Low-Frequency Structural Plasma Turbulence in the L-2M Stellarator

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Abstract Experiments in the L-2M stellarator have shown the occurrence of steady-state low-frequency strong structural (LFSS) turbulence throughout the entire plasma column. A key feature of LFSS turbulence is the presence of stochastic plasma structures. It is shown that different types of LFSS turbulence are correlated throughout the entire plasma volume. The LFSS turbulence is described by non-Gaussian probability densities. Modeling of the probability density distributions by scale mixtures of normal laws is considered.

1. Introduction

In recent years, low-frequency (LF) plasma turbulence in closed magnetic confinement systems has attracted considerable interest of plasma physicists. These studies are related both to a fundamental problem, namely of creating a model of structural plasma turbulence, and to applied problem, for example, in connection with attempts to explain anomalous heat and particle transport in the edge plasma in magnetic confinement systems (see, e.g., reports on studies of turbulence at recent conferences on plasma physics and control fusion: 2003 EPS, and 13th Toki conference [1]). A reason for increased interest in LF turbulence in toroidal devices is that many experimental facts directly indicate its influence on the macroscopic plasma parameters in closed magnetic confinement systems. In the last few years, systematic studies of low-frequency plasma turbulence have been carried out at the General Physics Institute in the L-2M stellarator.

This paper demonstrates that LFSS turbulence is present throughout the plasma volume of the L-2M stellarator. It is shown that the probability density distribution (PDF) for this stochastic process can be modeled by scale mixtures of normal laws.

2. Description of device and diagnostic techniques

The L-2M stellarator is a toroidal magnetic system for plasma confinement [2]. The radius of the torus is100 cm; the plasma cross section is elliptical, its mean radius (the mean radius of the magnetic separatrix) is 11.5 cm and can be reduced by inserting a limiter. Plasma is produced and heated by one or two gyrotrons (the wavelength is 4 mm and the total power is up to 350 kW). The discharge duration is about 10 ms. In L-2M, fluctuations were measured in several poloidal sections by using different diagnostic techniques so as to cover the plasma region from the axis to the separatrix. As an illustration, Figure 1 schematically shows the arrangement of the diagnostics in one poloidal section. Plasma density fluctuations in the heating region were measured by the scattering of the heating gyrotron radiation [3]. Fluctuations of the density, potential, electric field, and particle flux in the edge plasma were measured with the help of single and triple Langmuir probes positioned in several sections along the torus [4]. Magnetic-field fluctuations were measured with the help of magnetic pick-up coils. The results of measurements from all the diagnostics were unified arrays of fluctuating amplitudes in the form of time samples to which the same program package for numerical evaluating could be applied. The length of some samples was up to 256 thousands of readings, the sampling rate being from 0.1 to 40 MHz. The program package included the multidimensional spectral Fourier analysis, the correlation analysis, the wavelet analysis [5], the drawing of histograms and the statistical separation of finite normal mixtures [6].

3. Results of studies

As noted above, LF fluctuations are naturally present throughout the entire plasma column of the L-2M stellarator — from the center to the boundary. In this paper, we only consider the general features of fluctuations regardless of their localization in the plasma column.

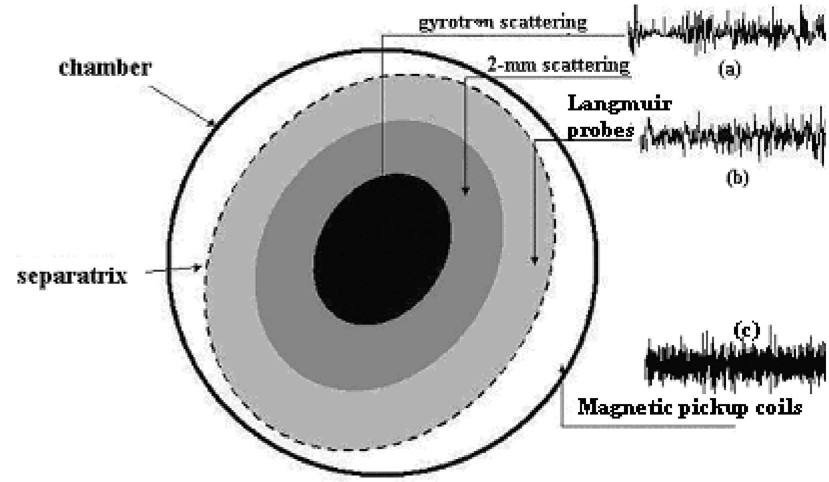

Fig. 1. Arrangement of diagnostics and time samples of the magnitudes of (a) density fluctuations in the high-temperature plasma, (b) potential fluctuations in the edge plasma, and (c) magnetic-field fluctuations outside the plasma. The frequencies below 1 kHz are filtered.

Figure 1 shows the time samples of the magnitudes of (a) density fluctuations in the high-temperature plasma in the heating region, (b) potential fluctuations in the low-temperature edge plasma, and (c) fluctuations of the magnetic field outside the plasma. The time samples consist of bursts of different durations and pauses between them. The level of fluctuations was fairly large as compared to the average values of the fluctuating parameters [7].

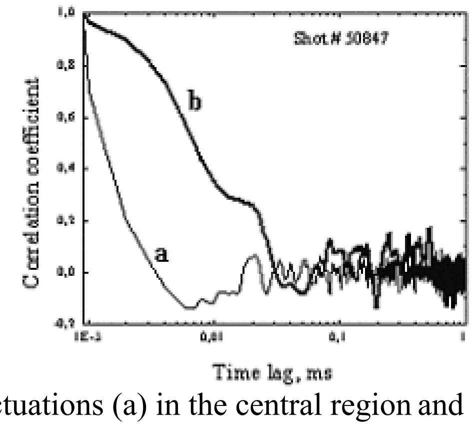

Fig. 2. ACFs of density fluctuations (a) in the central region and (b) near the plasma edge.

The autocorrelation functions (ACFs) of time samples of LF turbulent fluctuations in the L-2M consist of two components: a finite-width (rather than a δ-shaped) maximum and a slowly decreasing tail with repetitive bursts. Figure 2 shows the ACFs of density fluctuations in the central and edge plasmas. The long-term components of the ACF usually comprise up to 10--30% of the energy of the density, potential, magnetic-field, and electric-field fluctuations (the noise level in these measurements usually does not exceed 1--2%). The measured ACFs, indicate, on the one hand, a strongly turbulent character of fluctuations and, on the other hand, the presence of long-term correlated components in this turbulence.

Time samples of any fluctuating plasma parameter in L-2M are more adequately described by finite-duration oscillating wavelets rapidly decaying in time (rather than infinitely long harmonic oscillations). Analysis has revealed similar features in the spectral and correlation characteristics of LFSS turbulence in both the high-temperature plasma and the low-temperature edge plasma: wavelet spectra contain quasi-harmonics.

With the probe method, the characteristic spatial scale of individual pulsations was estimated as ≤4 mm in the radial direction (the minimum spatial scale could not be exactly determined by using the probe 1 mm diameter) and as 4—7 mm to 12—20 cm in the poloidal direction. The radial velocity of some structures attained 4 x 10^6 cm/s. The toroidal coherence coefficient could be reliably measured only in the regime with a boronized chamber wall, when the gas flux from the wall was minimum. In some time intervals, the toroidal wavelet-coherence coefficient for plasma density fluctuations reached a level of 0.3—0.7 in the frequency range 25—150 kHz. Irregularly emerging structures with large poloidal sizes are also extended in the toroidal direction [8].

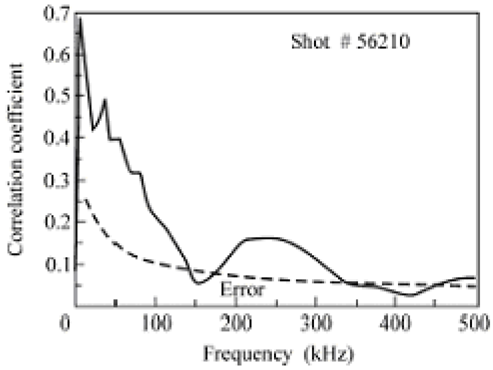

Fig. 3. Cross-coherence spectrum between edge potential fluctuations and magnetic-field fluctuations outside the plasma.

A key characteristic feature of LFSS turbulence is the presence of stochastic plasma structures. The nonlinear structures comprise a considerable fraction (from 10% to 30% in different plasma regions) of the turbulence energy. Observations in the L-2M stellarator revealed two general classes of stochastic plasma structures in LFSS turbulence: extended radial and poloidal MHD structures in the edge plasma and drift vortices at the mid-radius of the plasma column. Analyzing the increments of fluctuating plasma parameters (density, potential, and turbulent flux), we could estimate the dynamic times of LFSS turbulence in the L-2M stellarator. Note that high wavelet coherence (up to 50% for frequencies below 150 kHz) between time samples of the magnitudes of density fluctuations in the central and edge plasmas of L-2M was observed in previous experiments [3]. In addition, the cross-coherence wavelet spectra of potential fluctuations in the edge plasma and magnetic-field fluctuations outside the plasma column have been measured in recent experiment (Fig. 3). Thus, fluctuations in LFSS turbulence observed in different plasma regions turn out to be correlated. This may be interpreted as evidence of the presence of ensembles of stochastic plasma structures. Different mechanisms are responsible for the excitation of turbulence in different plasma regions because of the onset of various instabilities: drift-dissipative instability, MHD resistive ballooning instability [9], and instability driven by trapped electrons [3].

Another characteristic feature of LFSS turbulence is that the PDF of fluctuations differs from a normal distribution by heavier tails and a larger peakedness [7]. The probability of events with large signal magnitudes in this type of turbulence far exceeds the probability of the occurrence of such events for fluctuations described by a Gaussian PDF. Non-Gaussian probability densities of stochastic plasma processes point to non-Brownian character of the motion of particles. The role of rare events related to stochastic plasma processes with larger spatial and temporal scale becomes important. The difference from a Gaussian PDF is most pronounced for PDFs of fluctuations of the local particle flux in the low-temperature edge plasma of L-2M [10]. The PDFs of both the magnitudes and first-order differences of turbulent fluxes differ from normal distributions. The local turbulent flux in L-2M was shown to be a doubly stochastic diffusion process (or, what is formally the same, a diffusion process with random time). The processes of this kind result from the passage to the limit in a generalized Cox process [11]: the doubly stochastic Poisson process has the form $N^{(k)}(t) = N_1(\Lambda_k(t))$, where N_1 is a homogeneous Poisson process with a unit intensity and Λ_k are random processes independent of N_1.

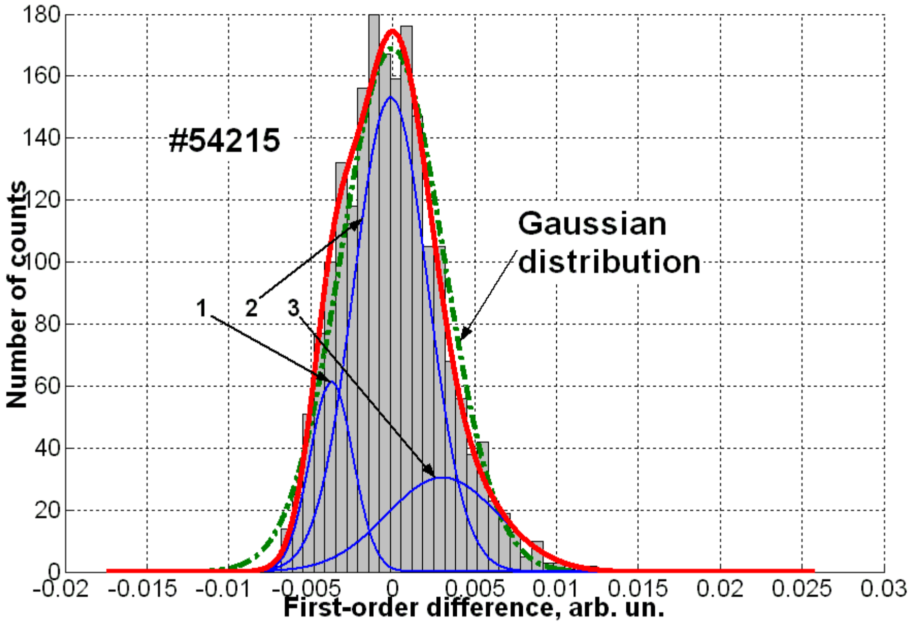

Fig.4. Modeling of the PDF of a time sample of first-order difference of density fluctuations in L-2M by mixing three Gaussian distributions, labeled by 1, 2 and 3, respectively.

For the LFSS plasma turbulence, the time sample is not homogeneous and independent (the ACF demonstrates the presence of a long-lived component). The independence of the first-order differences in the structural plasma turbulence is evidenced by the absence of long-term correlations in their ACF. Figure 4 shows the histogram of the first-order differences of density fluctuations in the central region, measured by 2nd harmonic gyrotron scattering [12]. This probability distribution is a mixture of Gaussians with different scales. A three-component mixture of normal distributions fits well to this time sample: P-value=0.9688 (from the Kolmogorov—Smirnov test). Recall, the mixture of three Gaussian distributions takes the form

$$f(x;p,\mu_1,\mu_2,\mu_3,\sigma_1,\sigma_2,\sigma_3) == \sum_{k=1}^{3} \frac{p_k}{\sqrt{2\pi}\sigma_k} \exp\{-\frac{(x-\mu_k)^2}{2\sigma_k^2}\}, \quad p_k > 0, p_1 + p_2 + p_3 = 1,$$

where p1=0.1521, μ1=-0.0037, σ1 =0.0013; p2=0.6497, μ2=-0.0001, σ2 =0.0023; p3=0.1982, μ3=0.0031, σ3=0.0034. The corresponding model distributions and their sum with calculated weights are shown in Fig. 4 [12].

4. Conclusions

Steady-state low-frequency strong structural (LFSS) turbulence has been observed in magnetized plasma of the L-2M stellarator.

LFSS turbulence was observed in the L-2M stellarator throughout the plasma volume, although different mechanisms are responsible for the excitation of turbulence in different plasma regions because of the onset of various instabilities: drift-dissipative instability, MHD resistive ballooning instability, and instability driven by trapped electrons. LFSS turbulence in both the high-temperature plasma and the low-temperature edge plasma is characterized by the same spectral and correlation characteristics: wavelet spectra with quasi-harmonics and correlation functions with pulsating tails. A key feature of LFSS turbulence is the presence of stochastic plasma structures. Fluctuations in LFSS turbulence observed in different plasma regions are correlated, which, probably, indicates the presence of ensembles of stochastic plasma structures in the high-temperature plasma. Main characteristic feature of LFSS turbulence is that the PDF of fluctuations differs from a normal distribution by heavier tails and a larger peakedness. Stable non-Gaussian PDFs were measured for plasma density fluctuations in the central region and for the local turbulent flux in the edge plasma.

The registered process of LHSS turbulence in L-2M stellarator can be successfully modeled by a combination of a finite number of diffusive processes (the scale mixtures of normal laws) each of which corresponds to a certain diffusive mechanism related to the structural turbulence in a plasma transport process. This combination is a subordinated Wiener process with a subordinator having a discrete distribution. As this is so, the characteristics of the combined process (the shares of each diffusion component as well as their drift and diffusive rates) can be estimated automatically, say, by the EM-algorithm.

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