Search of Self-Organized Criticality Processes in Magnetically Confined Plasmas: Hints from the Reversed Field Pinch Configuration

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In order to test the self-organized criticality (SOC) paradigm in transport processes, a novel technique has been applied for the first time to plasmas confined in reversed field pinch configuration. This technique consists of an analysis of the probability distribution function of the times between bursts in density fluctuations measured by microwave reflectometry and electrostatic probes. The same analysis has also been applied to intermittent events sorted out from the Gaussian background. In both cases, the experimental results disagree with the predictions for a SOC system.

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Plasmas for thermonuclear fusion research magnetically confined in toroidal devices are dominated by anomalous transport driven by plasma turbulence [1]. Plasma parameters such as temperature, density, and plasma potential exhibit large fluctuations with bursty behavior as well as the associated particle and energy fluxes [2]. These turbulence properties joined with the observation of plasma profile critical gradients and resilience [3] have been observed [4] to be consistent with the phenomenology of self-organized criticality (SOC) systems, as described in [5] [referred to as the "Bak-Tang-Wiesenfeld (BTW) model" in the following]. This conjecture has motivated the search in magnetically confined plasmas of avalanchelike processes, which rule the dynamics of SOC systems. Since these processes are hidden in the plasma turbulence phenomenology, the search thus far has focused on those properties of plasma parameter fluctuations which are considered the salient ones for avalanchelike processes, i.e., bursty behavior, power law decay in frequency spectra, and long range and long distance correlations. Concerning this last property, an extensive analysis, based on the computation of the Hurst coefficient [6] in several fusion experiments with different magnetic configurations and spanning a wide range of plasma parameters, has shown indeed that plasma turbulence exhibits long range time correlations. This behavior was observed to be consistent with BTW model predictions and, owing to the large number of experiments investigated, was observed to be proof in favor of SOC processes in fusion devices. On the other hand, it is worth mentioning that some authors [7] also reported long range correlation for non-SOC systems. More recently experimental evidence of avalanchelike processes has been claimed in the tokamak DIII-D from the analysis of electron cyclotron emission data in the plasma core [8] which also exhibited, among the other properties consistent with the SOC system, evidence of radial propagation of impulsive events (bursts).

In this paper we report the results of an analysis of density fluctuations focused to identify avalanchelike processes in the magnetically confined plasma obtained in the RFX experiment. The analysis was performed by considering a property of turbulence so far not considered in fusion experiments, i.e., the time interval between bursts (referred to as "laminar time" in the following). The analysis, applied to astrophysical plasmas and described in Ref. [9] (referred to as "B99" in the following), is based on the statistical distribution of the laminar times. The bursts have been identified by an algorithm similar to that applied in Ref. [9]. In order to improve the accuracy of the results, the analysis has also been performed on the laminar times between intermittent events, as properly identified by an algorithm [10,11] which sorts out these events from the Gaussian fluctuation background. The outcome of the analysis indicates that the experimental findings in RFX are not consistent with the predictions for a SOC system as described in the BTW model.

The RFX experiment is a toroidal device with minor radius $a = 0.457$ m and major radius $R = 2$ m, aimed to confine plasma in reversed field pinch (RFP) configuration for controlled thermonuclear fusion research. The results in this paper refer to an experimental campaign with toroidal plasma current $I = 350$ kA and average plasma density in the range from 1.5 to 3.5×10^{19} m^{-3}. The energy and particle confinement times were of the order of 1 ms and the discharges typically lasted approximately 80 ms. For the purpose of this paper, some relevant properties of the plasma turbulence in RFX are worth mentioning: fluctuations of plasma parameters exhibit a bursty behavior and, as reported in [6], evidence of long range time correlations in the low frequency range. Most of the particle transport at the edge is carried by electrostatic turbulence [12]; electrostatic transport can be reduced by acting on cross phase between plasma potential and density fluctuations, as recently demonstrated by an edge biasing experiment

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[13]. An interesting feature, which reinforces the conjecture of some common underlying process, is that all these properties are similar to the properties of turbulence and related transport observed in other magnetic configurations (tokamaks and stellarators). The data considered in this paper refer to the density fluctuations, which are related to the particle transport, measured by means of microwave reflectometry and by a set of Langmuir probes. It is worth noticing that the two techniques are complementary in the sense that the reflectometer provides high frequency resolution, while probes provide high spatial resolution.

The reflectometer [14] was configured to launch the microwave radiation in O mode, between 37.35 and 38.55 GHz (critical electron density $n_c = (1.73-1.84) \times 10^{19}\ \mathrm{m}^{-3}$). In the subsequent analysis we have considered those discharges having the cutoff layer between 2 and 4 cm inside the plasma; the diameter of the reflecting surface seen by the reflectometer has been estimated to be 10–12 cm. The microwave source sweeps the frequency range in 250 ns, with a repetition rate of 4 MHz. The homodyne signal from the reflectometer was sampled at 250 MHz and the modulation rate was high enough to consider the plasma frozen during the measurement. Thus the amplitude and the phase can be obtained from the measured signal without ambiguities. The reflected power seen by the reflectometer, which has been estimated by averaging the signal amplitude for each sweep, exhibits strong variations (see Fig. 1). The variation of the cutoff position inferred from the phase signal, and confirmed by other diagnostics, cannot account for the amplitude modulation observed. This phenomenon has already been found in other fusion experiments and has been attributed to two-dimensional distortions of the cutoff layer induced by density fluctuations: when the fluctuation level increases a significant fraction of the radiation is scattered (incoherent reflection) diminishing the signal collected by the antenna at the specular reflection incidence (coherent reflection) [15,16]. In this paper we used the abrupt signal decrease in the reflected power to identify bursts of intense density fluctuation in front of the reflectometer.

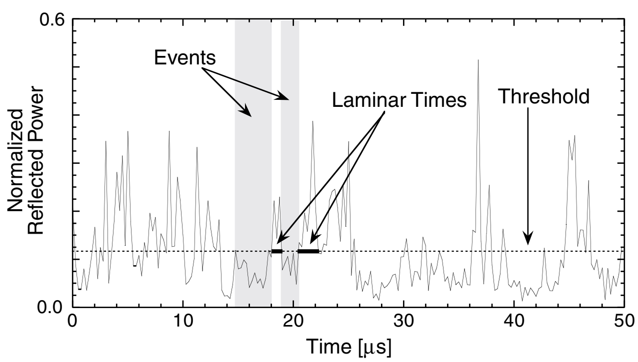

FIG. 1. A sample of the normalized reflected power signal collected by microwave reflectometer, along with some turbulent events identified from signal drops. The threshold is obtained using the algorithm described in the text.

Local measurements of density fluctuations were obtained from the ion saturation current density, j_s, measured by a Langmuir probe inserted in the edge region of the plasma. The data reported in this paper refer to the central pin of a five-pin triple probe described in [17]. Since the electron temperature fluctuation level is half that of the density fluctuations [18] in the region explored, the density fluctuations have been approximated by the ion saturation current fluctuations. The bandwidth of the measuring circuit was $\sim$400 kHz and the signals were digitally sampled at 1 MHz.

Since the analysis is based on the probability density function (PDF) of the laminar times between impulsive events, the method used to identify them constitutes a key issue of the procedure. For this reason we have applied two methods: the first one aimed to identify the bursts from the turbulent background by a threshold criterion and the second one aimed to sort out the intermittent events from the Gaussian background by a wavelet analysis.

The first method, adopted to identify the events within a signal $\psi_0(t)$, requires one to choose a threshold $\mathbf{S}$ to discriminate between bursts and normal fluctuations. To improve the noise immunity, the recursive algorithm for the threshold identification proposed in B99 [9] has been modified in the following way: a time series is obtained by setting $\psi_{i+1}(t) = \psi_i(t)$ if $\psi_i(t) < \overline{\psi_i(t)} + 2\sigma_i$ and $\psi_{i+1}(t) = \overline{\psi_i(t)} + 2\sigma_i$ if $\psi_i(t) \geq \overline{\psi_i(t)} + 2\sigma_i$, where $\overline{\psi_i(t)}$ is the average and σ_i is the standard deviation of $\psi_i(t)$. The convergence process starts iteration from the original signal ($i = 0$) and stops when the condition $|\overline{\psi_n} - \overline{\psi_{n-1}}| < \varepsilon$ is satisfied for an appropriate value of ε. The threshold $\mathbf{S}$ is chosen to be $\mathbf{S} = \overline{\psi_n(t)}$.

The second method is aimed at identifying intermittent events, i.e., those events which, for a given time scale, differ from a Gaussian distribution. Indeed it has already been reported that in RFX the PDFs of both electrostatic [19] and magnetic [20] fluctuations are not scale invariant and at small scale differ from Gaussian PDF, developing higher tails. To study the statistical properties of fluctuations a continuous wavelet transform has been applied to the signal $\psi_0(t)$:

$$C(t, \tau) = \frac{1}{\sqrt{\tau}} \int \psi_0(r) W\left(\frac{r - t}{\tau}\right) dr\,. \qquad (1)$$

The wavelet coefficients $C(t, \tau)$, which are a measure of typical fluctuations of signal $\delta\psi_\tau = \psi_0(t + \tau) - \psi_0(t)$, give a decomposition of $\psi_0(t)$ at the scale τ as a function of the parameter t.

In ordinary fluid the deviations of PDF's from Gaussianity are due to the generation of spatial structures (eddies) at all scales [10] which can be represented as coherent localized events within a sea of Gaussian turbulence.

For each time scale to identify the time occurrence of strong events due to PDF tails, we used a method introduced by Farge [10] and also developed by Onorato *et al.* [11] based on the so-called *local intermittency measure*

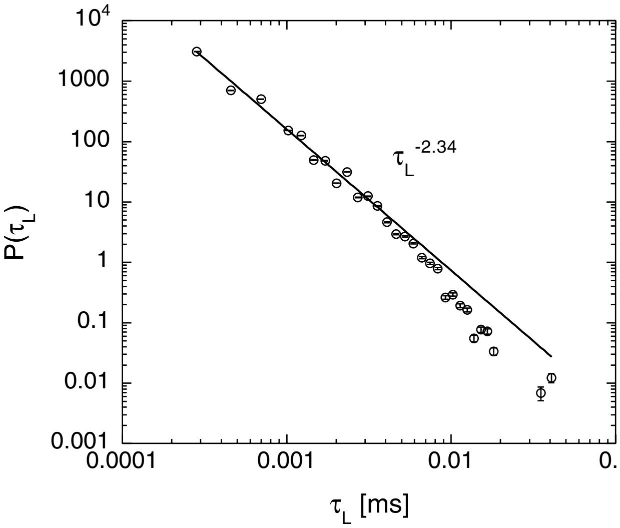

FIG. 2. Probability density of the laminar times $P(\tau_L)$ between subsequent drops of reflected signals. The straight line represents a weighted power law fit.

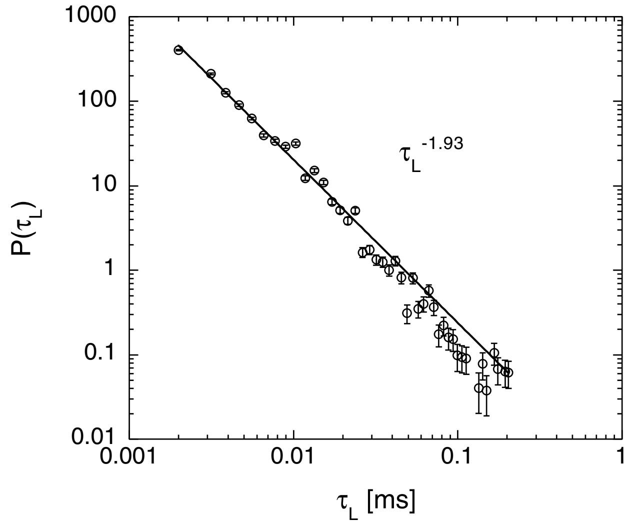

FIG. 3. Probability density of the laminar times $P(\tau_L)$ between subsequent events in the ion saturation current signal. The straight line represents a weighted power law fit.

(LIM) $L(t, \tau) = C(t, \tau)^2 / \overline{C(t, \tau)^2}$ (overbar indicates time average at the scale τ). This method, described in [11], allows us to identify the temporal occurrence of intermittent events, i.e., of non-Gaussian strong fluctuations at a given scale. The first method, named "modified B99" in the following, has been applied to all data, while the LIM method has been applied only to the Langmuir probe data.

An example of a reflected power signal is shown in Fig. 1 along with the laminar times identified by the modified B99 method. Since the signal is proportional to the reflected power, as discussed above, the laminar times are identified as the time intervals between periods in which the values are below a given threshold.

The PDF of laminar times for reflectometer data (shown in Fig. 2) refers to a statistical ensemble made by all the data collected in several discharges with similar plasma parameters. The density probability p_i for the interval $\Delta\tau_i$ is defined so that $p_i \Delta\tau_i = n_i / N_{\text{tot}}$, where n_i is the number of counts and N_{tot} is the total number of counts. The analysis clearly shows a power law distribution $P(\tau_L) = A\tau^{-\alpha}$ and a weighted fit gives an exponent $\alpha = 2.34 \pm 0.04$.

The same analysis has been applied to the ion saturation current signal. In Fig. 3 we show the PDF of these laminar times. As in the case of reflectometer data, these bursts are temporally distributed with a clear power law statistic with a value of the exponent $\alpha = 1.93 \pm 0.06$.

It must be emphasized that the power signal of the reflectometer is directly linked to the small scale fluctuation intensity [15,16], while its mean amplitude is weakly affected by the macroscopic plasma density evolution. In order to obtain similar information from the probe, the LIM method has been applied to the probe signal to separate the fluctuating part from the macroscopic behavior. The analysis has allowed intermittent events to be identified in a range of time scales from $\tau = 2$ μs to $\tau = 100$ μs. In Fig. 4 an example of probe signal and intermittent events in a 4 ms interval is shown: vertical dotted lines show the time occurrence of intermittent events at scale $\tau = 2$ μs and the laminar times between them are indicated. In Fig. 5 the PDF $P(\tau_L)$ of laminar times between subsequent intermittent events is plotted: even in this case the distribution is well fitted by a power law $P(\tau_L) = A\tau^{-\alpha}$ with $\alpha = 1.68 \pm 0.04$. The same analysis has also been performed for intermittent events at larger scales up to $\tau = 100$ μs and, in all the cases, a power law statistics has been found. Finally it is worth mentioning that a similar power law has been found for density fluctuations, as derived from the triple probe, though this measurement is spatially averaged over 1.8 cm spanned by the five pins.

In summary both methods applied to the density fluctuations in RFX indicate that the statistics of laminar times

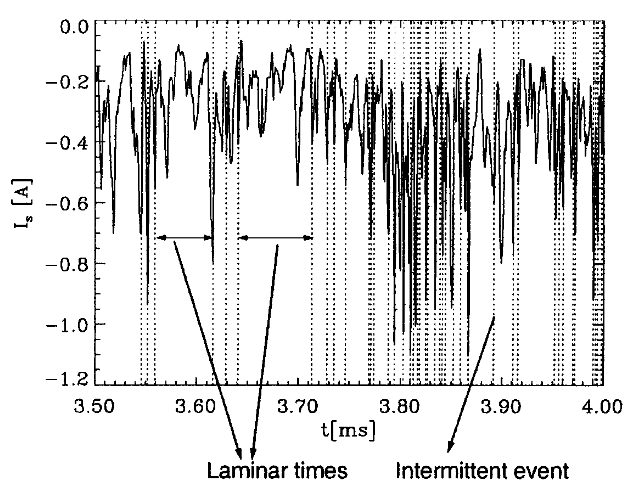

FIG. 4. Time evolution of the ion saturation current. The vertical dotted lines report the time occurrence of intermittent events at the scale $\tau = 2$ μs, and laminar times τ_L are also indicated.

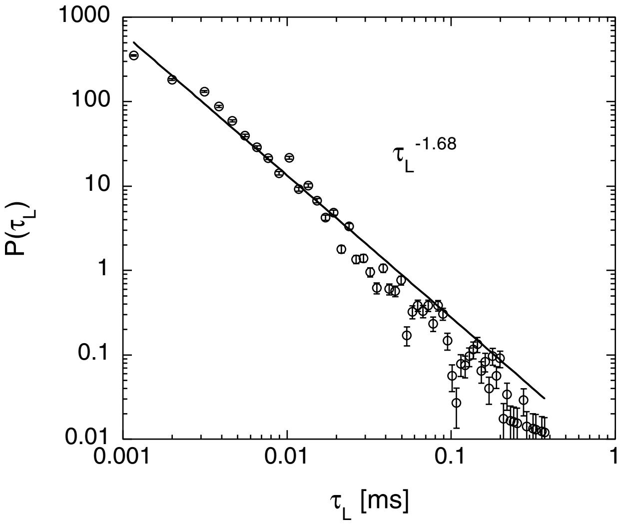

FIG. 5. Probability density of the laminar times $P(\tau_L)$ between subsequent intermittent events at temporal scale $\tau = 2\ \mu$s. The straight line represents a weighted power law fit.

between either burst or intermittent events obey a power law behavior. Since, as shown in B99, in a BTW SOC system the PDF of laminar times has an exponential behavior, the present results are therefore in contrast with the SOC paradigm. It is worth noticing that the occurrence of a power law in the distribution of laminar times has also been observed in solar flares [9,21] and in Omori's law for earthquakes [22], and has been interpreted as an indication of the existence of strong correlations between successive bursts. Far from being conclusive on the nonapplicability of the SOC paradigm to all magnetically confined plasmas, however, owing to the numerous similarities in turbulence and transport properties observed between RFP and other configurations, this result constitutes a first experimental inconsistency with SOC dynamics applied to these plasmas. On the other hand, our result is consistent with models, based on magnetohydrodynamic turbulence [23], which have been applied to interpret phenomena in solar wind [24] and in laboratory plasmas [19]. These models are based on the nonlinear interaction of logarithmically spaced fourier modes with close spatial structure and subjected to some conservation law (shell model [23]) and predict power law decay for the PDF of the laminar times between events. Referring to transport processes in magnetically confined plasmas, it is worth noticing that these models are reminiscent of streamer phenomena [25], occurring through nonlinear mode coupling, which were recently suggested as a possible mechanism for fast cross-field transport processes. As a final remark, analysis of other models, dubbed "near-SOC" and based on modified SOC dynamics (see, for example, [26]) becomes mandatory to ascertain their compatibility with power laws for laminar times.

In conclusion, the results of an analysis applied for the first time to density fluctuations in a magnetically confined plasma show that in a RFP configuration the statistic of laminar times between impulsive events is in contrast with the predictions of a SOC system. This result, if confirmed in other magnetic configurations, would question the applicability of SOC paradigm to magnetically confined plasmas for thermonuclear research.

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