The role of the separatrix in intermittency of SOL turbulence

W. A. Gracias [1,a], P. Tamain[2], L. García[1], R. A. Pitts[3], E. Serre[4]
[1] Universidad Carlos III de Madrid, Leganés 28911, Madrid, Spain
[2] IRFM, CEA Cadarache, F-13108 St-Paul-lez-Durance Cedex, France
[3] ITER Organization, Route de Vinon sur Verdon, CS 90 046, 13067 St-Paul-lez-Durance, Cedex, France
[4] Aix-Marseille Univ, CNRS, Centrale Marseille, M2P2, Marseille, France
[a] current affiliation: ITER Organization, Route de Vinon sur Verdon, CS 90 046, 13067 St-Paul-lez-Durance, Cedex, France (email: william.gracias@iter.org)

Introduction

Tokamak scrape-off layer (SOL) modelling has evolved over the years from 2D fluid models of the gradient and flux driven type [1-3] to more complex 2D and 3D codes that are today attempting to include more and more details in the underlying equations and numerics with fine-scale phenomena (non-"frozen" thermal and electromagnetic fields evolving in time, kinetics/gyrokinetics, neutrals and atomic physics, integration with core models). They are more computationally expensive and more difficult to analyse, but the physics description is more comprehensive. An intermediate approach using electrostatic models is still very useful in studying turbulence and understanding its role in transport for a lower computational cost. The TOKAM3X code is one such robust 3D fluid code in electrostatic and isothermal mode, used here for making quick simulations to gain insight into the dominant transport and flow structures in the SOL [4-6]. In this article, this code is used to study a 3D slab domain that includes a magnetic separatrix and is compared against a case where no separatrix is present; both are devoid of any other geometrical complexities. The differences observed in the transport of the two cases are crucial to singling out and understanding the role played by the presence of a separatrix in the vicinity of the SOL, which represents a shear in the velocity field of the plasma in the edge region. It also demonstrates the robustness of using an electrostatic model to recover many turbulent transport characteristics.

Numerical setup

The passage of plasma particles from nested flux surfaces to open surfaces connecting solid surfaces is marked by the strong parallel velocity component of the particles due to the formation of the plasma sheath at the ends of the field lines at the targets. The 3D slab geometry considered here is 100 larmor radii (ρ_L) radially and poloidally into the SOL, and 14 m in the parallel direction from target to target, and is based on a MAST-like machine. Two types of slabs are analysed (Fig. 1(a)): (a) with separatrix (2 numerical zones i.e. core and SOL), (b) without separatrix (1 numerical zone i.e. SOL). Apart from the presence or absence of the separatrix, all other parameters are kept constant, and the particle source term is located on the radially innermost position of the numerical domain, poloidally and toroidally uniform. More information on the simulations can be found in [7]). In particular, both cases have the same SOL volume and the number of particles entering the SOL is equal. A typical density field snapshot of the poloidal plane (at $\varphi = \varphi_{mid}$) equidistant from both targets after the simulation has reached a turbulent steady state is shown in Figs. 1 (b) & (c).

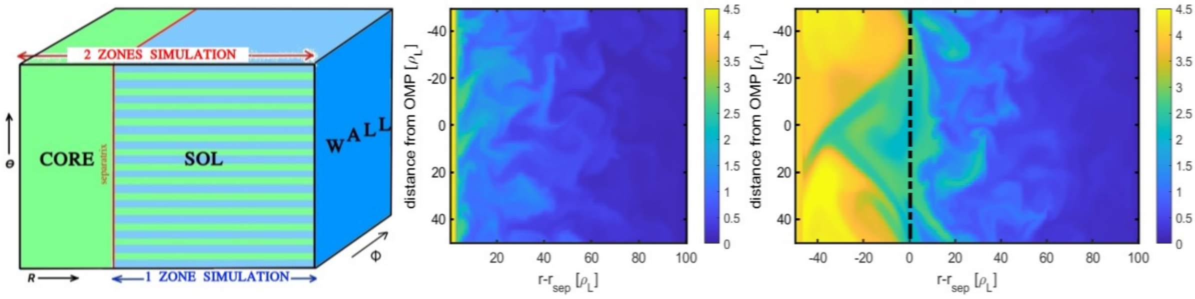

Figure 1: (a) schematic of numerical domain used with green and hashed region for one case with separatrix and only the hashed region for the other case without separatrix; snapshot of density (normalized to 3.e18 m^{-3}) in the poloidal plane φ_{mid} (b) in the case without separatrix and (c) with separatrix

Intermittency: signature of turbulence in SOL

Upon reaching a steady state, the mean radial profiles for the density (N) and potential (ϕ) fields for both the simulated cases are shown in Fig. 2. The steep density shoulder observed next to the separatrix, in the case without separatrix (blue curve) is because of a source term present in the buffer cells near that location, whilst in the case with separatrix (red curve) it is due to the transition from core to SOL via the separatrix. Both cases are well matched in the SOL region, but as shown later, the transport features in either case differ. The mechanisms through which they arrive at these steady state profiles are key to understanding the possible differences that lie in the transport processes.

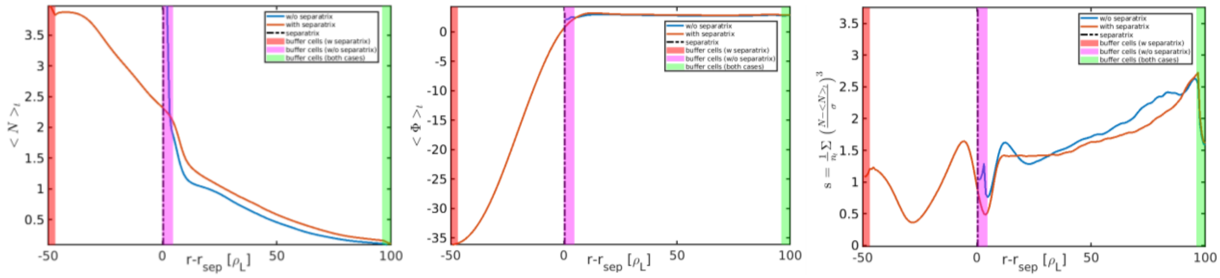

Figure 2: Profiles in the poloidal plane at $\varphi = \varphi_{mid}$ (a) radial profile of N (normalized to 3.e18 m^{-3}); (b) ϕ (normalised to 12 V), (c) skewness of fluctuations of N. All profiles are averaged over all poloidal positions in the poloidal plane.

Fig. 2 (c) shows the skewness of the density fluctuations for both cases where the similarities in the vicinity of the separatrix are significant since only one of the two cases (red curve) actually contains the separatrix, and events occurring radially downstream from the separatrix are influenced by its presence/absence. The radially increasing skewness (and hence intermittency) trend typically observed experimentally in the tokamak SOL (for similar quantities, such as the ion saturation current measured by Langmuir probes) is captured in both cases. The probability density functions of the density fluctuations for the same radial position in both cases (Fig. 3) shows that the number of density fluctuation events detected in the far SOL (green curves) are higher for the case without a separatrix, pointing to a difference in transport in the far SOL over the same time period (the time-series datasets of both cases are of equal lengths). This can be due to a decoupling between near and far separatrix events (via anomalous transport) in the case containing the separatrix. Over the same time period, since one case generates more (or less) numbers of intermittent events, then the temporal dynamics of fluctuating quantities are not be similar in both.

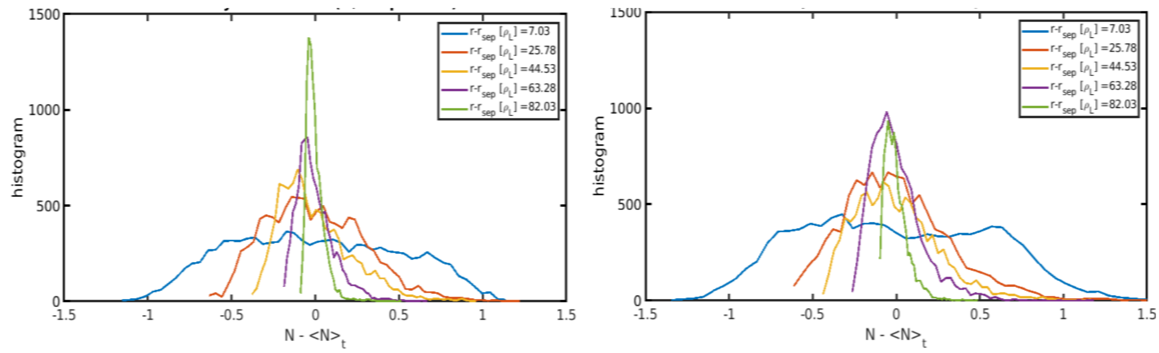

Figure 3: Histogram of density fluctuations for different radial positions: without (a) and with (b) separatrix.

Evidence of different transport mechanisms

The difference in temporal dynamics between the two cases becomes clearer when looking at the conditionally averaged signals for the same radial locations referred to in Fig. 3. The bursty nature (faster rise and slower decay) of the signal is recovered by both cases (see Fig. 4 (top)), but the rise is much faster when a separatrix is present. The reduction in intensity of bursts (i.e. rate of rise and fall of the signal) with distance from the separatrix is consistent with experimental observations of SOL plasma filaments which are observed to be faster for higher filament densities typically found closer to the separatrix, and slower for lower filament densities typically found away from the separatrix [8]. For the case without a separatrix (blue curves), the bursty activity stays the same in intensity relative to the local density and shows no visible trend with changing radial position.

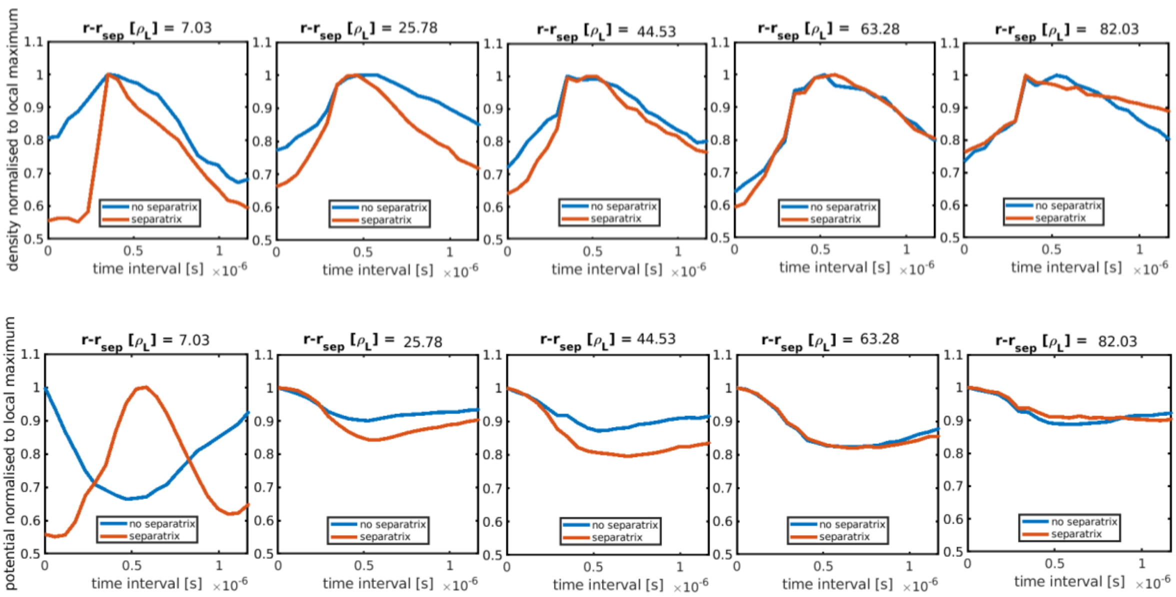

Figure 4: (top) Normalised conditionally averaged waveform for plasma density (threshold at 2 σ); (bottom) Normalised average electric potential corresponding to same time interval of conditionally average density waveform.

The view that the absence of the separatrix in one of the simulated cases is changing the nature of the transport is strengthened further when looking at the density gradient length $L_N(r) =$

$\left[\frac{1}{N(r)}\frac{\partial N(r)}{\partial r}\right]^{-1}$ and its evolution in time for the same dataset for either case. The number of times the local density gradient length exceeds (or drops below) that of the time-averaged density at that location is more frequent in the case when the separatrix is not included (Fig. 5 (a), blue circles and teal dots). Such fluctuations of the density gradient length in time indicate that cross-field transport in the case without separatrix is stronger. In the case with the separatrix, the stronger $E\times B$ shear that is present around the location of the separatrix impedes cross-field transport for that case. And therefore for the case with a separatrix a more or less equal number of positive and negative fluctuations in the density gradient length profile is seen in the same SOL region (Fig. 5 (a) black circles and dots).

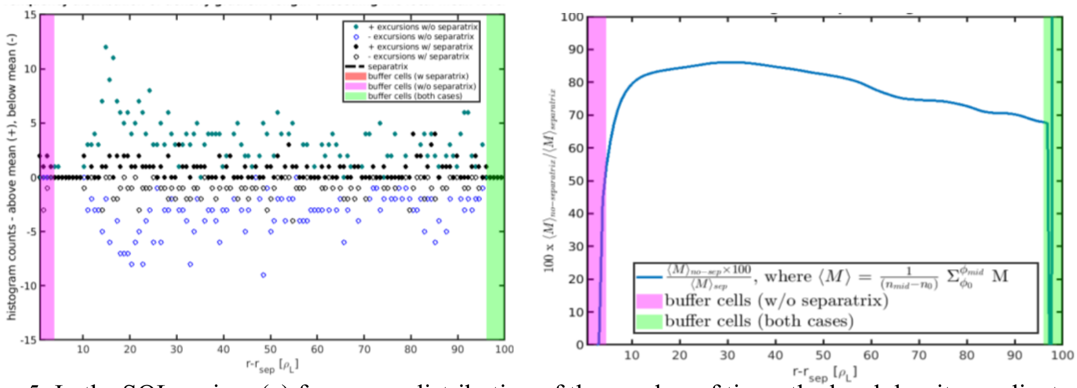

Figure 5: In the SOL region: (a) frequency distribution of the number of times the local density gradient exceeds or drops below the time-averaged mean density gradient; (b) radial profile of the percentage of Mach number (averaged over θ, and from φ_0 to φ_{mid}) for the case without separatrix wrt to the case with separatrix.

Further, it is seen that the average percentage of Mach number for the case without the separatrix (wrt the case with separatrix) increases with radial distance from separatrix location (Fig. 5 (b)). In this case, a good match in parallel transport would show a flat 100% match in the curve in Fig. 5 (b). Via a simple reservoir model, the incoming cross-field transport has to be balanced by the parallel transport in the SOL. The relatively lower Mach number for the case without separatrix is indicative of the higher cross-field transport playing a more dominant role in this case in the near-SOL.

Conclusion

The intermittency transport features were compared in the presence and absence of a separatrix uisng a 3D slab model approximation of the tokamak SOL via the TOKAM3X code. The inclusion of the separatix in the model has shown to provoke changes in temporal dynamics of the intermittent events via modification of cross-field and parallel transport when compared to a case without a separatrix.

Abstract References

1) Garbet, X. et al, Nucl. Fusion 39, 2063 (1999)
2) Garcia, O. E. et al, Phys. Plasmas,12, 062309 (2005)
3) Sarazin, Y., Ghendrih, P., Physics of Plasmas, 5(12) 4214-4228 (1998)
4) Tamain, P. et al, J. Comp. Phys., 321, 606-623 (2016)
5) Galassi, D. et al, Fluids 4, 50 (2019)
6) Gracias, W. et al., Nucl. Matls. and Energy 12, 798-807 (2017)
7) Gracias, W. A., PhD Thesis, Universidad Carlos III de Madrid and Aix-Marseille Université (2018)
8) D'Ippolito et al, Phys. Plasmas 18, 060501 (2011)