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THE LOG-POISSON MODEL OF EDGE PLASMA TURBULENCE IN FUSION DEVICES

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Turbulence is a natural state of the plasma in fusion devices. Its statistical properties are essential for the understanding of the confinement in fusion devices. Experimental investigations of the plasma turbulence have shown a deviation (due to a strong intermittency) from the Kolmogorov's K41 model [1]. The fluctuations observed in stellarators, tokamaks and linear machines (see, e.g., [2]) are self-similar. It supposes some universal self-similarity properties of edge magnetized plasmas. They are responsible for the memory effects and a large-scale correlation in the space and the time due to intermittent structures. It leads to substantial losses above the ones predicted by a classic diffusive scaling. There are numerous experimental observations of the magnetized plasma turbulence, they share a lot of features of a neutral fluid turbulence (see, e.g., [3]) including many scales, cascades, a strong mixing, anomalous scalings and so on. In spite of a lot of experimental data obtained in fusion devices, our understanding of the turbulence and diffusive transport in magnetized plasmas is still rather limited. In this paper, we focus on a quantitative estimation of scaling laws in frame of the log-Poisson model of intermittent turbulence.

The signals from Langmuir probes (density fluctuations n_e(t) deduced from the ion saturation current I_{sat}(t) and cross-field particle transport from I_{sat}(t) and poloidal electric field) were used. On T-10 tokamak [2] (major radius of 1.5 m, minor radius of 0.4 m, plasma current I_p=200÷220 kA, magnetic field B=2.2÷2.4 T), multi-pine probe was composed from the tungsten tips with 0.5 mm in a diameter and 3 mm in a length. A rail limiter was positioned at 30 cm producing scrape-off layer (SOL) at r>30 cm. A natural shear of a poloidal rotation (shear layer) is observed at r≈29.5 cm in the vicinity of the last closed magnetic flux surface (LCFS). No evidence of a probe-induced plasma perturbation on the fluctuation has been observed in these experiments. The data were collected with a sampling rate of 1.0 MHz during 0.5 seconds at a steady state of repetitive ohmic discharges with no large-scale MHD activity.

The classical approach for an exploration of turbulence features is an analysis of statistical moments (structure functions) $S_q(\tau)= \langle|X(t+\tau)-X(t)|^q\rangle$, where $\langle\ldots\rangle$- means an ensemble average, X(t) is a time-dependent signal. The structure function technique is equivalent to the detailed investigation of the probability distribution function of the turbulent fluctuation. The Kolmogorov theory K41 of isotropic turbulence infers Gaussian statistics for fluctuations. It predicts the structure function scaling $S_q(\tau)\sim\tau^{\zeta(q)}$, $\zeta(q)=q/3$, in the inertial range. Intermittent turbulence is characterized by a non-linear function ζ(q). We treat experimental scalings in the frame of the log-Poisson turbulence model [4,5] predicted a scaling:

$$\zeta(q) = (1-\Delta)\frac{q}{3} + \frac{\Delta}{1-\beta}\left[1-\beta^{\frac{q}{3}}\right] \qquad (1).$$

It is based on the hypotheses of a "hidden symmetry" and a hierarchical structure of the moments of the energy dissipation. The logarithm of energy dissipation obeys the Poisson statistics (so-called the log-Poisson statistics) characterized by special scale-covariance properties. A hidden symmetry can be interpreted as a generalized scale covariance and β is a characteristic of the intermittency of the energy dissipation (β=1 for non-intermittent fully developed turbulence). The most intermittent dissipative structures have a divergent scaling $\varepsilon_l^\infty \sim l^{-\Delta}$, as $l \to 0$, where Δ is a parameter depended on the dimension of the dissipative structures. In an isotropic 3D turbulence Δ= β=2/3 (She-Leveque standard log-Poisson model) which is obtained if the most dissipative structures are filaments.

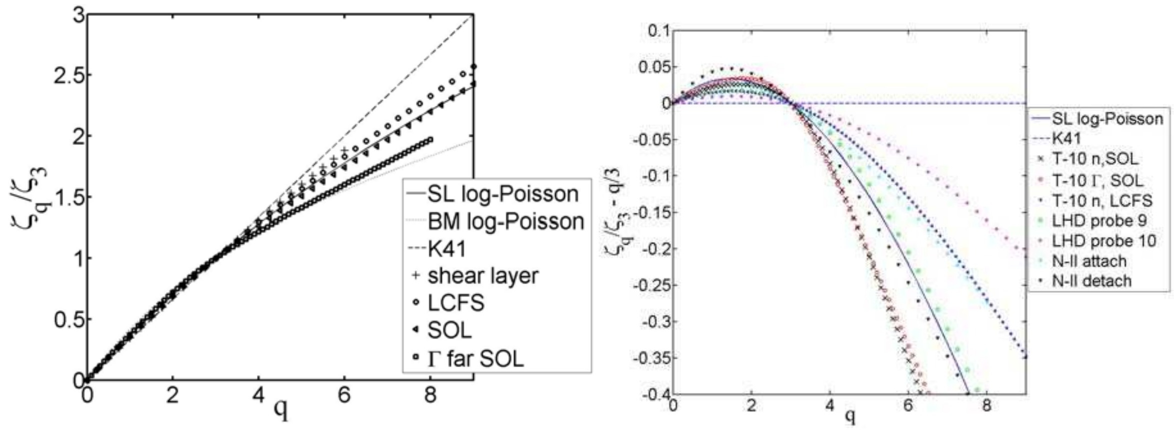

Fig.1. (a) Structure function scaling vs. order q. Kolmogorov K41 (a dashed line) and She-Leveque (SL) standard log-Poisson (a solid line) models, T-10 tokamak and (b) a departure of the scaling from the K41 for different fusion devices [2].

We used a property of extended self-similarity (ESS) [6] to estimate ζ(*q*) from experimental signals by the wavelet transform modulus maxima method (WTMM) [7]. The scaling of the third-order moment can be deduced analytically (ζ(3) =1), therefore scaling of ζ(*q*)/ ζ(3) can be analyzed in experiments to improve the precision of the scaling estimation. In fig.1a, the scalings ζ(*q*)/ ζ(3) are shown in the same plot with the scalings predicted by the

K41 and the standard log-Poisson models. The scalings are anomalously deviated from the K41 scaling. Similar scalings observed in the SOL of different fusion devices [2], fig.1b. Each experimental scaling could be fitted by (1) with adjusted parameters Δ and β, fig 2. A solving of non-linear least-squares problem of fitting to (1) gives indexes in the range Δ =0.15 ÷ 0.8, β=0.25 ÷0.7 in different fusion devices [2].

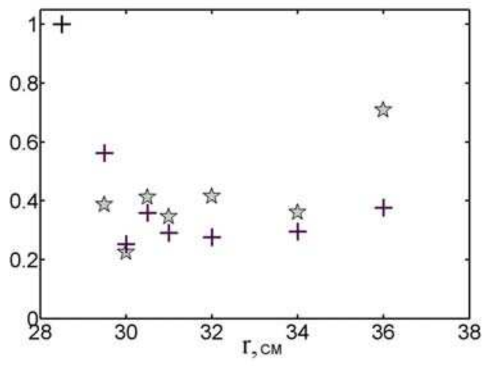

Fig.2. Parameters Δ (stars) and β (+) for T-10 SOL turbulence.

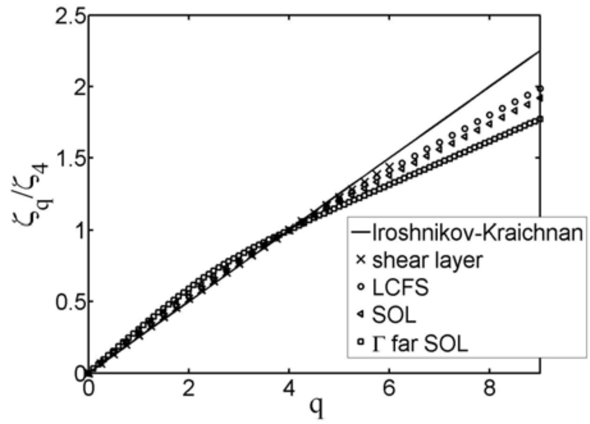

Fig.3 Scaling of T-10 SOL turbulence in frame of Iroshniov-Kraichnan phenomenology. Iroshnikov-Kraichnan scaling q/4 (line).

Traditional approach to the turbulence in magnetized plasmas is to account for the Iroshnikov-Kraichnan (IK) phenomenology (see [8]). To test IK phenomenology in SOL tokamak plasma we plot in fig.3 relative exponents $\zeta(q)/\zeta(4)$ compared to the IK scaling $q/4$. The data from the SOL are deviated strongly from the IK scaling. It can be interpreted that the IK phenomenology is not available for a treatment of the SOL plasma turbulence.

Biskamp and Mueller approach [8] considers two-dimensional dissipative structures and predicts a scaling:

$$\zeta(q)=q/g^2+1-(1/g)^{q/g} \qquad (2)\ .$$

We proposed [10] an anomalous scaling that captures one-dimensional filament-like dissipative structures:

$$\varsigma_f(q)=\frac{q}{g_f^{\ 2}}+2\left(1-\left(\frac{1+g_f}{2g_f}\right)^{\frac{q}{g_f}}\right) \qquad (3)\ .$$

The quantities $g/3$ and $g_f/3$ express the cascade strength relative to the isotropic K41 case. In fig. 5 we plot parameters g and g_f for T-10 SOL. Parameters g_f is closer to a level of 3 supposing that scaling (3) available for an intermittency description in SOL plasma. It assumes one-dimension filament-like dissipative structures.

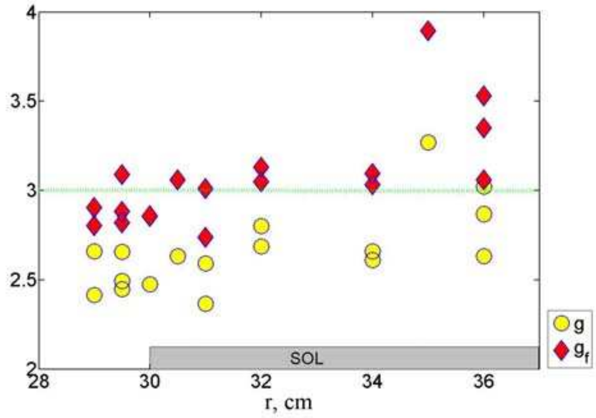

Fig.4. Scaling parameters g and g_f of scalings (2) and (3) for intermittent turbulence in T-10 SOL

The log-Poisson model could be used to estimate a transport scaling based on the self-similarity indexes β and Δ (1). The diffusion scaling depends on the structure function scaling as $D \propto \tau^{K(-1)}$, $K(q)=q-\zeta(3q)$, (see [10]). A displacement of particles across a magnetic field with time τ is scaled as $\langle \delta x^2 \rangle \propto D\tau \propto \tau^{\alpha}$ with an exponent $\alpha \propto 1+ K(-1)=1.4 \div 1.87$ [10]. It supposes superdiffusion.

In conclusion, scalings of the structure functions strongly deviate from the Kolmogorov's K41 theory prediction. Experimental scalings are described in the frame of the log-Poisson model. One-dimension filament structures are likely the most intermittent dissipative structures. The similar behaviour of the scalings has been observed in the edge of fusion devices with different magnetic topology and heating. It supports a view that the edge plasma turbulence displays universality. By using self-similarity indexes, transport scaling indexes are estimated. The results of our study improve our understanding of intermittent turbulence in the edge of fusion devices.

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