Runaway electrons termination dynamics in fusion plasmas

The presence of runaway electrons (RE) poses a significant challenge to the operation of tokamak fusion reactors. These high-energy particles can reach the surrounding walls and cause irreparable damage upon collision with tokamak components. To address this issue, the fusion community is exploring various mitigation techniques. However, the full impact of these mitigation strategies on the RE population and the background plasma is not yet fully understood. For instance, an SPI technique is utilized to suppress the RE generation by rapidly increasing plasma density and cooling it down in current reactors. In certain scenarios, the SPI injection can trigger bursts of plasma magnetohydrodynamic (MHD) activity. Among these activities, magnetic reconnection (MR) plays a crucial role. This instability is driven by the presence of RE, whose characteristics, in turn, are significantly affected by the topological changes (formation of magnetic island) in the plasma magnetic field. Understanding this mutual influence is crucial for developing strategies to ensure the safe termination of RE. Moreover, the behavior of the first wall materials when exposed to RE beam, potentially critical, requires comprehensive study.

The primary aim of this thesis is to investigate the termination dynamics of the RE current in a post-disruption fusion plasma. The research begins by studying the influence of the RE current on the evolution of MR (or tearing modes) in a 2D slab configuration characterized by a single magnetic island. In the initial phase, the nonlinear two-fluid reduced MHD code SCOPE3D was validated based on existing results. This allowed to focus on nonlinear studies about the island rotation and the presence of microscales in asymmetric configuration (mismatch between the radial current profile peak and island resonant surface position). This study identified the presence of microlayers in the RE current profile, which influenced the system transition from the linear to the nonlinear phase. The island rotation was found to become zero once the saturation was reached. The research further demonstrates that electron inertia effects lead to the formation of microscales on the thermal electron current profile, which might impact plasma stability.

In the second phase of the research, the impact of plasma background resistivity on the benign termination of RE observed in the JET experiment #95135 after an SPI injection was investigated. The nonlinear MHD code JOREK was used in this study with RE transport modelled through advection at the speed of light. The RE termination is driven by magnetic stochasticity resulting from the interaction of a double tearing mode with secondary modes. In our study, higher resistivity values enhanced chaotic plasma dynamics, with the double tearing mode emerging as the dominant contributor to RE loss. In contrast, lower resistivity values allowed secondary modes to play a critical role in the evolution of magnetic stochasticity. This analysis indicated that, despite losing similar RE current amplitudes in various cases, the intense magnetic stochasticity observed with high resistivities resulted in a larger wetted area on the wall, contributing to a more benign termination of RE.

Finally, the thesis addresses the impact of the RE beam on the Tokamak First Wall. A detailed examination was conducted to assess the damage inflicted by a highly energetic RE beam on Beryllium (Be) and Tungsten (W) materials, employing FLUKA and FreeFEM++ simulation tools. FLUKA was utilized to calculate energy deposition profiles, beginning from a customized energy distribution function for RE, representing a novel approach in this work. The apparent heat capacity method was implemented in FreeFEM++ in collaboration with a PhD colleague to simulate the thermal response of the material following RE energy deposition. The findings revealed that W higher stopping power results in greater energy deposition near its surface due to elastic scattering and delta-ray production, making it a more effective material for limiting damage. Conversely, in Be, photon energy deposition becomes dominant near the opposite border, while in W, photons become the primary energy carriers after just a few millimetres of penetration. The thermal response analysis demonstrated that W effectively limits melting to the near-surface region, necessitating a higher RE current for melting initiation compared to Be.