From midplane to divertor: an experimental characterization of edge turbulence in L-mode plasmas on the COMPASS tokamak

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Introduction

In L-mode plasmas, cross-field transport in the scrape-off layer (SOL) is predominantly driven by turbulent filamentary structures known as blobs [1]. Blobs contribute to enhanced particle and heat transport, affecting edge plasma confinement, divertor heat loads, and plasma-wall interactions. While blob dynamics at the midplane have been studied extensively [2, 3], their downstream impact at the divertor and the dependence of fluctuation statistics on plasma parameters remains underexplored. Even current 3D edge (SOL) turbulence simulations do not yet fully reproduce the observed divertor intermittency statistics [4, 5].

The COMPASS tokamak is equipped with Langmuir and ball-pen probes at both the midplane and divertor, enabling simultaneous measurements of plasma fluctuations with microsecond time resolution [6, 7]. In this work, fluctuations measured by reciprocating (RCP) probes, divertor probes, and Li-beam emission spectroscopy (Li-BES) are analyzed across a line-averaged density scan. Midplane and divertor are mapped using EFIT reconstruction corrected by two-point model [8]. The analysis focuses on probability density functions, higher-order moments, and waiting-time statistics to characterize blob-induced fluctuations at both the midplane and divertor, and to compare their statistical properties upstream and downstream along the same flux tubes, as a first step to understand better parallel transport of blobs and their impact on divertor conditions.

Experimental setup

The probes are equipped with Langmuir and ball-pen probes, providing sub-microsecond measurements of ion saturation current I_{sat}, floating potential V_{fl}, ball-pen potential V_{BPP}, and electron temperature T_e. The plasma potential was estimated from ball-pen probe measurements as $V_p = V_{BPP} + 0.6T_e \approx V_{BPP}$, while temperature can be calculated as $T_e = (V_p - V_{fl})/\alpha$, where $\alpha = 2.2$ for RCP probe and $\alpha = 1.4$ for divertor probes [7, 9]. Due to the limited accuracy of the EFIT magnetic reconstruction, the separatrix position could not be determined with sufficient precision [10].

Therefore, the velocity shear layer (VSL), defined by radial electric field as E_r= 0 and corresponding maximum of the plasma potential profile, was used as a proxy for the separatrix position and the two-point model was used to correct discrepances in poloidal mapping between midplane and divertor. In two point model it is assumed that heat flux and momentum are conserved along field lines. All radial coordinates presented in this work are expressed relative to the VSL, while errors are calculated with bootstrapping.

Fluctuation analysis was performed on high-pass filtered signals, normalized to their standard deviation, with cut-off frequency 1 kHz. Statistical properties of the fluctuations were characterized using probability density functions, skewness, kurtosis, and waiting-time distributions between large-amplitude events (blobs).

Results

Probability density functions (PDFs) of the ion saturation current measured by the divertor probes are shown in Fig. 1(a) and Fig. 1(b) for the radial and line-averaged density scans, respectively. The PDFs broaden with increasing $R - R_{VSL}$ and develop the characteristic Gamma-like shape associated with intermittent blob transport, similarly to the well-known behavior of turbulence at midplane [2]. In contrast, the influence of line-averaged density is comparatively weak, indicating that radial position is more dominant parameter of SOL intermittency within the investigated parameter range then density. This behavior is reflected in the increase of skewness (S) and kurtosis (K) with radial distance, while their dependence on density remains relatively weak (Fig. 2). Furthermore, the measured K-S relation follows the characteristic parabolic scaling expected for a Poisson process, consistent with fluctuations arising from a superposition of random and independent blob events (Fig. 3) [2].

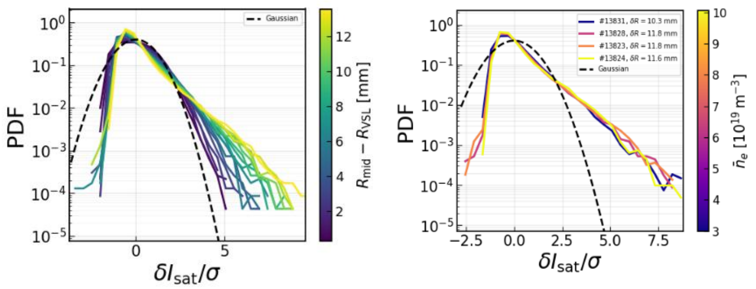

Figure 1: (a) PDFs of I_{sat} coming from divertor probes in (a) radial scan with fixed shot number #13823 with $n_e = 8 \cdot 10^{19} m^{-3}$ (b) density scan for fixed $R - R_{VSL} = 12mm$.

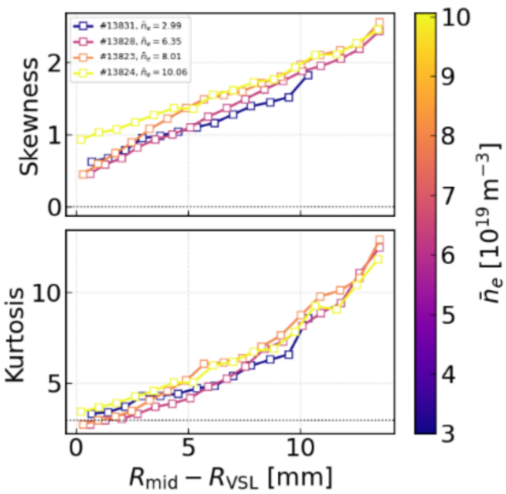

Figure 2: Radial profiles of higher moments: skewness and kurtosis in a density scan at the divertor

The agreement is the most statistically significant for the divertor probes, which provide the largest statistical ensemble due to continuous measurements throughout the the flat top phase of the discharge. The larger scatter observed for the RCP measurements is attributed to the smaller number of samples available at each radial position during probe reciprocation which is moving. Li-BES follows the same overall trend but exhibits increased scatter, reflecting the fact that it measures light emission rather than ion saturation current fluctuations directly. Exponential waiting-time distributions between blob events on the divertor are consistently observed across the investigated radial positions and plasma densities, with a representative example shown in Fig. 4. Together with the Gamma-like PDFs and parabolic K-S scaling, these results provide evidence that divertor fluctuations are governed by a stochastic Poisson blob process similarly to midplane fluctuations. Figure 5(a) compares the radial evolution of skewness and kurtosis obtained from RCP, divertor probe and Li-BES measurements. All three diagnostics exhibit increasing intermittency with radial distance and attain similar values at matched $R - R_{\mathrm{VSL}}$.

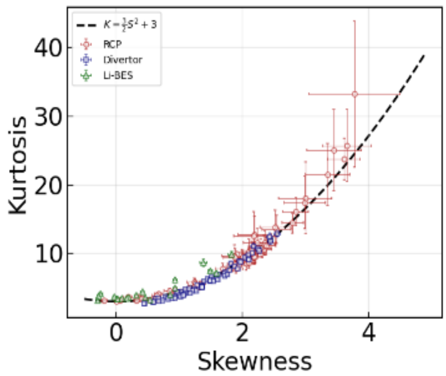

Figure 3: Parabolic K-S relation for all three diagnostics: RCP probe, divertor probes and Li-BES.

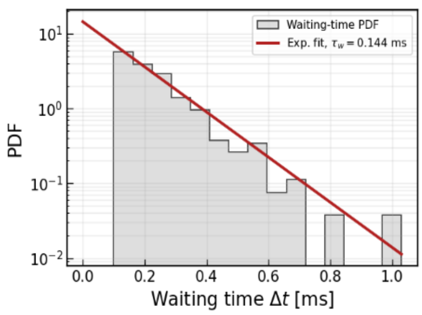

Figure 4: Exponential distribution of waiting times between blobs at the divertor, with 2.5σ threshold

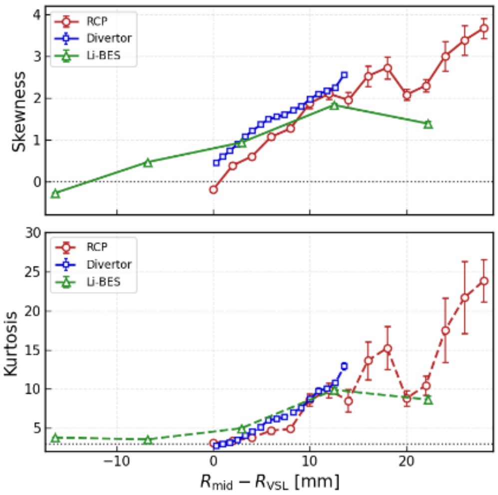

Figure 5: Radial profiles of skewness and kurtosis for a fixed shot #13823 for all three diagnostics, with density $n_e = 8 \cdot 10^{19} m^{-3}$

While the divertor measurements show the most robust statistics, the overall agreement demonstrates that the same underlying blob dynamics are observed by all diagnostics. Using EFIT equilibrium reconstruction and two-point-model correction, measurements can be compared directly at matched flux surfaces. Figure 6 shows remarkably similar PDFs and intermittency statistics in the midplane and divertor at $R - R_{\mathrm{VSL}} \approx 12$mm.

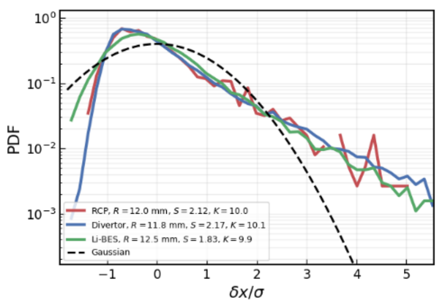

Figure 6: PDFs of I_{sat} at the same radial distance $R - R_{\mathrm{VSL}} = 12mm$ for all three diagnostics, where divertor is mapped to the midplane for comparison. kurtosis for a fixed. Shot number is #13823 with density $n_e = 8 \cdot 10^{19} m^{-3}$

The close agreement suggests that blob properties are largely preserved during parallel transport along the magnetic field line, from the midplane to the divertor target.

Summary

Divertor fluctuations of ion saturation current exhibit the same characteristic statistical signatures as SOL blob transport at the midplane, including Gamma-like PDFs, parabolic (K)-(S) scaling and exponential waiting-time distributions. The consistency of these independent measures indicates that divertor fluctuations are well described by a stochastic Poisson blob process on the COMPASS tokamak. The close agreement of PDFs and intermittency statistics at matched flux surfaces indicates that blob properties are largely preserved from the midplane to the divertor along the magnetic field line, although a more systematic comparison is required to fully quantify this relationship. Next step is to extend the analysis to fluctuations of other plasma parameters, such as electron temperature and plasma potential measured by probe diagnostics, to determine whether the same statistical behavior and conclusions also apply to these quantities. In overall, these results establish divertor probe measurements as a robust tool for quantitative studies of SOL blob intermittency and provide an experimental benchmark for future modelling of blob transport and divertor fluctuations.

Acknowledgements

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