Detection of Cascading in Drift Wave Turbulence Using Probe Array in Linear Plasmas

Takuma YAMADA, Sanae -I. ITOH, Takashi MARUTA[1)], Shunjiro SHINOHARA[1)], Naohiro KASUYA[2)], Yoshihiko NAGASHIMA, Masatoshi YAGI, Kenichiro TERASAKA[1)], Masato KAWAGUCHI[1)], Shigeru INAGAKI, Yoshinobu KAWAI, Masayuki FUKAO[3)], Akihide FUJISAWA[2)] and Kimitaka ITOH[2)]

Research Institute for Applied Mechanics, Kyushu University, Kasuga 816-8580, Japan
[1)]*Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga 816-8580, Japan*
[2)]*National Institute for Fusion Science, Toki 509-5292, Japan*
[3)]*Myojocho, Uji 611-0014, Japan*

(Received 18 September 2007 / Accepted 12 November 2007)

Measurement of drift wave turbulence using multi-probe systems was performed in the Large Mirror Device-Upgrade linear plasma. We compared a drift wave's two-dimensional (poloidal wave number and frequency) power spectrum with its calculated linear dispersion relation. As a result, a few wave modes that satisfy the linear dispersion relation were observed. Moreover, cascades to non-mode peaks and broadband components that do not satisfy the dispersion relation were identified.

Keywords: linear plasma, drift wave, turbulence, cascading process, non-mode excitation, broadband fluctuation

DOI: 10.1585/pfr.2.051

Recently, special attention has been given to the nonlinear interaction between drift waves that produces zonal flows and streamers [1, 2], and experiments in linear and toroidal plasma devices are under progress [3–14]. In particular, multi-point measurements using poloidal Langmuir probe arrays have also been performed in the Kiel Instrument for Wave Investigations [3, 4] and Large Mirror Device-Upgrade (LMD-U) linear plasmas to provide the two-dimensional (poloidal wave number k and frequency ω) power spectrum of drift wave turbulence [15]. In this rapid communication, we report the significant finding of the existence of non-mode peaks caused by the cascading of parent modes obeying the drift wave dispersion relation expected from a simulation [16]. We further compare this with the dispersions obtained using multi-probe arrays and the traditional two-point technique.

The experiment at LMD-U was performed under the following conditions: argon pressure of 2 mTorr, rf power of 3 kW, and magnetic field of 0.09 T. The diameter of the LMD-U plasma column is about 100 mm, and the electron density and temperature are about $10^{19}\,\mathrm{m}^{-3}$ and 3 eV, respectively. The measurement was performed using a 64-channel poloidal probe array, designed to obtain precise poloidal wave numbers [17]. The measuring radius r_p is 40 mm, and each tungsten probe tip is 0.8 mm in diameter and 3-mm long. The power spectrum of the ion saturation-current fluctuation was obtained by spectral analysis of the spatiotemporal data $I(\theta, t)$. Figure 1 shows the power spectrum $S(m, f)$, where, m ($= r_\mathrm{p}k$) is the poloidal mode number, and $f = \omega/2\pi$. Two-dimensional Fourier transformation can determine the poloidal flow direction in the form of the signs of the mode number (when frequency is set to $f \geq 0$). A positive mode number corresponds to the electron diamagnetic direction. An average of the results from 300 time windows (each time window is 10-ms long) during discharges was used to refine the power spectrum $S(m, f)$.

There are two distinct features in $S(m, f)$. First is the presence of some sharp peaks, as seen in Fig. 1. The strongest peak a occurs at $(m, f) = (1,\ 2.8\,\mathrm{kHz})$. Linear eigen-frequencies of drift wave instabilities calculated by numerical code analysis [16] are represented by black lines in Fig. 1. The broken line shows the case with no radial electric field. For the solid line, the uniform rotation is due to an imposed dc radial electric field, the magnitude of which is set by adjusting the peak a to the eigen-frequency. This electric field is within an error-bar of the potential profile measurement by a radially movable probe [15]. The sharp peak at $(m, f) = (2,\ 3.2\,\mathrm{kHz})$, which is labeled as b, is on this solid line. Therefore, if we assume a as a drift wave mode, b may also be considered a drift wave mode. By labeling the peak in the ion diamagnetic direction $(m, f) = (-1,\ 0.9\,\mathrm{kHz})$ as c, all the other peaks are expressed by addition and/or subtraction of a, b, and c; i.e., $a - c$, $b + c$, $2a$, $2a - c$, $a + b \pm c$, $3a$, $2a + b + c$. These peaks do not satisfy the linear dispersion relation. Fluctuations that do not satisfy the dispersion relation are also excited by nonlinear

author's e-mail: takuma@riam.kyushu-u.ac.jp

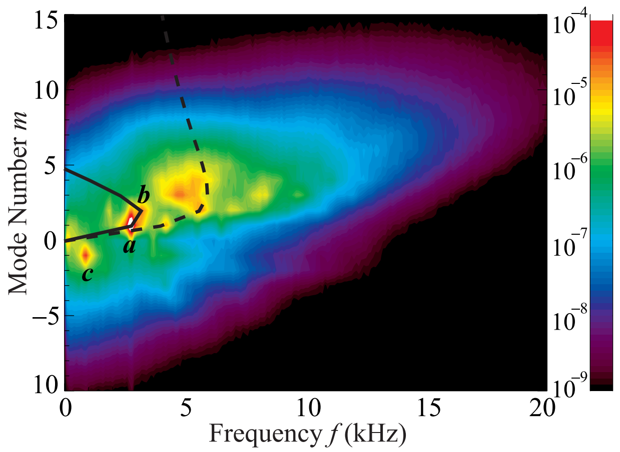

Fig. 1 Contour plot of power spectrum $S(m, f)$ superimposed with calculated linear dispersion relation without (broken line) and with (solid line) radial electric field.

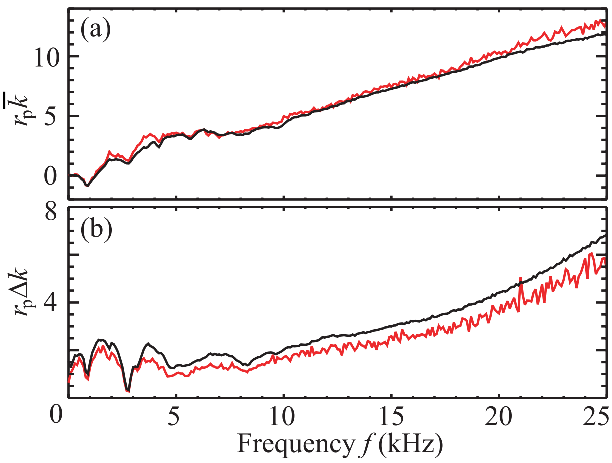

Fig. 2 (a) Frequency dependence of weighted mean of wave number (black), and wave number measured from phase difference of two probes (red). (b) Spread of wave number (black), and deviation of wave number measured with two probes (red).

couplings of the primary modes in turbulent plasmas [18]; these are called "non-modes" in this paper. The nonlinear couplings among these non-mode peaks and primary modes were confirmed by bi-spectral analysis [12]. The pair of the drift wave modes varies according to different assumptions of radial electric field. However, a and b are likely to be the parent modes because they have sharper spectra compared to other modes (non-mode peaks will have broader spectra than primary modes). In any case, the turbulence consists of two drift wave modes, c, and cascading non-mode peaks.

Second, there are broadband fluctuations in the region of $f > 10$ kHz. These do not satisfy the drift wave linear dispersion relation and are also non-modes. (Note that the frequency of drift waves at larger poloidal mode numbers is limited due to the finite gyroradius effects.) Nonlinear couplings between broadband fluctuations and fluctuation peaks were also confirmed by bi-spectral analysis. Thus, the cascade of energy to the non-mode excitation away from the wave dispersion relation is demonstrated.

In order to quantify these two features, we analyzed the mean poloidal wave number and its spread (see Fig. 2). They are defined in this article as $r_p\bar{k}(f) = \sum_m mS(m, f)/\sum_m S(m, f)$, $\left[r_p\Delta k(f)\right]^2 = \sum_m \left[m - r_p\bar{k}(f)\right]^2 S(m, f)/\sum_m S(m, f)$. The mean poloidal wave number shows the presence of several sharp peaks in the low frequency regime. In addition, in the higher frequency region, the mean is a smooth function of the frequency, being fitted as $\bar{k} \propto \omega$, which is expected for the cascade to non-modes. This spread is also significant. First, at the sharp peaks in $S(m, f)$, the spread Δk shows a dip, indicating that the fluctuation has long coherence length at this frequency. Next, in the regime of cascade to non-modes (i.e., $f > 10$ kHz), the relative spread $\Delta k/\bar{k}$ is an increasing function of the mean. Therefore, the spread provides a basis for future quantitative testing of models.

We examined the validity of the poloidal wave number that was deduced from two probes separated in the poloidal direction by comparing with the result from the 64-channel probe array. This "two-point estimate" is calculated from the cross power spectrum $S_{12} = \langle \hat{I}_1(\theta_1, f)\hat{I}_2(\theta_2, f)^*\rangle$, where subscripts 1, 2 indicate probe number and $\hat{I}(\theta, f)$ is the Fourier transform of $I(\theta, t)$. The mean poloidal mode number of the two-point estimate is given by the argument of S_{12} divided by $\theta_2 - \theta_1$. As shown in Fig. 2 (a), the $\bar{k}$ derived from the 64-channel probe array and the two probes are in fairly good agreement. Two-point estimate calculations may have a large statistical error, particularly for large wave numbers, as is mentioned in the previous work [3]. However, we consider that the averaging of a large number of measurements (up to 300) increased the reliability of the two-point estimate. The deviation of the two-point estimate plotted in Fig. 2 (b) is noisy but similar to the spread Δk obtained in the 64-channel estimate.

In summary, we measured drift wave turbulence in a linear plasma using a poloidal probe array, and the observed two-dimensional power spectrum $S(m, f)$ showed excitation of drift wave modes and cascade to non-mode peaks and broadband components ($\bar{k} \propto \omega$). The estimate of $\bar{k}$ from a pair of probes was backed up by our results, although it was subject to deviations and statistical variances.

The authors thank Prof. P.H. Diamond, Prof. A. Fukuyama, Dr. F. Greiner, Dr. O. Grulke, Prof. U. Stroth, and Prof. G.R. Tynan for valuable discussions. This work was supported by Grant-in-Aid for Specially-Promoted Research of MEXT (16002005) (Itoh Project), by the collaboration programs of NIFS (NIFS07KOAP017) and RIAM, Kyushu University, and by Grant-in-Aid for Young Scientists (B) of JSPS (19760597).

[1] P.H. Diamond *et al.*, Plasma Phys. Control. Fusion **47**, R35 (2005).
[2] A. Yoshizawa *et al.*, *Plasma and Fluid Turbulence, Theory and Modelling* (Institute of Physics Publishing, Bristol and Philadelphia, 2003).
[3] A. Latten *et al.*, Rev. Sci. Instrum. **66**, 3254 (1995).
[4] T. Klinger *et al.*, Phys. Rev. Lett. **79**, 3913 (1997).
[5] M. Kono *et al.*, Phys. Rev. Lett. **84**, 4369 (2000).
[6] C. Schröder *et al.*, Phys. Rev. Lett. **86**, 5711 (2001).
[7] T. Kaneko *et al.*, Phys. Rev. Lett. **90**, 125001 (2003).
[8] V. Sokolov *et al.*, Phys. Rev. Lett. **92**, 165002 (2004).
[9] M.J. Burin *et al.*, Phys. Plasmas **12**, 052320 (2005).
[10] G.R. Tynan *et al.*, Plasma Phys. Control. Fusion **48**, S51 (2006).
[11] C. Lechte *et al.*, New J. Phys. **4**, 34 (2002).
[12] Y. Nagashima *et al.*, Phys. Rev. Lett. **95**, 095002 (2005).
[13] Y. Hamada *et al.*, Phys. Rev. Lett. **96**, 115003 (2006).
[14] F.M. Poli *et al.*, Phys. Plasmas **13**, 102104 (2006).
[15] K. Terasaka *et al.*, Plasma Fusion Res. **2**, 031 (2007).
[16] N. Kasuya *et al.*, J. Phys. Soc. Jpn. **76**, 044501 (2007).
[17] T. Yamada *et al.*, Rev. Sci. Instrum. **78**, 123501 (2007).
[18] B.B. Kadomtsev, *Plasma Turbulence* (Academic Press, London, 1965) p. 53.