LONG-RANGE CORRELATIONS AND UNIVERSALITY IN PLASMA EDGE TURBULENCE

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Abstract

Long-range correlations in turbulence, associated with self-similarity of the fluctuations, are a signature of transport by avalanches as occurs in Self-Organized Critical systems. We have investigated long-range correlations in plasma edge fluctuations in a variety of fusion devices, using the Rescaled-Range and similar techniques. We find that the degree of self-similarity in confining devices is high and similar between devices, and much different from non-confining devices where it is low. Likewise, we find that turbulent spectra show a high degree of similarity between devices. These findings strongly indicate the existence of universality in plasma edge (ohmic) turbulence, and demonstrate its non-Gaussian character.

1. INTRODUCTION

A characteristic property of self-organized critical (SOC) systems [1] is that these systems relax through transport events of all sizes (transport by avalanches). This transport mechanism translates into long-range time and space correlations for the fluctuating quantities. In this situation, both the correlation functions and the probability distribution function (PDF) of fluxes display algebraic "tails", i.e. at long time lags they decay as a power of the lag rather than exponentially. SOC dynamics hold the promise of explaining some of the properties of transport in magnetically confined plasmas [2,3]. In particular, a SOC model could explain the existence of (a) critical gradients (the observed "profile consistency"), (b) long-range correlations (superdiffusive transport and heat/cold pulses) and (c) Bohm scaling of transport due to long correlation lengths. Thus, clearly, techniques for accurately quantifying the asymptotic behavior of the correlation functions and PDFs are needed. In this paper, we review some of these techniques and their application to plasma fluctuations. In developing and applying these techniques, we have often used the running sandpile model [1,4,5] as a guidance.

2. LONG-RANGE CORRELATIONS

A feature of the turbulence induced fluxes at the plasma edge is that they are bursty. A PDF of these fluxes (Fig. 1) shows a long tail with 10% of the largest flux events being responsible for 50% of the transport [6-8]. These sparse but strong flux events are what Mandelbrot dubbed the "Noah effect" [9], and are associated with algebraic "tails" of the PDF of the integrated fluxes, which is a characteristic property of turbulent transport having long-range correlations.

In the case of plasma fluctuations, we have to specify what we mean by long-range time and radial correlations. The standard decorrelation time and radial correlation length are determined by the $1/e$ width of the corresponding correlation function (Fig. 2). The decorrelation time, τ_c, is basically an eddy turn-over time and at the plasma edge of an ohmic plasma it is of the order of several microseconds. We can also expect τ_c to be of the order of the inverse linear growth rate of the dominant microinstability. The radial correlation length, l_c, is of the order of the eddy size and at the plasma edge it is about 1 cm. Theoretically it is expected to be of the order of the ion Larmor radius, ρ_i. The long-range correlations investigated here are over times which are longer than τ_c and lengths several times longer than l_c.

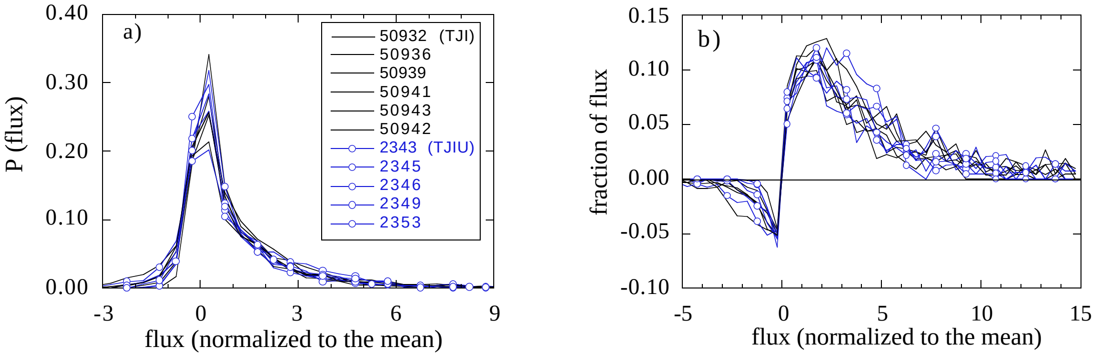

Fig. 1. Distribution function of the particle flux (a) and fraction of transport versus the amplitude of the flux (b) in the TJ-I and TJ-IU devices.

3. METHODS AND RESULTS

To investigate the properties of these long-range correlations, we have analyzed plasma density and electrostatic potential fluctuations using several techniques, such as the rescaled range (R/S) analysis [9,10] and the scaled window variance (SWV) technique [11-13]. These methods determine the Hurst exponent [14], *H*, which is directly related to the fractal dimension of the time series and to the decay exponent of the algebraic "tail" of the autocorrelation function (ACF). It can be shown that these techniques are (mathematically) equivalent to analyzing a double integral of the ACF rather than the ACF itself, which strongly reduces the problems due to noise that hinders the direct determination of the decay of the ACF at large lags [15]. In effect, the R/S and SWV techniques are rather unsensitive to perturbations by uncorrelated noise [12,15] and are therefore very suitable for the analysis of experimental data.

The analysis of electrostatic plasma edge fluctuations has been done on data from a broad range of magnetic configurations. We have analyzed data from three stellarators, TJ-IU [16], Wendelstein 7 Advanced Stellarator (W7-AS) [17], and the Advanced Toroidal Facility (ATF) [18], in the Electron Cyclotron heated regime. We have also analyzed fluctuation data records from two tokamaks, TJ-I [19] and the Joint European Torus (JET) [20], in the ohmically heated regime, as well as a reversed field pinch, the Reversed Field Experiment (RFX) [21]. This analysis has led to values of *H* that concentrated mostly between about 0.62 and 0.75 within the plasma (Fig. 3), although the spread in

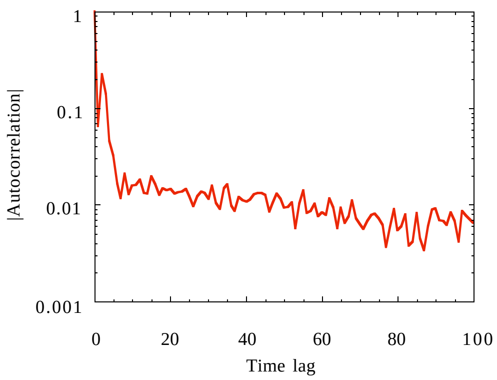

Fig. 2. Absolute value of the auto-correlation function showing a peak at small time-lag that is due to fluctuations and a tail coresponding to long-range time correlations.

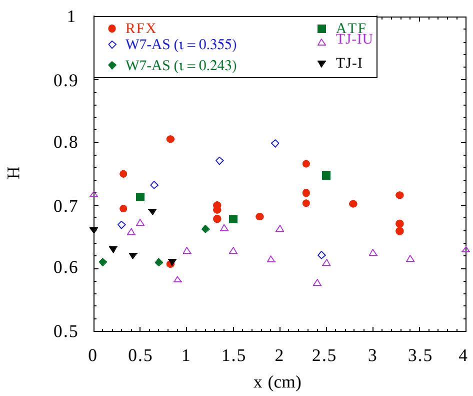

Fig. 3. Determination of the self-similarity parameter H in 6 different configurations (5 devices). x is the distance inside the velocity shear layer in cm.

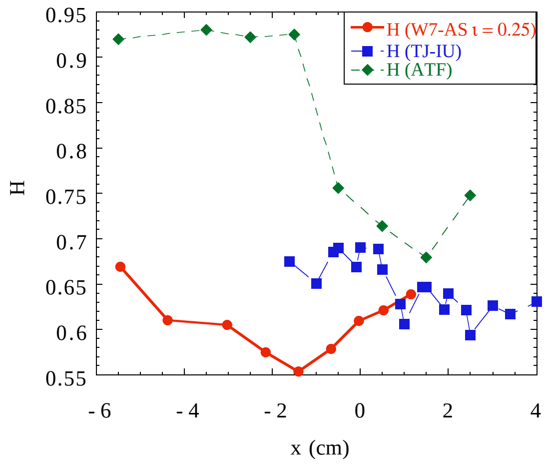

Fig. 4. Hurst exponent as a function of the minor radius for three stellarator configurations. The zero position corresponds to the plasma edge velocity shear layer and positive x is inside.

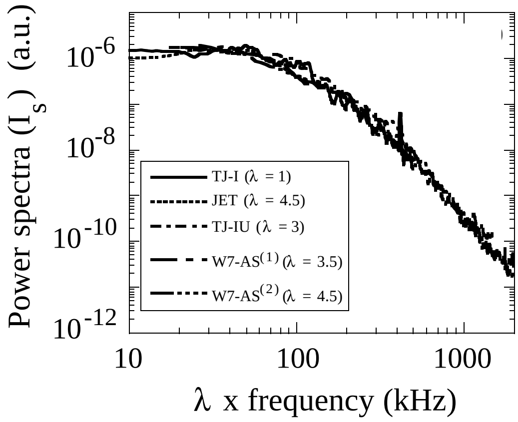

Fig. 5. Rescaled plasma edge ion saturation current fluctuation spectra for different devices.

values outside the plasma was much larger (e.g. Fig. 4) [22]. These results are evidence of the existence of long-range correlations in the plasma edge turbulence in all those confinement devices. They also demonstrate the self-similar nature of the plasma edge fluctuations. The narrow range of variation of the self-similarity parameter, *H*, points to a universal character of the plasma edge turbulence dynamics. We have also compared these results to the ones obtained from the Thorello device [23], a toroidal device without rotational transform and with relatively cold plasmas (T_e, T_i < 1 eV). In the latter case, the Hurst exponent is about 0.5. This result indicates that long range correlations are only present in fluctuations measured in confined plasmas.

The narrow range of values of *H* found in different plasma confinement devices is also an indication of the similarity of the low frequency range of the fluctuation spectra in those experiments. However, the similarity of spectra goes beyond the low frequency range. Using a rescaling transformation of the spectra that accounts for the unknown influence of machine size or other geometry-related parameters on the spectral distribution, the similarity of the plasma edge electrostatic fluctuation spectra over the whole frequency range can be demonstrated [23]. The fluctuation spectra have been rescaled using the ad-hoc expression $P(\omega) = g(\lambda\omega) / \beta$, where λ and β are parameters to be determined for each machine and operational conditions. As in the case of the sand pile, if the function g exists, the spectra belong to a universal class. The value of λ then indicates how frequency ranges between different machines must be compared. In carrying out the spectral comparison between several devices, we have taken spectra in the velocity shear layer, at the zero-velocity point, in order to avoid Doppler shift effects. With this precaution, indeed a function g can be found for the spectra studied as is shown in Fig. 5.

Some of the techniques used in the detection of the long-range time dependence can be extended to the detection of cross correlations for long time lags [15]. This extension allows the determination of radial (spatial) correlations such as the ones expected from avalanche transport. The application of these cross-analysis techniques to experimental data is in progress.

4. DISCUSSION

The observed existence of long-range time correlations and radial correlations at large time lags is expected from SOC dynamical behavior, but it is not the unique signature of SOC dynamics and may have different causes. Therefore, we can only state that the results of the analysis presented here are consistent with SOC dynamics.

On the other hand, these observations and analyses provide us with two important facts about the plasma turbulence in magnetically confined plasmas that go beyond the validity of the SOC concept. First, the electrostatic fluctuations clearly do not verify Gaussian statistics over times longer than an eddy turn-over time, and any turbulence model pretending to describe plasma edge turbulence should also exhibit this feature. Second, we find that the fluctuations exhibit a universal character that is largely independent of magnetic configuration details, at least in the plasma edge, and for ohmic and ohmic-like regimes.

The existence of long-range radial correlations in the fluxes suggests the possibility of a superdiffusive component in the plasma transport [24,25]. The existence of such a superdiffusive component has been suggested on the basis of magnetic fluctuation induced transport [26]. Similar results can be obtained in a SOC model. Therefore, superdiffusivity may result from both magnetic and electrostatic induced plasma transport. A superdiffusive component would be consistent with Bohm type scaling observed in tokamak plasma transport. A direct experimental determination of such a superdiffusive component is a challenging future goal.

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