MODELLING DIVERTOR SOLUTIONS FOR POWER EXHAUST: IN-DEPTH EXPERIMENTAL VALIDATION IN TCV

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Power exhaust remains a critical challenge for tokamak-based nuclear fusion, requiring accurate prediction and mitigation of heat loads on divertor targets. Increasing divertor closure and exploiting alternative divertor configurations (ADCs) are identified as effective strategies for reducing heat and particle flux to the divertor. The Tokamak à Configuration Variable (TCV) [1] is well-suited for investigating both approaches. The Power Exhaust (PEX) upgrade [2], with replaceable baffles, enables systematic studies of divertor closure effects, while TCV's magnetic configuration flexibility facilitates the exploration of divertor configurations with variable flux expansion and multiple X-points [3]. TCV has wide diagnostic coverage in the divertor region, providing data on electron and ion temperatures (T_e, T_i), electron density (n_e), ion parallel velocity ($v_{i,||}$), deuterium (D$_\alpha$) and impurity (e.g., CIII) emissivity, wall heat fluxes ($q_\perp$), and neutral pressure (p_n). Herein, these measurements, acquired in tailored L-mode discharges in TCV, form a detailed experimental database for validating SOLPS-ITER simulations [4,5].

A Long Leg Divertor (LLD) scenario (Figure 1.a), which maximises divertor diagnostic coverage, is first considered. Sweeping the outer leg at fixed core density provides two-dimensional maps of T_e and n_e from divertor Thomson Scattering (TS), T_i and $v_{i,||}$ from a novel Tangential Divertor Spectroscopy System (TDSS), for direct comparison with edge simulations. A synthetic diagnostic based on SOLPS results generates CIII emissivity maps, that are compared to tomographic reconstructions from TCV Multispectral Imaging System (MANTIS). This demonstrated the influence of species-dependent chemical sputtering in accurately predicting carbon concentration and distribution in the divertor. Ongoing efforts focus on implementing wide-grid SOLPS simulations to include also the main chamber carbon source consistently.

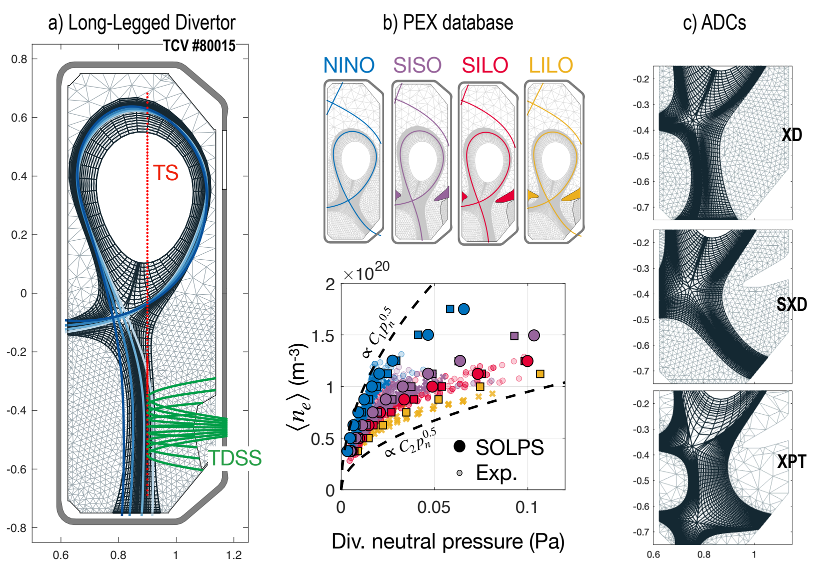

Figure 1: The different power exhaust solutions used for SOLPS-ITER validation. (a) SOLPS-ITER mesh and experimental diagnostic coverage for the LLD. (b) Line integrated core density vs. divertor neutral pressure for different baffle configurations: SOLPS-ITER vs. experiments and analytical predictions [2]. (c) Different ADCs investigated using SOLPS-ITER.

The PEX experimental database, collected from the repetition of a reference L-mode scenario across all TCV campaigns employing diverse baffle configurations, is employed to assess SOLPS's ability to quantitatively reproduce the experimental power dissipation across different levels of divertor closure. Legacy SOLPS-ITER simulations were

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found to overestimate dissipative effects in the divertor of TCV by predicting overly dense and cold target conditions [6]. This work addresses core-edge coupling by informing SOLPS-ITER simulations with core transport models from the JINTRAC framework. Kinetic corrections in the scrape-off layer, implemented as ion flux limiters, are shown to significantly impact target conditions and are the subject of detailed study. The availability of an extensive experimental dataset, combined with several refinements in the plasma description, has significantly improved the agreement between simulations and experiments. Figure 1.b compares simulated and experimental divertor neutral pressure as a function of the line-averaged density $\langle n_e \rangle$, showing quantitative consistency of the results and reproducing the increase of neutral compression with larger divertor closure.

The power exhaust performance of several ADCs is analysed by comparing a reference Lower Single-Null (LSN) L-mode scenario with similar X Divertor (XD), Super-X Divertor (SXD) and X-Point Target (XPT) scenarios (figure 1.c). Substantial advantages are observed in the XPT configuration, while the sole flux expansion of the SXD and XD was of limited benefit compared to the LSN. SOLPS-ITER simulations performed for these configurations show similar trends and provide a unique and valuable insight into the physics of power exhaust in ADCs.

This work benefits from the effective use of convergence speedup schemes, which facilitate the study of drift-related effects without substantially increasing the simulation time. This comprehensive model investigation, based on systematic comparisons between simulations and tailored experiments, represents a significant advance in SOLPS-ITER code validation.

Insights from modelling existing scenarios have been instrumental in the predictive modelling of TCV's upcoming divertor upgrade [7]. The Tightly Baffled Long-Leg Divertor (TBLLD) implements tighter neutral baffling around the outer divertor leg, increasing neutral density gradients towards the target and resulting in enhanced particle and heat dissipation. Preliminary simulations using the refined SOLPS-ITER model indicate that the TBLLD can achieve high levels of plasma detachment while maintaining effective impurity control, making it a promising candidate for addressing the power exhaust challenge in future fusion reactors.

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