Hybrid kinetic-MHD studies of runaway electron beam termination events

Hannes Bergström[1], Shi-Jie Liu[1], Vinodh Bandaru[2], Fiona Wouters[1], Matthias Hoelzl[1], JOREK Team[3], JET Contributors[4]

[1] *Max Planck Institute for Plasma Physics, Garching b. M., Germany* [2] *Indian Institute of Technology Guwahati, Assam, India* [3] *See the author list of [M Hoelzl et al. Nuclear Fusion 64, 112016 (2024)]* [4] *See the author list of [J Mailloux et al. Nuclear Fusion 62, 042026 (2022)]*
Email: hannes.bergstroem@ipp.mpg.de

Disruptions remain one of the largest unsolved problems for realizing a tokamak based fusion power plant. In addition to the loss of plasma confinement, threatening to bring about large heat fluxes on plasma facing components, and strong electromagnetic vessel forces, the acceleration of thermal electrons to relativistic energies could result in sub-surface melting of wall material as the particles deposit their energy in a highly localized manner. Commonly referred to as runaway electrons (REs), estimates have found that these particles could carry currents of up to several MAs in larger devices such as ITER, even with the use of mitigation techniques [1, 2]. High fidelity predictive modeling is essential for determining the extent of RE production and acceleration throughout the disruption, and devising strategies to alleviate the resulting wall loads. This work represents a large step forward for the self-consistent modeling of REs and their interaction with magnetohydrodynamics (MHD). A hybrid kinetic-MHD model has been developed for the JOREK code using a full-f particle-in-cell approach, capable of simulating global non-linear MHD activity while retaining the RE phase space information and the mutual coupling to the bulk plasma. Benchmarks with analytical predictions for the force balance and linear growth rates of resistive tearing mode (TM) instabilities show good agreement and the model is in addition able to capture a highly non-linear RE beam termination event resulting from a violent burst of MHD activity.

Due to their large parallel energy, REs can have a significant curvature drift, where the resulting current density yields a $\mathbf{J}\times\mathbf{B}$ force consistent with the centripetal acceleration needed to maintain their toroidal motion. Because of this, a RE beam equilibrium cannot be considered force-free in spite of the cold background plasma. In addition to a relative shift between flux surfaces and drift orbits, there is a Shafranov-like shift of flux surfaces proportional to the RE energy, as illustrated in Figure 1. The hybrid model is shown to quantitatively agree with the analytical predictions for RE beam equilibria made in Ref. [3], both for the spatial dependence of the shifts and the energy scaling. The model also needs to capture the 3D MHD dynamics in a RE beam accurately. For TMs, literature shows that the scaling of the linear growth rate with respect to the resistivity differs from a scenario with purely Ohmic current [4]. This was further studied in Ref. [5] where it was also noted that the REs introduce a rotational frequency to the mode. The latter provided analytical estimates for the linear growth rate and rotation frequency of a $(m,n)=(2,1)$ TM at different values of the normalized resistivity $\tilde{\eta}$, also comparing to numerical results from an eigenvalue solver and the M3D-C[1] code. Figure 2 compares the values presented in that paper to the ones obtained with JOREK simulations using

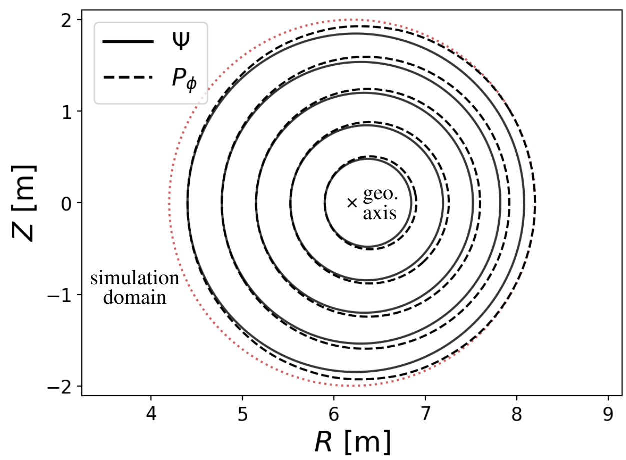

Figure 1: Flux surfaces and drift orbit surfaces (surfaces of constant canonical angular momentum P_ϕ) for a plasma with mono-energetic high energy REs.

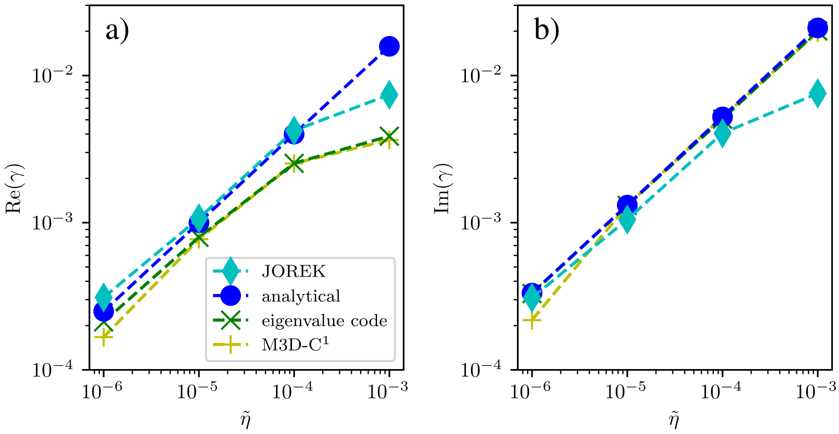

Figure 2: Real (a) and imaginary (b) parts of γ, corresponding to linear growth rate and rotation frequency of a $(2,1)$ TM instability, as a function of the normalized resistivity of a plasma with RE current. Data obtained from JOREK simulations are compared to data from Ref. [5].

the hybrid model. Again, good agreement is found with respect to the analytical results, with some discrepancies appearing at high values of $\tilde{\eta}$, possibly resulting from the size of the resistive layer becoming comparable to the minor radius of the plasma, where the analytical model loses validity.

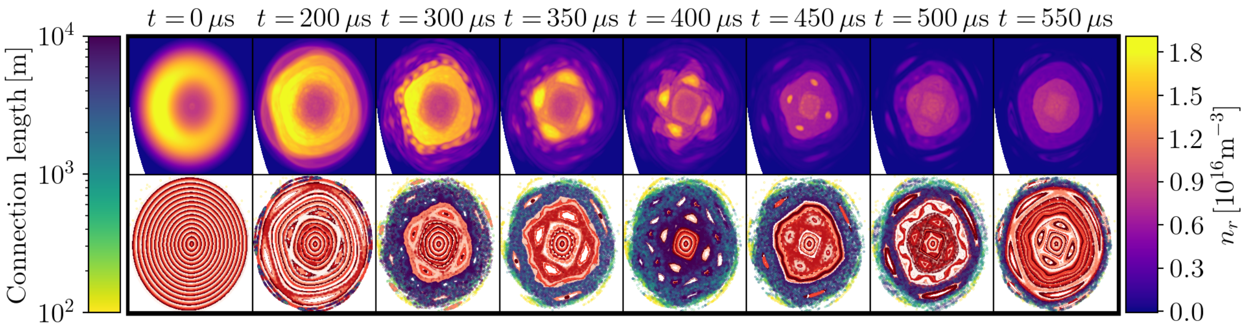

Figure 3: RE density (upper row) and Poincaré plots (lower row) analyzing the time evolution of the termination of a 2 MeV RE beam induced by a double $(m,n) = (4,1)$ TM instability.

Finally, non-linear 3D simulations of a RE beam termination (JET discharge #95135) were carried out, repeating earlier work using a RE fluid approach [6, 7] now with the hybrid model. As starting point, we use an unstable equilibrium based on experimental data just a few ms before the crash. The simulations see the prompt growth of a $(m,n) = (4,1)$ double TM instability resulting in the stochastization of the magnetic field and transport of REs, as illustrated in Figure 3. The model succeeds to capture the highly non-linear dynamics and the back-conversion of RE current described by PiC approach into thermal current carried by the plasma fluid.

Owing to the large time scale separation between RE transport and MHD transients, self-consistent simulations of disruption events accounting for the generation and losses of REs, which retain the phase space information and can provide estimates for resulting heat loads, are very challenging. The novel hybrid model presented here is able to correctly capture the major-radial force balance and the growth rates of MHD modes in a RE beam. It is also capable of simulating highly non-linear scenarios as they arise in the context of research on benign RE termination. Advanced diagnostic capabilities allow to determine the exact distribution of REs across 3D wall structures as it is needed for RE wall damage predictions.

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