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Self-organized criticality in MHD driven plasma edge turbulence

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A B S T R A C T

We analyze long-range time correlations and self-similar characteristics of the electrostatic turbulence at the plasma edge and scrape-off layer in the Tokamak Chauffage Alfvén Brésillien (TCABR), with low and high Magnetohydrodynamics (MHD) activity. We find evidence of self-organized criticality (SOC), mainly in the region near the tokamak limiter. Comparative analyses of data before and during the MHD activity reveals that during the high MHD activity the Hurst parameter decreases. Finally, we present a cellular automaton whose parameters are adjusted to simulate the analyzed turbulence SOC change with the MHD activity variation.

1. Introduction

In tokamaks and stellarators [1], the plasma edge electrostatic turbulence is the main cause of the anomalous particle and energy transport that limits the magnetic confinement performance [2,3]. Despite the expressive progress that has been achieved in the last decades, much investigation is still necessary to better understand and to control the electrostatic turbulence in tokamaks.

Fluctuation spectrum [4], recurrence [5–7], and self-organized criticality (SOC) [8,9] are among subjects recently investigated to determine basic statistical properties of the electrostatic plasma turbulence and transport [10]. In particular, evidences of SOC, that bring together the ideas of self-organization of nonlinear dynamics systems with the often observed near-critical behavior [11,12], have been found in the tokamak plasma turbulence experimentally [8] and in numerical simulations [10].

Some features of turbulence observed in all tokamak discharges can be computationally investigated, independent of any physical model to interpret the turbulent fluctuations, by the SOC dynamics of cellular automata models of running sandpile dynamics [13]. Similar models have been applied to study self-organization in other dynamical systems, as cancerous cells proliferation [14], traffic flow [15], neural network [16], ecosystems [17], and spatial pattern formation [18]. In these models avalanche events appear naturally and can account for some specific SOC features [19].

In the tokamak TCABR, when the MHD activity increases it synchronizes with the electrostatic fluctuations and their frequency spectra have the same peaks [20,21]. The high MHD activity modifies the plasma turbulence leading to a new dynamic scenario in the plasma edge. The main differences in the turbulence with low and high MHD activities have been recently analyzed [8,19,22]. In this Letter we report alterations on the turbulence SOC behavior whenever the MHD activity increases in TCABR.

In our analyzes of the plasma edge turbulence in TCABR tokamak, with low and high MHD activity, we find that the obtained power spectra, autocorrelation, and Hurst parameter radial profiles are compatible with those expected for turbulent fluctuations with SOC dynamics. Besides that, we find that during the turbulence driven high MHD activity the Hurst parameter, a relevant SOC indicator, decreases in all frequency range. Moreover, we simulate all the described characteristics and changes obtained in the analyzed data with a modified cellular automaton which is a sandpile model with an external perturbation. We also find that during the high MHD activity the Hurst parameter of the electrostatic turbulence decreases.

This Letter is organized as follows: in Section 2 we present the experimental setup. Section 3 shows the radial dependence of SOC in the experimental results. Section 4 treats the self-organized criticality during MHD driven turbulence. Section 5

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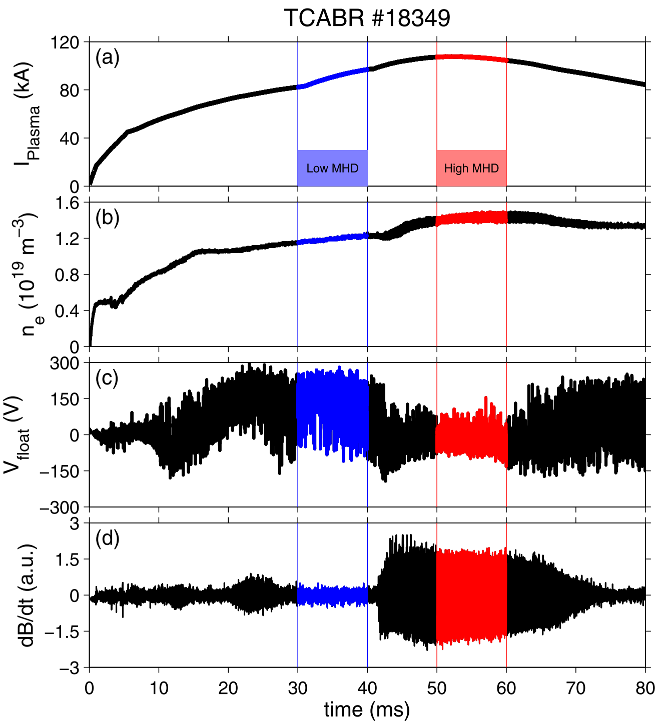

Fig. 1. Time evolution of plasma discharge in TCABR tokamak. (a) Plasma current, (b) central chord plasma mean density, (c) floating electrostatic potential for a typical discharge inside the limiter ($r = 17$ cm), (d) ion saturated current from the vertical lines indicate the analyzed time interval.

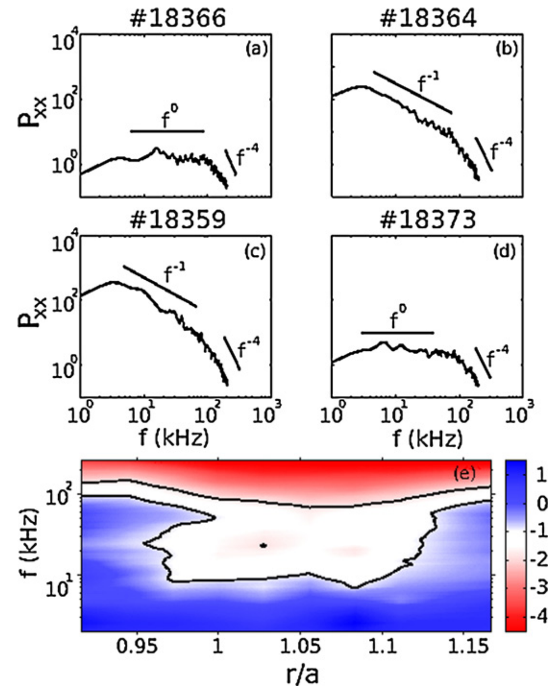

Fig. 2. Power spectrum P_{xx} of the floating potential fluctuation at four different radial positions: (a) $r/a = 0.91$ (inside the plasma column); (b) $r/a = 1.00$ (limiter); (c) $r/a = 1.05$ and (d) $r/a = 1.16$ (outside the plasma column), respectively. (e) Local decay exponent in function of the frequency and the radial position obtained from 28 shots. (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

shows a theoretical model that we use to simulate the behavior observed in experiments. The last section presents the conclusions.

2. Experimental setup

The experiments are done in TCABR [23], a small size tokamak (major radius $R = 0.6$ m, minor radius $a = 0.18$ m, central toroidal magnetic field $B_0 = 1$ T) in which the MHD activity can increase and saturates without disruptions by an appropriated selection of the plasma current evolution [20,22] or by biasing an electrode inserted at the plasma edge [24].

The turbulence is measured at the edge and the scrape off layer (SOL) regions by Langmuir probes. The floating potential configuration is recorded with an acquisition rate of 1 MHz. The probes can be moved between successive shots in the radial position ranging from $r = 16.5$ to 21 cm (corresponding to r/a between 0.92 to 1.17). Fig. 1 shows the typical evolution of the plasma during the discharges considered in this work. As it can be seen in Fig. 1, in the interval from 30 to 40 ms, the plasma current increases, while the MHD activity is low and the fluctuating potential and density are almost stationary. But, after the time 40 ms, the MHD activity amplitude starts increasing and saturates by the time 50 ms. In the interval from 50 to 60 ms, during the MHD activity enhancement, the plasma density reaches a second plateau. For all the analyzed discharges, we selected two time intervals corresponding to the low and high MHD activity conditions [25]. We choose the first time windows in the almost stationary stage just before the growth of the MHD activity (50 ms–60 ms for the shot in Fig. 1). Complementary, we select a second time window during the interval with saturated high MHD activity.

3. Self-organized criticality radial dependence

The first objective of this study is to verify the existence of SOC dynamics in the plasma edge region of TCABR during the usual low MHD activity [26–28] (as commonly observed in other tokamaks), and to evaluate how this dynamic is dependent of the radius [29]. In order to perform it, we analyze some typical features associated with SOC dynamics in the floating electrostatic potential, such as: power spectrum (Fig. 2), autocorrelation function (ACF) (Fig. 3) and the Hurst parameter of the fluctuations (Fig. 4).

In SOC systems, the power spectra are expected to be nearly $1/f$ noise for a given range of frequencies [11], separated by two frequency intervals quite different, at least in our case [29]. For the TCABR tokamak data from the inside plasma column at $r/a = 0.91$ [Fig. 2(a)] and far outside for $r/a = 1.16$ [Fig. 2(d)], the frequency spectra show two distinct frequency intervals range with approximate decay slope of 0 and -4. The spectral decay with the $1/f^4$ dependence occurs for high frequencies ($\geqslant 200$ kHz) while the $1/f^0$ spectral dependence occurs for low frequencies ($\leqslant 100$ kHz). The turbulence in these positions does not show evidences of SOC dynamics. However, in Fig. 2(b) for $r/a = 1.00$ and (c) for $r/a = 1.05$ we can observe the $1/f$ spectral dependence ($3\text{ kHz} \leqslant f \leqslant 100$ kHz). In order to evaluate the spectral range in which the decay slope is close to -1, we fit the slope of the power spectra considering only a small range of the frequency spectra.

By doing it, we determine the local slope in function of the radial position and mean frequency of each frequency range used to determine the local slope. The radial dependence of the decay slope obtained from the fit of 28 shots is summarized in Fig. 2(e). The black contour lines in Fig. 2(e) limit the region in which the local slope is close to -1: the regions with local slopes close to -1 are marked in white, while slopes below -1 are indicated in red and the blue is used to mark the regions with slopes above -1. As it can be seen in Fig. 2(e), a broad frequency range in which the slope is close to -1 is observed for the radial positions close to the plasma edge ($0.97 < r/a < 1.13$), while only a narrow frequency range with slope close to -1 is observed in the most internal ($r/a \sim 0.93$) and external ($r/a \sim 1.16$) positions