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A Comparison of Intermittency in Neutral Fluids and Magnetically Confined Plasmas

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Intermittency in the scrape-off layer (SOL) region of magnetically confined plasma and velocity intermittency of helium gas are compared from the aspect of global and local multifractal properties. The analysis reveals subtle differences in the global aspect between turbulent fluctuations of confined plasmas and neutral fluid as well as differences among magnetically confined devices themselves especially with respect to energy cascade mechanisms in the corresponding systems. Analysis of local multifractal characteristics reveals even more pronounced differences.

Keywords: turbulence, plasma edge turbulence, intermittency, multifractal

1 Introduction

Velocity field statistics are an essential tool and the major source of information in neutral fluid turbulence. The theory of local velocity field structure of incompressible hydrodynamic turbulence, introduced by Kolmogorov in 1941 and usually denoted as K41, is based on the assumptions of homogeneity, isotropy, and the existence of an inertial range. The inertial range in the kinetic energy spectrum is a range in wave number, $k\tilde{}1/l$ where l is the separation length between two points (eddie size), which is located between typical large scales and small dissipative scales and is therefore independent of external drive or output dissipation. The spectrum in the inertial range does not depend on viscosity and is characterized by the power law dependence of the form $E(k) = C_K \langle\epsilon\rangle^{-2/3} k^{-5/3}$, where C_K is the Kolmogorov constant and $\langle\epsilon\rangle$ is the average rate of energy dissipation per unit mass.

The influence of the external magnetic field on turbulent flow of an incompressible fluid leads to much more complicated behavior which modifies turbulent motions. Even more dramatic effects are observed in the case of compressible fluids. Hence, significant differences exist between turbulent flows of neutral fluids and confined plasma. In particular, nonlinearities in plasma turbulence are more numerous having different spectral cascade directions in addition to the $E \times B$ nonlinearity, leading to more complex fluctuating characteristics. One of the most important differences is that time and space measurements lead to different information on the structure of turbulence [1]. Driving mechanisms and damping characteristics are reflected in the temporal aspect of fluctuations while measurements at different spatial locations provide information on spatial structures for various scale lengths. For the case of neutral fluids, time records of turbulent velocity at a single spatial location obtained with the use of a hot-wire or laser Doppler anemometer, are usually interpreted via Taylor's frozen flow hypotheses, as one-dimensional spatial cuts through the flow. However, this approach that generates information about temporal measurements from spatial ones and vice versa, is not applicable in the case of plasma turbulence. Specifically, turbulence in the case of neutral fluids is generated at a certain spatial position and carried by the flow past the probe location so that recordings at different times at a fixed location are equivalent to simultaneous recordings at different spatial locations along the flow. However, in plasma turbulence due to specific nature of nonlinearities, turbulence is created and damped at the same spatial position where measurements are taken so that spatial and temporal informations are interwoven. For the same reason the inertial range [2], may exist only locally in space or in time, and the extent of this range changes along the temporal scale as well as along space, for example along poloidal direction.

In this study we present differences between these two types of turbulences from the aspect of their global and local multifractal properties. In particular we are interested in the intermittency phenomenon in the two cases, and in the case of confined plasma we study the intermittency in the scrape-off layer (SOL) and also compare three different confinement regimes, the L-mode, dithering H-mode and the H-mode. The quantity of interest in the case of neutral fluid turbulence is one-component fluid velocity while in the plasma case it is the ion saturation current fluctuations of recipro-

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cating Langmuir probe installed at the edge of magnetic confinement devices. We study intermittency properties of the MAST spherical tokamak (L-mode, dithering H-mode and H-mode) and the Tore Supra tokamak with limiter configuration (L-mode). Intermittency of liquid helium recorded in a specially designed cryogenic apparatus [3], is considered in the case of neutral fluid turbulence. The specific design of the apparatus enabled access to a wide range of Reynolds numbers at constant geometry.

The important issue in the multifractal spectra analysis of intermittent plasma turbulence is the choice of relevant measure. In neutral fluid turbulence, in addition to velocity, enstrophy and energy dissipation represent quantities of particular interest although they cannot be constructed in their entirety from a single point velocity time-series. To overcome the difficulty surrogate dissipation

$$\epsilon_{surr}(x) = C\nu \left(\frac{\partial v_x}{\partial x}\right)^2, \tag{1}$$

where C is a constant, sometimes taken equal to 15 is usually used . Using Taylor's frozen flow hypothesis which is naturally justified in neutral fluid turbulence, expression (1) becomes

$$\epsilon_{surr}(t) \sim \nu \left(\frac{\partial v_x}{\partial t}\right)^2. \tag{2}$$

In the plasma case, based on the arguments explained in detail in [4], we devise two measures yielding identical multifractal spectra

$$\epsilon = c \cdot \frac{\left(\left|n\frac{dn}{dt}\right| - \left\langle\left|n\frac{dn}{dt}\right|\right\rangle\right)^2}{\left\langle\left(\left|n\frac{dn}{dt}\right| - \left\langle\left|n\frac{dn}{dt}\right|\right\rangle\right)^2\right\rangle}, \tag{3}$$

and

$$\epsilon = c \cdot \frac{\left(\left(n\frac{dn}{dt}\right)^2 - \left\langle\left(n\frac{dn}{dt}\right)^2\right\rangle\right)^2}{\left\langle\left(\left(n\frac{dn}{dt}\right)^2 - \left\langle\left(n\frac{dn}{dt}\right)^2\right\rangle\right)^2\right\rangle}, \tag{4}$$

where c is a constant.

2 Large Deviation Spectra

The datasets analyzed here consist of measurements of the ion saturation current (I_{SAT}) performed by the moveable Langmuir probe located at the outboard midplane on MAST device [5], at a sampling rate of 1 MHz. Discharge 6861 is high density L-mode plasma and 9031 represents a dithering H-mode with heating power close to the threshold for L-H transition with intermittent high frequency edge localized modes (ELMs), while 5738 is an H-mode with ELMs

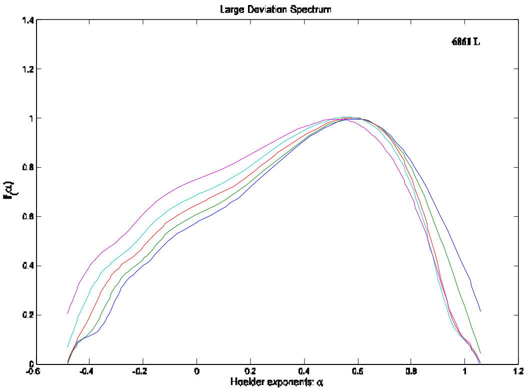

Fig. 1 Fig. 1 LDS of 6861 L-mode of the MAST device

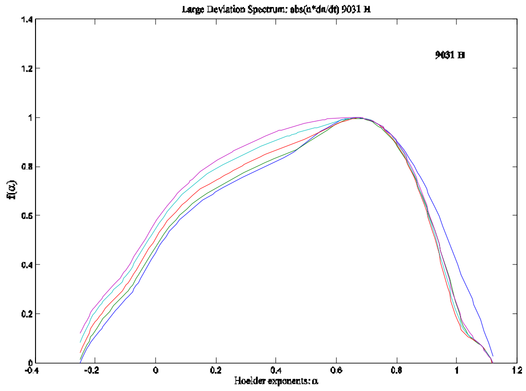

Fig. 2 Fig. 2 LDS of 9031 L-mode of the MAST device

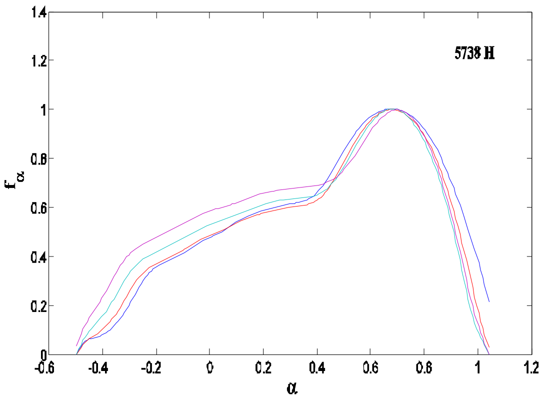

Fig. 3 LDS of the H-mode of the MAST device

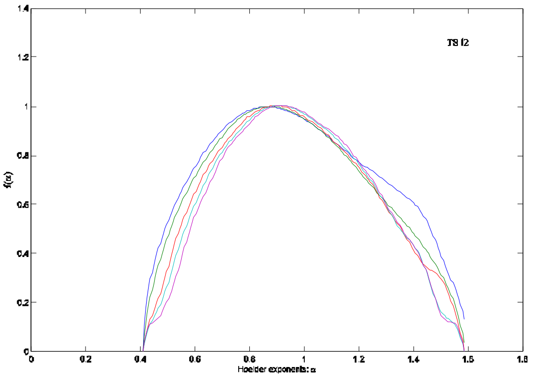

Fig. 4 LDS of the L-mode of Torre Supra.

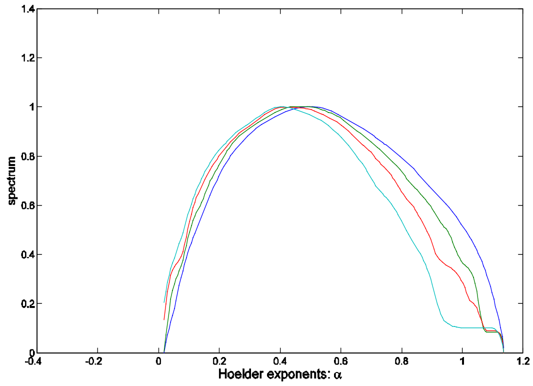

Fig. 5 LDS for the neutral fluid turbulence, Re=328.

at 400 Hz. The corresponding Large Deviation Spectra (LDS) are presented in Figs. 1, 2 and 3. LDS [6] reveal differences between each confinement regime as well as between the two devices. The most striking feature of the MAST spectra (Figs. 1,2 and 3) is their departure from a pure bell-shape and concavity and is a good example where LDS provide more information than Legendre spectra, which are strictly concave although they may be asymmetrical. Their shape reflects existence of several multiplicative laws underlying the cascade processes so that there is a lumping of measures whose supports are disjoint. It is evident that the L-mode of MAST has more complex multifractal structure in the sense that there are more α-values at which the irregularity of the spectrum occurs (i.e. more phase changes) than in the case of L/H-mode or H-mode of MAST. The most striking feature in the Tore Supra L-mode spectra is nonexistence or very mild lumping of measures with no superposition of measures. In Fig. 5 we show the LDS for the case of neutral fluid turbulence.The LDS reveal multifractal similarity of neutral fluid turbulence and the Tore Supra L-mode, while a striking difference with respect to the MAST turbulence.

3 Local Turbulence properties

Local properties of turbulence are modeled with fractal Brownian motion [7]. Since fBm is a self-similar process it provides unique parameter values for H and σ in the restricted temporal domain in which turbulent signal is self-similar (the Hurst exponent H determines the correlation distance for the increments of the process and the quantity σ^2 quantifies the absolute level of correlations). For this purpose a range of frequencies over which the power law

$$P_{B_H} \propto \sigma^2 \left|\omega\right|^{-(2H+1)} . \tag{5}$$

pertains is detected and then the parameters from the same expression are evaluated. Wavelet scale spectra are used for this purpose because they provide time-scale decomposition that is compliant with power law processes, independent of their stationarity. Parameters of the power-law model, σ and H are functions of time and model is applied only over a subset of scales known as the inertial range. Usually multifractal data, besides variations in σ and H, show variations in the inertial range itself.

The main steps in estimation of local turbulence properties are the following:

1. Partitioning of data into segments of equal temporal extent within which turbulent signal is approximately stationary. A special filtering procedure is devised in order to remove dependence of the estimated parameters on segmentation.

2. Wavelet decomposition of the data and evaluation of the scale spectra within each segment.

3. Determination of the inertial range of the scale spectra and evaluation of the power law parameters based on the fBm model. The turbulent data corresponding to the inertial range are assumed to be statistically well represented by fractal Brownian motion. Local turbulence parameters σ and H are therefore determined from the scale spectra corresponding to the inertial range. The extent of the inertial range varies from segment to segment and is rarely equal to the segment size. Since inertial range exists over specific scales (or equivalently over corresponding time range) evaluated parameters have local character.

In Figs.6 and 7 we present temporal variations of the Hurst exponent for the MAST L-mode and the L-mode of Tore Supra. The same quantities are presented in Fig. 8 for the case of neutral fluid turbulence.

A brief comparison of Figs. 6, 7 and 8 shows that there are considerable differences in values of the local Hurst exponent and variance at unit lag for the two magnetic confinement devices and for the neutral fluid

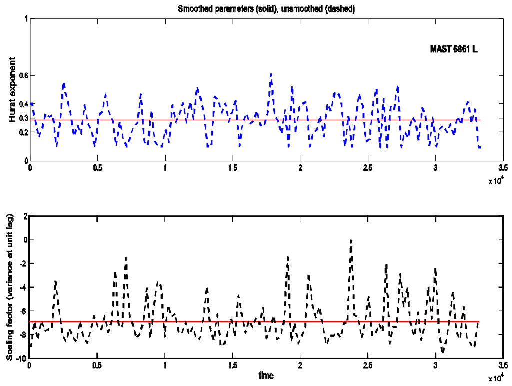

Fig. 6 Parameters of the fBm model, Hurst exponent and the variance at unit lag for the L-mode in MAST. Note random variations of each parameter reflecting multifractal character of the plasma density fluctuations.

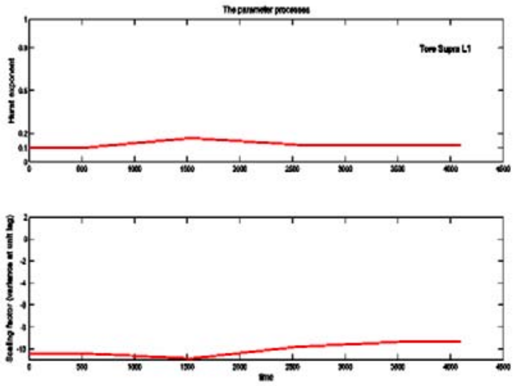

Fig. 7 Parameters of the fBm model, Hurst exponent and the variance at unit lag for the L-mode of Torre Supra. Note very small variations of both quantity.

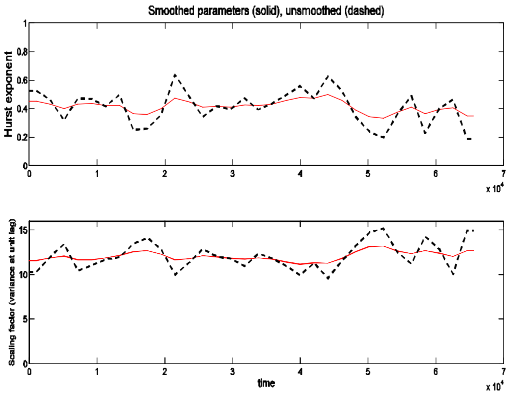

Fig. 8 Parameters of the fBm model, Hurst exponent and the variance at unit lag for the neutral fluid case, Re=328.

turbulence. Namely, these local fractal quantities exhibit purely stochastic variation for the case of MAST L-mode while for the case of the L-mode of Tore Supra these variations are very small and deterministic-like. On the other hand stochastic variations are evident in the case of neutral fluid turbulence indicating its multifractal character, however the values of H and σ are very much different in two cases (and in all cases presented here). Hence, in spite of similarity of large-deviation spectra for the L-mode of Tore Supra and the neutral fluid turbulence, their local (multi)fractal characteristics are very different. Briefly summarizing the multifractal features of each type of turbulence, several characteristics are immediately evident:

1. Large deviation spectra reveal considerable differences between different regimes and different devices of magnetically confined plasma. These disparities indicate different cascade mechanisms of energy transfer among coherent structures.

2. Local features of turbulence in all cases exhibit unique variability and range of values with the possibility of multifractional behavior (not purely multifractal) in certain devices instead of the multifractal properties which dominate both the magnetically confined plasma turbulence and neutral fluid turbulence.

3. Neutral fluid turbulence has very well defined inertial range which is well captured in the wavelet scale spectra irrespective of the segmentation of the turbulent signal. On the other hand scale spectra reveal that in the plasma case inertial ranges are hard to detect and to a large extent depend on the segmentation of the signal. These properties pertain to all regimes in spite of particular features of each. Moreover the extent of inertial ranges is different for all cases considered.

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