Self-similarity of the HL-1M Tokamak Plasma Edge Turbulence

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Abstract. Some statistics techniques are applied to test avalanche-like transport dynamics in HL-1M plasma edge fluctuations. It is found that the radial particle flux is on average outward and exhibits a bursty behavior; the Hurst parameter is high, ranging from 0.67 to 0.81; the probability distribution function (PDF) of laminar times between successive bursts has a power law distribution, but the PDF of the wavelet coefficients on a τ is not a Gaussian distribution.

1. Introduction

Anomalous transport is generally considered to result from the turbulent fluctuations caused by various instabilities existing in confined plasmas. Some characteristics of the turbulent transport suggest that the self-organized criticality (SOC) dynamic [1] may play an important role in plasma transport in magnetically confined plasmas [2,3]. These characteristics are: (a) the existence of critical gradients (the observed “profile consistency”), (b) the existence of transport events that do not obey diffusive equations and (c) Bohm scaling of transport due to long correlation lengths. An important characteristic of SOC systems is that these systems relax through avalanche-like events on all space scales allowed by the system size. This transport mechanism translates into long-range time and space correlations for the fluctuating quantities. To investigate the properties of these long-range correlations, some statistics techniques are applied to the turbulence-induced particle flux measured at the plasma edge region of the HL-1M tokamak with a triple Langmuir probe, sampled at 1 MHz with a 12-bit digitizer. The HL-1M plasma is circular in cross-section with major radius $R = 1.02$ m and minor radius $a = 0.26$ m. The experimental data are from the measurements in the ohmic heating regime of hydrogen discharges during the period of the plasma current plateau.

2. Results

The time-resolved normalized turbulent flux Γ_n, measured in the proximity of the velocity shear layer which is located around r = 25 cm [4], and the PDF of the Γ_n, are shown in Fig. 1. Γ_n is the normalized turbulent flux defined as $\Gamma_n \equiv \Gamma(t)/<\Gamma(t)>$ [5], where $<\bullet>$ denotes the time averaged value of particle flux. A feature of the turbulence induced fluxes at the HL-1M plasma edge is that they are bursty and mostly radially outwards, i.e., a large group of the flux is carried outwards by a few large events. By integrating the transport events in magnitude, the results show that nearly 14% of the events are responsible for 52% of the outward transport flux.

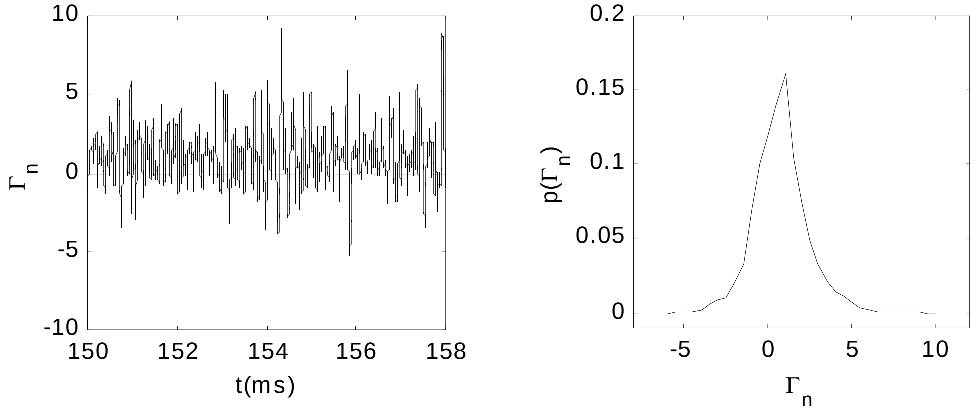

Fig. 1. Left: Time evolution of the turbulent particle flux $\Gamma_n(t)$ at the plasma edge in the HL-1M device in the proximity of the velocity shear layer location. Right: The PDF of the particle flux $\Gamma_n(t)$.

The high "tail" of the PDF of the integrated fluxes is a characteristic property of turbulent transport having long-range correlations. We use the rescaled range (R/S) analysis technique to investigate the properties of these long-range correlations. This method determines the Hurst exponent, H, which is directly related to the fractal dimension of the time series. H = 0.5 for a random signal, and 0.5 < H < 1 for a time series having long-range time correlations. The radial profile of H for turbulent particle flux measured at the HL-1M plasma edge, as shown in Fig. 2(a), was measured on a shot-to-shot basis at each radial position under identical discharge conditions.

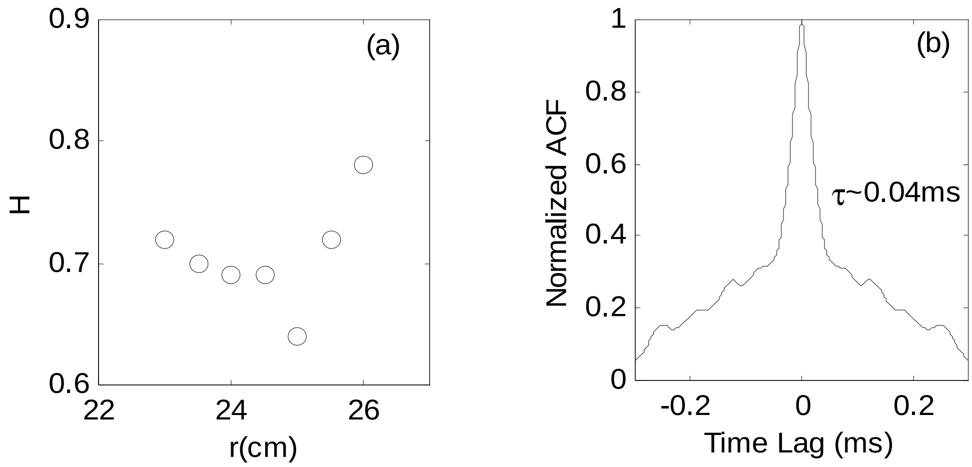

Fig. 2. Left: The radial profile of the Hurst parameter. Right: Autocorrelation function of ion saturation current fluctuation measured at the zero-velocity position, with a peak at small time lag due to fluctuations and a tail corresponding to long-range time correlations.

The high value of the H parameter, in the range 0.64 to 0.78, indicates the existence of long-range correlations and self-similarity, and is closely related to the decay of the autocorrelation function (ACF) at large lags, as shown in Fig. 2(b). The typical decorrelation time is about 0.04 ms, and H is valued in the time range 0.5 ms to 8 ms. The radial profile of the H value has a minimum near the V_p ~ 0 position, in accordance with the effect of reducing

H by shear flow predicted by SOC models [6,7]. The observed evidence of self-similarity and long-range correlations at the HL-1M plasma edge is consistent with SOC, but it is not the unique signature of SOC dynamics and other mechanisms might also generate this behavior. Thus other statistical analyses should be applied to test the consistency between experimental results and predictions of SOC models.

We follow the method of the PDF analysis for the burst behavior of fluctuations reported in Refs [8,9], where the authors reported that the PDF of laminar times between successive bursts has a power law distribution $p(t_L) \sim t_L^{-\alpha}$, with α = (1.79 $\pm$ 0.02) for flux Γ [9] and α = (1.93 $\pm$ 0.06) for the ion saturation current signal [8]. Such a PDF of laminar times is consistent with predictions of a running sandpile SOC model with high input rate J_{in}, but inconsistent with predictions of the BTW SOC model, which behaves as the case of the running sandpile model in the limit of vanishing J_{in}. We applied the same statistical analysis to particle flux Γ measured at the HL-1M plasma edge. The PDF exhibits a power law decay in a range of time scales from 6 to 50 μs, with α = 1.72, as shown in Fig. 3.

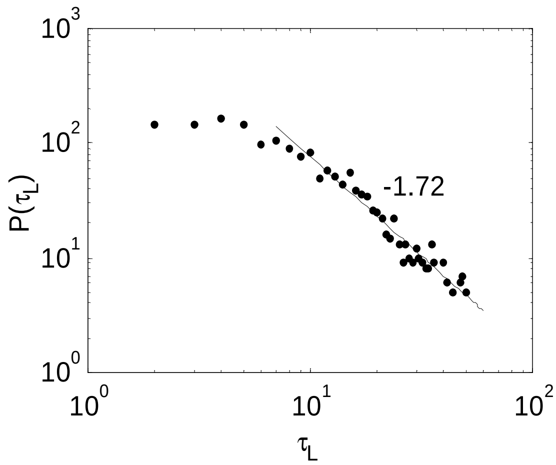

Fig. 3. The PDF of the laminar times $p(t_L)$ between successive bursts in flux fluctuations. The line presents a power law fitting.

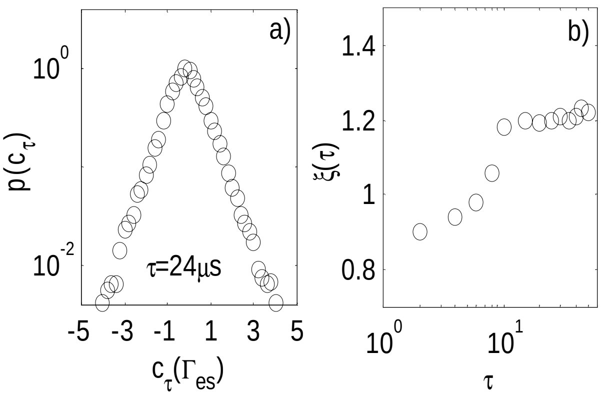

Fig. 4. (a) PDF of flux fluctuations at time scale τ = 24 μs; (b) the parameter $\varsigma(\tau)$ calculated from stretched exponential fit as a function of time scale τ.

It is well known that the scaling properties of a fluctuation are the same as those of its wavelet decomposition coefficients, i.e., the wavelet coefficients $C(t,\tau)$ have the same scaling properties of Γ fluctuations with time scale τ. At each time scale the coefficients $C(t,\tau)$ are normalized by subtracting the average and dividing by the standard deviation as $c_\tau(t) = [C(t,\tau) - < C(t,\tau) >]/\sigma_\tau$ [9]; then the probability distribution function of the coefficients $p(c_\tau)$ is obtained. An example of normalized PDF for one time scale (τ =

$24\,\mu s$) is shown in Fig. 4(a). It appears that the PDF is not a Gaussian distribution. The dependence of the PDFs with τ can be recovered by fitting the data by a three parameter stretched exponential function $P(X) \sim A\exp(-b\,|\,X\,|^{\varsigma})$ [9], and the scaling behavior of the PDF is derived from the scaling of the parameter $\varsigma(\tau)$ with τ. As shown in Fig. 4(b), $\varsigma(\tau)$ exhibits two different behaviors. In the range $2 \le \tau \le 10\,\mu s$, $\varsigma(\tau)$ is not constant and therefore the particle flux fluctuations are not self-similar, while in the range $10 \le \tau \le 50\,\mu s$, $\varsigma(\tau)$ is almost constant, with a value of 1.21. Yet in the latter case, the PDF and $\varsigma(\tau)$ are not consistent with those predicted by the running sandpile SOC model with high input rate. For this kind SOC model, the same PDF analysis shows that the PDF is close to a Gaussian distribution and $\varsigma(\tau)$ is almost constant, with a value of 1.9 [9].

3. Conclusions

New statistical analyses show that the experimental results of HL-1M experiments are not consistent with some predictions of SOC models. The PDF of the laminar times was found to be consistent with that predicted by the running sandpile SOC model with high J_{in}, but the experimental scaling properties of the particle flux fluctuations appear inconsistent with the predictions of the SOC model.

Acknowledgements

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