The impact of modeling the separatrix in 3D slab edge simulations

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Abstract
The role of the separatrix in triggering instabilities like filamentation in the edge region is not fully understood. 3D fluid simulations for a slab domain with a separatrix are compared to simulations without the separatrix. The differences observed in the transport of the two cases show that the separatrix plays a role in establishing a radial velocity gradient which possibly contributes to establishing global poloidal flows. But simulation without the separatrix continue to replicate near-separatrix features inspite of the absence of the separatrix. While turbulence around the separatrix may be one of the contributing factors to filamentation, these simulations show that filaments are also observed when the separatrix is absent.

Introduction
For magnetically confined nuclear fusion to reach viable levels of steady state operation, gaining insight into the role of the edge region and the separatrix of the confined plasma is key to understanding how good confinement of particles and energy may be achieved. Furthermore, the particles in the edge are evacuated from the plasma via the scrape-off layer (SOL) after they are transported beyond the separatrix along the established radial density gradient which is maintained by the cross-field and parallel transport processes. This transition of particles from a closed field-line region to an open field-line region is accompanied by poloidal flows and turbulence \cite{1, 2} making the study of this region complex. The nature of transport around the separatrix is therefore key to understanding the role of the separatrix in edge transport, and the particle and heat fluxes on the plasma facing components.

2D fluid simulations until a decade ago focussed on simulating only the SOL (by neglecting toroidal effects) and including appropriate numerical boundary conditions to mimic effects like the out-flux of particles from the core on the inner radial boundary, and the recycling of particles at the target surfaces. More recently, 3D fluid simulations have had considerable success in recovering the statistical behaviour of plasma fluctuations in the SOL \cite{3, 4}. Explicitly incorporating a separatrix in these models is an addition of a non-trivial degree of complexity to the already complex physics of edge transport when studied in an electrostatic framework. But more recently, several 3D models have incorporated the separatrix explicitly (and even the x-point) and reproduce globally the turbulence statistics of a typical SOL. The separatrix is believed to play an important role in the triggering of instabilities near the edge, like
filamentation, and in poloidal shear flows and these have been observed in experiments and simulations alike [2]. A closer look at the addition of the separatrix to the problem of SOL transport is needed. In this paper, in an electrostatic framework, slab simulations with a separatrix are compared to those without the separatrix using the TOKAM3X fluid code [3, 4, 5].

The differences observed in the transport of the two cases are crucial to singling out and understanding the role of the separatrix. The simulations are based on MAST-like device in slab domain, with separatrix being the distinguishing feature. The case without the separatrix contains a larger (double) SOL volume, but for the comparisons only the portion of the domain immediately outside the separatrix shall be studied (fig. 1). More details on the simulation parameters can be found in [6]. The separatrix comes into existence due to the presence of closed magnetic flux surfaces next to open magnetic flux surfaces in the SOL and it is the interface that essentially separates these two regions in the edge (see fig. 2). The passage of plasma particles from closed to open flux 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 near the targets.

**Results of statistical analysis**

The density and electrostatic potential field were analysed over long steady-state time series ($\approx 4$ ms) to develop the following statistical picture of the region immediately outside the separatrix. Both cases show a steep drop in density just outside the location of the separatrix (3 (left), solid curves). As for the electrostatic potential field, one notices that the two cases are nearly the same, except for the kinks in the buffer cells for the 1 zone case (3 (right), solid curves). The standard deviation of the density fluctuations plotted (dashed curves) displays a dual slope curve for the 1 zone case thus necessitating the division of the SOL into two regions (dashed green vertical lines), from $\sim 80 – 100$ radial units, and $\geq 100$ radial units.
The potential field fluctuations persist for the 1 zone case far away from the separatrix indicating possibility of turbulent mixing via $E \times B$ drifts very much active even far away from the separatrix location even though it has no separatrix. The density fluctuations in both cases skew positively immediately outside the separatrix indicating the strong presence of higher amplitude fluctuations here (fig. 4, left).

This peaking of both cases occurs $\sim 77$ radial units mark for both cases, before then dropping slightly and increasing again. What can be noted here is that the trend of the first half of the 2 zones curve is radially scaled and spread out over the entire radial domain in the case of the 1 zone case (so also for kurtosis, not plotted here). While this scaling of the 1 zone profile may be linked to the size of its domain, the fact that it replicates the near separatrix trend is nonetheless interesting. The total radial fluxes (poloidal direction is periodic) that are achieved in the vicinity of the separatrix in either case are similar in orders of magnitude, with decaying trends towards the radial end of their domains (fig. 5, left).

The $E \times B$ drift (dashed curves) contributes the majority portion to these fluxes, with the single zone case showing varying slopes compared to the 2 zones case with the separatrix where the curve is more monotonic, re-enforcing the view discussed earlier that the standard deviation here is an indication of active $E \times B$ activity.
Discussion on role of the separatrix

While the differences between the two cases discussed here are subtle, the impact of the separatrix on some fluctuation statistics is present, especially in the region immediately outside the separatrix. And this impact is the clearest when looking at the standard deviation of density and potential fluctuations, and confirmed by the poloidal component of the $E \times B$ drift velocity (fig. 6, left) which shows that the single zone case (red curve) is nearly zero immediately outside the separatrix, whereas for the two zones case there is a strong non-null poloidal component outside the separatrix (blue curve). And this strengthens the picture of poloidal flows that are triggered by transport barriers (such as the separatrix) in the edge [7]. More interestingly, key turbulent properties like the creation of filaments have long been suspected to be linked to the location of the separatrix [8, 9].

Filamentary structures were detected with an algorithm for the two cases. In fig. 6 (right), the trend in radial frequency of detection of the filamentary structures (or blobs) in these simulations seem to cluster outside the separatrix for both cases, in spite of the separatrix not being present in the single zone case. This points to the possibility of multiple mechanism pathways for triggering of filamentary structures (i.e. without a destabilised separatrix) that are out of the scope of this article. As a consequence, it is essential to characterise the universal properties of filamentary transport so as to determine whether their behaviour is truly independent of the mechanisms which lead to their formation. Further detailed studies are needed towards that end with a critical eye on the mechanisms for filamentation.

References