Avalanche statistics and long-term correlations in the SPLM

O. Castellanos[1], E. Anabitarte[1], Juan M. López[2], J.M. Sentíes[1] and J.A. Mier[1]

[1]*Departamento de Física Aplicada, Universidad de Cantabria, Santander, Spain*

[2]*Instituto de Física de Cantabria (IFCA), CSIC-UC, Santander, Spain*

Introduction

Slowly driven many-body systems in nature often exhibit an intermittent dynamics in the form of avalanches or bursts of activity [1]. Physical examples include the jerky motion of domain walls in magnetic systems, acoustic emission in stressed materials, or fluid imbibition fronts in porous media, among many others. This complex behavior can be found in a wide range of scales from a few nanometers or micrometers (like the examples above) up to the scale of several hundred or thousand kilometers like earthquakes or solar flares. Plasmas for thermonuclear fusion research magnetically confined in toroidal devices have been reported to exhibit an intermittent response [2, 3] driven by plasma turbulence. This suggests the presence of anomalous transport in confined plasmas. From the theoretical point of view, non-diffusive transport models have been studied [4]. In this work we study the turbulent dynamics and anomalous transport in an helium plasma at the SPLM [5]. In our experiment we obtain very long time series with a high temporal resolution at different distances from the center of the vessel. This experimental setup allows us to study the fluctuation-induced particle flux properties for different plasma regions.

Experimental Setup

Our experimental setup consists of a cylindrical glass vessel with an internal diameter of 0.07 m and a length of 1 m. The vessel is located inside a circular waveguide of 0.08 m in diameter. A magnetized plasma is produced by launching longitudinally electromagnetic waves with a frequency $f = 2.45$ GHz. The incident power (PLMG) is in the range 0.6 kW< PLMG < 6 kW and the system operates in a continuous regime. The stationary longitudinal magnetic field (0.05 T $< B_0 <$ 0.15 T) is generated by six water cooled coils, which are concentric with the waveguide. Further details can be found in Ref. [5].

Measurements reported in this paper were performed for a helium plasma with a magnetic field $B_0 = 0.12$ T. The mean electron density is determined using an 8 mm interferometer, and typically ranges from 10^{15} m^{-3} to 10^{18} m^{-3}. Electron temperatures are in the range 5 − 40 eV. A radially movable array of Langmuir probes provides local values for ion saturation current, floating potential, electron temperature and their fluctuations along the whole plasma radial column. From the measured values of density $n_e(t)$ and poloidal electric field $E_\theta(t)$ we compute the fluctuation induced particle flux as $\delta\Gamma_{E\times B}(t) = \delta n_e(t)\delta E_\theta(t)/B_0$, where B_0 is the axial magnetic field. The plasma that we produce in our linear machine has cylindrical symmetry, so its properties vary radially with the distance to the longitudinal axis or radius r. We have examined a great number of flux data obtained by moving the Langmuir probe radially and measuring the flux at twelve different radii from r = 0.20 cm to r = 2.79 cm. We let the plasma to stabilize and reach the stationary regime and check that the probability density function (PDF) of the absolute flux remains constant in time. Then, for each radius, we obtained time series with a temporal resolution of 1 μs and about 2×10^5 points in the stationary regime. This corresponds to 0.2 seconds of time evolution in a typical run, which is several orders of magnitude larger than the typical self correlation time ($\tau_c \approx$ 1 to 6 μs depending on the probe radial position)

Experimental results

Figure 1 shows a typical snapshot of the absolute value of the fluctuation-induced particle flux time series, $\delta\Gamma_{E\times B}(t)$, for the plasma at radius r = 0.20 cm. The complete series lasts for about 0.2 s and we zoom in a time window of less than one millisecond in order to better show the abrupt increases of the absolute flux above the noisy background. These strong fluctuations above the typical (Gaussian) background define a burst or avalanche event. To analyze these burst events, we select a finite detection threshold and define an avalanche as a burst of activity exceeding this threshold. The goal of thresholding is to identify the bursts from the Gaussian background. For a given burst, we measure the duration D and size S of the event. The latter is defined as the integral (area below the curve) of the flux over the burst time duration and physically represents the total number of particles (per unit area) that participated in the avalanche.

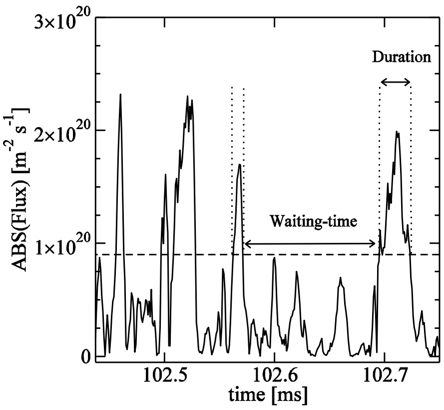

Fig.1 A sample for the absolute particle flux (r=0,2 cm)

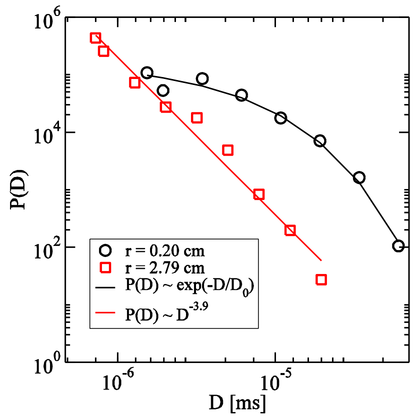

Fig.2 Probability distribution of avalanche duration

In Fig. 2 we plot the PDF of avalanche durations, P(D), for the smallest (r = 0.20 cm) and greatest (r = 2.79 cm) radius that we have studied in our experiment. We obtain that for r = 0.20 cm the avalanche durations are exponentially distributed with a typical average time $D_0 \simeq 6.25 \times 10^{-4}$ ms. In contrast, P(D) progressively deviates from a simple exponential as we probe larger radii. As shown in Fig. 2, for the largest radius r = 2.79 cm we find that the avalanche duration statistics is better described by a power law decay P(D) ~ $D^{-\alpha}$ with $\alpha = 3.9 \pm 0.2$. The burst duration progressively becomes power-law distributed as we move towards the outermost regions of the plasma.

Another interesting quantifier in avalanche statistics analysis is the size duration scaling relation which, as far as we know, has not been analyzed before in plasma experiments. The intermittent response is characterized by avalanches whose sizes are expected to scale with the durations as a power law, S(D) ~ D^{γ}. In Fig. 3 we plot the size-duration scaling relation for radii r = 0.20 cm and r = 2.79 cm. We find an asymptotic scaling relation with an exponent $\gamma = 1.43 \pm 0.04$ for the innermost region of the plasma. This value is close to $\gamma = 3/2$, which corresponds to the theoretical expectation for a random walk time series. In contrast, we find that $\gamma = 1.27 \pm 0.05$ for r = 2.79 cm, which deviates from the Gaussian value $\gamma = 3/2$ and strongly suggests that nondiffusive transport mechanisms govern the outermost region of the plasma.

We have also studied the existence of long-term correlations in the flux time series. Interavalanche correlations are studied by measuring the waiting time between bursts as the first return time one has to wait to see the amplitude to go above threshold again after last avalanche finished (as depicted in Fig. 1). If avalanches are triggered by an uncorrelated process the theory of the Poisson process leads to a exponential distribution of the waiting times.

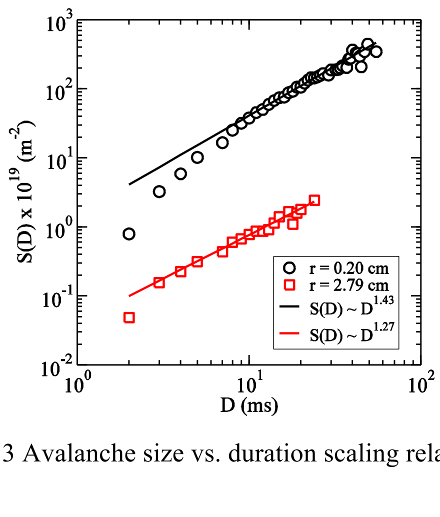

Fig. 3 Avalanche size vs. duration scaling relation

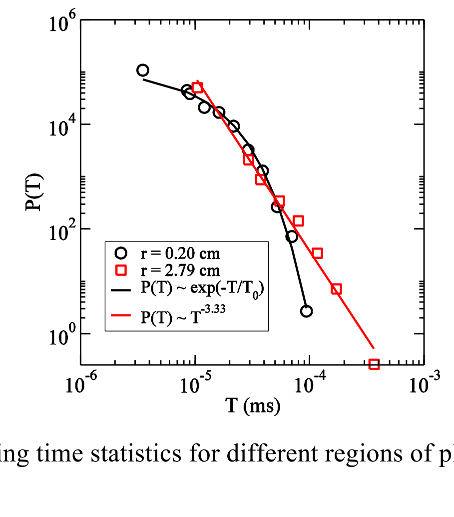

Fig. 4 Waiting time statistics for different regions of plasma

Deviations from the exponential decay can be interpreted as indicating the presence of correlations in the triggering process. Figure 4 shows the PDF of the waiting times T between bursts above threshold. For the innermost region we find that the waiting times are exponentially distributed with a characteristic time scale of $T_0 = 9.0 \times 10^{-4}$ ms, which is consistent with a Poisson statistics and diffusion dominated transport. This strongly contrasts with the distribution of waiting times for the outermost shell of the plasma in our experiment that shows a power-law decay as $P(T) \sim T^{-\beta}$ with $\beta = 3.33 \pm 0.15$. This means that, as we move toward the edge of the plasma, avalanche triggerings are correlated in a highly nontrivial fashion, which is incompatible with diffusive-like transport.

Summary and conclusions

To conclude we have studied a helium plasma in a nonconfining configuration with cylindrical symmetry. Our setup allows us to explore the particle transport at different distances from the plasma center. We find that the transport is diffusive in the innermost regions of the plasma, whereas nondiffusive features clearly develop as we probe regions further away from the center. In the outermost regions of the plasma, particle flux is strongly non-diffusive as shown by the avalanche duration statistics and the size-duration scaling relation. Detailed mesurements of the electron temperature radial profiles, $T_e(r)$, in our device show that $T_e(r)$ is roughly constant for the inner shell of the device but exhibits a large drop localized around a radius $r = 2.50$ cm. Indeed, our data show that $\partial_r T_e(r)$ has an acute maximum around $r \approx 2.50$, where the electron temperature drops about 50% in a narrow radius interval. This strongly suggests the picture of a dynamical instability induced by electron temperature gradient [6].

We also studied the existence of long-term memory in the particle flux fluctuations. The existence of correlations in avalanche triggerings that we measured at the outermost shell of our plasma, is a highly non trivial phenomenon indeed. Note that many self-organized critical systems, for instance, do not show long-term correlations even though they are paradigmatic examples of anomalous transport [7]. Our results should offer a guide and help in the search of adequate theoretical models to describe the complex of turbulent plasmas.

* We acknowledge financial support from MICINN (Spain) through projects ENE2009-12213-C03-02 and FIS2009-12964-C05-05

References

[1] J. P. Sethna, K. A. Dahmen, and C. R. Myers, Nature 410, 242 (2001)
[2] B. A. Carreras et al. Phys. Rev. Lett. 80, 4438 (1998)
[3] R. Sánchez et al Phys. Rev. Lett. 90, 185005 (2003)
[4] B. P. van Milligen, R. Sánchez, and B. A. Carreras, Physics of Plasmas 11, 2272 (2004)
[5] O. F. Castellanos et al. Plasma Phys. Controlled Fusion 47, 2067 (2005)
[6] W. Dorland, F. Jenko, M. Kotschenreuther, and B. N. Rogers, Phys. Rev. Lett. 85, 5579 (2000)
[7] H. J. Jensen, Self-Organized Criticality (Cambridge University Press, ADDRESS, 1998)