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Analysis and Simulation of Effective Runaway Electron Mitigation Using a Passive Coil in J-TEXT Tokamak

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Disruptions and runaway electrons (REs) pose a significant challenge to the safety and stability of tokamak-based fusion reactors. The passive coil has been proposed as a strategy to mitigate RE generation during the current quench phase of tokamak disruptions [1]. Recently, the J-TEXT team installed a helical coil in the tokamak to test the concept of runaway electron mitigation coil (REMC) in their disruption experiments. With the coil activated, complete suppression of the RE current plateau was observed, demonstrating the effectiveness of the passive coil. However, initial simulations using NIMROD and DREAM indicated that the perturbed fields from the coil were insufficient to generate large magnetic islands near the plasma core or significantly diffuse REs, contradicting the experimental observations.

In this work, we used the M3D-C1 code [2] to conduct self-consistent simulations of J-TEXT disruptions in the presence of the REMC, incorporating both RE current generation and its interaction with MHD instabilities. To accurately model the helical coil in J-TEXT, the resistive wall module in M3D-C1 was upgraded to include a low-resistivity helical structure representing the passive coil. The coil's thickness and resistivity were tuned to reproduce an induced current consistent with experimental observations. A peaked RE current profile was initialized at the start of the current quench to reflect the outcome of hot-tail generation, serving as the seed for avalanche multiplication. The simulated avalanche growth was modified to account for contributions from bound electrons released by injected argon.

The simulation confirms that magnetic perturbations from both the passive coil and MHD instabilities can enhance RE diffusion and prevent the formation of a RE current plateau. Accurately capturing this process requires modeling the intricate coupling between the RE current, MHD activity, and the passive coil. When the contribution of RE current is included, it helps sustain a strongly peaked total current profile, which is prone to MHD instabilities driven by current gradients. The magnetic perturbations generated by the passive coil can serve as seeds for magnetic island formation. In contrast, simulations that exclude RE contributions show that MHD modes remain stable, and the flux surfaces are only weakly perturbed by the coil current due to the absence of resonant surfaces.

The excitation of MHD instabilities can lead to the formation of magnetic islands and field stochasticity, which in turn drives rapid convection of REs from the core to the outer regions. The redistributed REs form a new gradient near the separatrix between closed flux surfaces and the stochastic region. The repetition of process can trigger a cascade of additional MHD instabilities, creating a pathway for sustained RE transport from the core to the edge. Notably, this sequence of MHD mode excitations can occur even in the absence of the helical coil, as confirmed by Mirnov probe measurements. However, the presence of the helical coil significantly amplifies the MHD modes and facilitates enhanced RE loss.

The simulation results indicate that the effectiveness of REMC during the current quench should be evaluated using a self-consistent approach that couples MHD and RE modeling, as the growth of RE current can significantly influence MHD stability characteristics.

References
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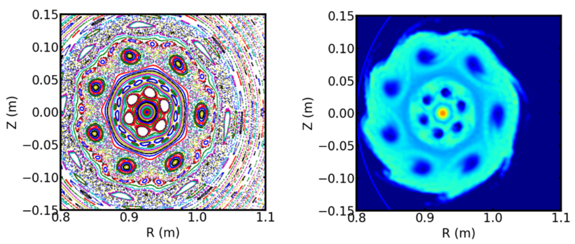

Fig 1. Poincaré plot of magnetic field topology and RE density in M3D-C1 simulation of J-TEXT disruption in presence of REMC, showing the influence of multiple MHD mode excitation.