UDC 533.9

STOCHASTIC STRUCTURES IN THE LOW-FREQUENCY PLASMA TURBULENCE: MEASUREMENT OF CHARACTERISTICS AND DETERMINATION OF GENERAL FEATURES

Nina N. Skvortsova, Karen A. Sarksyan, Nikolai K. Kharchev
General Physics Institute, 117942 Moscow, Russia, e-mail:nina@fpl.gpi.ru

Results are presented from the experimental and statistical studies of low-frequency turbulence in a magnetized plasma. It is shown that, for all types of driving instability (drift, ion-acoustic, MHD instability), this turbulence is accompanied by the formation of stochastic structures demonstrating a statistically consistent behavior and similar correlation, spectral, probability characteristics. The stochastic structures that are existing in the state of dynamic equilibrium and non-random interaction determine all common features of very different turbulent processes: ion-acoustic nonlinear solitons, drift vortices, and MHD spatial structures. It follows that the structural turbulence is a non-Gaussian probability process with the long memory, i.e., a self-similar probability process.

1. Introduction

At present, studies of a stochastic structure of low-frequency plasma turbulence attract particular attention. 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.

In the last few years, systematic studies of low-frequency plasma turbulence have been carried out at the General Physics Institute in two different experimental devices, namely, the TAU-1 device and the L-2M stellarator. The former is a linear system in which plasma is created by an injected electron beam, whereas the latter is a toroidal magnetic confinement system in which a plasma is created and heated by a high-power microwave beam. These two essentially different plasma sources with individual instability features allowed us to carry out a comparative analysis of associated turbulent processes. It was shown experimentally that, in a magnetized plasma, regardless of the type of turbulence (drift or ion-acoustic turbulence) [1] or the type of magnetic confinement system (stellarator or linear device) [2–5], low-frequency turbulence demonstrated a number of characteristic features.

As is known, statistical studies of fast plasma fluctuations require adequate techniques of data processing and experimental equipment. During the last two decades, computerized data acquisition systems have been commonly used in plasma experiments. These systems capable of accumulating and processing long arrays of experimental data from a large number of detectors situated in various points in a plasma offer a new means for studying the spectral, correlation, and statistical properties of both steady and transient states of plasma turbulence. The ability to analyze these properties theoretically and computationally, which confidence in the validity of the results of the analysis, is a very important attribute of such systems. The problem is overcome by using many supplementary methods for statistical treatment of experimental data: all traditional versions of multidimensional Fourier analysis, bispectral analysis, wavelet analysis, correlation analysis, probability methods of analysis, analysis of long-living correlations [5,6].

2. Stochastic structures in ion-acoustic turbulence in the TAU-1

The first experiments, where the stochastic structures in the ion-sound plasma turbulence were observed, were carried out in the TAU-1 device. This device was constructed especially for studying nonlinear plasma processes. Low-frequency turbulence is excited at frequencies of the ion-acoustic frequency range after the onset of current instability. The device end experiments are described in detail in [5,6]. Here, we only list the main parameters of a plasma: the cylindrical plasma column is 4 cm in diameter and 100 cm in length, the working gas is argon, the electron density is n = (0.9-2) $\times 10^{10}$ cm $^{-3}$, the electron temperature is T_e = 5–7 eV, and the ion temperature is $T_i \approx 0.1T_e$. The steady-state operating conditions can be maintained for 3–5 h.

Fluctuations in the electron density, plasma potential, and electron flux were measured with Langmuir probes. Two 2-mm-spaced probes (0.1 mm in diameter and 10 mm in length) were oriented along the magnetic field. After amplification and filtration, the probe signals were led to analog-to-digital converters (ADC); for data processing, we used a local computer net. In this experiment, we used CAMAC ADCs with a 10-kB buffer and OS-2 ADC plates with a 256-kB buffer. The sampling frequency was 10 MHz.

In the experiment, turbulent acoustic oscillations with a continuum frequency spectrum extending up to the plasma frequency (near 5 MHz) were excited by the electron current. The use of wavelet analysis allowed us to trace the time evolution of the structures, their emergence and disappearance in the spectrum. The frequency wavelet spectrum was repeatedly computed. Interpolation was used to diminish the computer time. Figure 1 shows the time evolution of the spectrum of plasma-potential fluctuations which is compiled from ten spectra computed for successive intervals of 20μs. The initial time is chosen arbitrarily. The amplitude of spectral components (in arb. units) is shown by gray shading; dark regions show highest amplitude and may be attributed to quasi-harmonics. The frequency corresponding to the wavelet duration is plotted on the abscissa, and the time is plotted on the ordinate. The spectrum of ion-acoustic fluctuations varies substantially with time, whereas both the macroscopic plasma parameters and the average oscillation energy remain constant. First, a single quasi-harmonic is seen in the spectrum; then, there two quasi-harmonics; and, finally, a single quasi-harmonic remains in the spectrum. The structure lifetime ranges from tens to hundreds of characteristic ion-acoustic oscillation periods (from 10^{-5} to 10^{-4} s). Structures in the structural ion-acoustic turbulence interact with each other; only a fraction of them is excited spontaneously. In the experiment, we observed the processes of the nonlinear coupling and decay of structures and measured the characteristic time of one cycle of the nonlinear interaction between structures. This time is a maximum measured characteristic time of the structural ion-acoustic turbulence. It ranges from 0.5 to 2–3 ms which is the maximum turbulence time.

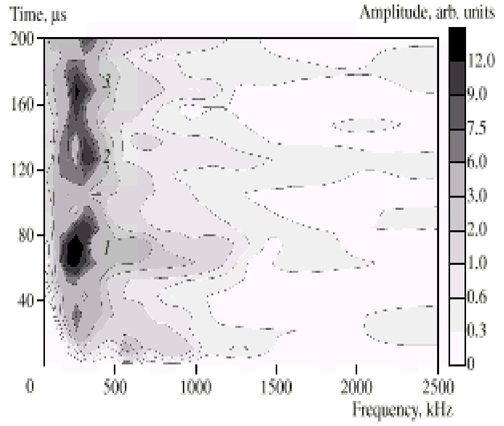

Fig. 1. Temporal evolution of the wavelet spectrum of potential-fluctuation amplitudes for H = 500 Oe, p = 3 ×10⁻⁴ torr, I_b = 60 mA, and U_b = 90 V

The steady-state structural ion-acoustic turbulence exists in the form of the dynamic equilibrium of nonlinearly interacting solitons.

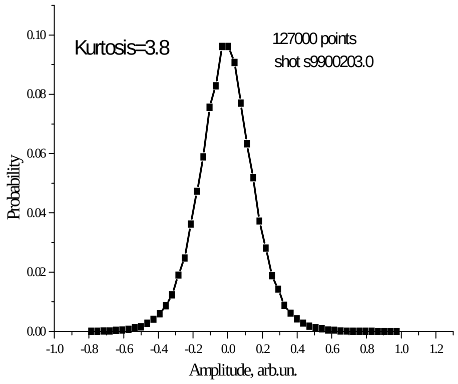

Fig.2. Probability distribution function of ion-sound turbulent signal. The total time window is 25.4 ms, H = 500 Oe, p = 3 × 10⁻⁴ torr, I $_b$ =200 mA,U $_b$ = 120 V

Probability distribution function of the ion-sound signals differs from the Gaussian (normal) distribution.The PDF usually has a more peaked profile and heavy wings. A histogram representing the distribution of amplitudes of turbulent signals is illustrated in Fig.2. Note that the fourth moment (kurtosis) is equal to 3.8. It should be recalled that the long-living correlation was observed for ion-acoustic turbulent signals [5]; it determines the characteristic “memory” time of the process. This indirectly indicates that low-frequency plasma turbulence is as a self-similar probability process [7] rather than a Gaussian probability process.

The self-similarity parameter is determined by two temporal influenced functions, describing the appearance of stochastic structures in turbulence and non-linear interaction between the structures.

3. Stochastic turbulent structures in the edge plasma of the L-2M stellarator

The experiments considered in this Section were carried out in the edge plasma of the L-2M stellarator. The L-2M stellarator is a toroidal magnetic system for plasma confinement [8,9]. The radius of the torus is R = 100 cm; the plasma cross section is elliptical, its mean radius (the mean radius of the magnetic sparatrix) is $< r_s >$= 11.5 cm and can be reduced by inserting a limiter. A helium plasma is produced and heated by a microwave beam (the wavelength is 4 mm and the power is up to 200 kW). The discharge duration is about 10 ms.

Edge fluctuations were measured with Langmuir probes which can be inserted into the plasma (Fig. 3) to the radius r = (0.8 - 0.9) r_s, where the density is n(r) = (1-2) x 10^{12} cm^{-3}, the electron temperature is close to $T_e(r)$=30 - 40 eV. The relative level of the density fluctuations is $(\delta n/n)_{out}$ = 0.2 - 0.25 in the outer regions and $(\delta n/n)_{in}$=0.1 in the inner regions of the plasma.

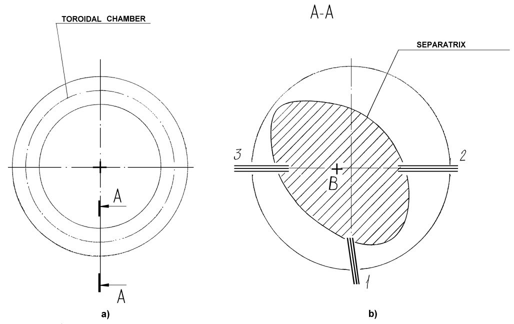

Fig.3. Arrangement of the probe devices: a) top view of the toroidal chamber, b) poloidal section A-A; 1 – vertical probe, 2 – outer horizontal probe, 3 – inner horizontal probe; distances between probes l_{12} ~ 20 cm, l_{13} ~ 15 cm, l_{23} ~ 35 cm

Each probe device consisted of several (two or three) individual cylindrical probes separated from each other by distances l = 7-4 mm in the radial and poloidal directions. The distance between the probe devices in the poloidal direction was equal to tens of centimeters. Probe signals were digitized at 1 MHz using a 10-bit digitizer. The probes detected fluctuations in the plasma density δn (specifically, the ion saturation current I_s, so $\delta I_s \sim \delta n$) and floating potential δϕ.

Wavelet coherences in the poloidal (4 mm) and in the radial (7 mm) directions were investigated for density and potential fluctuations. Figure 4 demonstrates a high level of the wavelet coherence in these directions for density fluctuations, which is evidence of structure existence. One can notice that the shape of the frequency resolved radial and poloidal coherence of fluctuations is asymmetric, i.e. the structures have different scales in these directions. It should be noted that the presented wavelet coherence spectra were computed for signals measured by probes radially separated by 7 mm with zero delay time. With increasing the delay time between signals to $\Delta t = 3$ μs, the coherence coefficient decreases remarkably. From the time delay in the maximum of the cross-coherence and the dispersion relation (phase versus frequency), we estimated the propagation velocity of the radially correlated fluctuations, which value turned out to be close to $4 \cdot 10^4$ m/s. It is suggested that mode coupling effects responsible for a high radial correlation of fluctuations in the high frequency range /4/.

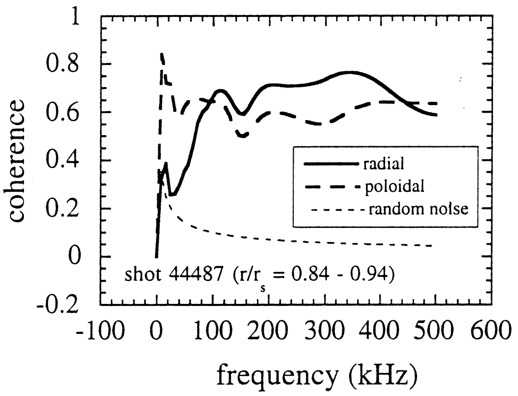

Fig. 4. Radial and poloidal coherence of fluctuations

These measurements showed a high degree of correlation of fluctuations at large distances in the poloidal direction, with a correlation length as large as $l_{cor} = 20$ cm. The radial correlation length reached 7 mm. The highly correlated fluctuations are localized predominantly in the outer region of the plasma column. According to theoretical predictions, such fluctuations may be attributed to magnetohydrodynamic (MHD) resistive ballooning instability. The arising stochastic structures determine the spatial (poloidal and radial) correlation length of MHD turbulence in the edge plasma of the L-2M stellarator.

4. Conclusions

It has been shown in the experiments in the TAU-1 device that the structures exist in ion-acoustic turbulence of current-carrying magnetized plasma. Structures in this low-frequency turbulence are spatially correlated. We suggest that these structures are nonlinear ion-acoustic solitons in nature. Nonlinear soliton structures interact with each other. Only fraction of them is excited spontaneously. In the experiment, we observed the processes of the nonlinear coupling and decay of structures and measured the time of one cycle of nonlinear interaction between structures (the maximum characteristic time of the process). The steady-state structural ion-acoustic turbulence exists in the form of the dynamic equilibrium of nonlinearly interacting structures. This turbulence is a self-similar probability process rather than Gaussian probability process. Experiments on studying turbulence in the edge plasma on the L-2M stellarator confirm that low-frequency plasma turbulence with resistive-interchange MHD modes appears in the form of radial-poloidal structures. It should be noted, that in this case too, the structural low-frequency turbulence in the edge plasma exists also in the form of dynamic equilibrium nonlinearly interacting plasma structures and cannot be described as a Gaussian process. Two types of turbulent structures are observed: nonlinear MHD structures near the separatrix surface and drift vortex structures in deeper plasma layers. MHD structures govern the dynamic behavior and non-Gaussian probability characteristics of turbulent flux in the boundary plasma region.

Therefore, the turbulence under study can be called the structural plasma turbulence. The stochastic structures that are existing in the state of dynamic equilibrium and non-random interaction determine all common features of turbulence caused by essentially different (drift, ion-acoustic, MHD) instabilities. This leads us to the conclusion that, in general case, the non-Gaussian probability process with the long memory determines the characteristic features of plasma turbulence over a wide range of its state – from weak to strong turbulence.

This work was supported in part by the Russian Foundation for Basic Research, projects no.98-02-16345 and no.00-02-16345.

References

1. Batanov, G.M., Sarksian, K.A., Sapozhnikov A.V.,et al., Proc. IV Int. Conf. on Nonlinear and Turbulent Processes in Physics, Kiev (1989) vol. 1, 231.
2. N.N. Skvortsova, G.M. Batanov, O.I. Fedianin, N.K. Kharchev et al. J.Plasma Fusion Research SERIES (Japan), Vol.1 (1998) 298.
3. C.Hidalgo, B.Ph. van Milligen, M.A. Pedrosa, E. Sanchez, et al**.** J.Plasma Fusion Research SERIES, Vol.1 (1998) 94.
4. G.M. Batanov, O.I. Fedianin, N.K. Kharchev, Yu.V. Khol'nov, et al. Plasma Physics and Control Nuclear Fusion, 40 (1998), 1241
5. K.A. Sarksyan, N. N. Skvortsova, N. K. Kharchev and B. Ph. van Milligen, Plasma Physics Reports, (1999)Vol. 25, No. 4, 312.
6. A.N. Kolmogorov, Reports of Academy of Science (1941), v. XXX, 299.
7. N. N. Skvortsova, N.K. Kharchev, K.A. Sarksyan, JETP LETTERS (1999) v.70(3), p.201.
8. G.M. Batanov, A.E. Petrov, K.A. Sarksyan, N. N. Skvortsova et al.JETP LETTERS (1998), Vol 67, 662. D.K. Akulina, G.M. Batanov, A.E. Petrov, L.V. Kolik, K.A. Sarksyan, et al. JETP LETTERS (1999), Vol. 69, 407.