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Multifractal analysis of tokamak plasma turbulence in biasing experiments

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Introduction

The anomalous transport of particles in tokamaks is attached to the turbulent character of high-temperature plasmas. Usually, different types and scales of turbulences exist in plasma simultaneously [1, 2]. Large-scale intermittent bursts are followed by the formation of coherent structures which are the result of self-organization. These structures, which can transfer much of energy, have strong correlations and non-Gaussian probability density function (pdf). The multifractal statistics of the plasma turbulence has been detected as an evidence of rich scaling property of self-similarity and long-range correlations. Multifractality is a notation related to the generalization of the classical definition of self-similarity and underlying cascading process. We have used the wavelet technique for the multifractal analysis [2]. It is considered that the scaling behavior of the structure function M(q,l) of time series $X(t)$ (e.g. density or floating potential signal) with increments $\delta_l X=X(t+l) - X(t)$, is M$(q,l) = \langle|\delta_l X|\rangle^q \sim l^{\tau(q)}$. The multifractal process posseses a nonlinear scaling and is described by a convex function $\tau(q) = qH - \lambda^2 q^2$. Exponent λ^2, as a parameter of the deviation from Gaussianity, is used as a notation and a level of multifractality ($\lambda^2 = 0$ for monofractal, e.g. fractional Brownian motion).

Reduction of fluctuations and turbulent transport by means of externally driven electric field (biasing) has been systematically investigating on the Castor tokamak (R = 0.4 m, a = 0.85 m) [3, 4]. The multifractal analysis enables to demonstrate clearly the turbulent properties of the plasma during biasing. Influence of biasing parameters (electrode voltage and radial position) is shown here including the creation of the low multifractality region in the edge plasma of CASTOR.

Experimental setup

The mushroom-type electrode is movable on a shot-to-shot basis in the range from r_B = 95 mm to r_B = 40 mm, see Fig. 1. Both positive and negative biasing voltages were applied. The data for the analysis were collected from the fast (1μs) diagnostic tools: the rake probe, the bolometers and the microwave reflectometers. The rake probe is an array of 16 Langmuire probes with 2.5 mm spacing. The tips measure the radial profile of either the floating potential Ufl or the saturation current Isat. The bolometry on Castor consists of two systems of wideband detectors which pick-up chordal radiation of vertical and horizontal profiles [5]. The reflectometer consists of two homodyne 35 GHz systems with O- and X-mode antenna horns positioned by 80° along the torus [6, 7]. For an O–mode polarized beam the cutoff lies close to the plasma centre depending on the plasma density only. For an X–mode polarized beam the cutoff lies close to the plasma edge depending on the plasma density and magnetic field.

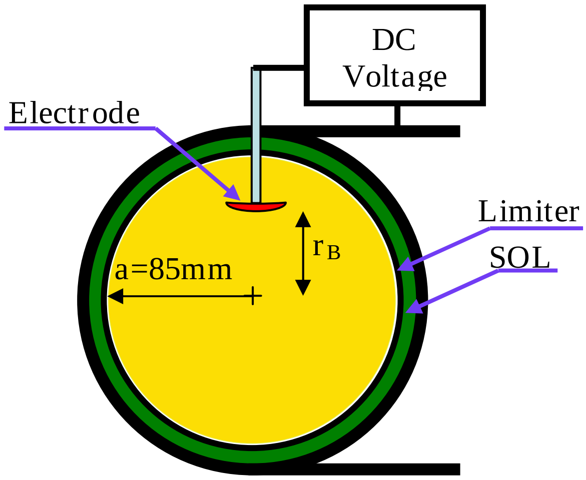

Fig. 1.

Experimental results

The biasing current was growing with the biasing voltage and the electrode depth in the plasma. The current at the positive voltage was more than one order higher than at negative voltage. The dominant manifestation of improved confinement at the positive biasing is the plasma electron density boost. If some confinement thresholds are exceeded (approximitelly at voltages above +250 V and -350 V), a strong plasma instabilities occur [8]. To characterize the multifractal process and long-range correlation we have used the multifractality exponent λ^2 defined above. The time lag of the multifractal analysis was chosen 3 ms – sufficiently shorter than the biasing duration of 5 ms but enough to obtain credible results. There are two types of graphs shown here. The first is the time development of the multifractality exponent during the shot (the time is here in fact the centre of the 3 ms lag). The influence of the biasing on turbulent fractal structures is seen in these graphs. The other type of graphs was made from shot-to-shot series when either biasing voltage or electrode radial position were scaned. The dependence of multifractality exponent on the biasing parameters is shown in these graphs. In contour plots the red colour means high values of the multifractality exponent and the blue represents the low ones.

The diagnostics used in the experiments take the fluctuating signals by different ways and from different parts of the plasma. The rake probe measures properties of the SOL plasma with a very good radial localization. In Fig. 2, there is dependance of Isat and Ufl on the biasing voltage. Position of the electrode was 75 mm. At the positive biasing it is seen, that the low multifractality of both Isat (propotional the plasma density) and Ufl between the electrode and tokamak wall demonstrates the supressing of turbulences around the limiter. A little bit increased multifractality of Isat towards the plasma core at the positive biasing is probably due to the increased plasma flow in this direction as a result of better confinement. A very weak supression of Isat towards the plasma core at the negative biasing is noticable as well as the plasma instability at the highest negative voltage.

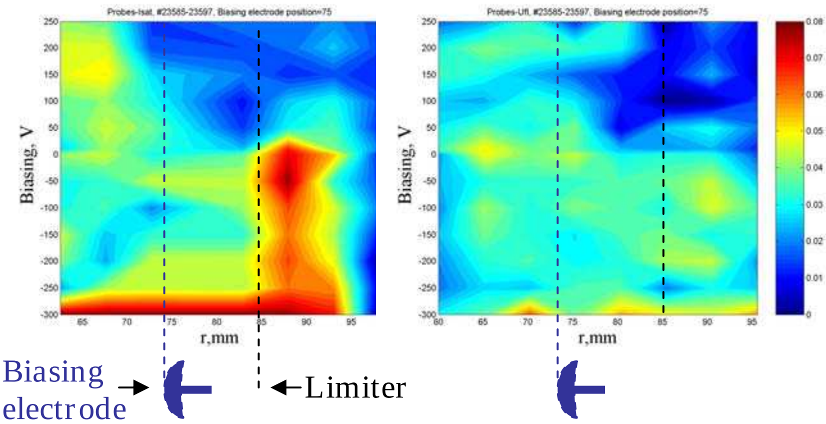

Fig. 2 Rake probe / bias. voltage, Isat (left) and Ufl (right)

The bolometry as a chord-integrated diagnostics is not usually used for the fluctuation analysis because the localization of the dominant supply is uncertain. Yet, the comparison of the relative level between chords gives interesting information over the whole plasma profile. In Fig. 3, there is the time evolution of the multifractality exponent of the vertical bolometry system. During the positive biasing period (13 – 18 ms), it is evident that multifractality of the whole plasma is lower. This may be interpreted as a decreasing of long-range correlation.

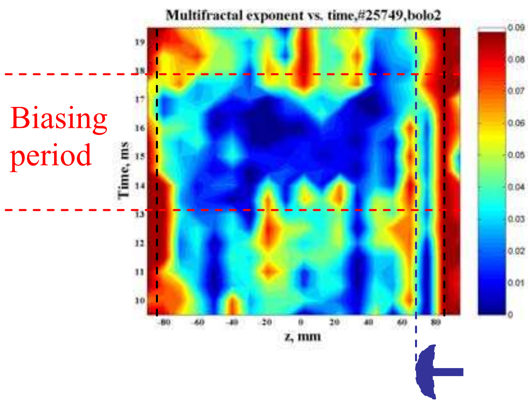

Fig. 3 Bolometry, time evolution, bias. voltage +250 V, r_B=70 mm

The reflectometry can inspect both plasma periphery and core depending on the chosen frequency and polarization. The localization at small tokamaks is rather pure because of relatively wide microwave beam. In Fig. 4, there is the time evolution of the

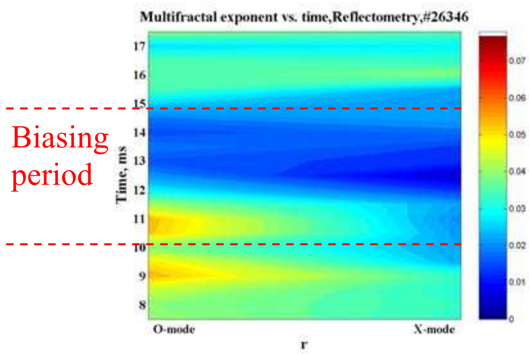

Fig. 4 Reflectometry, time evolution, bias. voltage +180 V, r_B=70 mm

multifractality exponent of O-mode (left side of the graph, core plasma) and X-mode (right side of the graph, the edge plasma). Influence during the biasing (10 – 15 ms) is apparent. In Fig.5, there is a scan of the electrode radial position at biasing voltage +180 V. At r_B = 60 – 65 mm the O-mode signal had significantly higher multifractality in oposition to the X-mode.

Summary

Multifractal analysis is one of the statistical aproaches to study the plasma turbulences. It complements “traditional” methods (correlation functions, spectral analysis, pdf analysis etc.) and illustrates self-similarity property and long-range correlation of the plasma turbulence. The multifractal property of the Castor plasma is manifestation of the existence of coherent turbulent structures. The ability of the biasing to suppress these turbulences was verified. By various diagnostic tools, the influence of the biasing was demonstrated in both edge and core plasma. The positive biasing has strong effect on the multifractality suppression in the area between the electrode and the tokamak wall which can be interpreted as a lost of long range correlation. The negative biasing had generally very weak effect – it is known that it depens on the electrode material [8]. The big difference of the multifractality between the edge and core plasma was typical for the bolometric data. In reflectometric data the X-mode response to the positive biasing was stronger than the O-mode one. It seems that used electrode with the sprayed tungsten coating was most effective at the radius around 65 mm.

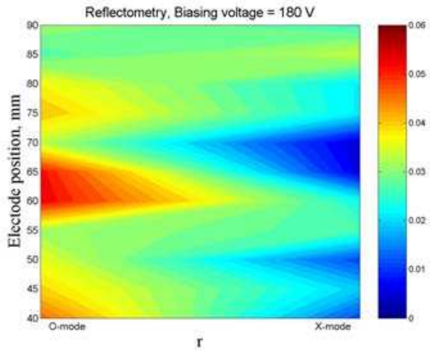

Fig. 5 Reflectometry, r_B=40–90 mm, bias. voltage +180 V

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