Hybrid kinetic-MHD simulations of interactions between tearing modes and runaway electrons

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Runaway electrons (REs) are of particular importance to the safe operation of tokamaks. Electrons may be accelerated by the large toroidal electric field arising during a major disruption and cause substantial damage when reaching material walls. Via collisions, an avalanche can set in such that eventually a large fraction of the pre-disruption plasma current can be converted into relativistic runaway electron current. Previous work [1] suggests that the post-disruption runaway current could be strongly peaked in the center, making it susceptible to tearing-mode instabilities. This work aims at contributing to the understanding of MHD mode activity in RE beams, as it plays an important role for instance in the development of benign RE beam termination scenarios that aim to avoid wall damage.

A classical resistive tearing mode instability, characterized by the reconnection of magnetic field lines, arises due to the plasma's finite resistivity leading to the formation of magnetic islands. But compared to the resistive bulk plasma, the nearly collisionless runaway current will exhibit different mechanisms for driving tearing mode instabilities, modifying both linear stability and non-linear dynamics. This has been confirmed by theoretical and simulation studies [2,3].

In the JOREK code [4], RE physics can be studied in several ways. The first method relies on a fluid treatment of the REs, self-consistently coupled to the background plasmas [5]. For the runaway current, the contributions from the parallel velocity to the magnetic field and the electric drift velocity are considered. This model does not include the energy/pitch-angle distribution of the particles or the accurate kinetic orbits, limiting the accuracy with respect to transport predictions. Another approach available in JOREK relies on kinetic test particles.

The most accurate approach relies on a self-consistent coupling of the full-f relativistic particle-in-cell model for REs to the background plasmas, with a full-orbit model [6] and the computationally more efficient gyro/drift kinetic treatment (this work). For the coupling, moments are calculated from the kinetic RE distribution, and then accounted for in the MHD equations to capture the mutual interaction between REs and MHD.

In this work, first, the accurate representation of the major-radial force balance of a RE beam is verified by comparing to analytical results [7]. Then, a comparison to literature [2] is performed for the linear growth rates of 3D tearing modes. The growth rates in the presence of REs are found to be larger than in a thermal plasma, qualitatively and quantitatively reproducing the theory predictions. Moreover, non-linear results (Poincaré plots shown in Figure 1) are presented for tearing modes in the presence of runaway electrons, demonstrating that the saturated island size is substantially enhanced due to the presence of REs.. Finally, the influence of the RE kinetic energies and the corresponding drift orbit shifts onto the linear and non-linear dynamics of TMs is investigated. Future work will extend efforts towards double tearing modes and external kink modes that are particularly relevant for achieving benign termination.

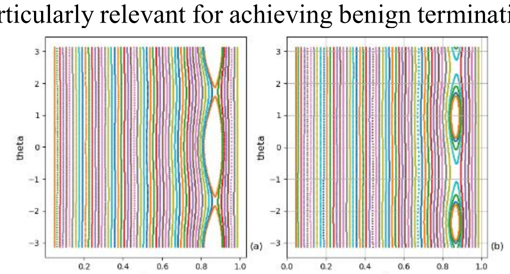

Figure 1. Poincaré plots about nonlinear saturated islands with (left) and without (right) REs.

References
[1] L.-G. Eriksson, et al. 2004. Phys. Rev. Lett. 92, 205004.
[2] Liu, Chang, et al. 2020. Physics of Plasmas 27 (9), 092507.
[3] P. Helander, et al. 2007. Physics of Plasmas 14 (12), 122102.
[4] Hoelzl, M., et al. 2024. Nuclear Fusion 64, 112016.
[5] V. Bandaru, et al. 2019 Phys. Rev. E 99, 063317.
[6] Hannes Bergstroem, et al. 2025. (submitted to PPCF)
[7] Bandaru, V. & Hoelzl, M. 2023. Physics of Plasmas 30 (9), 092508.