A Study on Low-Frequency Fluctuations Using New Azimuthal Probe Array in High-Density Helicon Linear Plasma

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In a high-density plasma produced by helicon waves in a linear device, a change from the coherent to broad-band density fluctuations was observed on increasing the magnetic field. The coherent mode exhibited the drift wave features, and a steady oscillation state was observed. When the magnetic field was increased, the fluctuation level increased, and the higher azimuthal Fourier components were excited. When the spectrum became broad at the higher magnetic field, the behavior of the azimuthal structure became complex and changed rapidly with time. The analysis performed using the movable probe array (48ch.-probe) decomposed the short-lived structure into poloidal mode-frequency space and indicated mode-mode coupling in the broad-band spectrum.

Keywords: drift wave, turbulence, probe array, wavenumber-frequency spectrum, helicon plasma.

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In fusion plasmas, turbulence, particularly the drift wave turbulence, has been investigated actively. Recent works indicate that the mutual interaction between fluctuations, which have different temporal and spatial scales, plays an important role in turbulence dynamics. Thus, many studies have been conducted with torus and linear devices (e.g. [1–4]), but the detailed spatiotemporal structure and the interactions between fluctuations in turbulence have not been well understood. The electrostatic probe array can directly determine the turbulence structure, and multiple probe arrays [5, 6] have been used in linear and torus devices. However, conventional arrays are fixed in space and cannot cover a wide measuring region. We have recently developed a new probe array consisting of 48 probes extended in the poloidal direction. Since this array is movable in the radial direction, it can measure plasma parameters in a wide radial-poloidal region, and thus, the poloidal mode-frequency space spectra, $S(m, f)$, can be analyzed. In this Rapid Communication, we report the first result from the proposed 48ch.-probe array.

The 48ch.-probe has 16 modules using an individual 1.5 inch port. In addition, each module has three tungsten tips (the diameter and length are 0.8 mm and 4.0 mm, respectively), with the separation of 5.2 mm between two tips in the poloidal direction. In this experiment, all movable modules were set at $r = 40$ mm (hence 5.2 mm apart between all adjacent tips) and 1625 mm axially away from the end of a helicon source tube. Drift wave measurements with the new probe array were performed in Large Mirror Device-Upgrade (LMD-U), which is a modification of the previous device [7]. The LMD-U consists of a cylindrical vacuum vessel, which is 3740 mm long and has a 445 mm inner diameter. The high-density helicon plasma is produced using a double-loop antenna with a width of 40 mm and axial central distance of 100 mm. The antenna is wound around a quartz tube, which is 400 mm long and has a 95 mm inner diameter. A magnetic field of up to 1500 G is generated by the coils around the vacuum vessel. In this experiment, argon gas was used with a pressure of 2 mTorr, and the RF power (frequency) was 3 kW (7 MHz). The typical electron density was $\leq 10^{19}\,\mathrm{m}^{-3}$ with electron temperature of 3 eV.

The experimental condition of drift wave turbulence was conducted by scanning the magnetic field B (200-900 G). The field dependence of frequency power spectrum of the ion saturation current I_{is} fluctuation, which is proportional to the density fluctuation, is shown in Fig. 1. Here, B is changed at an interval of 20 G and the frequency resolution is 61 Hz. At this measuring radius ($r = 40$ mm), the normalized density gradient was steep: $|\nabla_r n_0/n_0| \sim 60\,\mathrm{m}^{-1}$ at $B = 900$ G. Since the central electron density increased with an increase in the magnetic field, the normalized density gradient at $r = 40$ mm ($n_{\mathrm{e}} \sim 2 \times 10^{18}\,\mathrm{m}^{-3}$ did not change appreciably at this point) also bcame steeper. A low-frequency coherent density fluctuation with a fre-

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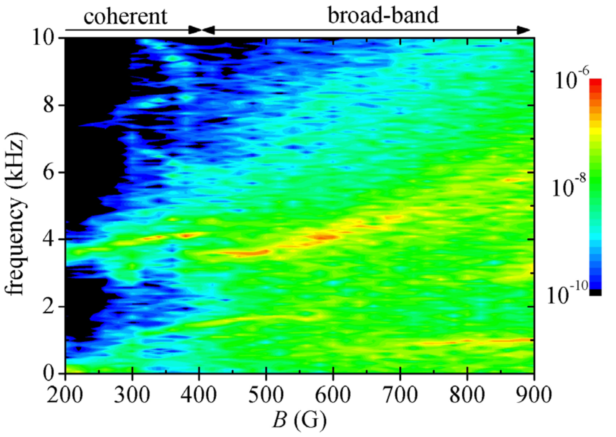

Fig. 1 Dependence of the frequency spectrum of I_{is} on the magnetic field. The color plot is shown in a logarithmic scale.

quency f of 3.8 kHz was observed in the low magnetic field region (B = 200-340 G). The frequency was close to the linear drift wave eigen frequency [8]. The relative density fluctuation level was a few percent and was comparable to the normalized potential fluctuation level; the density fluctuation led to the potential fluctuation of 10-30 degrees. These observations indicated that the fluctuations were caused by drift waves. The observed frequency of the dominant mode changed gradually with an increase in the magnetic field. Another coherent mode with f = 1.2 kHz was excited at B = 350 G, which showed the coexistence of the two modes. The spectrum clearly changed at $B \sim 400$ G: the amplitude of the coherent mode with f = 3.8 kHz decreased and some peaks were excited. Then, the spectrum was broadened up to the f = 5 kHz region at B = 440 G. The valley levels between the peaks increased and the band width of the ~3 kHz mode became wider. The broad-band range expanded on increasing the magnetic field (the normalized density gradient became steeper with an increase in the field, as mentioned above) and reached up to $f \sim 10$ kHz at B = 900 G. Here, the spectrum also had some peaks in the broad-band state.

Figure 2 shows temporal behaviors of the poloidal structure of the relative density fluctuation at B = 200 G and 900 G. The shift between plasma and probe array centers resulted in a slight error in the poloidal structure. The probe positions were calibrated relative to the plasma and were therefore, based on 2-dimensional density measurement. The effect of radial wavenumber was neglected in this measurement. The coherent mode with the poloidal mode number m = 3 appeared clearly at B = 200 G (Fig. 2 (a)). This mode propagated in the electron diamagnetic drift direction (from the upper left to the lower right in this figure) with f = 3.8 kHz and remained in a steady oscillation state. In the case of B = 900 G (Fig. 2 (b)), the wave structure changed into a complex state and no clear modes appeared in a long time scale: the stable structure

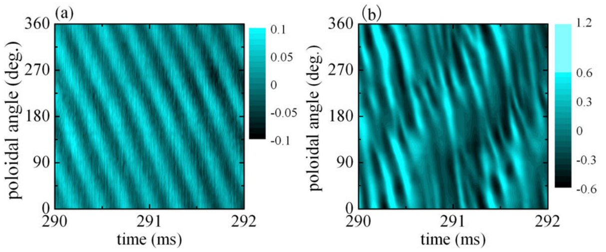

Fig. 2 Spatiotemporal contour map of relative density fluctuation at B = (a) 200 G and (b) 900 G (linear scale). Here, a single color is used when $\tilde{I}_{is}/I_{is} > 0.6$.

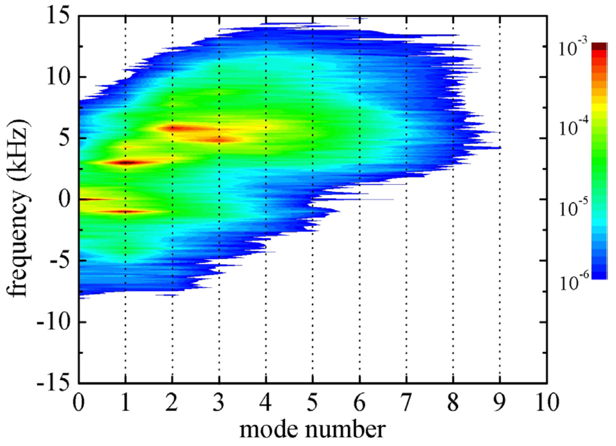

Fig. 3 Contour map of $S(m, f)$ from I_{is} at B = 900 G. The color plot is in a logarithmic scale.

could not hold during one poloidal rotation. Under this condition, the wave modulation and/or branches were observed at short intervals, which indicated that the correlation length in the disturbed state was much shorter than that in the steady oscillation.

In Fig. 3, the two-dimensional Fourier analysis, i.e. spectrum of $S(m, f)$, at B = 900 G is shown. The positive (negative) frequency refers to the propagation in the electron (ion) diamagnetic direction. Here, the frequency resolution was 122 Hz, and the number of data ensemble was 15. From this, we found multiple peaks in the broad-band background spectrum, e.g. (m, f [kHz]) = (1, 2.9), (1, −1), (2, 5.7), (3, 4.8), etc. Note that the peak at (m_2, f_2) = (2, 5.7) satisfied the second harmonics condition for (m_1, f_1) = (1, 2.9) (i.e. $m_2 = 2m_1$, and $f_2 = 2f_1$). The three peaks, (m_2, f_2), (m_3, f_3) = (3, 4.8) and (m_4, f_4) = (1, −1), satisfied the matching conditions of $m_3 = m_2 + m_4$ and $f_3 = f_2 + f_4$.

In summary, the turbulence structure was investigated by a new azimuthal probe array. The experimental results revealed the following: (1) a coherent mode was excited in the low-field operation, and multi-modes with broad background were observed in the high-field operation; (2) transition from coherent to broad-band modes was observed at

$B = 400\,\mathrm{G}$; (3) poloidal structure indicated a mode-mode coupling in the background broad-band spectrum.

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[1] K. Itoh, S.-I. Itoh and A. Fukuyama, *Transport and Structural Formation in Plasmas* (IOP, Bristol, 1999).
[2] P.H. Diamond *et al*., Plasma Phys. Control. Fusion **47**, R35 (2005).
[3] W. Horton, Rev. Mod. Phys. **71**, 735 (1999).
[4] C. Schröder *et al*., Phys. Plasmas **12**, 042103 (2005).
[5] A. Latten *et al*., Rev. Sci. Instrum. **66**, 3254 (1995).
[6] U. Stroth *et al*., Phys. Plasmas **1**, 2558 (2004).
[7] S. Shinohara *et al*., Plasma Phys. Control. Fusion **39**,1479 (1997).
[8] N. Kasuya *et al.*, J. Phys. Soc. Jpn. **76**, 044501 (2007).