Frequency Spectra and Statistical Characteristics of Plasma Density Fluctuations Measured by Doppler Reflectometry in ECR Heated Plasma in the Presence of Induction Current in the L-2M Stellarator

Nina N. SKVORTSOVA[1)], Vyacheslav V. SAENKO[1)], Viktor Yu. KOROLEV[2)], German M. BATANOV [1)], Dmitrii V. MALAKHOV[1)], Anton A. PSHENICHNIKOV[1)], Aleksandr E. PETROV[1)], Karen A. SARKSYAN[1)], Nikolai K. KHARCHEV[1)]

[1)] *A.M. Prokhorov General Physics Institute, Moscow, 119991 Russia*

[2)] *Moscow State University, Moscow, 119899 Russia*

Data on the parameters of plasma density fluctuations in the edge plasma of the L-2M stellarator are presented. The density fluctuations were measured by Doppler reflectometry. Studies were made in the basic magnetic configuration of L-2M under ECRH conditions and in modified magnetic configurations where the rotational transform at $r/a \le 0.6$ (a being the radius of the last closed flux surface) was decreased to negative values by exciting induction current in the plasma. It is shown that induction current results in a shear of the poloidal plasma velocity at the edge of the plasma column. The probability density functions of plasma fluctuations are found to be different from normal (Gaussian) distributions and have heavy tails in both regimes. This type of turbulence is fairly described by shift-scale mixtures of 3 - 4 stochastic plasma processes, each with a normal probability density function. The induction current affects shift-scale mixtures, and components with high mean velocities (convective components) appear in some processes. The experiments showed that the characteristics of turbulent fluctuations in the edge plasma are sensitive to changes in the magnetic structure of the core plasma.

Keywords: plasma turbulence, non-Gaussian process, stellarator, Doppler reflectometry.

1. Inroduction

Experimental studies of low-frequency fluctuations of plasma density, plasma potential and particle flux in the L-2M stellarator have revealed the state of structural turbulence over all the volume of the plasma column [1]. The state of structural turbulence combines determinate-chaotic nature with the existence of ensembles of stochastic structures (vortices, solitons, wave packages) is superimposed on strong plasma turbulence [2].

The present paper reports on experimental studies of spectra and probability characteristics of structural turbulence in the edge plasma of the L-2M stellarator. Experiments were carried out under conditions that the "standard" magnetic configuration was modified by exciting an additional induction current. Plasma density fluctuations were studied with the use of a Doppler reflectometer [3].

2. Experimental conditions

The L-2M stellarator has two helical windings ($l = 2$), a major radius R = 100 cm, and a mean plasma radius $\langle a \rangle = 11.5$ cm [4]. The plasma was created and heated by one or two 75-GHz gyrotrons (at the 2nd harmonic of the electron gyrofrequency). The magnetic field at the center of the plasma was $B_t = 1.3–1.4$ T. The gyrotron power was $P_0 = 150–300$ kW, and the microwave pulse duration was up to 15 ms. Measurements were performed in a hydrogen plasma with mean density $\langle n \rangle = (0.8–2.0)\cdot 10^{13}$ cm^{-3} and central temperature $T_e = 0.6–1.0$ keV. In the edge plasma at radius r/a = 0.9, the density was at a level of n (r) = (1–2) 10^{12} cm^{-3} and the electron temperature was T_e (r) = 30–40 eV. The duration of the steady-state phase of the discharge was 10 ms.

In the magnetic configuration of the L-2M stellarator, an induction current excited in the opposite direction to the toroidal magnetic field (hereafter referred to as a negative current) was used to change the value and sign of rotational transform and to increase the shear of magnetic lines. In [5], the radial profiles of rotational transform $i/2\pi$ were calculated for various values of the induction current. According calculations, the induction current of 10-15 kA may result in two large magnetic islands located in the central region, whereas at the plasma edge at r/a = 0.8, the magnetic structure changes only slightly.

The probing frequencies used in our experiment correspond to the peripheral regions where the electron density drops from $\sim 1.7\cdot 10^{13}$ cm^{-3} to $\sim 1.1\cdot 10^{13}$ cm^{-3}. The angles of incidence of the probing beam of the reflectometer are 4°, 8° and 12° with respect to the normal

author's e-mail: nina@fpl.gpi.ru

to the last closed magnetic surface According to the Bragg condition, the scattered signal corresponds to plasma fluctuations with poloidal wavenumber $k \approx 2\ cm^{-1}$.

The stray signal from heating gyrotron radiation was suppressed with the help of a waveguide resonance filter, which provided 30-dB attenuation at a frequency of 75.3 GHz. The polarization of the probing radiation in the plasma corresponded to an ordinary wave. We used quadrature detection. Signals from two microwave diodes were amplified in wideband amplifiers with gain of 10 and were recorded by a 10-digit ADC operating at a sampling rate of 5 MHz. The time resolution of the diagnostic system was 200 ns.

A Doppler shift, which corresponds to the poloidal rotation velocity, was determined from the shift of the Fourier spectrum of a complex signal. In addition to complex Fourier spectra, we estimated and studied autocorrelation functions, probability density functions of fluctuation amplitudes and their increments for time samples recorded in one of two reflectometer channels.

3. Experimental results

As an illustration, Fig. 1 shows a time sample of the reflectometer signal in an ECRH discharge with an additional induction current.

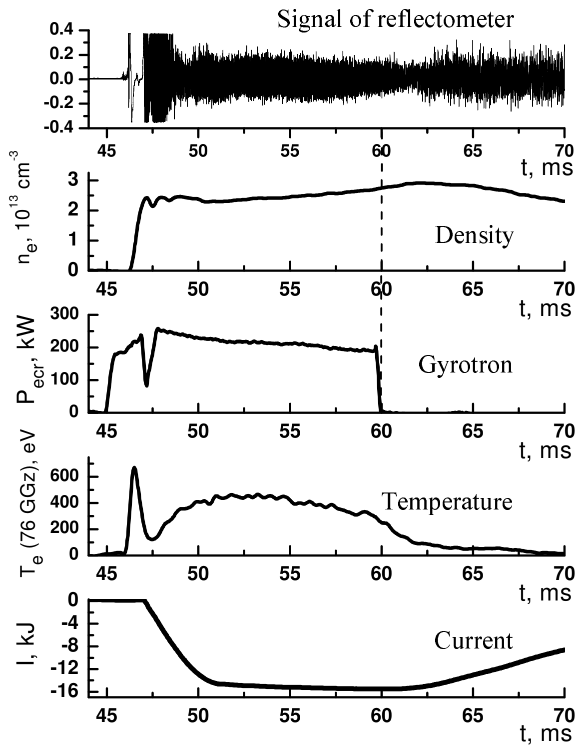

Fig.1. Time behavior of the refectometer signal, average plasma density, gyrotron power, central electron temperature, and plasma energy in a discharge with current I= –15 kA.

Also shown are time dependences of the average plasma density, gyrotron power, central electron temperature (ECE signal), and plasma energy. Note that the electron density is maintained during more than 10 ms after the gyrotron power is switched off. A similar behavior of the electron density and fluctuations is observed in discharges without induction current.

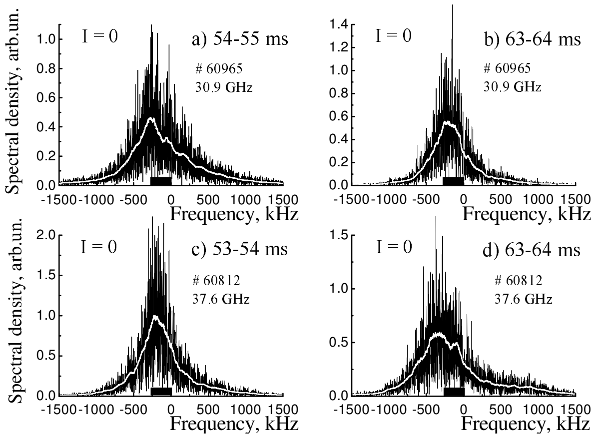

Fig.2. Spectra of the complex signals for two probing frequencies 30.9 GHz and 37.6 GHz for an ECRH discharge: (a, b) during and (b, d) after the gyrotron pulse. Black segments on the frequency axis show Doppler shifts.

Figure 2 shows spectra of the complex signals for two probing frequencies 30.9 GHz and 37.6 GHz for an ECRH discharge in the absence of induction current. Black segments on the frequency axis indicate Doppler shifts. The scattered spectra are continuous with feebly marked bands of width 50 kHz. It can be seen that the spectra are continuous with feebly marked bands of width 50 kHz. The peak of spectral intensity is shifted from the zero (probing) frequency by nearly 250 kHz into the red region. The spectrum is asymmetric: the spectral intensity falls sharply in the red wing, whereas it decreases smoothly in the blue wing of the spectrum. The shift of the peak intensity over frequency is usually interpreted as a Doppler shift.

Figure 2 shows spectra of the complex signals for two probing frequencies 30.9 GHz and 37.6 GHz for an ECRH discharge in the absence of induction current. Black segments on the frequency axis indicate Doppler shifts. The probing frequencies, it will be recalled, correspond to different plasma regions: the higher the frequency, the higher the plasma density. It can be seen from these spectra that the Doppler shift is the same for both probing frequencies during the heating pulse and in the plasma decay phase. The poloidal velocity corresponding to this shift is about 10^6 cm/s. In the absence of an induction current, the shape of the spectrum does not change during the ECR heating pulse and for 2-3 ms after its end. The Fourier spectra for probing frequencies 30.9 GHz and 37.6 GHz have the same values of the width and Doppler shift, which indicates that the poloidal plasma velocity is uniform a shear is absent in the edge plasma in the ECRH regime.

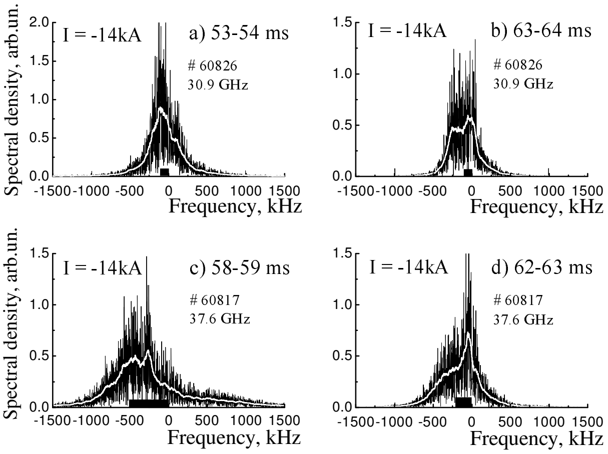

Fig.3. Spectra of the complex signals for two probing frequencies 30.9 GHz and 37.6 GHz for an ECRH discharge with additional induction current: (a, b) during and (b, d) after the gyrotron pulse. Black segments on the frequency axis show Doppler shifts.

Figure 3 shows spectra of the complex signals for two probing frequencies 30.9 GHz and 37.6 GHz for an ECRH discharge with additional induction current. Black segments on the frequency axis indicate Doppler shifts. The spectra in this regime change markedly, depending on the probing frequency. FWHM of the spectrum measured with a probing frequency of 30.9 GHz is smaller. At the same time, an intense spectral band (its intensity is nearly equal to the intensity of the continuous spectrum) appears in the frequency range 150-200 kHz. The red edge of the spectrum is shifts toward a lower frequency. In the scattered spectrum for a probing frequency of 37.6 GHz, the shift of the red edge increases from -500 kHz to -750 kHz. The scattered spectrum for a probing frequency of 34.8 GHz contains two intense bands in the range of -200 kHz and -400 kHz. Their intensity varies in time, but their positions are fixed.

Hence, the generation of a magnetic island structure in the inner region of the plasma column involves a change in behavior of the spectra measured in the narrow region near the last closed magnetic surface. The Doppler shifts of the spectra corresponding to different radii prove to be different, which is evidence for a radial shear of the poloidal plasma velocity.

As noted above, the reflectometer data were also used to study probability characteristics of plasma density fluctuations. Characteristically, the autocorrelation functions of fluctuation amplitudes demonstrated long-lived tails. Histograms showed that the probability density functions (PDFs) of fluctuation amplitudes and increments differ from Gaussian distributions by heavy tails. Previously, it was proposed to apply doubly stochastic Poison process to describing the PDFs of the increments of fluctuation amplitudes in structural plasma turbulence [6]. Taking this approach, we used the model of shift-scale mixtures of Gaussian distributions. A finite shift-scale mixture of Gaussian (normal) distributions is represented in the form

$$P\{X < x\} = \sum_{j=1}^{n} p_j \Phi\left(\frac{x - a_j}{\sigma_j}\right), \quad x \in \text{Ў}$$

where $\Phi(y)$ is the normal distribution function; p_j is the weight; n-number of component of mixtures, a_j and σ_j are the mathematical expectation and dispersion of the normal distribution, respectively.

Each component of the mixture is determined by a certain stochastic plasma process, such as the presence of an ensemble of stochastic plasma structures, the interaction between structures, etc. As applied to structural plasma turbulence, the concept of volatility as a multidimensional vector determining the behavior of fluctuations was considered in [7]. When processing the increments of fluctuations measured by the Doppler reflectometer, we calculated the volatility components, in which values of a_j and σ_j give information about the average rates and dispersion of rates of turbulence in each particular process and their total effect. Modeling the PDFs of fluctuation increments with the use of the Estimation Maximization algorithm [8] allowed us to determine the number and weight of such processes and to trace behavior of the components.

We studied how the mixture components and the PDF fluctuations alter in response to a change introduced in the magnetic configuration by the induction current.

It was found that the turbulent process in the edge plasma is fairly described by a mixture of 3 - 4 stochastic plasma processes for both the ECRH regime and the regime with an additional induction current. The velocity value deduced from the Doppler shift is a sum of two components: the poloidal rotation velocity and the phase velocity of the measured fluctuation. In our case, the latter component is a sum of phase velocities of particular processes:

$$u = u_{E\times B} + \sum_{k=1}^{n} u^{k}{}_{phase} ,$$

where k is the number of processes determined following the Estimation Maximization algorithm, and $u^{k}{}_{phase}$ are their phase velocities. For plasma density fluctuations measured in the regime with induction current, we observed the mixture components characterized by larger average velocities in comparison with similar components in the regime without induction current.

Figure 4 shows the results of numerical simulation of the PDF of increments of density fluctuations in the regime with additional induction current. Turbulence is described by a mixture of four processes of which one has a large average velocity characteristic of regimes with current. It is found that the characteristics of shift-scale mixtures of Gaussians change substantially in the presence of induction current.

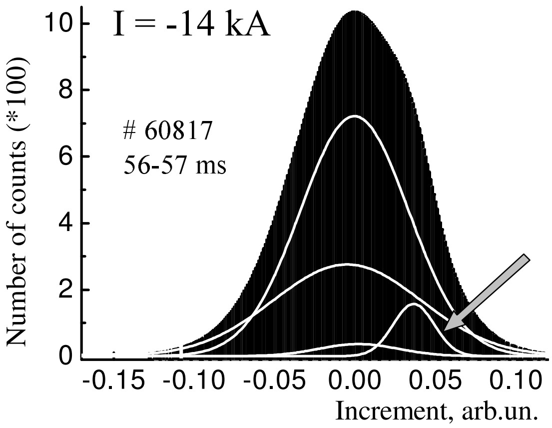

Fig.4. Modeling of the PDF of density fluctuation increments in the regime with additional induction current. An arrow indicates the process characterized by a large mathematical expectation.

The so-called "sliding separation of mixtures" [7] was used to trace the temporal evolution of the components of average velocity. In the ECRH regime, the average velocities of processes do not change during 3-5 ms after the heating pulse is switched off. In the regime with current, the average velocities in the mixture of processes drop by an order of magnitude with 0.1-0.2 ms after the ECRH pulse is switched off.

4. Conclusions

The spectra of turbulent fluctuations in ECR regime have nearly the same width and Doppler shift, which indicates that the poloidal plasma velocity is uniform over the region of observation. In the presence of the additional induction current, the characteristics of Fourier spectra of complex signals in the narrow near-separatrix region changed markedly and the Doppler shifts for three probing frequencies became different, which is evidence for a shear of the poloidal plasma velocity.

The processing the results of measurements by the Doppler reflectometer demonstrated efficiency of statistical methods of shift-scale mixtures of Gaussian distributions and the sliding separation of mixtures of Gaussian distributions. It is shown that, in structural plasma turbulence developing in the edge plasma of the L-2M stellarator, there exist 3-4 independent Gaussian processes, each having its particular propagation velocity. The algorithm of sliding separation of mixtures works and makes it possible to distinguish between the pure ECRH regime and the ECRH regime with additional induction current. A comparison between the pure ECRH regime and the ECRH regime with additional induction current shows that the behavior of subcomponents of volatility for these regimes is different and is an inherent characteristic of the regime.

As a result, it has been established that the frequency and probability characteristics of turbulent fluctuations in the edge plasma are sensitive to changes in the magnetic structure of the core plasma.

This work was supported by the Dynasty Foundation, the CRDF Program for Basic Research, and the RF Presidential Program "Support of Leading Scientific Schools" (project 5382.2006.2) and the Russian Foundation for Basic Research (project nos. 07-02-00455, 07-01-00517).

References

[1] G. M. Batanov, V. E. Bening, V. Yu. Korolev, et al., JETP Lett. **78**, 502 (2003).

[2] V. Yu. Korolev and N.N. Skvortsova. (Eds) “Stochastic Models of Structural Plasma Turbulence”. VSP, Leiden - Boston, The Netherlands. (2006).

[3] A. A. Pshenichnikov, L. V. Kolik, et al. Plasma Physics Reports. **31**, 554 (2005).

[4] V. V. Abrakov, D. K. Akulina, E. D. Andryukhina, et al., Nucl. Fusion **37**, (1997) 233.

[5] S.V.Shchepetov, D.K.Akulina, et al. 15 Stellarator Workshop. Madrid. **Or-2** (2006).

[6] N.N. Skvortsova, V.Yu. Korolev, G.M. Batanov et al Plasma Phys. Contr. Fusion. (2006). **48**. A393.

[7] V.Yu. Korolev, N.N. Skvortsova. A new method of the probabilistic and statistical analysis in case of plasma turbulence processes. In “The systems and means of informatics.” Ed. I.A. Sokolov. Moscow. The Institute of Informatics Problems (IPI RAN). 126, (2005). (In Russian).

[8] Skvortsova N. N., Batanov G. M. et al., New possibilities for the mathematical modeling of turbulent transport processes in plasma. in ”Stochastic Models of Structurial Plasma Turbulence” (V. Yu. Korolev and N. N. Skvortsova eds.) – Leiden, Boston: VSP, 87 (2006).