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Defining Operational Scenarios for DTT in metallic environment: A Modeling Study of Core-Edge Dynamics and Plasma-Wall Interaction

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This study presents an integrated modelling effort for the Divertor Test Tokamak (DTT) experiment, the new nuclear fusion device currently under construction in Frascati [1]. The DTT experiment with full metallic divertor and first wall (W made) has been designed to address challenges in plasma control and plasma-wall interactions (PWI) while providing insights for ITER operation [2]. The integrated predictive modelling covers the core, edge, and plasma-wall interaction regions. This is essential to optimise tokamak performance, ensure compatibility with engineering constraints, and contribute to machine design [3][4].

Several operational phases are currently evisaged for DTT, which will operate over a range of magnetic fields, currents, and auxiliary input powers [5]. The following three main nominal scenarios have been defined and addressed in this work: Scenarios A, C, and E [6], representing increasing values of magnetic field (2.9, 5.85 T), current (3, 5.5 MA), and P_{add} (7, 14, 45 MW).

The overall activity is aimed at simulating DTT operational scenarios, including the ramp-up to the flat-top phase. In this study we focus in particular on the edge and plasma-wall interactions which in a metallic device such as DTT need to be optimised to achieve optimal plasma conditions that reduce W contamination. The aim of the study for the ramp-up phase is to reduced loop voltage (V_{loop}) and minimise sputtering [7] particularly during the limiter phase; in this phase, W accumulation in the core can deny the transition to the H-mode [8] by increasing the radiation and reducing the power crossing the separatrix. In the flat-top phase, the focus is on determining edge plasma parameters, such as the separatrix density and the impurity concentration, to achieve the plasma performance required to study the power dissipation in conditions as close as possible to those expected in ITER and DEMO.

The methodology used a multi-stage approach to optimise and validate the ramp-up phase and plasma-wall interactions. A preliminary ramp-up model was run using METIS, with boundary conditions for the limiter phase based on temperatures from existing scalings. Once the scheme was optimised, it was validated using core plasma modelling with ASTRA and edge plasma modelling with SOLEDGE2D-EIRENE [9]. The edge code can simulate plasma behaviour up to the entire first wall, was used to model key ramp-up times. Transport parameters were derived from both existing scalings and ASTRA simulations, which provided temperature and density estimates. Power fluxes, wall temperatures, impurity sources and first wall temperature profiles were calculated. These profiles were then fed into the ERO2.0 code [10] to assess tungsten sputtering and contamination from plasma-wall interactions. The methodology employed ensures that the ramp-up scheme is designed to minimise V_{loop} and tungsten sputtering whilst optimising plasma performance for DTT operation.

The transport coefficients (TCs) employed in SOLEDGE2D-EIRENE were derived using different methodologies across the various discharge phases: limiter, diverted L-mode and diverted H-mode.

During the limiter phase, transport coefficients in both the far-SOL and near-SOL were set to satisfy the respective empirical scalings [11][12]. Additionally, for the near-SOL, transport coefficients obtained from ASTRA edge plasma modeling were also employed to refine the estimates. For the divertor L-mode phase, transport coefficients were derived using both empirical scalings [13] and ASTRA-based modeling. The two methodologies yielded estimates that were highly comparable for Scenario A, but diverged for Scenario E, owing to the substantially more intense magnetic field relative to the machines from which the scaling was derived. In the H-mode phase, the transport parameters aligned with the prevailing scaling and edge modelling of the plasma and pedestal [14]. During the ramp-up phase, oxygen was utilised to simulate the effect of medium-Z impurities.

This methodology led to the definition of edge plasma characteristics during the flat-top phase for the three scenarios and to the optimization of a ramp-up scheme for Scenarios A and E.

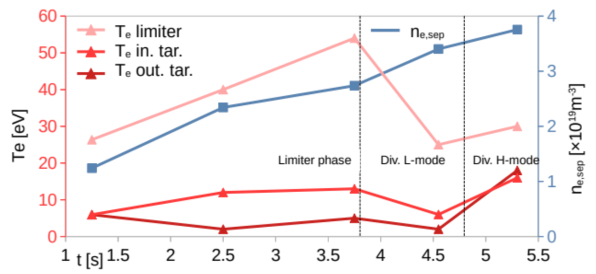

Fig. 1. Time evolution of $n_{e,sep}$ and T_e at first wall and divertor for DTT Scenario A (B=2.9T I_p=3MA)

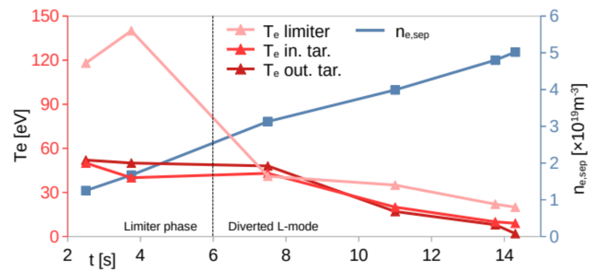

Fig 2. Time evolution of $n_{e,sep}$ and T_e at first wall and divertor for DTT Scenario E (B=5.85T I_p=5.5MA)

The temperature, power fluxes, and particle fluxes deposited on the inner limiter and divertor estimated at different time points during the discharge are shown in Figures 1 and 2. For Scenario A, the estimated temperatures and densities are lower than those observed in current metal-wall tokamaks. In contrast, in Scenario E, the inner limiter temperature is expected to exceed 100 eV at high density. With ERO2.0 the impact of these conditions on wall erosion and tungsten concentration in the plasma core has been estimated with different inner limiter configurations, guiding the geometric optimization of this component. The predicted tungsten concentration varies depending on the first wall material, but remains within the range observed in current experiments, aligning with the assumptions used in ASTRA transport modeling; this completed the integrated modelling.

For the flat-top phase, integrated core-edge modelling was completed for all three scenarios. This approach enabled the definition of a wide range of plasma edge parameters (P_{sep}, $n_{e,sep}$ and Z_{eff}), which ensured the machine's expected nominal performance and the achievement of detachment.

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