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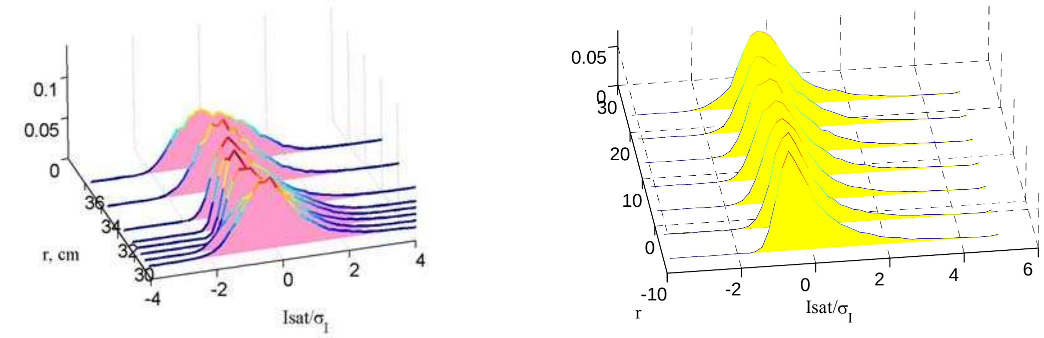
The Characterization of Edge Plasma Intermittency in T-10 and TCABR Tokamaks

V.P. Budaev[1], S.A. Grashin[1], G.S. Kirnev[1], B.V. Kuteev[1],
Yu.K. Kuznetsov[2], Z.O. Guimarães-Filho[2], I.C. Nascimento[2], I. L. Caldas[2],
R.M.O. Galvão[2,3], M.P. Gryaznevich[4], G. Van Oost[5]
[1]*Nuclear Fusion Institute, RRC Kurchatov Institute, 123182, Kurchatov Sq.1, Moscow, Russia*
[2]*Institute of Physics, University of São Paulo, 05508-900, São Paulo, Brazil*
[3]*Brazilian Center for Research in Physics, 22290-180, Rio de Janeiro, Brazil*
[4]*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, UK*
[5]*Ghent University, Ghent, Belgium*

Turbulence is the natural state of plasma in fusion devices [1]. Its statistical properties are essential for the understanding of the confinement in tokamak. The fluctuations observed in tokamaks, stellarators and linear machines (see, e.g., [2]) are self-similar, suggesting the universality of self-similarity properties at the edge of magnetized plasmas. The self-similarity properties of the edge turbulence are responsible for the memory effect and large-scale correlation in space and time due to intermittent structures. Intermittent transport resulting from coherent structures such as vortices, zonal flows, streamers, and blobs, leads to substantial losses above the ones predicted by classic diffusive scaling [1]. Experimental investigations of plasma turbulence have highlighted deviation (due to the strong intermittency) from Kolmogorov's K41 model prediction [3]. There are numerous experimental observations of magnetized plasma turbulence that share a lot of features of neutral fluid turbulence (see [4]) including many scales, cascades, strong mixing, anomalous scaling and so on. Despite the large amount of experimental data that has been obtained in fusion devices, our understanding of the turbulence and diffusive transport process in magnetized plasmas is still rather limited. In this work, we focus on quantitative estimate of self-similarity and intermittency of edge plasma turbulence in T-10 and in TCABR tokamaks.

The signals from Langmuir probes (density fluctuation n_e deduced from the ion saturation current I_{sat}) were analyzed. 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_t = 2.2-2.4 T, rail limiter at 30 cm), the multi-pine probe was composed of tungsten tips with 0.5 mm in diameter and 3 mm in length, > 30 cm. In the vicinity of the last closed magnetic flux surface (LCFS), a natural shear of poloidal rotation (shear layer) at $r \approx 29.5$ cm was observed. No evidence of probe-induced plasma perturbation on the fluctuation has been observed in these experiments. On TCABR tokamak [5] (major radius of 0.61 m, minor radius of 0.18 m, plasma current I_p = 100 kA, magnetic field B_t = 1.07 T, circular graphite limiter at 18 cm), the rake-probe was composed of tungsten tips with 0.6 mm in diameter and 5 mm in length. The data were collected with a sampling rate of 1.0 MHz during 0.5 s (on T-10) and 0.1 s (on TCABR) during steady state of repetitive ohmic discharges with no MHD activity. The signals demonstrate strong intermittency. The typical burst time is in the range ~50-200 μs [2]. Fourier spectra and correlation function [2] do not allow to investigate in detail the whole properties of the intermittency observed at the edge plasma. A probabilistic approach is more effective to describe plasma turbulence. The probability distribution function (PDF) varies with minor radius (Fig. 1) demonstrating evolution from strong non-gaussianity in the far SOL towards close to the Gaussian in the vicinity of the LCFS. It is difficult to describe the shape of the PDF using the theory of probability.



(a) (b)

Fig. 1. The PDF vs. radius in the SOL of T-10(a) and TCABR(b)

Usually, intermittency in turbulence is studied by looking at the scaling of structure functions (see, e.g., [6]) of different orders versus space or time separation (Eulerian statistics). The q-th order structure velocity functions are defined as the ensemble averages of the velocity difference across a separation in time τ, $\delta\upsilon_\tau = \upsilon(t+\tau)-\upsilon(t)$, $S_q(\tau) \equiv <|\delta\upsilon_\tau|^q>$. We estimate the structure functions from time-dependent signals of the ion saturation current $I_{sat}(t)$ (related to local plasma density fluctuations) by ensemble averaging, $S_q(\tau)=<(I_{sat}(t+\tau) - I_{sat}(t))^q>$, for order of moments q =1-8. An inertial range corresponding to a linear behavior of the structure functions $S_q(\tau)$ in the log-log plot is typically observed only on the limited range of time scales of 1-1.5 orders. At the same time, the plot of the high-order structure functions vs. third-order structure function demonstrates a linear behaviour for the extended range over three decades of time scales. It is interpreted as the extended self-similarity (ESS).

Kolmogorov's K41 theory is based on the assumption that at each point of velocity field there exist the same scaling behavior $\delta\upsilon_l \sim l^{1/3}$, which gives the energy spectrum $E_k \sim k^{-5/3}$. Nonlinear behavior of scaling $\zeta(q)$ of structure function $S_q(l) \sim l^{\zeta(q)}$ is a direct consequence of the existing of spatial fluctuations in the local regularity (so-called intermittency, [7], [8]) of the velocity field, $\delta\upsilon_l \sim l^{h(l)}$. Intermittency is considered in geometrical framework [4] invoking fractal formalism: for each h, there exists structures with the fractal dimension D(h) of the set for which $\delta\upsilon_l \sim l^h$. Considering the structure function scaling one can bridge the singularity spectrum $D(h)$ and the set of scaling exponents $\zeta(q)$ (see [2]). A nonlinear $\zeta(q)$ spectrum is equivalent to the assumption that there exist more then a single scaling exponent h. Singularity spectrum $D(h)$ and scaling $\zeta(q)$ are computed from experimental time-signals using wavelet technique [2]. Typical shape of $D(h)$ is convex as shown in Fig. 2. For all data D(h) is broadened indicating multifractality property of the process. For monofractal process (e.g., Kolmogorov's K41), the singularity spectrum collapsees into a point. From the analogy between the multifractal formalism and statistical thermodynamics, $\zeta(q)$ plays the role of a thermodynamical potential, which intrinsically contains only some degenerate information about the Hamiltonian of the problem, i.e., the underlying cascading process. Therefore experimental estimation of the $\zeta(q)$ spectrum may provide a test for various cascade models of turbulence. Width of the singularity spectrum D(h), a difference h_{max} - h_{min} can be used to characterize the multifractality degree. Such parameter is plotted vs. normalized radius in Fig. 3. This width has similar radial dependence in both tokamaks decreasing in the regions where turbulent eddies are likely destroyed by shear of poloidal velocity and by other mechanisms leaded to a decorrelation effect. The radial profile versus normalized radius is similar in both tokamaks. It means likely that the whole SOL region is responsible for the intermittent property of the edge tokamak.

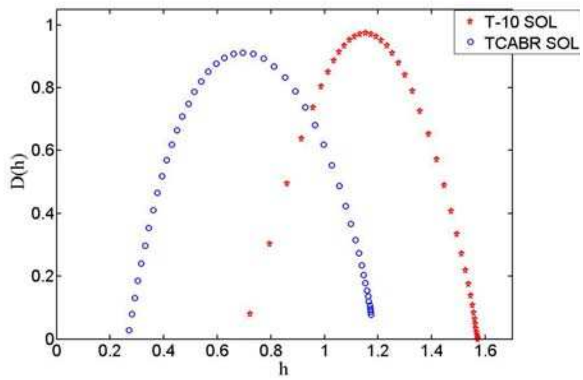


Fig.2. The singularity spectra D(h) depending on the Hoelder exponent h

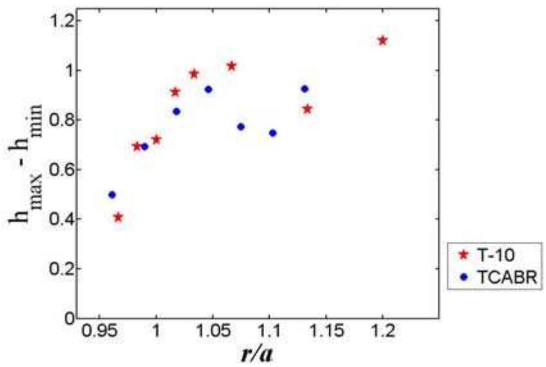


Fig.3. Width h_{max}-h_{min} of singularity spectrum D(h) (as a multifractality degree) vs. normalized radius

In neutral fluid turbulence, Benzi et al [9] showed that scaling properties of the velocity increments can be extended up to dissipative range: $S_q(l)$ has a power-law dependence on $S_3(l)$, $S_q(l) \sim S_3(l)^{\zeta(q)/\zeta(3)}$, over a range substantially longer (for long ranges of scale $l \geq 5\eta$, η is Kolmogorov's scale) than the scaling range obtained by plotting $S_q(l)$ as a function of l. This behavior holds even at moderate Reynolds number. It was named the Extended Self-Similarity (ESS). We observed extended self-similarity for all turbulence signals from T-10 and TCABR. From the Navier-Stokes equations $\zeta(3)=1$, $S_3(l) =< \delta\upsilon(l)^3 >\sim l$, the scaling of $\zeta(q)/\zeta(3)$ can be analyzed to improve the precision of the scaling estimation by using the ESS plotting S_q as a function of S_3. A theoretical treatment [11] indicates that the ESS originates from some statistical hidden symmetry (generalized scale covariance) of Navier-Stokes equations. Logarithm of energy dissipation obeys Poisson statistics (so-called log-Poisson statistics, the log-Poisson model) that is characterized by special scale-covariance properties. The ESS corresponds to considering the scaling in a turbulent cascade not with respect to the usual distance, but with respect to an effective scale defined by the third order moment of the velocity field. The property of the ESS is involved in the log-Poisson model. The direct and inverse cascades may be considered in frame of the log-Poisson model. The scaling properties in the turbulence should not be investigated as a function of l, the resolution scale, but rather as a function of the generalized scale $\xi(l,\eta)$. They can be interpreted as the natural generalization of scale dilation in systems in which the cut-off scale is always relevant. In Fig.4, the scalings $\zeta(q)/\zeta(3)$ are shown in the same plot with scalings predicted by Kolmogorov's K41 and the log-Poisson models. Scalings clearly deviate from the K41 scaling. The non-linear behavior of the scaling shows that plasma fluctuations possess multifractal statistics. Similar behaviour is observed in turbulent boundary layers of magnetized plasma in fusion devices with different magnetic topology and space plasma in magnetosheath of Earth [12].

In conclusion, the statistical properties of intermittent turbulence show a striking empirical similarity in the SOL of T-10 and TCABR tokamaks. The experimental results indicate that plasma fluctuations possess multifractal statistics. The scaling of the structure function deviates strongly from prediction of Kolmogorov's K41 theory. They are close to the log-Poisson model. The findings of our analysis can be interpreted as the whole SOL region being likely to be responsible for intermittent property of edge plasma turbulence. The fact that similar behavior of scaling is observed at edge of tokamaks with different sizes supports the view that edge plasma turbulence displays an universal property. The result of this study improves our understanding of intermittent turbulence in edge region of a tokamak.

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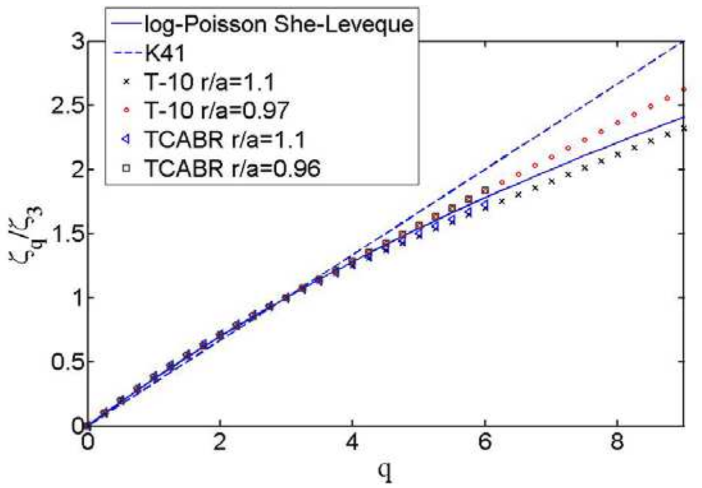

Fig. 4. Anomalous scaling of structure function ζ_q/ζ_3..Dashed line - K41 prediction (q/3); solid line - prediction of the log-Poisson She-Leveque model.

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