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STEP divertor design –finding a balance between multiple constraints

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Aiming at building a prototype reactor based on the spherical tokamak (ST) concept by 2040, the Spherical Tokamak for Energy Production (STEP) programme has just entered the second tranche (2025-2032) which focuses on detailed design work. As part of the broader machine design effort, significant progress has been made on the divertor, addressing both physics and engineering challenges.

Based on previous work, the current design has a double-null configuration with an inner X-divertor and a tightly baffled, extended outer divertor leg. The power entering the SOL, assumed to be Psep~150 MW, is dissipated using argon (Ar) seeding both from the outer and inner legs. Due to space limitations, only the outer divertor leg is actively pumped. A dome is included to aid transfer of neutrals from the inner leg to the outer leg.

To further improve the design, we have primarily worked on the following three areas: 1) Impurity distribution (minimising the impurity fraction upstream to improve core-edge integration), 2) impact of drifts, and 3) risks during transients.

For core-divertor compatibility, we first assessed the impact of fuelling location on the Ar distribution using the SOLPS-ITER code. This demonstrated the potential to reduce the upstream Ar content by fuelling from the inner-midplane as it affects the friction/thermal forces on the Ar ions from the background plasma. Regarding He, a preliminary result of an integrated core-edge simulation predicted an intolerable helium (He) concentration in the core (~11%) without increasing the pump speed, at least by a factor 4. Using SOLPS-ITER, different pump locations were explored. This showed that pumping from the private flux region together with a vertical target geometry may reduce the upstream He concentration, albeit at the cost of more difficult detachment access (target temperature < 5eV across the entire target).

Significant effort has gone into increasing fidelity beyond existing simulations by activating particle drifts. Preliminary results with fully activated drifts for the complete set of species (D, Ar and He) show some opposite trends to earlier drift-activated simulations with evolving D and a fixed fraction of Ar, suggesting that drift effects may play an important role in Ar transport.

Transient phases, not just the flat-top/burning phase, also pose challenges. One concern is detachment front movement due to power oscillation. This has been studied with the DLS(detachment location sensitivity)-Extended, which indicated that fully detached outer legs should withstand regular transitions to SN but further design optimisation is required to improve the stability and detachment window of the inner divertor.

To rapidly evaluate STEP plasma exhaust conditions during the current ramp phases, we developed the reduced model DART (Detachment Analysis with Reduced modelling Tools), which has been validated against a large database of STEP SOLPS-ITER simulations and experiments on AUG, JET, and MAST-U. Predictions from DART indicate that high levels of Ar seeding (2-3%) are required throughout the majority of the entire plasma scenario and that the densification phase at the end the current ramp-up is a key area of concern for core-edge compatibility.

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