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. Recently, a passive coil method for RE mitigation has been tested in the J-TEXT tokamak, achieving complete suppression of the RE current plateau. In this work, we present a self-consistent simulation of this RE suppression using the M3D-C1 code. The results align with experimental findings, including plasma and coil current evolution and RE current suppression. Analysis of the simulation indicates that RE current generated near the magnetic axis plays a crucial role in sustaining core current density and maintaining the q=2 rational surface, which is essential for magnetic field stochasticization. This study highlights the importance of incorporating RE current and its interaction with MHD instabilities when evaluating the effectiveness of the runaway electron mitigation coil (REMC).

The passive coil has been proposed as a strategy to mitigate RE generation during the current quench phase of tokamak disruptions [1]. Upon disruption detection, the non-axisymmetric coil is activated, and its current is induced by the plasma current decay. This process excites magnetic perturbations with multiple (m, n) components, generating magnetic islands and stochastic fields that enhance spatial diffusion of seed REs and suppress avalanche growth. Simulations of the current quench phase with a REMC in SPARC [2,3] and DIII-D [4] disruption scenarios have shown promising results, leading to the selection of REMC as the primary RE mitigation method for SPARC and ARC. Notably, previous simulations used passive coil models (such as COMSOL or ThinCurr) and resistive MHD models (like NIMROD or MARS-F) to compute perturbed magnetic fields, which were then input into RE simulations (e.g., ASCOT and DREAM). However, these studies did not account for the feedback of RE current on MHD mode evolution. REMC has been proposed for testing on several tokamak devices, including DIII-D, HBT-EP, and TCV.

Recently, the J-TEXT team installed a helical coil in the tokamak to test the concept of REMC in their disruption experiments (Fig. 1 (a)). With the coil activated, complete suppression of the RE current plateau was observed, demonstrating the effectiveness of the passive coil. The maximum coil current (~6 kA) was approximately 7.5% of the total plasma current before disruption (~80 kA), a ratio consistent with SPARC simulations and HBT-EP experimental results. 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 employed the M3D-C1 code to perform a self-consistent simulation of J-TEXT disruptions in the presence of REMC, incorporating both RE current generation and its interaction with MHD modes. In M3D-C1, REs are modeled as a fluid component coupled to the MHD equations through Ohm's law [5,6]. This model has previously been used to simulate the excitation of the resistive kink mode in DIII-D's RE-benign termination [7]. To accurately represent the helical coil in J-TEXT, the resistive wall model in M3D-C1 was upgraded to simulate a low-resistivity helical structure within the wall. Additionally, a large vacuum region was introduced outside the wall to minimize boundary condition effects. The resistivities of the plasma, wall, and vacuum were carefully tuned to ensure that the simulated current evolution (including plasma and wall currents) aligns with experimental observations. Furthermore, a dedicated routine was developed to solve the advection equation using a Lagrangian specification, which provides an efficient way to calculate the fast advection of the RE along magnetic fields with GPU acceleration and avoids numerical instabilities.

M3D-C1 simulations have confirmed that the REMC can induce magnetic islands and a stochastic region within the plasma, facilitating the transport and loss of REs (Fig. 1 (b)). This phase begins when the coil current reaches approximately 4 kA, driven by the overlap of (2,1) and (3,1) magnetic islands. It is important to note that the helical coil installed in J-TEXT follows an (m=1, n=1) configuration. However, the dominant (1,1) component of the magnetic perturbation primarily causes a kink in the magnetic axis rather than generating tearing islands.

Fourier analysis of the magnetic perturbations reveals that higher (*m, n*) components are predominantly localized inside the plasma. However, current quench simulations without the helical coil do not exhibit field stochasticity, indicating that while high-mode-number perturbations are amplified by MHD instabilities, their initial seed originates from REMC-induced perturbations.

DREAM simulations indicate that most seed REs in J-TEXT disruptions originate from hot-tail generation, with the avalanche mechanism contributing only a 4-5 fold increase in RE population. Additionally, the current quench duration in J-TEXT is significantly shorter than in SPARC simulations. Consequently, the coil current reaches its peak near the end of the current quench phase. A critical factor for the success of the REMC is maintaining plasma susceptibility to MHD instabilities throughout the entire current quench. In a separate simulation where the REMC was activated but the influence of RE current on MHD modes was disabled, the plasma current underwent uniform diffusion during the quench. This led to an increase in the q-profile, and minimal impact of helical coil on magnetic island formation (Fig. 1 (c)). These findings explain why experimental results cannot be replicated using a simulation model that excludes RE current feedback. The RE current helps sustain a peaked current profile, making the plasma more responsive to external magnetic perturbations and facilitating MHD mode excitation.

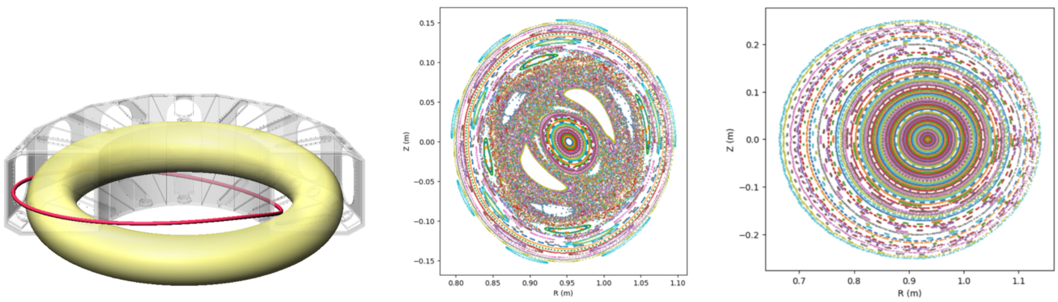

Fig 1. (a) Structure of helical coil in J-TEXT tokamak. (b) Poincaré plot of magnetic field topology in M3D-C1 simulation of J-TEXT disruption in presence of REMC. (c) Poincaré plot of M3D-C1 simulation with influence of RE current on MHD turned off.

In sum, the M3D-C1 disruption simulation model, after incorporating the influence of RE current on MHD activity, successfully reproduces the mitigation of REs in J-TEXT disruptions in the presence of the REMC. The avalanching RE current near the magnetic axis helps maintain a peaked current profile, making the plasma more susceptible to tearing instabilities and promoting island growth. These 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. In cases where the REMC perturbation is strong enough to sustain magnetic field stochasticity throughout the entire current quench and eliminate all seed REs, as demonstrated in [2], the feedback effect may be negligible. However, for smaller devices such as HBT-EP or TCV, self-consistent simulations provide a more accurate representation of RE current evolution.

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