LETTER

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Intermittent fluctuations in the TCV scrape-off layer

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Abstract
Probe measurements in the scrape-off layer of tokamak plasmas show that the ion saturation current signal is dominated by large amplitude bursts. Analysis of data time series from tokamak à configuration variable of unprecedented duration reveals that both burst amplitudes and waiting times are exponentially distributed. The average burst wave form has an exponential shape with a characteristic time that is independent of the burst amplitude. These results support a novel stochastic model, which suggests that the high particle density in the far scrape-off layer is due to the radial motion of uncorrelated blob-like structures. Predictions of the model describe the broad range of universality of plasma fluctuations in the boundary region of tokamak plasmas.

Keywords: scrape-off layer, fluctuations, turbulence, plasma-wall interactions, tcv, intermittency, transport

Cross-field transport of particles and heat in the scrape-off layer (SOL) of magnetically confined plasmas is dominated by the radial motion of blob-like structures [1–4]. The turbulence-driven transport results in broad plasma profiles in the far SOL and enhanced levels of plasma–wall interactions that may be an issue for the next generation plasma confinement experiments and future fusion power reactors. The average particle density and radial flux in the SOL evidently depend on the amplitude distribution of blob structures and their frequency of occurrence. Revealing the statistical properties of plasma fluctuations in the SOL is thus crucial for the prediction of average profiles and plasma–surface interactions [5–12].

Probe measurements on the tokamak à configuration variable (TCV) have demonstrated a remarkable degree of universality of the fluctuations in the SOL [13–18]. In particular, the probability density function (PDF) of the plasma fluctuation amplitudes are well described by a Gamma distribution and there is a parabolic relation between the skewness and kurtosis moments for a large range of plasma parameters. However, there remain several controversial aspects regarding the statistical properties of fluctuations in tokamak SOL plasmas, including the presence of long-range correlations, clustering and power law distributions [19–23]. Part of this has likely resulted from conclusions drawn from statistical analysis of small data sets, which does not allow unambiguous identification of scaling relationships.

In order to clarify the statistical properties of plasma fluctuations in the tokamak SOL, dedicated experiments were performed on TCV with the probe maintained at a fixed spatial position at the outboard mid-plane to record very long time series under stationary plasma conditions. These measurements were performed in an ohmically heated, lower single null, deuterium fuelled plasma in TCV. Here results are presented from discharge number 27601, with plasma current \( I_p = 340 \, \text{kA} \), line-averaged particle density \( \bar{n}_e = 4.5 \times 10^{19} \, \text{m}^{-3} \) and axial toroidal magnetic \( B_0 = 1.43 \, \text{T} \). The probe head was maintained at a fixed position 10 mm below the outboard mid-plane and 3 mm in front of the main chamber wall. The probe recorded the ion saturation current \( \dot{J} \) at a sampling rate of 6 MHz with a consecutive signal of nearly one second duration. The magnetic field, plasma current, line-averaged density and edge safety factor remained constant during the measurement time. Further information about the plasma configuration and measurements can be found in [13–18].

A short part of the raw time series for the ion saturation current fluctuation \( \dot{J} \) is presented in figure 1, revealing the
frequent appearance of bursts with peak amplitudes several times the root mean square (rms) value \( J_{\text{rms}} \). As a result, the amplitude PDF presented in figure 2 has an exponential tail for large values \([13–17]\). The PDF is well described by a Gamma distribution over four orders of magnitude on the ordinate. The saturation current signal has a skewness of 1.5 and a kurtosis of 6.7, quantifying the degree of intermittency. In figure 3 is shown the autocorrelation function for the ion saturation current signal. This is clearly well approximated by an exponential function with a characteristic time of 15 \( \mu \)s.

In order to reveal the statistical properties of large amplitude bursts in the time series, a standard conditional averaging technique is utilized \([24, 25]\). Events are recorded when the ion saturation current rises above a specified threshold value. For each conditional event, the peak amplitude and its time of occurrence is recorded together with a short part of the time series centered around the time of peak amplitude in order to reveal the wave form of each event. These sub-records are then averaged over all events to give a conditionally averaged wave form associated with large amplitude events in the signal. For peak amplitudes larger than 2.5 times the rms value, a total of 5585 upcrossings of the threshold are recorded in this long data time series, thus allowing to unambiguously determine the statistical properties of large amplitude fluctuations.

In figure 4 the conditionally averaged wave form is presented for events with peak amplitude larger than 2.5 times the rms value, using a conditional window length of 100 \( \mu \)s. This reveals a wave form with a double-exponential shape with a rise time of 5 \( \mu \)s and a fall time of 10 \( \mu \)s. Note that the total burst duration coincides with the correlation time derived from figure 3. Restricting the peak amplitude of conditional events to be within a range of 2–4, 4–6 and 6–8 times the rms value, the appropriately scaled conditional wave forms, also shown in figure 4, reveal that the average burst shape and duration do not depend on the burst amplitude.

From the occurrence times of the bursts, the distribution of waiting times between large amplitude events can be calculated. As shown in figure 5, for peak amplitudes larger than 2.5 times the rms value, the waiting times are well described by an exponential distribution over three orders of magnitude on the ordinate. This exponential distribution is in accordance with a Poisson process, implying that blobs in the far SOL are uncorrelated. Consistent with these findings,
The broken line shows an exponential fit to the data.

Figure 5. Complementary cumulative distribution function for waiting times between large amplitude events in the ion saturation current signal with peak amplitudes $\tilde{J} > 2.5 J_{\text{rms}}$. The broken line shows an exponential fit to the data.

Figure 6. Complementary cumulative distribution function for ion saturation current burst amplitudes with peak values $\tilde{J} > 2.5 J_{\text{rms}}$. The broken line shows an exponential fit to the data.

determined by the mean amplitude of the structures and the duration and average waiting time. The analytical model allows to calculate the lowest order statistical moments, amplitude distribution and correlation functions, which are found to compare favorably with experimental measurements. Moreover, level crossings and excess time statistics, including how long the signal on average stays above a certain threshold level, can be estimated and compared to synthetic as well as measurement data [26, 27]. Such work is now in progress and will hopefully provide quantitative predictions of plasma-wall interactions in magnetically confined fusion grade plasmas. Finally, it is emphasized that the present results are from measurements in an ohmically heated plasma. While previous work suggest that this extends to a broad range of plasma parameters, more extensive fluctuation measurements should be undertaken, in particular in high confinement mode plasmas.

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References


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