Perturbated turbulent transport in a laboratory magnetoplasma: Fluctuations, Correlations and Intermittency.

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Abstract. The effects of an edge biasing potential on the intermittent behaviour of the anomalous flux in a cold toroidal magnetoplasma is studied at different radial positions in the poloidal plane. It is found that both the fluctuations and cross-correlations between particle density and radial velocity vary as a function of the applied bias potential, leading to a strong reduction of the flux at the plasma core. The reduction is due to a large extent to the conspicuous decorrelation between density and velocity signals, while the corresponding fluctuations are much less sensitive to the applied field. The study of intermittent bursts indicates that a strong increase in their mean waiting times takes place at the core.

Keywords: Plasma turbulence, Fluctuation and Chaos, Confinement Devices

1. Introduction
Experiments on fusion plasma devices suggest the presence of a variety of anomalous behaviour such as long-time correlations and intermittency in the strongly fluctuating transport quantities [1, 2, 3, 4, 5, 6]. There are also indications that near the edge of a fusion plasma the associated turbulence displays aspects of universality [7, 8], similar to turbulence in ordinary fluids [9]. As a result, turbulence in plasmas and related transport behaviour have drawn a great deal of attention from a theoretical point of view, in which many different statistical and analytical approaches have been applied [10, 11, 12, 13, 14, 15].

Fusion plasmas are thus characterized by the occurrence of strong turbulent behaviour which needs to be reduced in order to achieve a controlled working regime. It is well known that a shear flow can reduce turbulent transport, in different ways (see Ref. [16, 17]). On the other hand, the study of external perturbations in non-fusion devices, still displaying a high degree of turbulent transport, permits to quantify the effects of a bias field on transport and are therefore interesting from a quite general point of view [18].

The mechanism underlying the reduction of transport has been investigated in a simple magnetized torus Thorello in which its hydrogen plasma is subject to an additional radial electric field, applied at its external edge by means of a dc biasing using a half-moon shaped limiter [18]. Experimentally, a drastic reduction of the anomalous radial particle flux is obtained when a positive polarization is applied to the limiter. At the same time, an improved confinement is achieved as testified by the global modification of the macroscopic plasma parameters.

In this work, we analyze data that have been obtained from Thorello [18] regarding the role of fluctuations and correlations, and the statistical behaviour of intermittency and burst rates. Other interesting aspects such as the possible existence of long-time auto-correlations in the signal (see e.g.
2. Statistical methods and Results

The experimental set-up is briefly discussed in the Appendix, together with the definitions of the (three-pin probe) quantities measured in the experiments at different radial positions \( r \) and times \( t_i = i\Delta t \) (with \( \Delta t = 10\mu s \)). They are, the fluctuating poloidal electric field, \( \tilde{E}_\theta(r, t_i) \), from which the fluctuating plasma radial velocity \( \tilde{v}_r(r, t_i) \propto \tilde{E}_\theta(r, t_i) \) is obtained, and the fluctuating plasma density \( \tilde{n}(r, t_i) \) calculated from the ion saturation current. The anomalous flux is then obtained as \( \Gamma(r, t_i) = \tilde{n}(r, t_i) \tilde{v}_r(r, t_i) \), and its temporal average \( \langle \Gamma(r) \rangle \) given by,

\[
\langle \Gamma(r) \rangle = \frac{1}{N} \sum_{i=1}^{N} \tilde{n}(r, t_i) \tilde{v}_r(r, t_i),
\]

where \( N \) is the total number of data measured. Here, we are interested in determining the degree of cross-correlation between radial velocity and density fluctuations. This can be done by computing the covariance \( \varrho \) (or cross-correlation) between them defined as,

\[
\varrho = \frac{1}{N} \sum_{i=1}^{N} \frac{\tilde{n}(r, t_i) \tilde{v}_r(r, t_i)}{\sigma_n\sigma_v} = \frac{\langle \tilde{n} \tilde{v} \rangle}{\sigma_n\sigma_v} = \frac{\langle \Gamma(r) \rangle}{\sigma_n\sigma_v},
\]

where \( \sigma_n \) are the corresponding standard deviations. From Eq. (2) we thus have,

\[
\langle \Gamma(r) \rangle = \varrho \sigma_n\sigma_v,
\]

quantity which we will discuss in the following.

2.1. Fluctuations and correlations

The standard deviations of flux, poloidal electric field (velocity), density and relative density fluctuations are shown in Fig. 1, for \( V_B = 0 \) and \( V_B = 4V \), for several radial positions inside Thorello. The dramatic decrease of flux fluctuations, i.e. \( \sigma_\Gamma \), near the radial positions of the limiter can be related to a similar behavior of the density, \( \sigma_n \). This is due to the fact that \( \sigma_\Gamma \propto \sigma_n \), relation which can be easily shown in the case that both density and velocity obey Gaussian probability density distributions, where \( \sigma_\Gamma = \sigma_n\sigma_v\sqrt{1 + \varrho^2} \) (see e.g. [20]).

According to Fig. 1, fluctuations of the poloidal electric field (velocity), as well as the relative density fluctuations, \( \sigma_n/\langle n(r) \rangle \), are rather insensitive to the applied external field. Different is the situation regarding correlations.

In Fig. 2, values of the average anomalous flux and cross-correlations are shown. As it is apparent from the figure, the conspicuous decrease of \( \langle \Gamma(r) \rangle \) is clearly related to the corresponding behaviour of \( \varrho \), following Eq. 3. Thus, one may conclude that the application of a bias field at the border of the plasma affects its transport behaviour near its plasma core, i.e. in a spatial zone far away from the position of the perturbation. This indicates the existence of a global decorrelation mechanism for turbulence, which is rather strong in the case of Thorello.

It is interesting to notice that cross-correlations between density and velocity can be visualized by studying the random walks (RWs) associated to the corresponding signals. This is done by defining the
Figure 1. Fluctuations of intermittent signals in Thorello: Standard deviations of flux (top left), poloidal electric field (bottom left), density (top right) and relative density fluctuations $\sigma_n / \langle n(r) \rangle$ (bottom right), versus radial position $r$ [cm] for the cases: Zero field (open circles) and a bias field $V_B = 4V$ (full circles). Error bars are about 50% for the flux and 30% for the remaining three plots. The extension of the limiter along the radial position is indicated by the shadowed rectangle.

positions of a RW for density and velocity, respectively as,

$$W_n(j) = \frac{1}{\sigma_n} \sum_{i=1}^{j} \tilde{n} (r, t_i) \quad W_v(j) = \frac{1}{\sigma_v} \sum_{i=1}^{j} \tilde{v} (r, t_i),$$

(4)

where the index $1 \leq j \leq N$. Such random walk 'profiles' are at the basis of the fluctuation analysis for determining the Hurst exponent of the signal [19, 20].

The RW functions defined in Eq. (4) are plotted in Fig. 3 as traces of the walks with coordinates $x_j = W_n(j)$ and $y_j = W_v(j)$. These plots illustrate in a simple way the degree of cross-correlations between density and velocity. The shape of the island roughly indicates the value of $\varrho$, i.e. the more elongated it is, the larger (in absolute value) is the value of $\varrho$. The orientation of the island gives a hint about the sign of the cross-correlations. More information can be extracted if one distinguishes (with different colors in this case) those points $(x_j, y_j)$ for which the value of the fluctuating flux $\tilde{\Gamma} (r, t_j)$ is larger than a given cut-off. In the figure, we have considered points for which $\tilde{\Gamma} (r, t_j) > 4\sigma_\Gamma$ and $\tilde{\Gamma} (r, t_j) > 5\sigma_\Gamma$. To be noted is that in the case of $V_B = 0$, larger values of $\tilde{\Gamma} (r, t_j) (> 5\sigma_\Gamma)$ already form the 'backbone' of the island, i.e. they are distributed uniformly along the RW trajectory. While in the presence of a strong bias, $V_B = 4V$, they are strongly dumped and look disconnected. In other words, anomalous transport has been reduced considerably by such biasing fields.
2.2. Intermittency and its characterization

Finally, we consider the effect of biasing on the statistical behaviour of intermittency in Thorello, described by the mean waiting times (WT) between bursts, defined as those events for which the generic signal $Y > 3\sigma_Y$. The results are shown in Fig. 4 for the flux and plasma density for $V_B = 0$ and bias $V_B = 4V$. The associated bursts rates, i.e. the temporal density of the bursts, are also included for convenience. A strong increase in the mean WTs near the plasma core is observed in the presence of the bias, corresponding to a decrease in the bursts rates. This is consistent with observations in other plasma devices (see e.g. [23, 24]), which states that anomalous transport is mainly an intermittent transport. So reducing the bursts, i.e. the intermittency, one decreases the transport. The effect is the opposite for the density in the neighborhood of the limiter, but the mean WTs there already overcome substantially those of the flux.

To get a further insight into the bursts behaviour, we have plotted in Fig. 5 the corresponding probability distribution functions (PDF) for the WTs, for both the flux and the density, for two radial positions at the plasma core. These results are consistent with those shown in Fig. 4, indicating that flux bursts behave similarly for both $r = 0$ and $r = 1$ cm (their PDF are almost identical), while the density bursts PDF differ significantly between the two positions as a consequence of the crossing of the WT curves for the density near $r = 1$ cm (see Fig. 4).

3. Conclusions

The effects of a bias electric field applied at the border of the device Thorello yields a strong reduction of transport at the plasma core, suggesting the existence of a non-local decorrelation mechanism for
Figure 3. The two-dimensional RW associated to density and poloidal electric field (velocity) according to Eq. (4) for the positions: $r = 0$ (left panels) and $r = 1$ cm (right panels), and fields: zero bias (upper panels) and bias field $V_B = 4$ V (lower panels). The full data is plotted by the blue symbols, points for which $\tilde{\Gamma} (r = 0, t_j) > 4\sigma_\Gamma$ are plotted in green, and those with $\tilde{\Gamma} (r = 0, t_j) > 5\sigma_\Gamma$ in red color. (Colors are available on line.)

Appendix A. Experimental set-up

The data analyzed here have been obtained from Thorello, a pure toroidally magnetized device (see [21] for more technical aspects on the device), for the following values of the experimental discharge parameters: neutral gas pressure of about $4 \times 10^{-4}$ mbar, discharge current 4 A, magnetic field 333 G. The latter yielding small magnetic ripples $\delta B/B < 0.05$. The obtained plasma is believed to be in a steady state, well-suited for statistical studies. The typical plasma density ranges from $10^9$ cm$^{-3}$ (plasma edge) to $10^{11}$ cm$^{-3}$ (plasma core). The typical electron temperature is $T_e \simeq (1 \div 3)$ eV [18].

Plasma diagnostic is performed using a Langmuir probe composed of three pins. We deal with three simultaneous discrete time-series, sampled by a four channel oscilloscope at equal time intervals $\Delta t = 10$ µs. The number of data is $N = 2^{15}$ per time series, and the total time span is $T = N\Delta t \simeq 0.33$ s. The equatorial positions $r$ considered range from $-1$ cm to $7.5$ cm, where $r = 0$ locates the center of the vacuum chamber (plasma centre). The half-moon shaped limiter is located between about $r = 4$ cm and the chamber edge at $r = 8$ cm.

The first two pins, which are poloidally oriented and separated by a distance of 0.6 cm, measure the turbulence, in such non-fusion devices. The statistics of intermittent bursts also indicates that a strong increase in the mean waiting times takes place at the core, consistent with the observations that in the anomalous transport the intermittent bursts have a high participation ratio.

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Figure 4. Mean waiting times [ms] (upper panels) and bursts rates [ms$^{-1}$] (lower panels) for the fluctuating flux (left panels) and plasma density (right panels) vs radial position, r [cm], for zero field case (open circles) and bias field $V_B = 4$V (full circles).

The third pin measures the ion saturation current $I_{ION}$ and is toroidally shifted from the first two by 0.54 cm. Neglecting again electronic temperature fluctuations, we can relate $I_{ION}$ to the ionic density, $n(r,t)$ according to, $I_{ION}(r,t) \propto n(r,t) \sqrt{T_e(r)}$. Similarly as for the velocity, we compute the fluctuating density with respect to its mean value,

$$\tilde{n}(r,t_i) = n(r,t_i) - \bar{n}(r).$$

Finally, the average of the anomalous flux is given by,

$$\bar{\Gamma}(r) = \frac{1}{N} \sum_{i=1}^{N} \tilde{n}(r,t_i) \tilde{v}_r(r,t_i), \quad (A.1)$$

and its temporal fluctuations become,

$$\tilde{\Gamma}(r,t_i) = \tilde{n}(r,t_i) \tilde{v}_r(r,t_i) - \bar{\Gamma}(r). \quad (A.2)$$
The plasma is perturbed by an additional electric field acting from a charged metallic piece (limiter) located near the border of Thorello. As any biased metallic probe plunged into the plasma, the limiter acts as a collector of charged particles. A characterization of this half-moon shaped limiter, leads to a current/potential curve very similar to a Langmuir’s one [18]. The data studied here corresponds to the zero field case, $V_B = 0$, considered as the reference state, and the case of the polarizing potential, $V_B = 4V$. The later determines the beginning of the electron saturation regime.

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