Numerical modelling of underexplored edge plasma scenarios in tokamaks using the SOLPS-ITER code

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The control of edge plasma and the associated phenomena—namely power exhaust, impurity control, and plasma–wall interaction (PWI) mitigation—remains one of the major challenges on the path toward magnetic confinement nuclear fusion. Alongside experimental analysis, numerical modelling plays a key role, not only in interpreting available results but also in providing predictive capabilities for scenarios not yet accessible in experiments.

In this context, this contribution numerically investigates two fusion-relevant, experimentally implemented edge plasma scenarios. The first focuses on comparing power exhaust properties in L-mode negative and positive triangularity discharges in the TCV tokamak. The second explores the edge characteristics of helium (He) H-mode plasmas in ASDEX Upgrade (AUG), with the goal of advancing the understanding of He behaviour under reactor-relevant conditions.

Both case studies are addressed using the same computational framework: the SOLPS-ITER code [1, 2], a state-of-the-art boundary plasma package that couples the non-turbulent multifluid plasma solver B2.5 with the kinetic Monte Carlo neutral transport code EIRENE. The results of the first investigation have been extensively discussed in the recent work by Mombelli et al. [3], to which the reader is referred for further details. The present paper is thus devoted to the analysis and discussion of the second scenario.

The SOLPS-ITER-based analysis of H-mode He plasmas in AUG aims to support the interpretation of dedicated PWI experiments [4] and to provide a well-characterized inter-ELM background plasma for subsequent erosion analysis with the ERO2.0 code. To the best of our knowledge, this represents the first application of SOLPS-ITER to H-mode He plasmas in AUG, and follows up on previous modelling efforts of L-mode He discharges [5].

The discharge analysed (#41471) is heated via Electron Cyclotron Resonance Heating and sustained by hydrogen Neutral Beam Injection (NBI). Experimental upstream profiles are obtained through the Integrated Data Analysis (IDA) algorithm, combining multiple diagnostics. Electron temperature and ion saturation current profiles at the outer divertor are provided by Langmuir probes (LPs) and filtered to exclude ELM-induced transients.

The simulation setup involves generating a computational mesh based on magnetic equilibrium reconstruction (Figure 1a), and defining pumping surfaces with absorption probabilities set according to the experimental pumping speeds. Boundary conditions include sheath conditions at the divertor targets and decay-type conditions for particles and energy at the outer Scrape-Off Layer (SOL) and Private Flux Region (PFR) boundaries (with λ_{decay} = 3 cm). The power entering the core boundary is set equal to the total heating power minus core radiative losses (~7 MW). A Dirichlet condition is applied at the core boundary for the He^{++} species to match the corresponding electron density to the experimental value, which ensures a consistent particle source and allows the manual gas puff to be set to zero. Drifts are turned off.

The modelling is carried out in steps of increasing complexity: starting with a pure helium plasma, then introducing hydrogen from the NBI to assess its impact on divertor fluxes, and finally adding a small fraction of radiating impurities to evaluate their effect on plasma profiles.

Under the assumption of a pure helium plasma, a good agreement with experimental data requires prescribing radially dependent profiles of anomalous particle and heat diffusivities with a typical "well-shaped" structure. This allows for the reproduction of the edge transport barrier characteristic of the H-mode regime. The resulting plasma profiles from the optimized transport setup are shown in Figure 1b. A radial shift of 5 mm towards the core has been applied to the experimental data, in line with the uncertainty affecting the separatrix position determination.

The simulation reveals an overestimation of the electron temperature (T_e) at the outer target (OT). However, it should be noted that some of the LP data points, particularly around 0.15 m along the divertor coordinate, appear to be scattered and may be affected by probe-related artefacts. This could partly contribute to the observed mismatch with simulations.

Analysis of particle fluxes to the OT indicates that both charge states, He^{+} and He^{2+}, contribute comparably to the total ion flux at the outer strike point—consistent with previous observations in L-mode, though with higher overall saturation current. Notably, He^{+} becomes the dominant ion species in the PFR (Figure 1c).

Hydrogen (H) is introduced by applying a Dirichlet boundary condition at the core boundary of the computational domain for the H^+ species (n_{H+}), similarly to what is done for He^{2+} (n_{He2+}). The boundary values are set such that the sum $n_{H+} + 2\, n_{He2+}$ matches the experimental electron density at the core boundary, and the He-to-electron density ratio (n_{He}/n_e) ranges between 40% and 45%, in agreement with experimentally measured core concentrations. The inclusion of H requires adjustments to the definition of pumping surfaces and their associated absorption probabilities—particularly for segments corresponding to cryopumps, which are ineffective for helium, and a reoptimization of anomalous transport coefficients.

The presence of H leads to a slight increase in the electron temperature at the outer target. H^+ competes with He ion species in contributing to the ion flux at the OSP, and, together with He^+, dominates the fluxes to the divertor target in the PFR (Figure 2b), where it tends to accumulate (Figure 2a). The plasma profiles discussed so far systematically overestimate the electron temperature at the outer target, suggesting a possible role of impurities—unavoidably present in the divertor region—that have so far been neglected.

To assess this effect, a nitrogen (N) gas puff was introduced in the divertor region, and its impact on plasma profiles was evaluated. N, which is typically present to some extent in ASDEX Upgrade discharges, was selected due to its strong radiative properties, serving as a proxy for a range of realistic impurities, including not only N itself but also carbon, oxygen, and tungsten. As the N puff rate increases, a clear reduction in T_e @ OT is observed, while upstream profiles remain essentially unchanged, thereby enabling the numerical plasma solution to closely reproduce the experimental profiles (Figure 3).

This work applied the SOLPS-ITER code to model helium H-mode plasmas in ASDEX Upgrade—an underexplored but relevant scenario for studying helium–first wall interactions in future fusion reactors. It provided a systematic analysis of divertor fluxes and a well-optimized background plasma, forming the basis for subsequent erosion modelling with ERO2.0, to be validated against available erosion experimental data in ongoing work.

References

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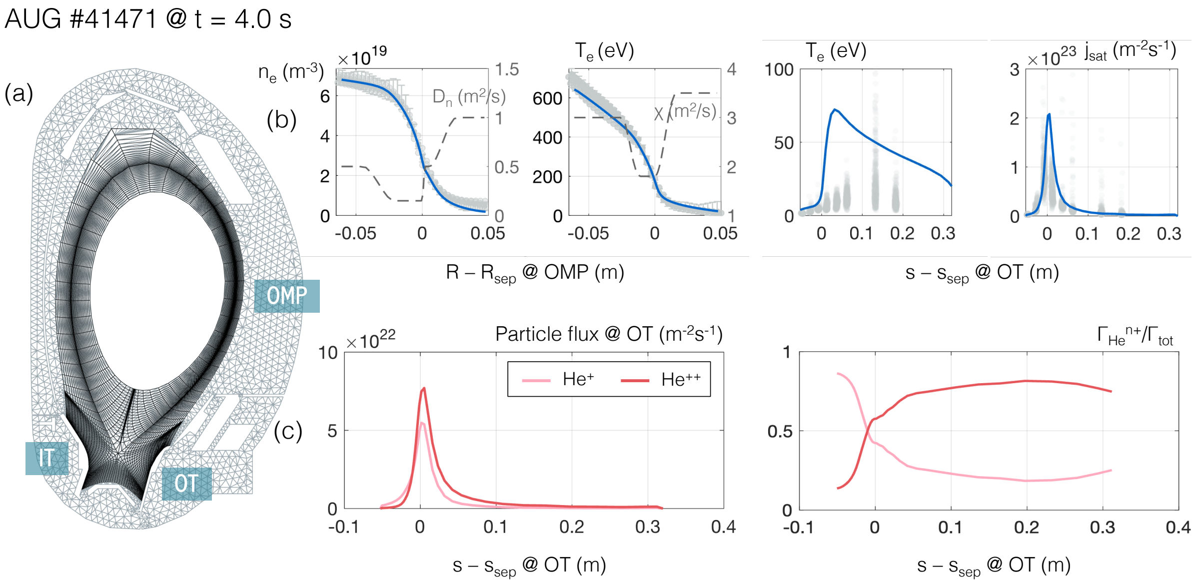

Figure 1. (a) B2.5 and EIRENE computational meshes, in black and grey respectively. (b) Comparison between optimized SOLPS-ITER plasma profiles for pure He case at Outer Midplane (OMP) and Outer Target (OT) and corresponding experimental data, and choice of particle and heat anomalous diffusivity profiles. (c) Analysis of He^{+} and He^{2+} fluxes to the OT: absolute magnitudes and ion flux fractions.

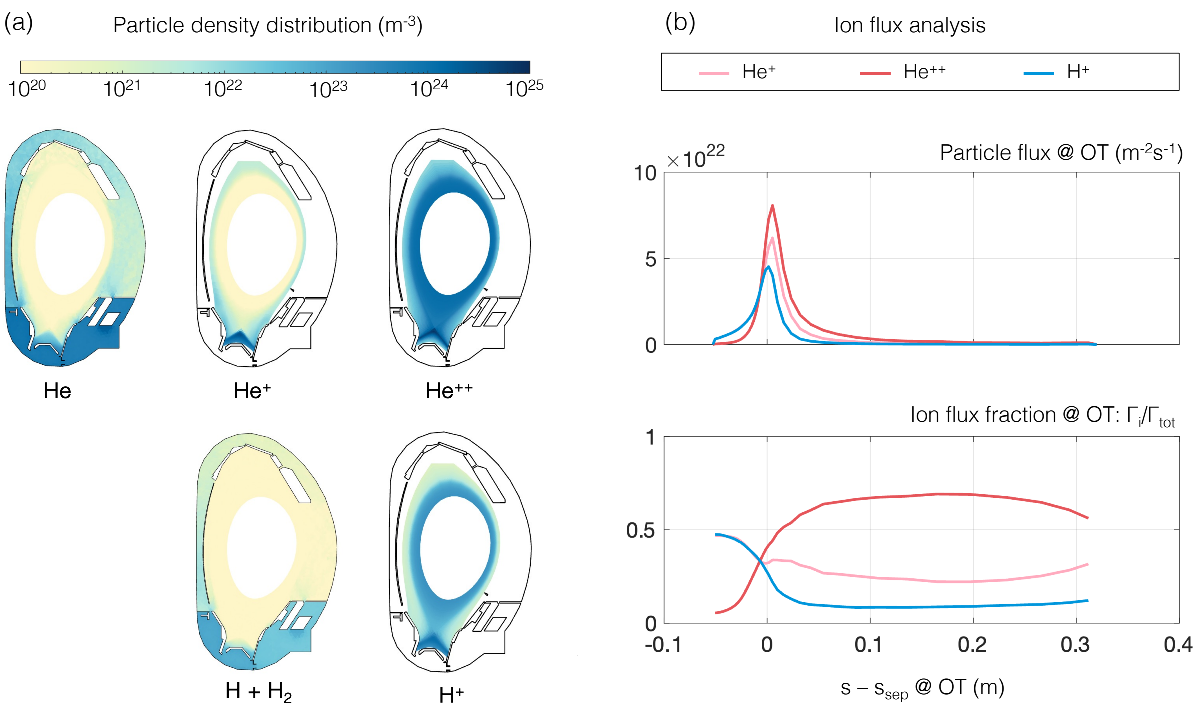

Figure 2. (a) Distribution of He and H plasma species over the computational volume in simulations performed with $n_{He}/n_e = 45\%$ at the core boundary. (b) Corresponding analysis of He^{+}, He^{2+} and H^{+} fluxes to the OT.

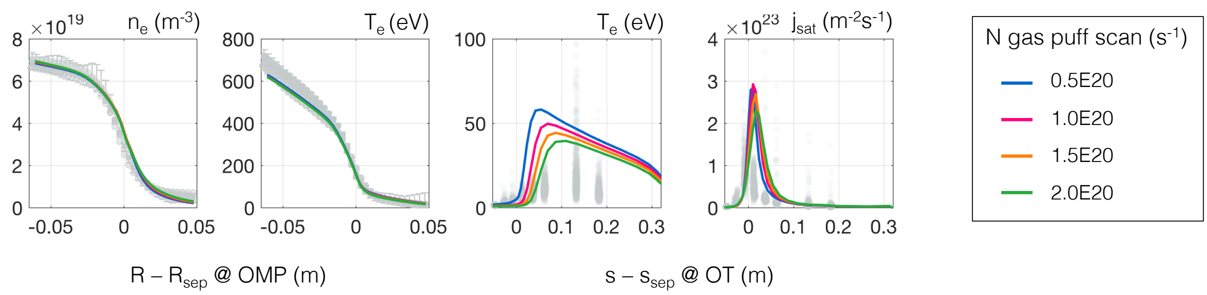

Figure 3. Plasma profiles for He + H + N case, resulting from a scan in N gas puff strength.