Numerical modelling of an enhanced perpendicular transport regime in the scrape-off layer of ASDEX Upgrade

A. Zito[1,2], M. Wischmeier[1], D. Carralero[3], P. Manz[1,2], I. Paradela Pérez[1]
and the ASDEX Upgrade team[4]

[1] *Max-Planck-Institut für Plasmaphysik, Garching, Germany*
[2] *Physik-Department E28, Technische Universität München, Garching, Germany*
[3] *Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain*
[4] *see the author list 'H. Meyer et al 2019 Nucl. Fusion 59 112014'*

One of the main open issues in nuclear fusion research is finding a way to reduce ion and heat loads striking the plasma-facing components (PFCs) to tolerable values under realistic operational scenarios for a power plant [1]. Recently, focus has been put on the possible effects of a regime of enhanced perpendicular transport in the scrape-off layer (SOL) in this regard. The presence of such a regime is usually attributed to the manifestation of advective transport phenomena in the SOL driven by turbulence, i.e. the radial ballistic propagation of filamentary structures [2].

A regime of enhanced perpendicular SOL transport has been recently observed at the ASDEX Upgrade (AUG) tokamak, where it has been related to a flattening of the SOL density profile at the outer midplane, called a density shoulder, at least in L-mode [3]. The achievement of a partial detachment of the divertor plasma has been also observed in the same conditions [4].

We performed a numerical experiment in order to develop a realistic model to simulate such transport in the SOL, and to clarify the physical mechanisms relevant for the interlink between perpendicular transport, shoulder formation and divertor detachment, in the framework of a realistic AUG scenario [5]. For this we used the SOLPS-ITER code package, which consists in the coupling between the 2D fluid plasma transport code B2.5 and the kinetic Monte Carlo neutral transport code EIRENE, to simulate the AUG L-mode discharge #33341. In the same discharge, which is a D_2-fuelled density ramp, two distinct scenarios were observed: a low density scenario characterized by a 'weak' filamentary transport regime in the SOL and an attached divertor plasma, which we denote as 'Case A', and a high density scenario characterized by 'strong' filamentary transport, a fully formed shoulder and a partially detached divertor plasma, which we denote as 'Case B' [4]. All simulations were performed as coupled B2.5-EIRENE runs. Drifts and currents in the B2.5 equations were neglected.

The simulation activity consisted in trying to obtain, in first instance, the most accurate fit to the experimental data at the outer SOL midplane for both scenarios. The increase of perpendicular transport was modelled through a purely diffusive approximation, i.e. imposing

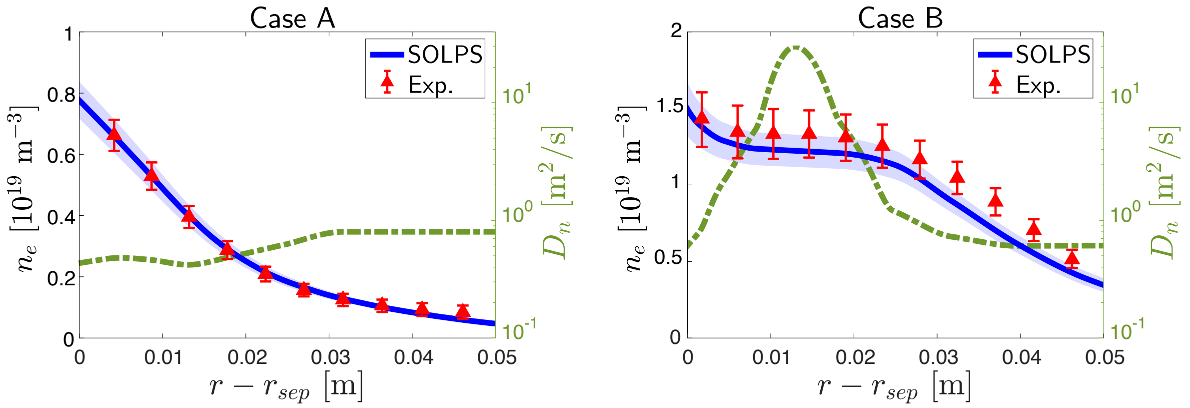

Figure 1: Modelled radial density profiles at the outer SOL midplane (blue solid lines) and comparison with experimental data (red triangles). The imposed particle diffusivity profiles for both cases are represented as green dashed lines.

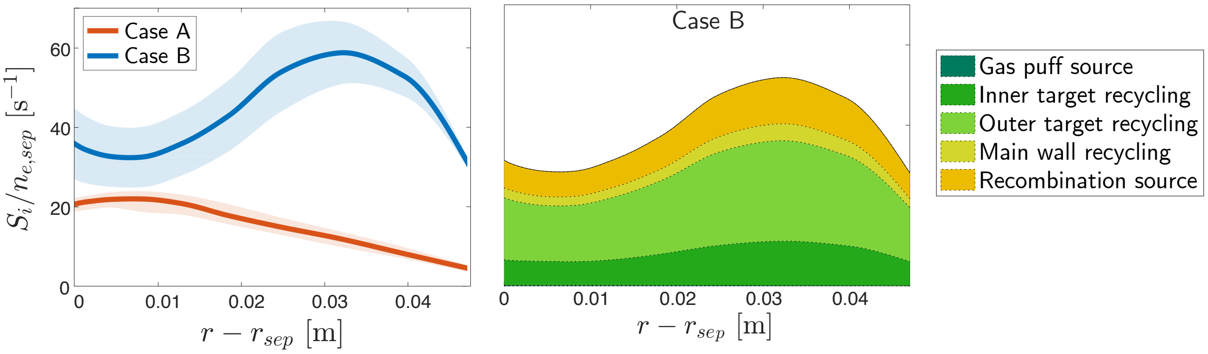

Figure 2: Left: Source of plasma particles by ionization at the outer SOL midplane in both cases, normalized to $n_{e,sep}$. Right: Decomposition of the ionization particle source for Case B in terms of the physical origin of the ionized neutrals (i.e. from the gas puff source, recycled from material surfaces or resulting from recombination processes).

in the simulations an adequate 'effective' particle diffusivity D_n, meant to simulate any processes related to perpendicular particle transport, regardless of their actual nature. Existing theoretical models justify indeed the interpretation of advective perpendicular transport phenomena in the SOL through a diffusive approximation [6].

For this we developed an iterative fitting algorithm, which allowed to find the adequate transport assumptions for both cases for achieving the best match between experimental and numerical plasma profiles (see Fig. 1) [5]. As a result, we found that in Case A the nearly exponentially decaying density profile could be modelled through a diffusivity of the order of the Bohm scaling. In Case B, instead, imposing extremely high values of such a coefficient, of the order of tens m^2/s, was needed in the region of flattened profile.

We found out that, in Case B, the presence of a flattened density profile coincides with a localized peak of the plasma particles source profile by ionization in the far SOL (see Fig. 2). This appears as the natural mechanism preventing neutrals from reaching the separatrix, and thus providing the 'additional' plasma particles in the far SOL to form the shoulder. Divertor recycling was seen as the major origin of these neutrals. Hence a correlation between shoulder formation and recycling profiles at the divertor, suggested in [7], appears plausible.

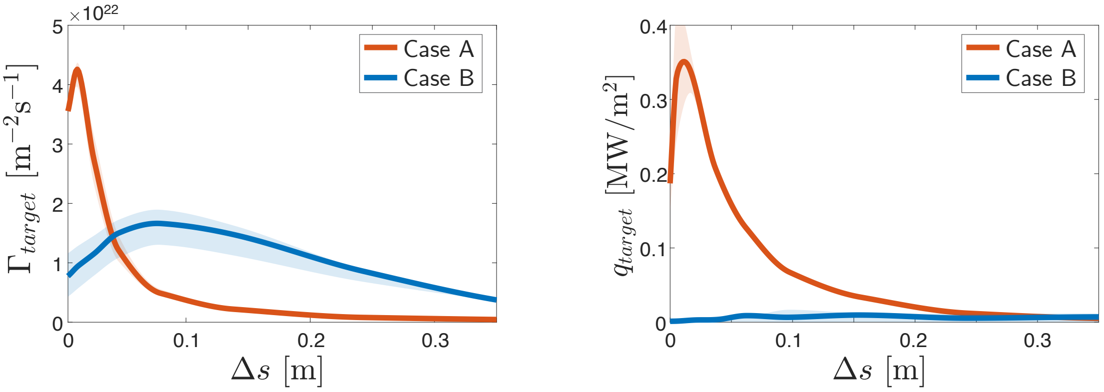

Figure 3: Modelled particle (i.e. ion) flux density (left) and heat flux density (right) striking the outer divertor target in normal direction for all cases. Δs is the distance, onto the target surface, from the separatrix strikepoint.

Additionally we observed that, as a direct consequence of the enhancement of radial particle transport, a significant increase of radial energy transport at the midplane in Case B takes place as well. This leads to a large fraction of the SOL input power still present at the midplane even several cm away from the separatrix, prevailing over the parallel losses, in agreement with the experiment [4]. As one could expect, the observed increase of radial energy transport is mainly driven by convection, which directly follows from an increased radial particle flow. We suggest that this is the main mechanism relating enhanced transport and shoulder formation. Namely, only thanks to the enhanced radial energy transport a sufficient amount of energy might reach the far SOL for sustaining an increased ionization of neutrals.

Investigating the divertor conditions revealed a drop of the ion flux onto the near-strikepoint portion of the outer target and a strong flattening of the heat flux profile onto the entire target in Case B (see Fig. 3), in qualitative agreement with the experiment [4]. This indicates that the experimentally observed detachment has been captured by the simulations as well.

Following the established assumption of a detached regime being related to an increase of parallel momentum losses in the plasma flow from midplane to target [8], we performed a quantitative analysis of momentum dissipation. From the parallel momentum balance equation solved by SOLPS-ITER we derived 2-point formulae relating the upstream and downstream conditions, following [9], and applied them to the numerical plasma solutions (see Fig. 4). In Case B, as expected, a strong increase of the total momentum loss was found, mainly concentrated close to the separatrix, i.e. precisely where the ion flux onto the target drops.

Decomposing this total loss in Case B in its physical components (see Fig. 5) one can see that the bulk of the loss is due to plasma-neutral interactions (e.g. CX collisions). However, a non negligible contribution from radial momentum transport can be observed in the near SOL, consisting in momentum being removed by flux tubes directly following an increased perpendicular particle flow. We suggest that the resulting momentum redistribution from near

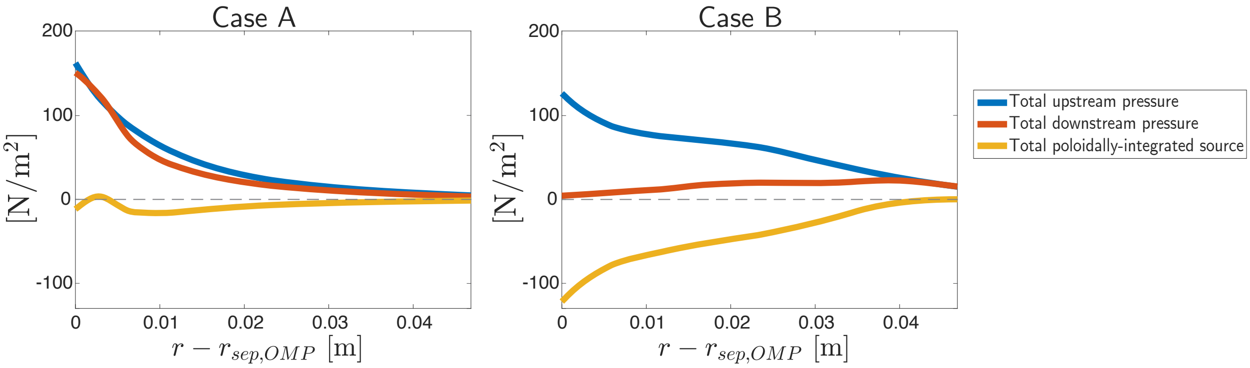

Figure 4: Result of the parallel momentum balance analysis applied to the numerical plasma solutions in both cases. According to such analysis, for each flux tube the difference between downstream (i.e. target, red lines) and upstream (i.e. midplane, blue lines) pressures can be equated to a poloidally-integrated momentum source/loss between such two poloidal locations (yellow lines). Radial coordinates are remapped to the outer midplane.

SOL to far SOL might have contributed in a significant way to drop the pressure onto the near-strikepoint portion of the target, which was already reduced due to plasma-neutral interactions, almost to zero, and hence to access a detached regime.

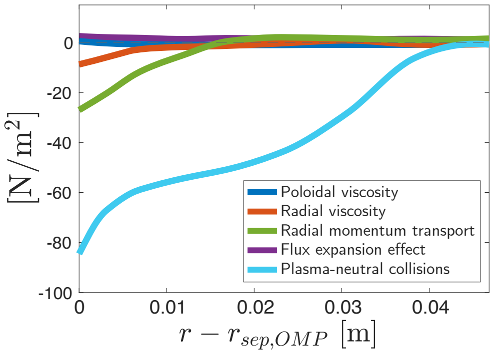

Figure 5: Decomposition of the total poloidally-integrated momentum loss between upstream and downstream for Case B. The sum of all these loss components corresponds to the yellow line in the corresponding plot in Fig. 4.

The performed simulations have shown an overall good match with the experimental data, and have provided possible explanations for the interlink between perpendicular SOL transport, density shoulder formation and divertor detachment which agree with the existing literature. However, further modelling effort might be devoted to improve these results, i.e. activating all drift terms in B2.5 or employing a wall-extended computational grid.

While a detached divertor is desired in future devices in order to reduce heat loads and erosion on the targets [1], a density shoulder is usually related to a risk of severe main wall sputtering [3]. Therefore taking into consideration the impact of perpendicular SOL transport on such phenomema will be essential in view of the design of the PCFs of future fusion devices.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training program 2014–2018 and 2019–2020 under Grant Agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] M. Wischmeier *et al* 2018 *27th IAEA Fusion Conf. (Gandhinagar)*
[2] D. Carralero *et al* 2015 *Phys. Rev. Lett.* **115** 215002
[3] D. Carralero *et al* 2017 *Nucl. Fusion* **57** 056044
[4] D. Carralero *et al* 2018 *Nucl. Fusion* **58** 096015
[5] A. Zito *et al* 2021 *Plasma Phys. Control. Fusion* **63** 075003
[6] P. Manz *et al* 2020 *Phys. Plasmas* **27** 022506
[7] A. Wynn *et al* 2018 *Nucl. Fusion* **58** 056001
[8] P.C. Stangeby 2000 *The Plasma Boundary of Magnetic Fusion Devices*
[9] V. Kotov and D. Reiter 2009 *Plasma Phys. Control. Fusion* **51** 115002