Probability Density Function of Density Fluctuations in Cylindrical Helicon Plasmas

Hiroyuki ARAKAWA, Shigeru INAGAKI[1)], Yoshihiko NAGASHIMA[2)], Takuma YAMADA[2)], Kunihiro KAMATAKI[1)], Tatsuya KOBAYASHI, Satoru SUGITA, Masatoshi YAGI[1)], Naohiro KASUYA[3)], Akihide FUJISAWA[1)], Sanae -I. ITOH[1)] and Kimitaka ITOH[3)]

Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Fukuoka 816-8580, Japan

[1)]Research Institute for Applied Mechanics, Kyushu University, Fukuoka 816-8580, Japan

[2)] Graduate School of Frontier Sciences, The University of Tokyo, Tokyo 277-8561, Japan

[3)] National Institute for Fusion Science, Toki 509-5292, Japan

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The turbulence fluctuation spectra of linear magnetized plasmas are measured under various neutral pressure conditions. Strong turbulent waves and symmetric waves are observed in low and high neutral pressure conditions. In this study, we compare the radial structure of the probability density function (PDF) of these fluctuations. The characteristics of the PDFs are related to those of the radial and poloidal turbulent structures.

Keywords: turbulence, probability density function, linear magnetized plasma

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1. Introduction

Turbulence-driven transport is crucial to the realization of a thermonuclear fusion reactor. Understanding the turbulence structure and its formation mechanism gives insight into nonlinear radial turbulent energy transport. For tokamak devices, intermittent phenomena known as plasma blobs in the scrape-off-layer (SOL) strongly influence recycling processes and impurity generation by damaging the first wall [1]. Phenomena observed in inhomogeneous magnetized plasma are considered to be the result of structure formation and have been studied in various laboratory plasmas [1–8]. Intermittency produces an asymmetry in the probability density function (PDF) of fluctuation signals. The PDF radial profile characterizes the spatiotemporal formation of turbulence. Such profiles have been reported in low neutral pressure conditions (~ 1 mTorr) in linear magnetized plasmas [6]. To comprehensively understand intermittent phenomena and related turbulence structures, more precise observations are required in a systematic manner.

In the Large Mirror Device Upgrade (LMD-U), the fluctuation spectra change depending on the neutral pressure because of drift wave damping through collisions with neutral particles [9–11]. In this paper, we report differences in the radial profiles of the density fluctuation PDF in two different turbulent states. The turbulence structures responsible for causing the differences in the PDFs are discussed.

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

2. Experimental Setup

Turbulence excitation experiments were performed on the LMD-U [12, 13]. A cylindrical plasma with approximately 0.1 m in diameter and 3.74 m in axial length is produced by an RF wave in a quartz tube (0.4 m axial length and 0.095 m inner diameter) and radially confined by a magnetic field (z: axial, r: radial, θ: poloidal direction). The typical operational conditions and plasma parameters are an RF power of 3 kW, a magnetic field of 0.09 T, a neutral argon pressure of 2 or 5 mTorr, a peak electron density of $6 \times 10^{18}\,\mathrm{m}^{-3}$, and an electron temperature of 3 eV. The diagnostic tools for turbulence are a two dimensionally movable Langmuir probe [13] and a 64-channel poloidal Langmuir probe array [14]. A movable probe, which is adjustable in the radial direction, is installed at the axial position $z = 1.375$ m and can measure from $r = 1.5$ cm to $r = 6$ cm at intervals of 0.5 cm. The axial and radial positions of the 64-channel probe array are $z = 1.885$ m and $r = 4$ cm, respectively. The sampling frequency in this experiment is 1 MHz. In this study, we characterized the radial profiles of turbulence fluctuation PDFs for two neutral pressure conditions (2 and 5 mTorr, argon gas) and compared the turbulence structures.

3. Density and Potential Fluctuations and PDF Analysis

Figure 1 shows typical time evolutions of the ion saturation current (I_{is}) and floating potential (V_{f}) at $r = 3.5$ cm at a neutral pressure of 2 or 5 mTorr. The fluctuations in I_{is} and V_{f} at 2 mTorr vary randomly and are thus strongly

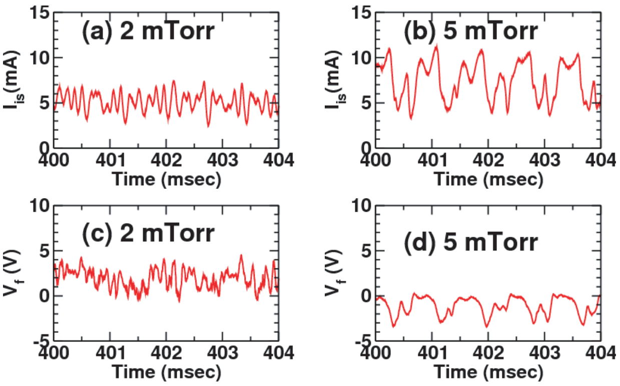

Fig. 1 Typical time evolutions of (a), (b) I_{is} and (c), (d) V_f at r = 3.5 cm. Neutral pressures are (a), (c) 2 mTorr and (b), (d) 5 mTorr.

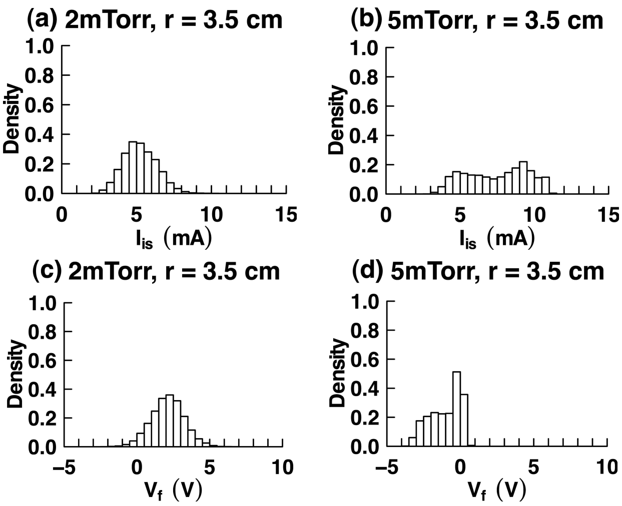

Fig. 2 PDFs of (a), (b) I_{is} and (c), (d) V_f at r = 3.5 cm. The experimental conditions are (a), (c) 2 mTorr and (b), (d) 5 mTorr.

turbulent. In contrast, those at 5 mTorr are similar to rectangular or triangle waves. The PDFs for these cases are shown in Fig. 2. In both Figs. 1 and 2, (a) shows I_{is} at 2 mTorr, (b) shows I_{is} at 5 mTorr, (c) shows V_f at 2 mTorr, and (d) shows V_f at 5 mTorr. The characteristics of the PDFs differ. At 2 mTorr, they are nearly Gaussian with a slightly positive skew. While at 5 mTorr, double peaks and a negative tail appear consistent with rectangular and/or triangular wave forms. The skewness and kurtosis of each PDF are 0.4 and 3.3 for I_{is} at 2 mTorr, 0.1 and 1.8 for I_{is} at 5 mTorr, 0.1 and 3.3 for V_f at 2 mTorr and −0.5 and 1.9 for V_f at 5 mTorr, respectively. (The skewness and kurtosis are defined as $\langle\tilde{x}^3\rangle/\langle\tilde{x}^2\rangle^{3/2}$ and $\langle\tilde{x}^4\rangle/\langle\tilde{x}^2\rangle^2$, respectively [1]. The normal Gaussian distribution has skewness = 0 and kurtosis = 3.)

Figure 3 shows radial profiles of the PDFs of (a), (b) I_{is}, (c), (d) fluctuation components normalized by the standard deviation $\tilde{I}_{is}/\sigma_{I_{is}}$ and (e), (f) $\tilde{I}_{is}$ power spectra. The neutral pressure in Figs. 3 (a), (c), and (e) is 2 mTorr, and

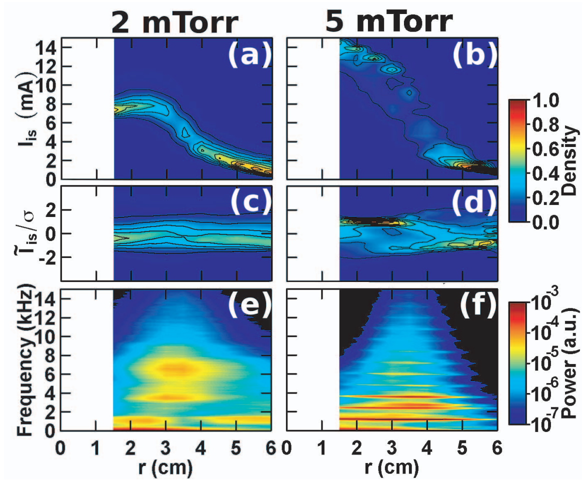

Fig. 3 Radial (r = 1.5-6 cm) PDF spectra of (a), (b) I_{is}, (c), (d) $\tilde{I}_{is}/\sigma_{I_{is}}$, (e), (f) power spectra of $\tilde{I}_{is}$ taken by 2D-movable probe. Neutral pressures are (a), (c), (e) 2 mTorr and (b), (d), (f) 5 mTorr. $\sigma_{I_{is}}$ is the standard deviation of $\tilde{I}_{is}$.

that in Figs. 3 (b), (d), and (f) is 5 mTorr. The power spectrum time window is 16384 μsec and 84 ensembles are averaged at each radial position. At 2 mTorr, the I_{is} gradient takes a maximum at r = 3.5 cm (Fig. 3 (a)). The PDFs of $\tilde{I}_{is}/\sigma_{I_{is}}$ at $r < 2.5$ cm and $r > 4$ cm have positive tails, and those at $r \sim 3.5$ cm have a broader, Gaussian-like spectrum (Fig. 3 (c)). A low-frequency (∼ 1 kHz) mode is observed at $r < 3$ cm and $r > 4$ cm but is weak at 3 cm $< r <$ 4 cm region. Broadband modes (> 2 kHz) appear at the 2.5 cm $< r <$ 4 cm region. At 5 mTorr, the maximum density is larger than that at 2 mTorr, and the maximum of the I_{is} gradient appears at r = 3.5 cm (Fig. 3 (b)). The PDFs of $\tilde{I}_{is}/\sigma_{I_{is}}$ have negative tails at r = 1.5-2.5 cm, double (positive and negative) peaks at r = 3-4 cm, and have positive tails at $r > 4.5$ cm region (Fig. 3 (d)). The double peaks in the PDFs are observed at the location where the maximum density gradient, largest fluctuation amplitude, and broadband modes are observed. Low-frequency (< 1 kHz) modes are observed over the entire plasma radius. The power spectra of $\tilde{V}_f$ have similar characteristics.

4. Spatiotemporal Structure of Turbulence

We will now discuss the spatiotemporal turbulence structure on the basis of the above analysis of the PDFs and power spectra.

At the 2 mTorr, the PDFs of $\tilde{I}_{is}/\sigma_{I_{is}}$ at $r > 4$ cm have a positive tail, and the $\tilde{I}_{is}$ power spectra at $r \sim 3.5$ cm have a broadband mode ($f > 2$ kHz). This indicates that positive density bursts generated by turbulence near r = 4 cm propagate outward. Similar PDF spectra and time evolutions of I_{is} have been observed in plasmas at ∼ 1 mTorr neutral pressure, as shown in Ref. [6], Figs. 5 (d-i). The PDFs at $r \sim 3.5$ cm tend to be broad and Gaussian-like, as

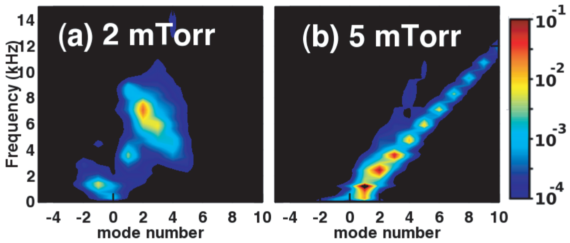

Fig. 4 Normalized power spectra of $\tilde{I}_{is}$ at $r = 4$ cm measured by 64-channel probe array. Neutral pressures are (a) 2 mTorr and (b) 5 mTorr. The time window of the power spectrum is 4096 μs and 840 ensembles are averaged.

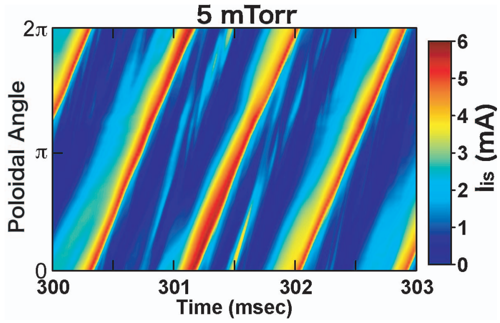

Fig. 5 Typical time evolution of I_{is} by 64-channel probe array at 5 mTorr.

in Fig. 2 (a). This can be explained by the radial profile of the power spectrum (Fig. 3 (e)) and the power spectrum in m-f space at $r = 4$ cm, where m is the poloidal mode number and f is the frequency. Figure 4 shows the S(m, f) power spectra observed with the poloidal probe array at (a) 2 mTorr and (b) 5 mTorr. The time window of the power spectrum is 4096 μs and 840 ensembles are averaged. The electron and ion diamagnetic directions are indicated by $m > 0$ and $m < 0$, respectively. The peaks in Fig. 4 (a) indicate that both $m > 0$ waves and $m < 0$ waves are excited, and the phase velocities f/m (including the $E \times B$ velocity, in this case) of $m > 0$ waves are not the same as those of $m < 0$ waves [13]. These turbulent waves have many degrees of freedom and thus have nearly Gaussian PDFs.

For 5 mTorr at $r = 4$ cm, the $\tilde{I}_{is}$ power spectrum peaks measured by the 64-channel probe array, shown in Fig. 4 (b), are on a straight line [14]. Straight aligned peaks indicate that the phase velocity f/m is the same with respect to all modes. Figure 5 shows a typical time evolution of I_{is} observed with the 64-channel probe array. The poloidal structures of the wave at $r = 4$ cm rotate while maintaining the phase. Moreover, the radial profiles of the $\tilde{I}_{is}$ and $\tilde{V}_f$ power spectrum have the same frequency peaks (Fig. 3 (f)) and the typical time evolutions repeat those rectangular or triangle wave forms, as in Figs. 1 (b) and (d). The poloidal structures at each radial position also rotate while maintaining the phase. The PDF structures in Fig. 3 (d) may correspond to the wave forms at each radial position. The positive peaked PDFs at $r = 1.5$-4 cm indicate that the plasma remains for a long time at a higher density level. At the plasma edge, the plasma is at a lower density level, as indicated by the negative peaked PDFs at $r > 3$ cm. The residence time at both density levels is almost the same in the 3 cm $< r <$ 4 cm region. Thus, the PDF has double peaks.

5. Summary

In this study, we observed the radial profiles of density and potential fluctuations and analyzed the PDFs and power spectra. At a neutral pressure of 2 mTorr, the PDFs are Gaussian-like (kurtosis ~ 3, skewness ~ 0) at $r = 2$-4 cm and have positive tails in the edge region ($r > 4$ cm). At a neutral pressure of 5 mTorr, the PDFs have double peaks at 3 cm $< r <$ 4 cm. The poloidal structures at each radial position are related to the these PDFs.

Acknowledgments

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