Analysis of Temporal Evolution of Dynamic and Diffusive Components in Drift Particle Fluxes in the Edge Plasma of the L-2M Stellarator Operated in Different Confinement Regimes

Nina N. SKVORTSOVA [1)], German M. BATANOV[1)], Nikolay K. KHARCHEV[1)], Yuryi V. KHOL'NOV[1)], Dmitryi V. MALAKHOV[1)], Alexander E. PETROV[1)], Vyacheslav V. SAENKO[1)], Karen A. SARKSYAN[1)], Dmitryi G. VASILKOV[1)], Victor Yu. KOROLEV[2)], Yuryi V. ZHUKOV[2)]

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

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

The article presents an analysis of dynamic and diffusive components in turbulent fluxes measured in the edge plasma of the L-2M stellarator. It is shown that a shift-scale mixture of several (three-four processes, depending on macroscopic characteristics of the plasma) normal processes adequately describes the measured particle fluxes. The Estimation Maximization algorithm is applied to probability densities of flux increments in order to determine the number of mixture components and the weight of each component in the mixture. The method of sliding separation of mixtures is applied to separate between the dynamic and diffusive components of volatility and to trace their temporal evolution. Some characteristic L-2M regimes are examined. It is shown that turbulent particle transport in the edge plasma occurs by both the ballistic and diffusive mechanisms, and their contributions are of the same order of magnitude.

Keywords: turbulence, turbulent flux, stellarator, non-Gaussian statistics, volatility, diffusion.

1. Introduction

Strong structural low-frequency turbulence in magnetoactive plasma is frequently observed in the course of investigations of low-frequency fluctuations in toroidal magnetic confinement systems [1]. A characteristic feature of strong structural low-frequency turbulence is the presence of ensembles of stochastic plasma structures and probability density functions (PDF) for all plasma variables differ from the normal distributions. In particular, PDFs of turbulent particle fluxes are leptokurtic and have heavy-tailed distributions.

The approach based on inhomogeneous random walks allows the PDF of increments of amplitudes of turbulent particle fluxes to be represented in the form of shift-scale mixtures of normal distributions. In this case, it is possible to separate dynamic (convective) and diffusive components in turbulent particle fluxes. This approach was applied to analyzing turbulent fluxes in the FT-2 tokamak and L-2M stellarator [2].

The article presents an analysis of dynamic and diffusive components in turbulent fluxes measured in the edge plasma of the L-2M stellarator. For analysis we use a wide database of experiments under diversified operating conditions (in the basic and modified magnetic configurations, the use of boronization of the chamber wall surface to suppress impurity fluxes from the wall).

2. Estimation of turbulent processes in plasma in terms of volatility

Turbulent processes in the edge plasma of the L-2M stellarator were estimated in terms of volatility. Volatility, as applied to turbulent fluxes, means "the degree of unpredictable change over time of edge turbulent fluxes". The probabilistic concept of volatility has long been in use in financial statistics; however, to our knowledge, this characteristic has never been employed in papers devoted to plasma turbulence. Volatility of a random process is determined by at least two types of factors. The first type can be characterized as a dynamic (convective) factor. The influence of the dynamic factor makes itself evident in the fact that the process varies because of the presence of a certain trend or a combination and, hence, interaction of trends that indicates the presence of structures in a plasma. The dynamic component corresponds to a drift (which can occur by a variety of processes), for example, to ballistic transport. The second type of factors is termed stochastic or diffusive. With the use of special mathematical statistical procedures, the diffusive component can be represented as a sum of subcomponents, each being related to a particular type of stochastic structures, their interaction,

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

etc. In the basic model of nonhomogeneous random walk described by a subordinate Cox process, volatility is naturally represented as a sum of the dynamic and diffusive components [3].

In previous studies of low-frequency turbulence, it was shown that processes of turbulent particle transport are described by subordinate Cox processes and is described, to a high degree of accuracy, by shift-scale mixtures of normal distributions [4]. If X is an increment of a random process under consideration, then its distribution is a shift-scale mixture of normal distributions if

$$P(X<x)=\iint \Phi(\frac{x-v}{u})dP(U<u,V<v)= \mathrm{E}\Phi(\frac{x-V}{U}), \quad x\in\Re, \tag{1}$$

where $U \geq 0$ and V are finite random variables. In this case, volatility is characterized by a vector containing components of three types: a weight (positive numbers, which add up 1), drift factors (averages), and diffusion coefficients (standard deviations) of the corresponding components. Each of these mixture components corresponds to a particular mechanism and a particular structure in plasma turbulence, which is characterized by parameters α_j и σ_j, whereas the weight p_j defines the proportion of structures of the *j*th type in the whole process of plasma turbulence.

In [5], it is shown that a finite shift-scale mixture of normal distributions (1) is represented in the form

$$\sum_{j=1}^{k} p_j \Phi(\frac{x-a_j}{s_j}) = \mathrm{E}\Phi(\frac{x-V}{U}), \tag{2}$$

where the pair of random variables U and V has a discrete distribution

$P((U,V)=(s_j,a_j)$, j = 1,..., k, so that

$$DV=\sum_{j=1}^{k} p_j (a_j-\overline{a})^2, \tag{3}$$

$$\mathrm{E}U^2=\sum_{j=1}^{k} p_j s_j^2, \quad \overline{a}=\sum_{j=1}^{k} p_j a_j. \tag{4}$$

Expression (3) defines that volatility component which is associated with the presence of local trends; it will be referred below as a "dynamic component" of volatility. Expression (4) defines a "diffusive component" of volatility. Total (multidimensional) volatility of the process is the square root of the sum of two components, one of which represents a spread of local trends, whereas the other characterizes diffusion.

3. Analysis of dynamic and diffusive components of turbulent fluxes

The L-2M stellarator has two helical windings (l= 2), a major radius R = 100, and a mean plasma radius <a> = 11.5 cm [6]. The plasma was created and heated by one or two 75-GHz gyrotrons under conditions of electron cyclotron resonance heating (ECRH) at the second harmonic of the electron gyrofrequency. The magnetic field at the plasma center 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 carried out in a hydrogen plasma with an average density of <n> = (0.8–2.0)·10^{13} cm^{-3} and central temperature of T_e = 0.6–1.0 keV. Turbulent flux was measured in the edge plasma at a 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 local fluctuating particle flux as defined as $\Gamma=(dn_e \cdot dv_r)$ [4], where dn_e denotes the plasma density fluctuations, and $dv_r = dE_\Theta / B$ expressed through the fluctuation of the poloidal electric field $d\mathrm{E}_\Theta = (dj_1 - dj_2)/r\Delta\Theta$, where dj is the floating-potential fluctuation in the plasma, and Θ is the poloidal angular coordinate, r is the middle radius. Local turbulent particle fluxes were measured in the edge plasma of L-2M by probe systems consisting of three single cylindrical probes. The flux was measured at different distances of the last closed flux surface (LCFS).

Time samples of local fluxes in L-2M are not homogeneous and independent. The PDFs of local fluxes in L-2M stellarator are leptokurtic and have heavier tails as compared to a Gaussian distribution Statistical analysis of characteristics of fluctuating particle flux is carried out with time samples of flux increments, which are homogeneous and independent.

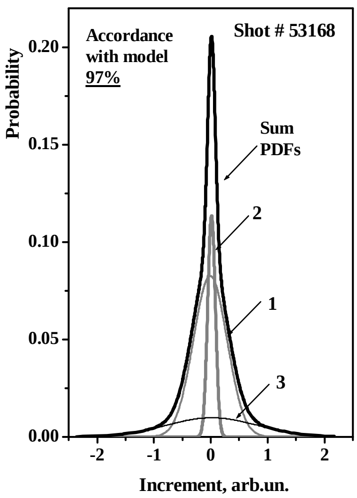

Fig.1. Modeling of PDF of increments of the turbulent flux measured in L-2M stellarator.

The finite mixtures of several (three or four, depending on macroscopic characteristics of the plasma) normal distributions adequately describe The PDFs of flux increments [5]. As an illustration, Fig. 1 shows the histogram of a time sample of the flux increments along with the result of processing. The Estimation Maximization (EM) algorithm was applied to probability densities of flux increments in order to determine the number of mixture components and the weight of each component in the mixture. In this particular case, the PDF of flux increments is a scale mixture of three normal distributions that correspond to three stochastic plasma processes. This particular experiment was conducted in the basic magnetic configuration (rotational transform at the magnetic axis is 0.175, mean plasma radius is 11.5 cm), with preliminary boronization.

The method of sliding separation of mixtures was used to separate between the dynamic and diffusive components of volatility and to trace their temporal evolution. Time variations in the components of the sums (3) and (4) were calculated using a time window "sliding" over a time sample of flux increments. This technique for analyzing the structural plasma turbulence is described in more detail in the review [3].

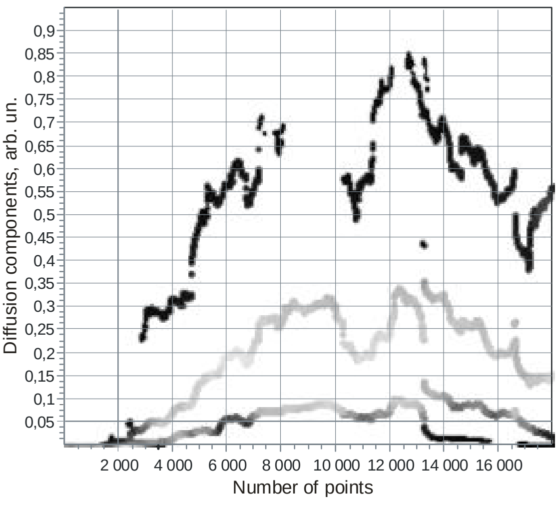

Fig.2. Time behavior of three subcomponents of the diffusive component of flux for shot No. 55623.

Figure 2 shows the time behavior of three diffusive subcomponents of volatility (i.e., summands in (3)) for the experiment conducted in the modified configuration of magnetic field (rotational transform 0.082, mean plasma radius 12.5 cm, the LCFS contacts with the chamber wall).

Note that the number of subcomponents remains unchanged, but their intensity varies with time. Hence, each of the components reflects a temporally continuous process, and the contribution from this process to the sum varies with time.

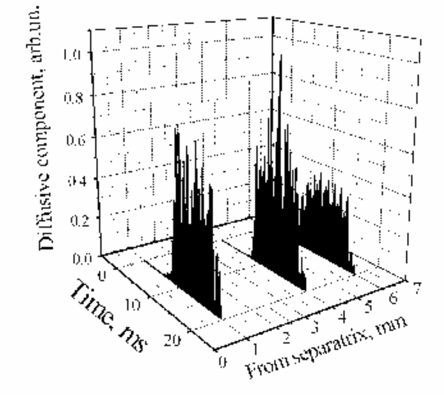

Fig.3. Time behavior of the diffusive component of volatility turbulent fluxes measured at different radial distances from LCFS in three shots.

Figure 3 and 4 show how the diffusive (4) and dynamic (3) components vary with time in the radial turbulent flux measured at different distances from LCFS. Measurements were performed from a shot to shot under identical experimental conditions. Characteristically, the dynamic component (which is associated with convection) is more volatile than the diffusive component.

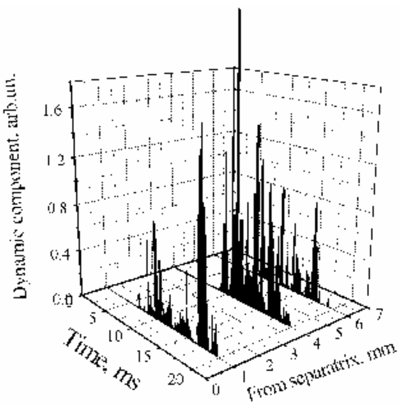

Fig.4. Time behavior of dynamic component of turbulent fluxes measured at different radial distances from LCFS in three shots.

Figure 5 shows the time behavior of the diffusive and dynamic components of volatility during the steady-state phase of the discharge. The flux radial turbulent was measured at a distance of 6 mm from LCFS. The experiment was conducted in the modified configuration of magnetic field (rotational transform 0.082, mean plasma radius 12.5 cm, the LCFS contacts with the wall).

From the curves in Fig. 5 it will be noticed the dynamic component compares with the diffusive component This is a typical example of discharges excited in the modified magnetic configuration, where the LCFS contacts with the chamber wall, and is also observed when the quality of the chamber wall surface is insufficient, when the effect of chamber wall boronization ceases.

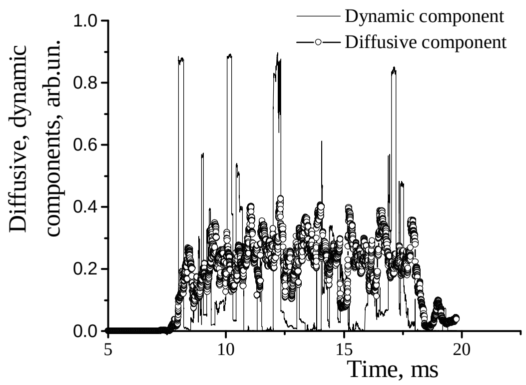

Fig.5. Time behavior of the dynamic and diffusive components for shot No. 55623.

Figure 6 shows the results of measurements of the local turbulent flux (a) before and (b) after boronization. The positive and negative values in the figure correspond to an outward and an inward flux, respectively. After boronization, the radial turbulent particle flux near the LCFS changes drastically and is preferentially directed outward.

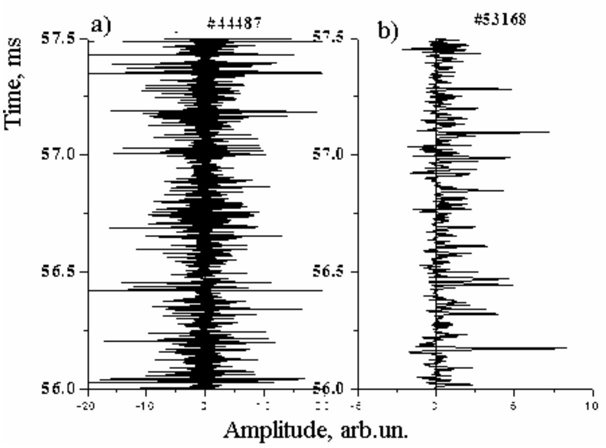

Fig.6. Comparison of the local turbulent flux (a) before and (b) after boronization, shot No.53163.

The time behavior of the dynamic and diffusive components for this case is shown in Fig. 7. Note that the component involved three turbulent processes in this case too. It can be seen that the diffusive component is dominant while the dynamic component is suppressed. Recall that the dynamic component is associated with convective transport, whereas the diffusive component characterizes the stochastic component of volatility.

The effect may be explained as follows. After boronization, the flux of carbon and oxygen from the chamber wall decreases; accordingly, radiative losses at the edge also decrease. As a result, the electron temperature at the plasma periphery increased to ~ 100 eV and a jump in T_e forms near the LCFS in a narrow r/a = 0.05) layer, with a very large temperature gradient [7]. The temperature gradient increases a shear of the electric field, which suppresses convection.

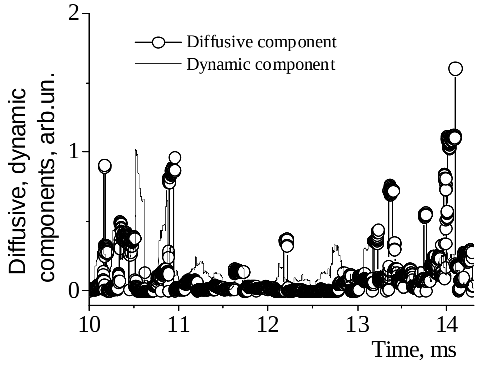

Fig.7. Time behavior of the dynamic and diffusive components for shot No. 53163.

4. Conclusions

A new approach, based on the analysis of time samples of the increments of turbulent particle fluxes, is used to estimate the dynamic and diffusive components in the edge turbulent flux of the L-2M stellarator. It is shown that a shift-scale mixture of several (three-four processes, depending on macroscopic characteristics of the plasma) normal processes adequately describes the PDFs of flux increments. The number of mixture components and the weight of each component are determined using the EM algorithm The method of sliding separation of mixtures is applied to separate between the dynamic and diffusive components of volatility and to trace their temporal evolution. With the above methods of analysis, some characteristic L-2M regimes have been examined. It is shown that turbulent particle transport in the edge plasma occurs by both the ballistic and diffusive mechanisms, and their contributions are roughly estimated.

This work was supported by the Dynasty Foundation, and the Russian Foundation for Basic Research (project nos. 07-02-00455).

References

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

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

[3] V.Yu. Korolev, N.N. Skvortsova. In “The systems and means of informatics.” Ed. I.A. Sokolov. IPI RAN. (2005) 126 (In Russian).

[4] N.N. Skvortsova, V.Yu. Korolev, et al. Plasma Physics Reports. **31** (2005) 57.

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

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

[7] G.S. Voronov, E.V. Voronova, D.K. Akulina et al. Plasma Phys. Contr. Fusion. **48** (2006) A303.