3D HYBRID FLUID-KINETIC SIMULATIONS OF LARGE SCALE PLASMA INSTABILITIES IN RUNAWAY ELECTRON BEAMS

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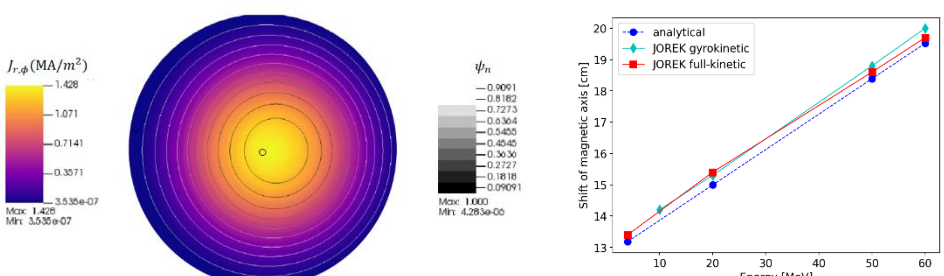
Runaway electrons (REs) are of particular importance to the safe operation of tokamaks. Electrons may be accelerated by the large toroidal electric field arising during a major disruption and cause substantial damage when reaching material walls. Via collisions, an avalanche can set in such that eventually 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, affecting resistive 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. Enabled by the finite plasma resistivity, current driven classical tearing modes lead to magnetic island formation. But while the bulk plasma of a RE beam is very resistive, the nearly collisionless runaway current changes the physical picture and modifies both the linear stability and non-linear dynamics as 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]. 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. A novel high-fidelity model was recently developed that overcomes these limitations. It relies on a self-consistent coupling of a full-f relativistic RE particle-in-cell model to the background plasmas, either kinetically with full orbits [6] or with a computationally more efficient gyro/drift kinetic approach (this work).

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]. In a cold plasma with a high-energetic runaway beam, the equilibrium cannot be force-free, and there will be a flux surface shift related to the runaway energy, which is attributed to the curvature drift of REs. Quantitative results are obtained via JOREK separately with a full-orbit [6] and a drift kinetic treatment. A good agreement with analytical predictions could be seen in Figure 1.



(a) (b)

Figure 1 (a) Contours of the poloidal magnetic flux and the RE current density in color, where the open symbol represents the geometric axis location. (b) Comparison of the magnetic axis shift by the REs versus the RE energy of the two JOREK models with analytical predictions.

Then, a comparison to literature [2] is performed for the linear growth rates of 3D tearing modes. REs can cause a sublayer structure inside the resistive layer that may be narrower than the resistive layer. The growth rates in the presence of REs are found to be larger than in a highly resistive plasma, qualitatively and quantitatively reproducing the theory predictions. Another effect that the presence of the REs has on the tearing modes is a rotation of the mode in the lab frame, i.e., a real frequency. The simulation results from JOREK, eigenvalue code, and M3D-C1 are shown in Figure 2.

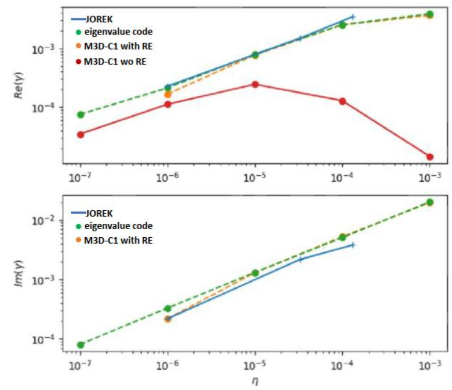


Figure 2 Real and imaginary parts of γ for the (2,1) tearing mode from Ref. [2] and JOREK.

Moreover, the nonlinear saturation of tearing modes is significantly influenced by the presence of REs. The REs also affect the non-linear dynamics and saturated state of tearing modes. Previous analytical studies [3] suggested that in the case of small Δ', the saturation width of the magnetic island driven by REs is roughly 1.5 times the island width in the Ohmic current scenario. Our simulations (Poincaré plots shown in Figure 3) are quantitatively in line with this prediction, confirming that runaway electron-driven tearing modes can lead to wider islands than those generated by thermal plasma alone. We carry out such simulations at varying values of Δ'.

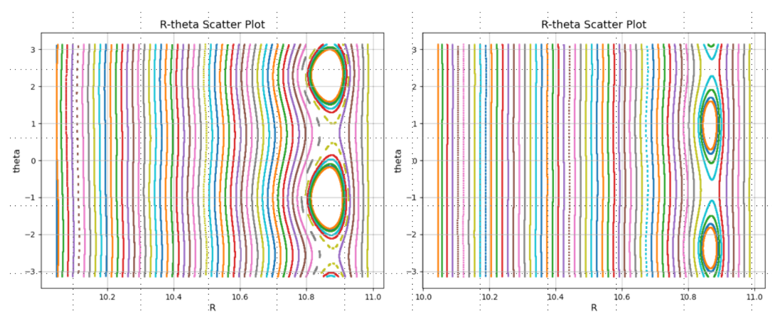


Figure 3. Poincaré plots showing nonlinear saturated islands with (left) and without (right) REs.

While the analytical predictions are based on fluid-like assumptions, the drift orbit shifts of highly energetic REs change the picture once more with respect to both an Ohmic plasma and RE beam where such shifts are not accounted for. We address the effect of these orbit shifts onto the linear and non-linear dynamics. Future work will extend efforts towards other instabilities like double tearing modes and external kink modes, as they are particularly relevant for achieving benign termination.

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. Plasma Phys. Control. Fusion 67, 035004.
[7] Bandaru, V. & Hoelzl, M. 2023. Physics of Plasmas 30 (9), 092508.