fluctuation at $f = f_1 + f_2$. This flux is not DC flux, but has a nonlinear effect on the modulating density fluctuation ($f_1 + f_2$). The cross-bicoherence $\sum \frac{|\langle \tilde{n}_\mathrm{e}(f_1)\tilde{\phi}(f_2)\tilde{n}^*_\mathrm{e}(f_1 \pm f_2)\rangle|^2}{\langle|\tilde{n}_\mathrm{e}(f_1)\tilde{\phi}(f_2)|^2\rangle\langle|\tilde{n}_\mathrm{e}(f_1 \pm f_2)|^2\rangle}$ indicates the process that the modulating density fluctuation $\tilde{n}_\mathrm{e}(f_1 \pm f_2)$ is affected by the radial particle transport (backward interaction). Figures 3 show quadratic spectra of $\tilde{\phi}_{\mathrm{float}}$. Three types of fluctuations were observed. First one is a low frequency coherent fluctuation around 4 kHz with a long-range poloidal correlation (Type A). This is the same fluctuation studied in Ref. [5] The second one is broadband fluctuations in several tens kHz. From correlation analysis, the second one has short poloidal correlation length (Type B). The third one is broadband fluctuations around a few hundreds kHz, which has also long-range correlation (Type C). Type A and C have significant correlation with $\tilde{I}_{\mathrm{i,\ sat}}$ and magnetic fluctuations. Figure 4 shows results of bispectral analy-

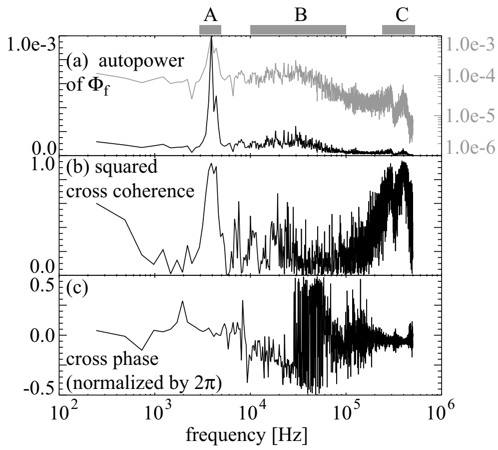

Figure 3: Quadratic $\tilde{\Phi}_\mathrm{f}$ spectra measured by two electrodes of the HP during *H*-mode, and classification them into three types (A, B, and C). (a) Auto-power, (b) poloidal coherence, and (c) cross-phase. Gray line in Fig. (a) indicates same plots as black line in log scale.

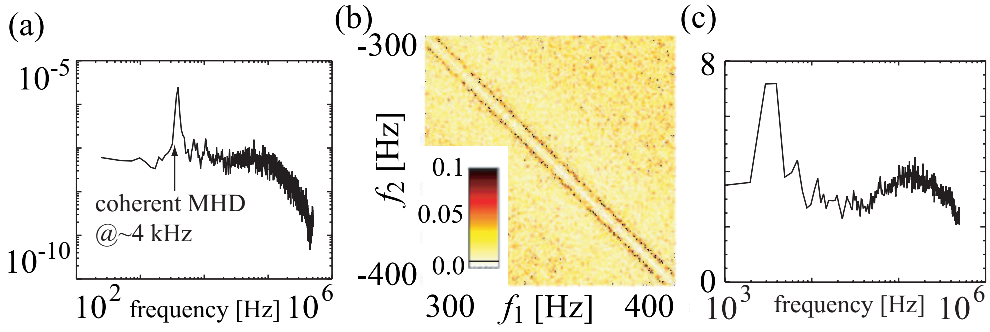

Figure 4: Results from CHS H-mode edge plasma. (a) Power spectra of $\tilde{I}_{\mathrm{i,sat}}$, (b) auto-bcoherence of $\tilde{I}_{\mathrm{i,sat}}$ in the 300-400 kHz range, and (c) the total squared cross-bicoherence $\sum_{f_1 \pm f_2 = \mathrm{const}} \frac{|\langle \tilde{I}_{\mathrm{i,\ sat}}(f_1)\tilde{\phi}(f_2)\tilde{I}^*_{\mathrm{i,\ sat}}(f_1 \pm f_2)\rangle|^2}{\langle|\tilde{I}_{\mathrm{i,\ sat}}(f_1)\tilde{\phi}(f_2)|^2\rangle\langle|\tilde{I}_{\mathrm{i,\ sat}}(f_1 \pm f_2)|^2\rangle}$.

sis applied to the hybrid probe data. Auto-power spectra of $\tilde{I}_{\mathrm{i,\ sat}}$, squared auto-bicoherence plane of $\tilde{I}_{\mathrm{i,\ sat}}$, and total squared cross-bicoherence $\sum \frac{|\langle \tilde{I}_{\mathrm{i,\ sat}}(f_1)\tilde{\phi}_{\mathrm{float}}(f_2)\tilde{I}^*_{\mathrm{i,\ sat}}(f_1 \pm f_2)\rangle|^2}{\langle|\tilde{I}_{\mathrm{i,\ sat}}(f_1)\tilde{\phi}_{\mathrm{float}}(f_2)|^2\rangle\langle|\tilde{I}_{\mathrm{i,\ sat}}(f_1 \pm f_2)|^2\rangle}$ are shown in Figs. 4(a), (b), and (c), respectively. The significant nonlinear couplings between type A and C are observed, indicating that the coherent fluctuation modulates type C. In the total squared cross-bicoherence, we can observe a spectral peak around the same frequency as type A, and this identifies existence of modulated radial particle flux and its effects on the modulating MHD fluctuation. In this paper, we have presented first observation that coherent magnetic fluctuations are interacted with the broadband fluctuations. For quantitative identification of radial fluxes by the modulation process, conclusive cross-bispectra well above the significance level should be obtained, and this is a future task.

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