Non-linear 3D hybrid kinetic-MHD studies of runaway electron beam termination events

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ABSTRACT

- A self-consistent treatment of runaway electron (RE) dynamics during disruptions is difficult due to the different length and time scales involved.
- Capturing accurate transport and accounting for the mutual interaction of REs with the 3D MHD is however important for predictive simulations of future machines.
- This work presents recent advancements in RE modeling using a hybrid kinetic-MHD framework in the JOREK code.
- Finally, ongoing work aiming to obtain realistic estimates for the RE distribution during a beam termination scenario in JET is shown.

1. HYBRID KINETIC-MHD MODEL

Kinetic model has been coupled to the MHD using a full-f particle-in-cell approach. The RE is distribution given by:

$$f_r(\boldsymbol{x},\boldsymbol{v},t)=\sum_{i=1}^{N_m} w_i\delta(\boldsymbol{x}_i(t))\delta(\boldsymbol{v}_i(t))$$

The MHD equations are modified based on the **pressure coupling scheme:**

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\boldsymbol{u})=S_\rho$$

$$\rho\left(\frac{\partial\boldsymbol{u}}{\partial t}+\boldsymbol{u}\cdot\nabla\boldsymbol{u}\right)=\boldsymbol{J}_{\text{tot}}\times\boldsymbol{B}-\nabla p-\left(\mathcal{P}_{r,\parallel}-\mathcal{P}_{r,\perp}\right)\boldsymbol{\kappa}-\nabla\mathcal{P}_{r,\perp}+\boldsymbol{S_u}$$

$$\frac{\partial p}{\partial t}+\boldsymbol{u}\cdot\nabla p+\Gamma p\nabla\cdot\boldsymbol{u}=(\Gamma-1)\left(Q-\nabla\cdot\boldsymbol{h}+S_p\right)$$

$$\boldsymbol{E}=-\boldsymbol{u}\times\boldsymbol{B}+\eta\left(\boldsymbol{J}_{\text{tot}}-\boldsymbol{J}_r\right)$$

where the RE contributions are calculated as:

$$\boldsymbol{J}_r=q\int \mathrm{d}^3v\,\boldsymbol{v}f_r,\quad \mathcal{P}_{r,\perp}=\frac{m}{2}\int \mathrm{d}^3v\gamma v_\perp^2 f_r,\quad \mathcal{P}_{r,\parallel}=m\int d^3v\,\gamma v_\parallel^2 f_r$$

2. BENCHMARKS OF HYBRID MODEL

- Both full orbit and gyrokinetic models have been benchmarked in 2D and 3D configurations.
- **2D benchmark** based on analytically predicted drift orbits and changes in force balance at high energies in an ITER-like geometry [9, 10]:

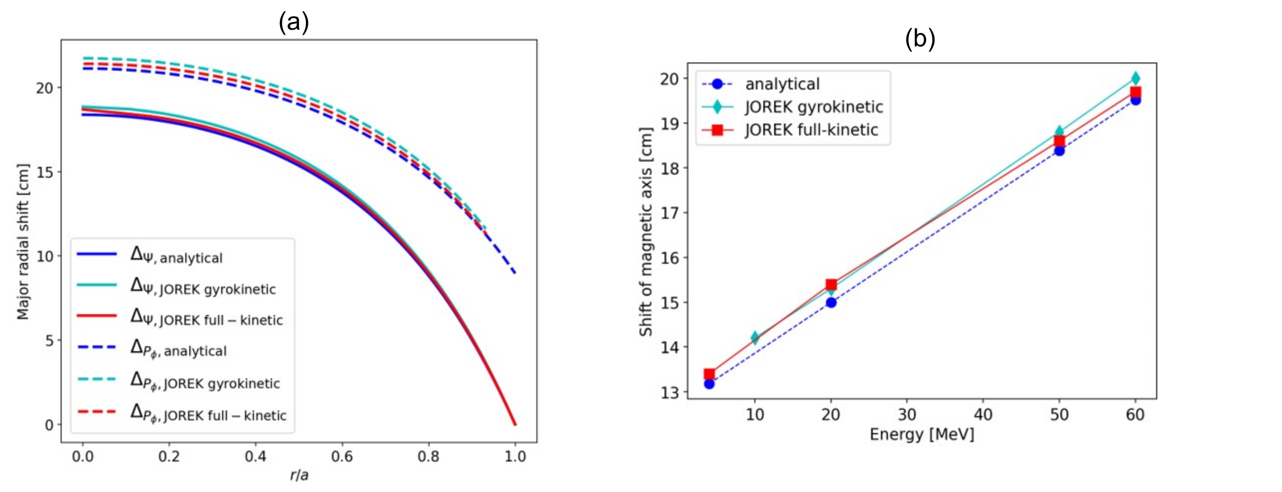

Figure 1: Minor radial profiles of the flux surface and drift orbit shifts in a plasma with 50 MeV REs (a) and the shift of the magnetic axis as a function of RE energy (b).

- **3D benchmark** compares growth rate and rotation frequency of (2,1) TM instability, to those analytically predicted in Helander *et al* [11] along with numerical results from Liu *et al* [12]:

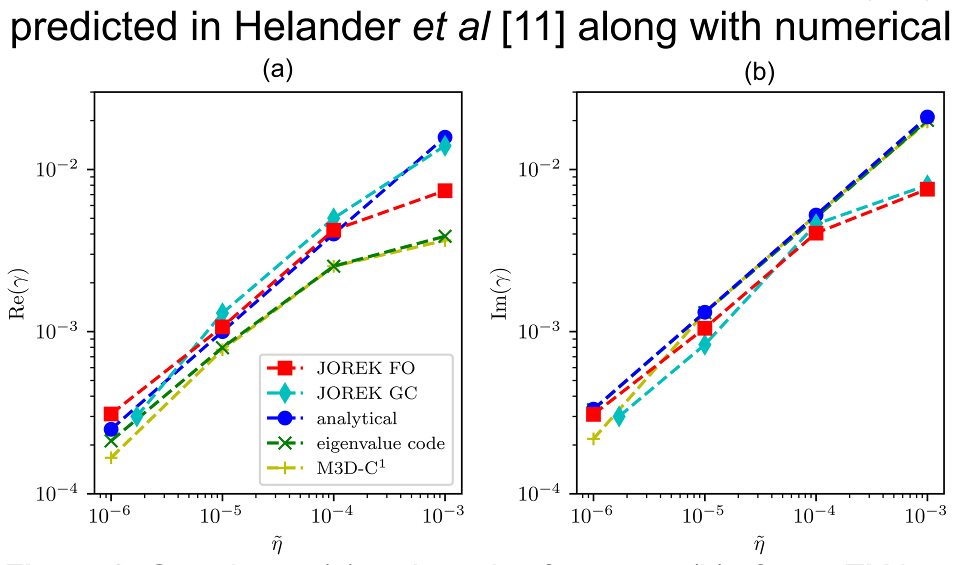

Figure 2: Growth rate (a) and rotation frequency (b) of (2,1) TM instability.

CONCLUSION

- A novel full-f particle-in-cell model for REs has been implemented and benchmarked using both full orbit and gyrokinetic markers.
- Application to beam termination scenario in JET shows interesting variations for higher RE energy distributions.
- DREAM simulations are used to estimate RE distribution throughout the experiment, strong dependence on argon density found for initial phase.
- Model developments including kinetic sources and GPU porting are underway [16, 17, 18].

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non-linear 3D extended MHD code suitable for complex geometries

Some key features

- Coupling to CARIDDI and STARWALL allows for free boundary simulations accounting for conducting structures [3, 4].
- Models for neutrals and impurities using either fluid or kinetic framework, as well as SPI [5,6,7].
- Fluid model of REs, including avalanche and nuclear sources [8].

Kinetic model of runaway electrons

- Uses particle tracing for accurate transport, retains phase space information.
- Both gyrokinetic and full-orbit model available.
- Can be self-consistently coupled to MHD equations using particle-in-cell scheme.

3. FIRST APPLICATION: BEAM TERMINATION IN JET

First application of hybrid model based on JET benign termination case in Bandaru *et al* [13, 14].

- Challenging highly non-linear scenario, acts as proof of principle.
- 10^7 mono-energetic full orbit markers initialized with $p_\parallel/p_{\text{tot}}=-0.99$.
- Growth of double (4,1) TM instability results in strong field line stochastization.
- Lower degree of stochastization and notably higher RE current remaining in 8 MeV scenario.

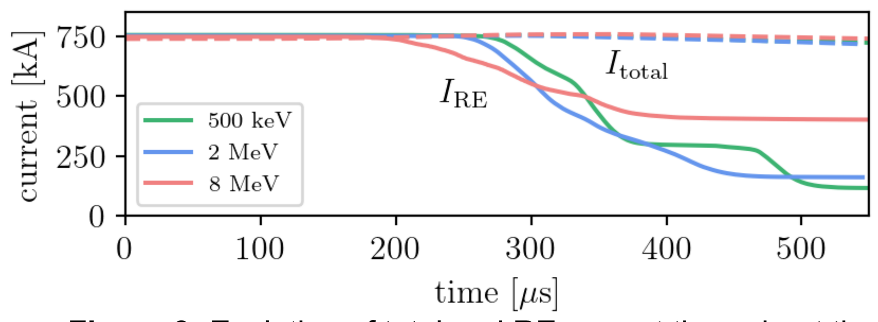

Figure 3: Evolution of total and RE current throughout the termination for simulations with different RE energy.

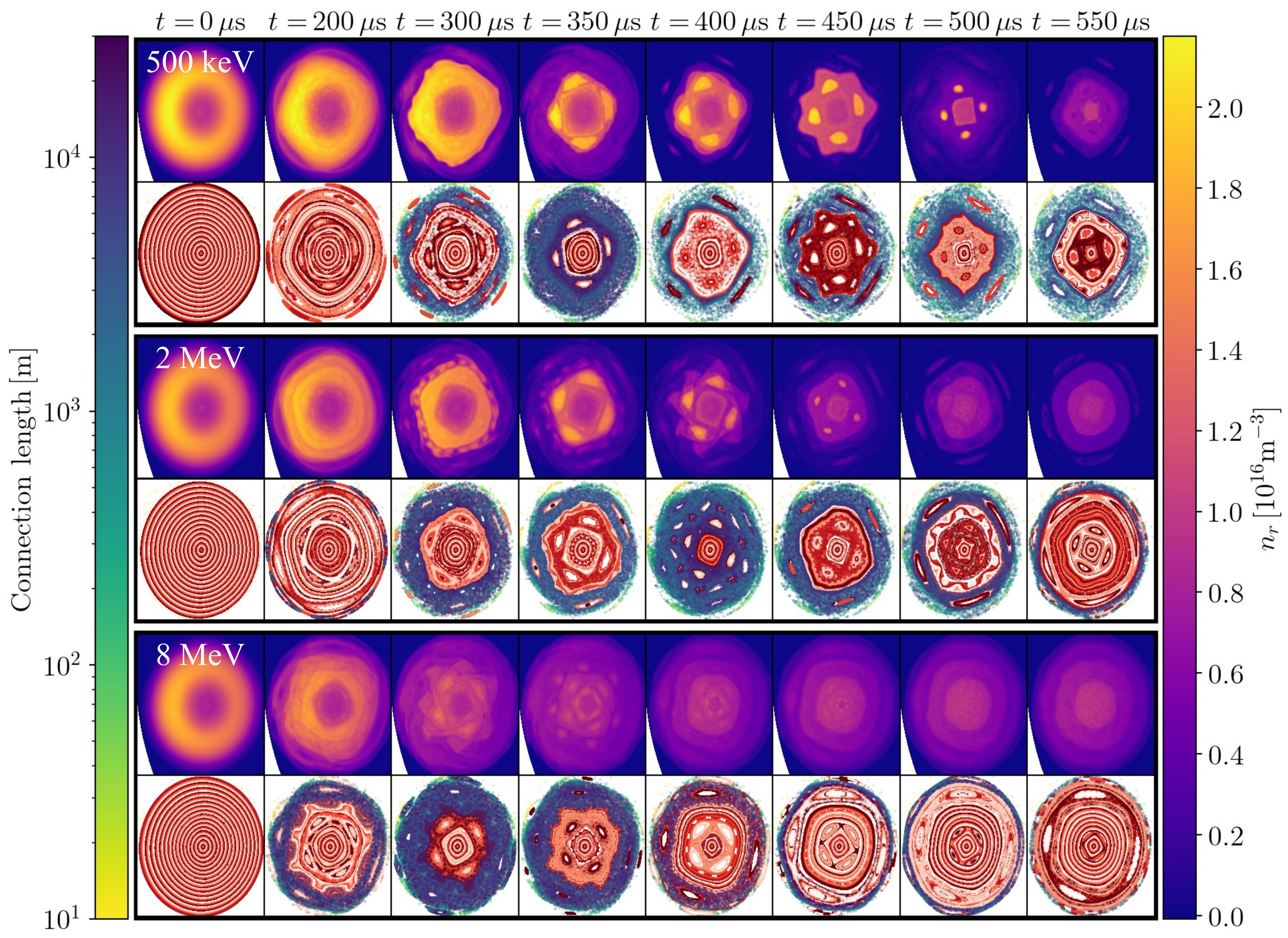

Figure 4: RE density (upper row) and Poincaré plots (lower row) analyzing the time evolution of the termination of RE beams with different energies induced by a double (4,1) TM instability.

4. TOWARDS MORE REALISTIC DISTRIBUTIONS

Idea: use 0D **DREAM** simulations to evolve f_{re} during phases with low MHD activity [15].

- Start from an avalanche distribution.
- n_{D} and n_{Ar} treated as unknowns.
- Bayesian optimization used to find best match w.r.t. I_{p} from experiment.
- So far, simulations of 1st phase have been carried out.
- Results found to strongly depend on n_{Ar}, best match at ~53% assimilation.
- At optimum, mean energy decreases from ~18 MeV to ~10.8 MeV.

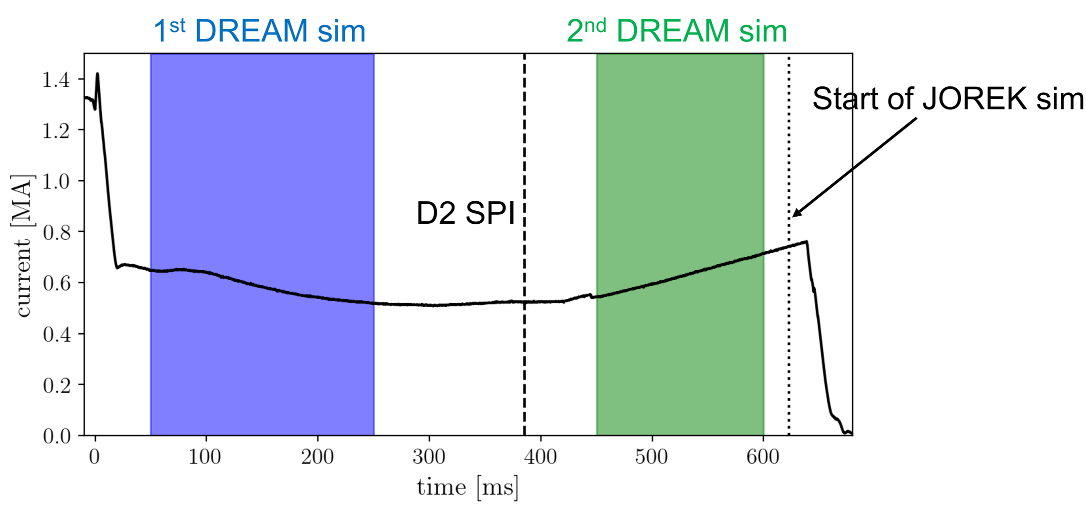

Figure 5: Total current evolution during the experiment with different simulation phases indicated.

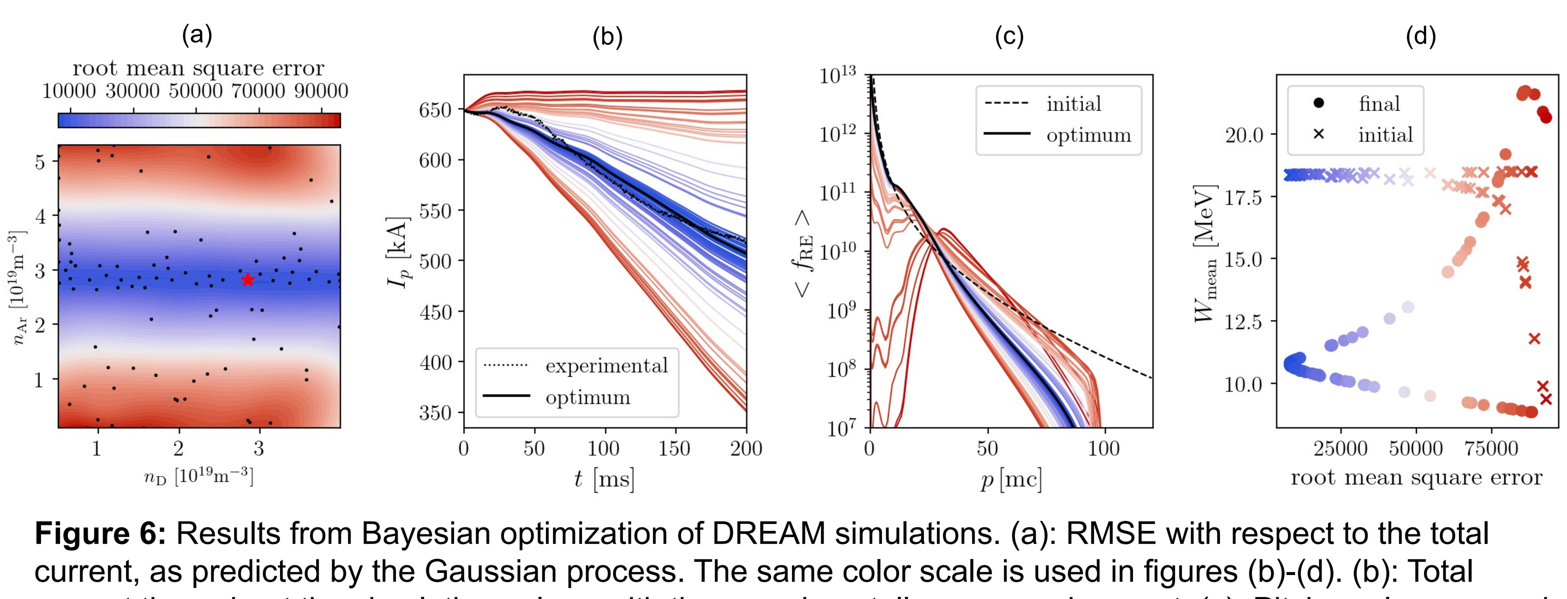

Figure 6: Results from Bayesian optimization of DREAM simulations. (a): RMSE with respect to the total current, as predicted by the Gaussian process. The same color scale is used in figures (b)-(d). (b): Total current throughout the simulations along with the experimentally measured current. (c): Pitch angle averaged RE distribution at the end of the simulation. (d): Average RE energy at the beginning and end of the simulations as a function of the RMSE.

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This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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