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Advanced studies by using the geodesic acoustic mode measurements: experimental identification of the separatrix location and search for zonal flows from the envelope of turbulent density fluctuations

Y. Nagashima[1], K. Itoh[2], A. Fujisawa[2], S.-I. Itoh[1], M. Yagi[1], K. Hoshino[3], K. Shinohara[3], T. Ido[2], Y. Miura[3], A. Ejiri[4],Y. Takase[4], and JFT-2M group[3]

[1] *RIAM, Kyushu Univ., Kasuga, Japan,* [2] *NIFS, Toki, Japan,* [3] *JAEA, Naka, Japan,*

[4] *Univ. Tokyo, Kashiwa, Japan*

Introduction

In fusion plasma research, observation of zonal flows (ZF) is one of the most attractive fields in relation with plasma confinement physics and control. The geodesic acoustic mode (GAM) [1] is an oscillatory zonal flow, which is poloidally and toroidally symmetric shear flow and has finite radial eigenmode. ZFs/GAMs have several unique features as follows. In term of the linear properties, ZFs propagate in the radial direction and is reflected at the magnetic separatrix because ZFs can exist only inside the last closed flux surface [2]. As a result, ZF radial profile forms the node at the magnetic separatrix [3]. In term of the excitation mechanism, zonal flows are linearly stable, however, are driven only by the parametric-modulational instability of drift-wave turbulence [4,5]. Therefore, it is possible to extract the GAM linear properties from the modulated envelope of turbulent fluctuations [6–8]. In this paper, we propose two types of advanced experimental studies by using the GAM measurements. One is experimental identification of the magnetic separatrix location by measuring the GAM radial profile. In a conventional study, the location of the separatrix has been es-

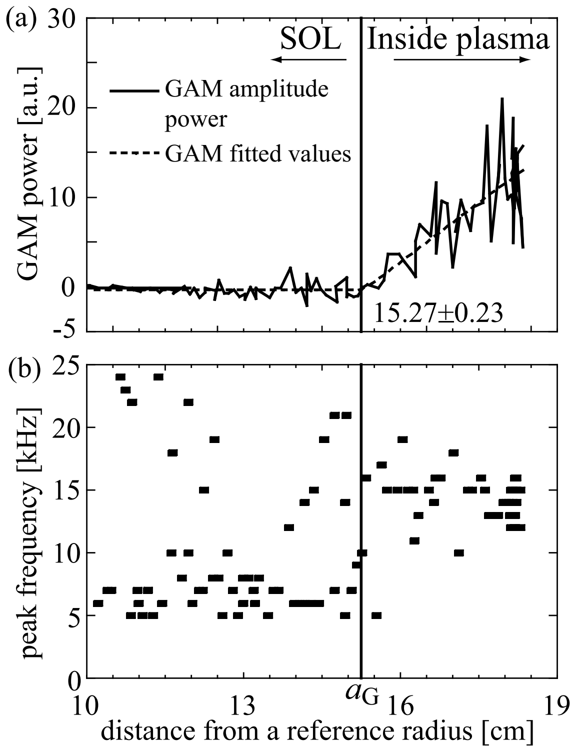

Figure 1: (a) GAM amplitude profile. Solid or dashed lines indicate data points or fitted lines. A black vertical line means the separatrix location derived from the cross point between two asymptotic lines of the fitted hyperbolic curve. (b) Profile of peak frequency in $\tilde{\Phi}_f$ auto-power spectrum.

timated by the magnetic reconstruction calculation, or Langmuir probe measurement under a strong assumption that edge temperature and density gradient change drastically at the separatrix. Here, we would identify the separatrix location from the GAM measurement, independent of any assumption of edge equilibrium profile, and we can compare the separatrix location derived from the magnetic reconstruction. The other study is the bispectral analysis between the GAM and the ambient fluctuations only by using density fluctuation measurements. The benefit of the study is that we can explore the GAM (or low frequency ZFs) study only by using density fluctuation data, without any fast electrostatic potential or plasma flow diagnostics. Firstly, we show the study of the separatrix identification by the GAM. Next, the study of GAM search by density fluctuation measurements is described. In these studies, experiments are performed in the JFT-2M tokamak, and edge fluctuations are measured by a reciprocating Langmuir probe (RLP) [5].

Experimental identification of the separatrix location by zonal flow measurements

Figure 1 shows the GAM amplitude profile and peak frequency of power spectrum vs location of the RLP relative to a reference radius (start position of the RLP). The amplitude is derived from auto-power spectra of the floating potential fluctuations Φ_f. The GAM frequency range is 10-15 kHz, however, there may be also finite components of the ambient fluctuations in the GAM frequency range. Therefore, we obtain the GAM amplitude from Φ_f spectrum after removal of the turbulent fluctuation components in the GAM frequency range. Performing fitting of the GAM amplitude to a hyperbolic curve, and the separatrix location is determined by the cross point of two asymptotic lines of the hyperbolic curve (a_G). We also compare the obtained separatrix location with edge equilibrium parameter profile. Figure 2 shows radial profiles of edge plasma equilibrium electron density and electron temperature in the same discharge as data in Fig. 1. Drastic changes of density and temperature gradient are clearly observed in the vicinity of the separatrix from the GAM amplitude profile.

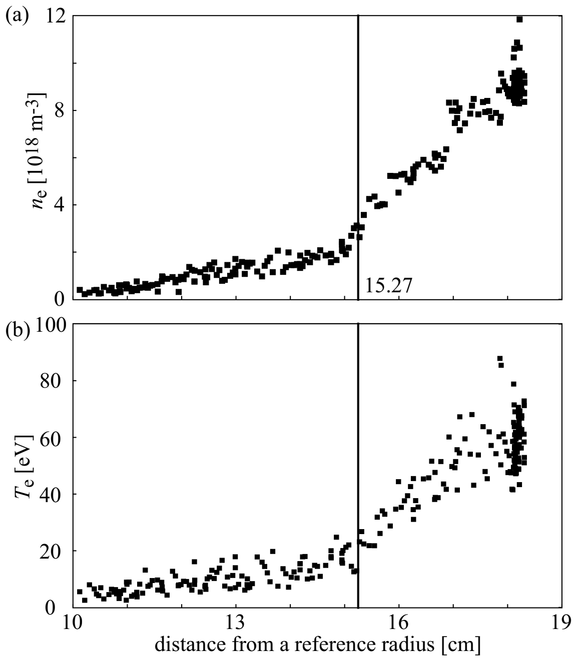

Figure 2: Radial profiles of equilibrium parameters. (a) the electron density, and (b) the electron temperature. The separatrix location derived by the GAM amplitude is also shown as a vertical line.

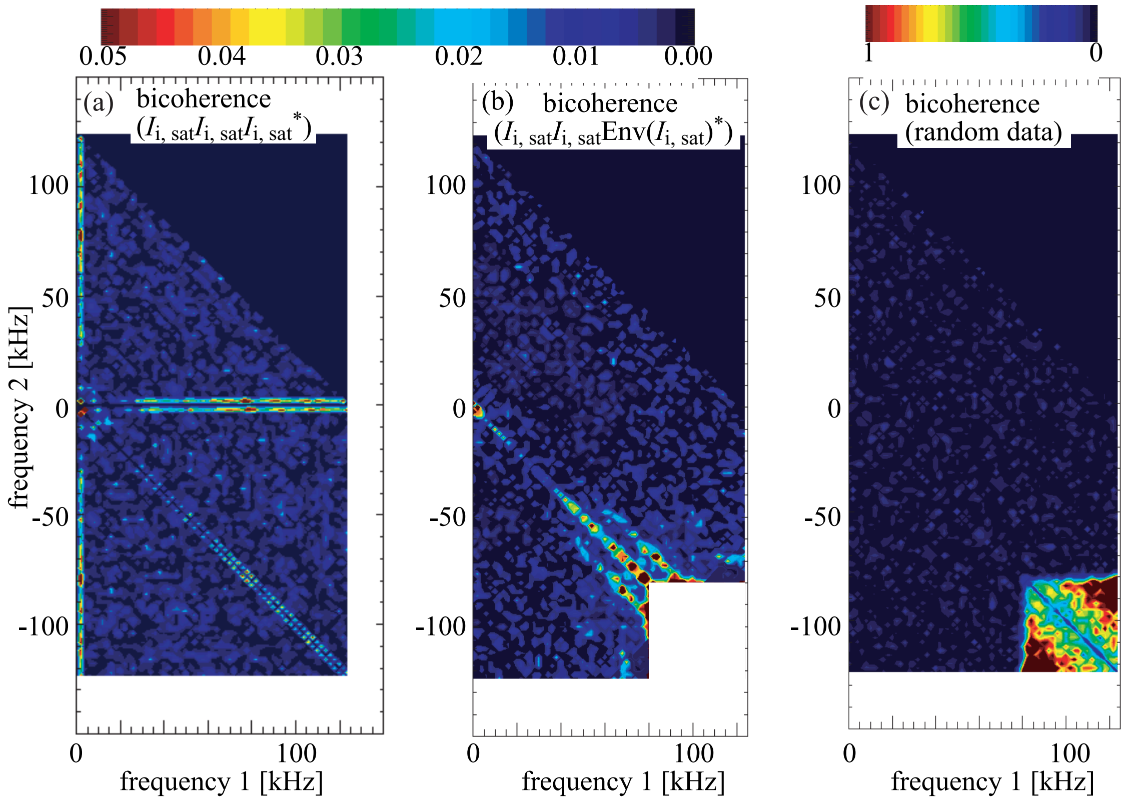

Figure 3: Auto and cross-bicoherence spectra. (a) Auto-bicoherence spectrum of $\tilde{I}_{i,sat}$. (b) Cross-bicoherence spectrum of original $\tilde{I}_{i,sat}$ to the envelope of $\tilde{I}_{i,sat}$, $\langle \tilde{I}_{i,sat}\tilde{I}_{i,sat}Env(\tilde{I}_{i,sat})^* \rangle$. (c) Cross-bicoherence spectrum of Gaussian noise data to the envelope of the Gaussian noise data. All spectra are averaged over 400 ensembles and the significance level is ~ 0.0025. In (b) and (c), the envelope is calculated after band-pass filtering in the frequency range from 80 to 125 kHz.

This observation confirms changes of heat/particle transport at the magnetic separatrix. In conclusion, we have succeeded in the experimental identification of the separatrix location without any assumption of edge equilibrium parameter profiles.

In search of zonal flows by using the envelope spectrum of turbulent density fluctuations

Density fluctuation diagnostics are more accessible to deep inside fusion plasmas than other potential or velocity fluctuation diagnostics. The GAM has small components in density, therefore, it is difficult to detect the nonlinear coupling between the GAM and the ambient turbulence through direct density fluctuation analysis. However, it is possible to measure the significant nonlinear couplings between the GAM in the envelope of the density fluctuations and the ambient density fluctuations. Comparison of the intensity of nonlinear couplings are made in Fig 3. Figure 3(a) shows the auto-bicoherence of $\tilde{I}_{i,sat}$, indicating direct density fluctuation analysis. Figure 3(b) shows cross-bicoherence of $\tilde{I}_{i,sat}$ to the envelope of $\tilde{I}_{i,sat}$. The envelope is calculated by the Hilbert transform after band-pass filtering from 80 to 125 kHz. Figure 3(c) is same as (b), but Gaussian noise data are used as the original data for a reference.

Firstly, we show that the envelope can introduce an artificial pollution in the bicoherence (in Fig. 3(c)). In the random Gaussian data, no mode couplings exist. Nevertheless, the cross-bicoherence between the envelope and the original Gaussian data becomes significant in the frequency domain that is used for the envelope analysis. This suggests that in deducing the envelope spectrum, an artificial nonlinear coupling with the original (independent) spectrum arises, and the information affects cross-bicoherence analysis. In Fig. 3 (b), such a pollution is also observed in the frequency region of $80 < f_1 < 125\,\mathrm{kHz}$ and of $-125 < f_2 < -80\,\mathrm{kHz}$. The frequency domains of the rectangular areas are the same as the frequency ranges from which the envelope was deduced.

Discriminating the data region of the artificial pollution, we can discuss physical meanings of nonlinear couplings among density fluctuations and the envelopes of the density fluctuations. In Fig. 3 (b), significant nonlinear couplings are observed between the GAM components of the envelope and the turbulent density fluctuations. Comparing the intensities, the nonlinear couplings between the GAM components of the original density fluctuations and turbulent density fluctuations, $\langle \tilde{I}_{\mathrm{i,sat}} \tilde{I}_{\mathrm{i,sat}} \tilde{I}^*_{\mathrm{i,sat}} \rangle$, are not much larger than the significance level (see Fig. 3(a)), and are much weaker than the nonlinear couplings between the envelope and turbulent density fluctuations, $\langle \tilde{I}_{\mathrm{i,sat}} \tilde{I}_{\mathrm{i,sat}} Env(\tilde{I}_{\mathrm{i,sat}})^* \rangle$. This indicates that the bispectral analysis using the envelopes is more efficient than that using the original density fluctuations.

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