JOREK simulations of runaway electron avalanche and beam formation in DTT

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The Divertor Tokamak Test (DTT) facility plays a strategic role in the European fusion roadmap by bridging the gap between the ITER and EU-DEMO tokamaks regarding power exhaust. Achieving the necessary exhaust conditions requires operating the device at challenging parameters, such as a plasma current of I_p = 5.5 MA. This high-current regime introduces the risk of severe disruptions and the generation of relativistic runaway electron (RE) beams via the avalanche mechanism. If uncontrolled, these beams can inflict critical, localized damage on plasma-facing components (PFCs). This thesis provides the first predictive assessment of RE avalanche dynamics in DTT, establishing operational boundaries for the commissioning phase (Day-0, I_p = 2 MA) and the Full Power scenario (I_p = 5.5 MA).

The analysis relies on the non-linear MHD code JOREK coupled with the STARWALL resistive wall code. A fluid RE model is employed to simulate the self-consistent interaction between REs and the background plasma. Using an artificial thermal quench method, the study systematically scans the parameter space of initial RE seed currents (I_seed) and impurity inventories (N_imp) to isolate the physics of the current quench (CQ).

The results reveal a fundamental divergence in behavior between the two DTT scenarios, resulting from the exponential sensitivity of the avalanche gain to the pre-disruption plasma current. The Day-0 scenario exhibits intrinsic robustness: due to the limited poloidal flux reservoir, the avalanche gain is moderate. Simulations reveal that even under pessimistic assumptions (i.e., massive neon injection and a high-amplitude initial seed of 20 kA), RE currents peak below 1 MA. These findings confirm that in the Day-0 scenario, REs pose minimal risks to the PFCs, thereby removing the immediate need for complex RE mitigation strategies.

Conversely, the Full Power scenario is characterized by a vanishingly small safety margin against RE formation. The simulations identify a critical impurity threshold at $N_\mathrm{imp} \approx 1 \cdot 10^{21}$. Below this value, the injection yields a partially mitigated disruption, leaving the device vulnerable to severe thermal and halo current loads. Above this limit, however, the high avalanche gain ($G_\mathrm{av} \sim 10^5$) amplifies even minimal RE seeds

(as low as 5.5 A) into macroscopic RE beams. In this regime, the RE beam effectively replaces the thermal current in the confined plasma region, stalling the CQ. The beam termination is subsequently governed by the vertical stability of the plasma column, since the RE current is determined by a competition between avalanche generation and the physical scraping-off of the plasma volume against the first wall during the vertical displacement event.

These findings indicate that the RE safety margins of the commissioning phase do not scale to full-current operations. Consequently, the disruption mitigation system for the Full Power scenario cannot rely on pure, massive high-Z injection, as this also enhances RE formation. Instead, strategies must prioritize optimized mixtures (e.g., deuterium-rich) to balance the suppression of RE generation with the mitigation of other disruption loads.