Intermittency in fast ion transport-regimes in turbulent toroidal plasmas

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Introduction

Fast ions commonly designate any fraction of the ion-population in a plasma with energies significantly above the thermal average. They are central to a wide range of phenomena, such as alpha-heating and neutral beam injection in fusion plasmas [1], Solar Energetic Particles (SEP) transport in astrophysical plasmas[2] and more. The propagation of fast ions in a plasma can be influenced by many factors, including turbulence. This interaction of fast ions with turbulence is studied extensively on the TORoidal Plasma Experiment at the Swiss Plasma Center [3].

Set-up and methods

TORPEX features a cold (~ 1 eV) hydrogen plasma in a helical open field-line configuration. Strong fluctuations from interchange-like instabilities drive turbulence that lead to the intermittent formation of coherent plasma filaments drifting outward, so called 'blobs'[4]. These structures are observed with two Langmuir-probe arrays covering the poloidal plane - the HEXagonal Turbulence Imaging Probe Upgrade (HEXTIP-U) [5]. A beam of Li-6 ions ($\lesssim 10\mu A$) is alternating between on- and off-phases at a distinctive frequency, injected toroidally into the region of blob formation and later detected with a set of Gridded Energy Analyzers (GEAs). The set-up is flexible to either record time-traces at a specific position in the poloidal plane or produce a time-averaged profile using lock-in detection. Detailed comparisons with the Global Braginskii Solver (GBS) code reveal several transport-regimes [6] as the radial transport exponent γ_R is determined by measuring the radial beam-variance σ_R^2 and fitting $\sigma_R^2 \sim t^{\gamma_R}$.

Established transport models

During the first orbit of the injected ions, transport appears ballistic ($\gamma_R \simeq 2$). When the influence of turbulent electric fields becomes appreciable, transport is driven primarily by $E \times B$-drifts and, for a given fluctuation amplitude, depends on the fast ion energy. During this 'interaction phase', ions of ~ 70 eV gyro-average over the typical length scales of the turbulent structures and their fields, so that they experience sub-diffusion ($\gamma_R < 1$). For energies of ~ 30 eV, this averaging is diminished and the locally more coherent fields lead to super-diffusion ($\gamma_R > 1$) [6]. Regarding the local time-traces of such ions, it appears that they reflect the intermittency (quantified by the Fisher-Pearson coefficient of skewness [7]) of underlying blobs as transport events, while this is not the case in sub-diffusion[8]. This seemed to corroborate the premise of deducing globally super-diffusive transport from locally intermittent fast-ion time traces, especially in settings with spatially limited data. For a more detailed picture of the interactions between fast-ions and plasma structures, the technique of Conditional Average Sampling (CAS) [8, 9] is employed on the GEA time-traces, using HEXTIP as reference. The last transport phase begins once the beam has spread enough for the radial variation of the plasma parameters to impact the ions asymmetrically. Transport in this ‘asymmetric phase’ is observed to either remain sub-diffusive or reduce from super- to quasi-diffusive ($\gamma_R \lesssim 1$) via locked-in profiles [6]. Time-trace analysis has only succeeded recently due to higher experimental difficulty.

Intermittency in the quasi-diffusive regime

When taking time-traces in the asymmetric phase, the time-average beam-width still agrees with earlier lock-in measurements. However, even in this quasi-diffusive regime, the skewness profile for 30 eV ions still indicates the presence of intermittent transport events. To compensate for the likewise radially increasing intermittency of the background plasma, we statistically combine the total (on-phase) skewness γ_{on} and background (off-phase) skewness γ_{off} to estimate the skewness of the fast ion current signal γ_{sig},

$$\gamma_{\text{sig}} = \frac{\gamma_{\text{on}}\sigma_{\text{on}}^3 - \gamma_{\text{off}}\sigma_{\text{off}}^3}{\left(\sigma_{\text{on}}^2 - \sigma_{\text{off}}^2\right)^{\frac{3}{2}}} \quad ,$$

where σ now denotes the time-trace standard deviations. This form only assumes a negligible covariance between background and ion-signal, which also leads to a simple linear error estimate under 20% up to the location of the highest on-phase skewness. While a minimum at the beam-centre is observed to emerge as in the interaction phase, it is clear that this signal skewness diverges in regions where there is a small SNR, so that the previously reported ’crown’ of skewness [8] around the beam-centre could not be observed. However, this measure does give a stronger quantitative indication that the intermittency is a direct feature of the ion signal.

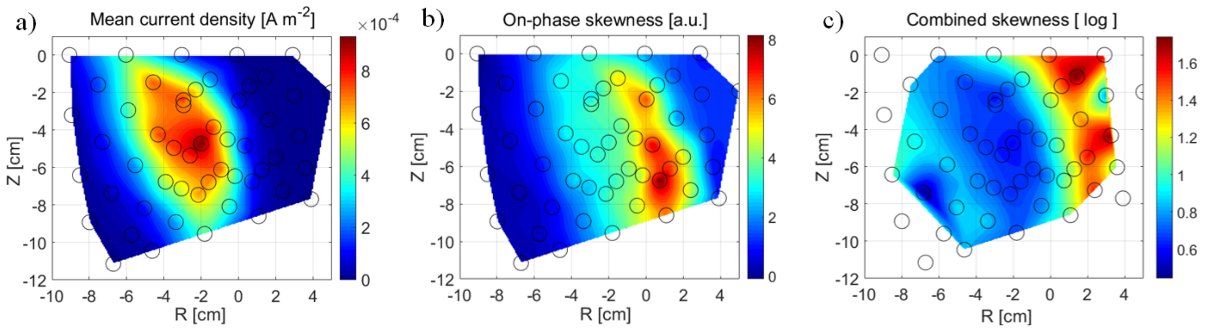

Figure 1: *Profiles of GEA time-trace properties: a) mean (background subtracted), b) on-phase skewness (γ_{on}), c) combined skewness (γ_{sig}) on log-scale for clarity*

An adjusted CAS-technique is used to study the 2D fast ion dynamics in this phase. The background (off-phase) conditional average was subtracted from that of the total (on-phase) and bounded by 0. The average of all negative points served as an error-estimate (usually $\lesssim 20$ %) that was globally subtracted to obtain a reasonable minimum upper bound. In accordance with similar studies in the interaction phase, it could be seen that larger than average blobs still have a stronger effect than smaller ones. However, the redistribution of the fast-ion beam can no longer be simply quantified using its centre-of-mass position, since its width is now comparable to that of blobs and the fast ion time-of-flight ($\sim 60\,\mu$s) to blob life-times. The ion-beam is strongly deformed as it experiences the $E \times B$-drifts induced by the passing fluctuation. This is still in excellent qualitative agreement with the model of blobs being associated with a dipolar structure of the electrostatic potential arising from charge separation induced by ∇B and curvature[8]. The ions are pushed first, then forced to redistribute themselves around the poles, and finally still pulled along to some degree. To corroborate observed trends and employed thresholds, the GEA signal itself was later taken as reference for a CAS of HEXTIP (reverse CAS).

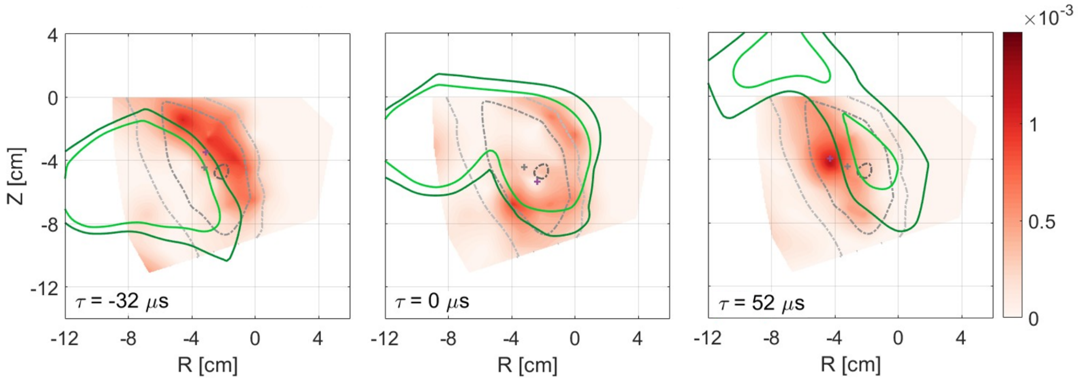

Figure 2: *CAS-profiles (in Am*$^{-2}$*) of the ion beam encountering large (*$n_{peak} \geq 3.5 \times 10^{15}\,m^{-3}$*) structures, given at time-indices (*τ*) relative to the peak at a reference on HEXTIP. The gray contours indicate the time-average ion-beam. The green contours outline the plasma structure at* $n = 5 \times 10^{14}\,m^{-3}$ *and* $n = 10^{15}\,m^{-3}$*. The gray and purple crosses show the centre-of-mass of the average and CAS ion-beam.*

The average blobs tend to decay increasingly close to the outer edge of the profile. This indicates that the change of transport-regime in this phase can in part be related directly to increased waiting-times between transport events. The decaying size of these blobs would in turn diminish transport due to lower $E \times B$-drifts as well as stronger gyro-averaging. Furthermore, it seems that the fast ions redistribute themselves around smaller blobs more locally and quickly, instead of being collectively pushed outward and upward as seen for larger structures. Therefore, a subset of small and mid-sized seems to dominate the distribution of the ion-beam into the lower, outer region of its time-average profile. This is consistently indicated by CAS and reverse CAS and thus seems a main source of the highest intermittency (skewness) measured in this region.

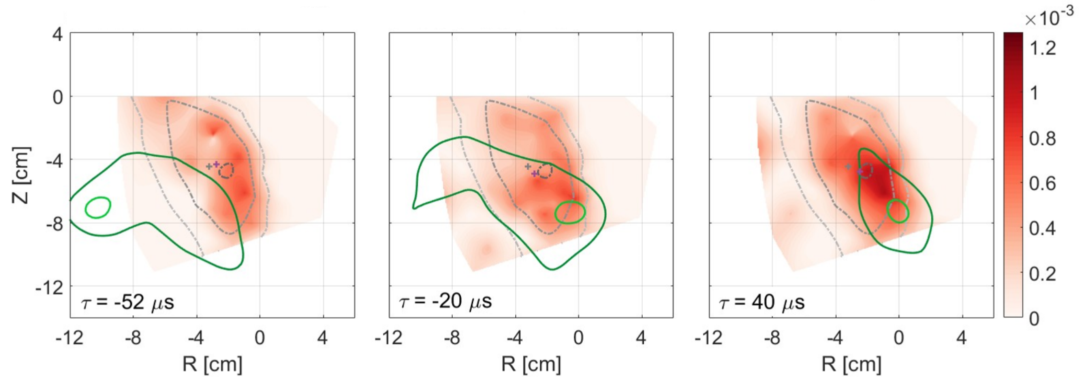

Figure 3: *CAS-profiles (in Am*$^{-2}$*) of the ion-beam encountering smaller (*$n_{peak} \leq 3.5 \times 10^{15}\, m^{-3}$*) structures.*

Conclusion and Outlook

Intermittent (skewed) time-traces of fast ion currents in turbulent plasmas were commonly used to deduce super-diffusive transport[8]. However, our experimental observations suggest - for the first time to our knowledge - that intermittency can also be a feature of quasi-diffusive transport. A detailed analysis using Conditional Average Sampling has been carried out and is consistent with the qualitative model of fast ion redistribution being strongly driven by $E \times B$-drifts around passing coherent plasma filaments (blobs) exhibiting a dipolar structure of the electrostatic potential. While the dependence of diffusivity on the average size of plasma structures has been studies in depth [6], the implications of their temporal evolution in later transport phases are only now in focus. Detailed studies on blob waiting-times and 2D structure analysis are to follow, as well as further comparisons with the GBS code. Extensions for fractional diffusion descriptions [10] are being discussed, as the limits on blob life-times and waiting-times combined with well defined propagation speeds may lend themselves to the definition of truncation length-scales [11] for the non-diffusive propagators.

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