

Validation of time-dependent boundary plasma simulations with SOLPS-ITER against dynamic detachment experiments in the ASDEX Upgrade tokamak

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Introduction

Detachment will be essential in future fusion reactors to keep the heat flux to the divertor surfaces within material limits. Time-dependent plasma boundary simulations could be an important contributor to power exhaust control design. SOLPS-ITER [1, 2] (Scrape-Off-Layer Plasma Simulator) is a mean-field plasma boundary code, historically used for the ITER divertor design. However, the code has been mostly used in steady-state, with only few recent attempts in dynamic mode [3, 4, 5]. This is partly because a fundamental validation of the code in time-dependent mode against experiments is missing.

The code consists of two main submodules: B2.5, a Braginskii finite-volume solver for the plasma fluid species, and a neutral solver, which has traditionally been the kinetic Monte Carlo (MC) code EIRENE, solving the Boltzmann equation. More recently, Advanced Fluid Neutral (AFN) models [6, 7] have demonstrated an accurate description of hydrogenic neutrals in high-collisionality regions. These models allow the neutral background to be computed by solving additional fluid equations within B2.5, reducing computational cost and avoiding the statistical errors inherent to MC approaches. In addition, the time-dependent algorithm of B2.5 has recently been numerically verified and improved [8] in the ‘wide-grids’ 3.2.1 code version [9]. In this contribution, we aim to validate SOLPS-ITER, using AFN neutral models, against dynamic detachment experiments in the ASDEX Upgrade (AUG) tokamak.

Experimental scenario

The experiments aim to produce a transient from an initial attached state to a final detached state. To keep the modelling simple, the detachment is triggered with a step in Deuterium (D)

puffing in the divertor, rather than impurity seeding. To make this possible, a low-power L-mode scenario is used, as detachment cannot otherwise be achieved with D only. The discharge is therefore purely Ohmically heated at approximately 600 kW.

The temporal evolution of the gas puff is shown in fig. 1, together with a proxy for the divertor temperature estimated from the shunt divertor current current, during discharge #42651. The puff is increased from an initial value of $2.3 \times 10^{20} \text{ Ds}^{-1}$ to $8.3 \times 10^{21} \text{ Ds}^{-1}$, leading to a drop in divertor temperature from $\sim 12 \text{ eV}$ to $\sim 2 \text{ eV}$, characteristic of detached conditions.

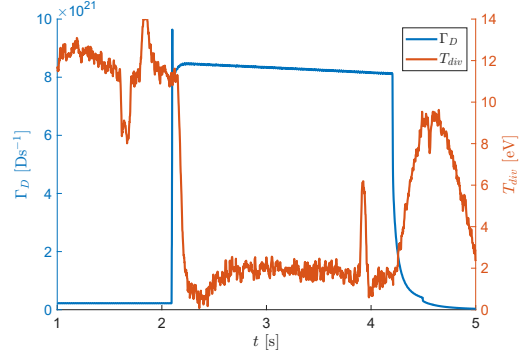


Figure 1: Gas puff signal (blue) and divertor temperature T_{div} (orange) during discharge #42651.

SOLPS-ITER Simulation

The SOLPS-ITER computational grid (fig. 2) is generated from the magnetic equilibrium. The puff is imposed (see location in fig. 2) close to the experimental values: starting from $2.8 \times 10^{20} \text{ Ds}^{-1}$, it is increased to $8.3 \times 10^{21} \text{ Ds}^{-1}$. The reflection coefficient at the simulated pumping surfaces (see location in fig. 2) is $R = 0.945$, corresponding to 5.5% neutral pumping on that surface. An ionizing core boundary condition is applied, where the neutral flux leaking in the core is returned as ion flux. The power through the core boundary is set to 400 kW, obtained by subtracting estimated core radiation from the 600 kW of Ohmic heating, split equally between ions and electrons. Anomalous transport coefficients are tuned to match experiments: $D_{\perp,core} = 0.18 \text{ m}^2\text{s}^{-1}$; $D_{\perp,SOL} = 0.4 \text{ m}^2\text{s}^{-1}$; $\chi_{e/i} = 0.7 \text{ m}^2\text{s}^{-1}$. The simulations include the electric potential equation, ensuring current continuity, but neglect plasma drifts. The AFN equations include a separate energy equation for D atoms.

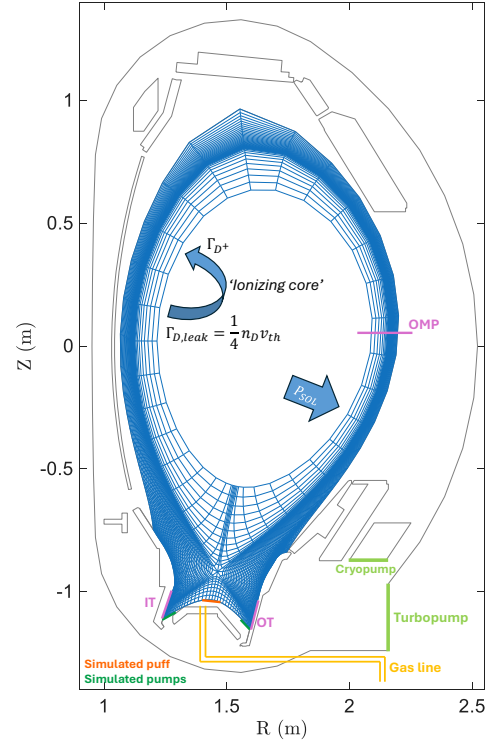


Figure 2: SOLPS-ITER grid based on magnetic equilibrium of AUG discharge #42651.

Steady-state

Figure 3 shows experimental and simulated profiles at the outer midplane (OMP). The puff increase leads to a higher electron density. Given the similar power level, the electron temperature drops. The initial state is well reproduced by the simulations, with only the temper-

ature being overestimated in the core. In the final state, the agreement remains good in the SOL, but the simulated core density is about a factor of two lower than in the experiment.

Outer target (OT) profiles (fig. 4) are obtained from 4 Langmuir triple probes measuring ion saturation current J_{sat} and electron temperature T_e , from which electron density n_e and pressure p_e are derived. The initial state is clearly attached, with peaked profiles near the strike point

and temperatures up to 20 eV. In the detached state, the temperature becomes flat around 1 eV, and the peak of the other quantities shifts further from the strike point. The simulations reproduce well the strike-point values in the initial state, although decay lengths are slightly mismatched and T_e is overestimated in the far SOL. In detached conditions, T_e from LP is unreliable; since n_e and p_e depend on it, only J_{sat} can be compared, for which the agreement between simulations and data is very good. However, the limited number of probes makes it difficult to know the peak location.

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Time-dependent

Time-dependent simulations are performed using a 2nd-order backward differentiation scheme [8] with a time step of $\Delta t = 10^{-6}$ s. A key aspect is that the gas flow is measured at the beginning of a 5-m long pipe, with a diameter of 4 mm. The simulated puff is however at the end of such pipe. To estimate the temporal evolution of

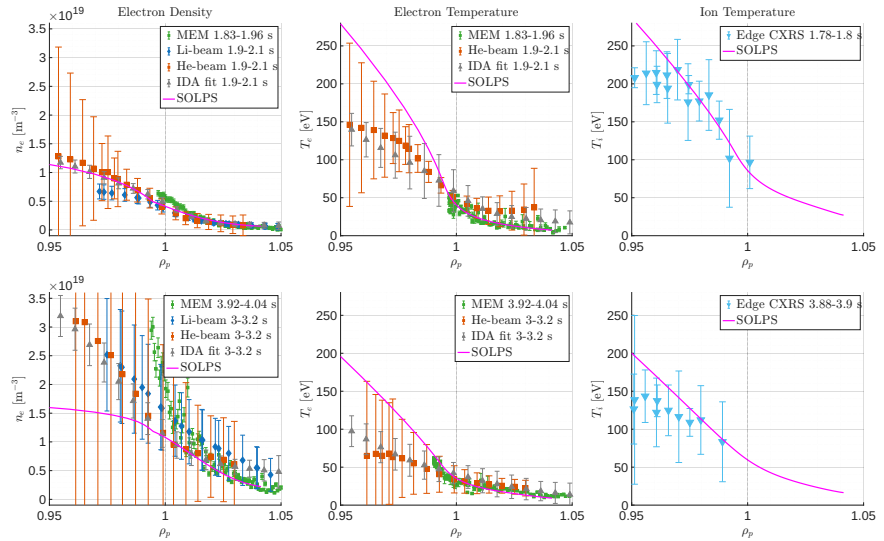


Figure 3: Outer midplane profiles of initial (upper row) and final (lower row) states. Diagnostics: MEM = midplane manipulator probe; IDA = Integrated Data Analysis of Li and He beams. CXRS = charge exchange recombination spectroscopy.

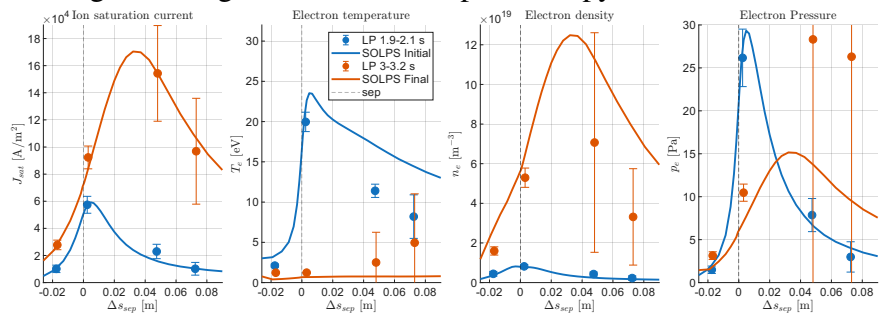


Figure 4: Outer target profiles of initial (upper row) and final (lower row) states. Diagnostics: LP = Langmuir triple probes.

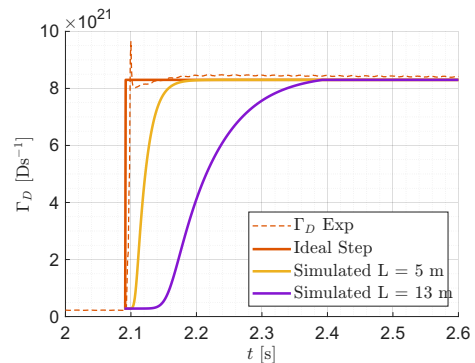


Figure 5: Gas flow at the end of a pipe: 0 m (ideal step), 5 m, 13 m.

the gas flow at the end of the pipe, when a step is imposed at the beginning of it, a 1D fluid model from [10] is used. The resulting trace for the 5 m pipe is shown in fig. 5, but underestimates the experimentally observed delay of ~ 70 ms, which can be recovered with a length of 13 m. Starting from the attached state, these puff profiles are applied in the simulation. Figure 6 shows the evolution of key quantities, compared with experimental traces. Comparable dynamics are only recovered when using the 13 m pipe. The need for an extended pipe length suggests either limitations of the pipe model or additional slow dynamics not captured (e.g. core). To clarify this, dedicated experiments will measure the delay by injecting gas into the empty vessel.

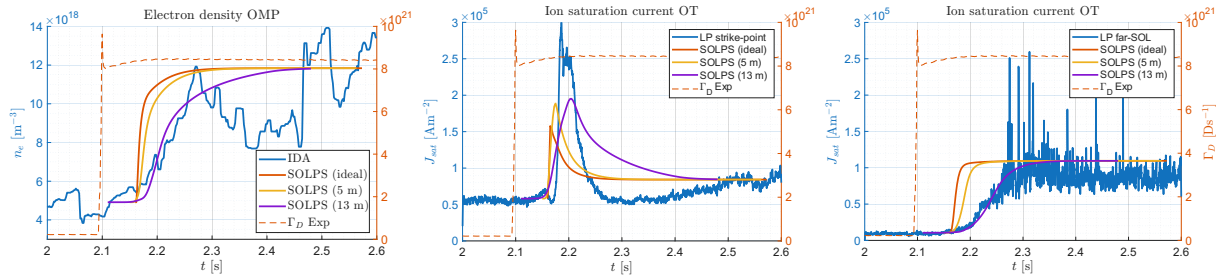


Figure 6: Time traces of main quantities during SOLPS simulation compared with experimental data: left: $n_{e,sep}$ at the OMP; center: J_{sat} at the strike point; right: J_{sat} in the far-SOL.

Conclusions

In this contribution, SOLPS-ITER with AFN neutral models was able to reproduce qualitative trends observed in experiments of dynamic detachment in AUG. Further work is required to achieve better quantitative agreement. Several key uncertainties remain and are subject of ongoing investigations: core dynamics, kinetic neutrals, molecular physics, pipe model, first wall recycling. Overall, the experimental scenario was not optimal for isolating fast SOL dynamics, as slower processes such as gas flow in the pipe affect the time evolution. New H-mode experiments are planned to better decouple upstream quantities from the divertor, although impurity seeding will be required.

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