Discussion on resistive kink mode simulation with RE for DIII-D disruptions

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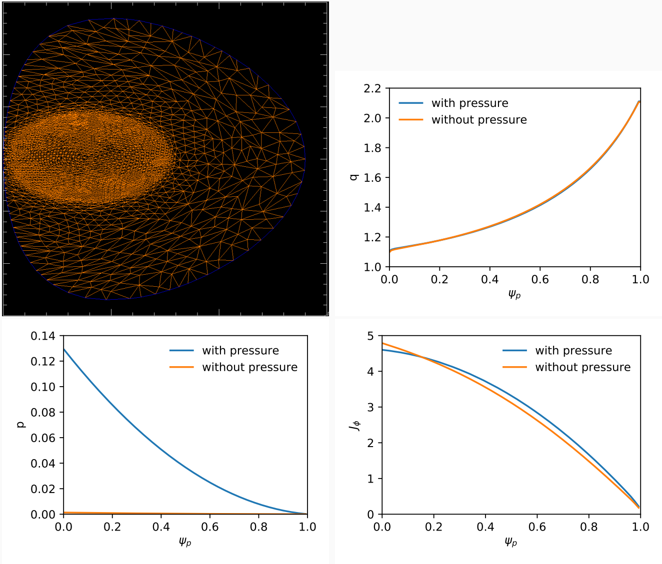
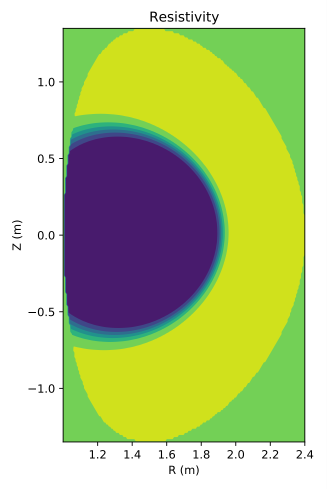
Equilibrium profile of shot 177040 at 1025ms

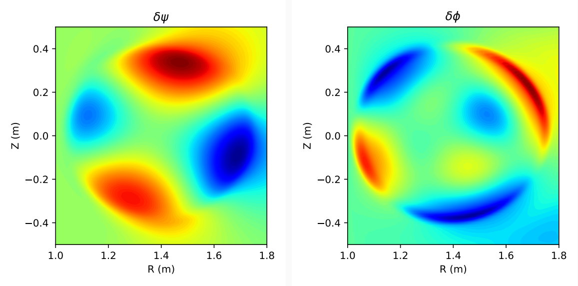


Resistivity profile

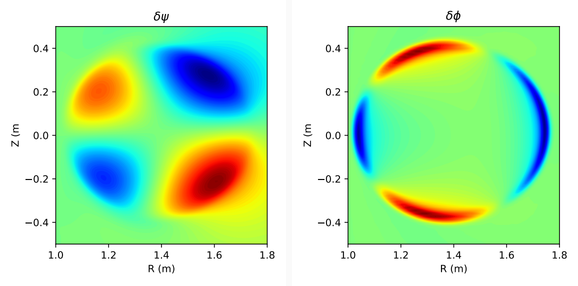
- A constant resistivty η_0 is set inside the last closed flux surface, which corresponds to the Spitzer resistivty for 2 eV plasma.
- Outside the last closed flux surface, η has a smooth transition profile to a very large value η_{vac}.



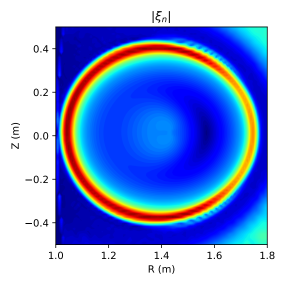
Resistive external kink mode growth rate and mode structure



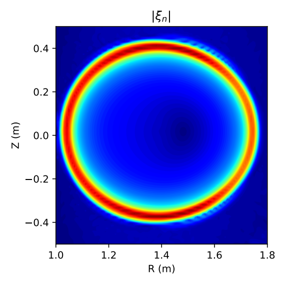
With pressure



Without pressure

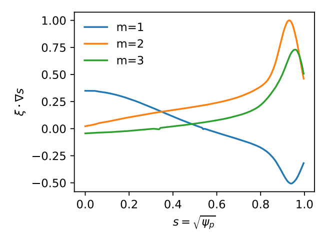


With pressure

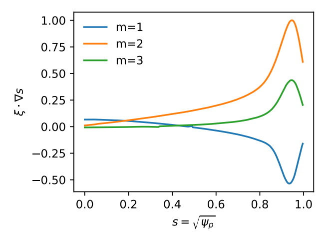


Without pressure

With pressure



Without pressure



- The growth rate is almost the same with and without pressure.
- In the high pressure case, the mode structure is in qualitatively agreement with MARS. The mode structure is smoother near the edge due to the smoother η profile. The high value of $m = 1$ mode near the edge may be due to th error in flux coordinate calculation.
- After removing the pressure, the $m = 1$ and $m = 3$ components become much smaller.

Impact of runaway electron current on linear growth rates

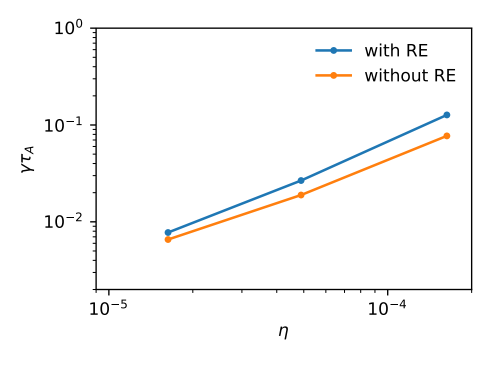
Introduction to RE module in M3D-C1

- We have implemented a fluid model of REs in M3D-C1 to study the coupling of RE current with MHD and its effect on MHD instabilities.
  - REs are described using a single fluid with parallel convection velocity *c*, and the current is coupled into the Ohm's law.
  - The $\mathbf{E} \times \mathbf{B}$ drift of RE is taken into account, but gradient and curvature drifts are not.
  - It is found that with RE carrying the equilibrium current, the tearing mode growth rate can be much larger for large η cases, and the mode can have a real frequency.
  - Source term for RE in now developed by Chen and it is used to simulate RE generation in DIII-D experiments.

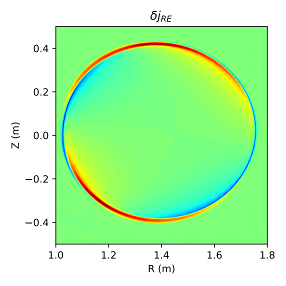
C. Zhao, C. Liu, S.C. Jardin, and N. Ferraro, Nucl. Fusion (2020)
C. Liu, C. Zhao, S.C. Jardin, A. Bhattacharjee, D.P. Brennan, and N.M. Ferraro, ArXiv:2006.08463

Mode growth rate in existence of RE current

- Here we assume 100% of current is carried by REs.
- Streaming speed of RE $c/v_A = 10$.
- η_0 is varied while η_{vac} is fixed.

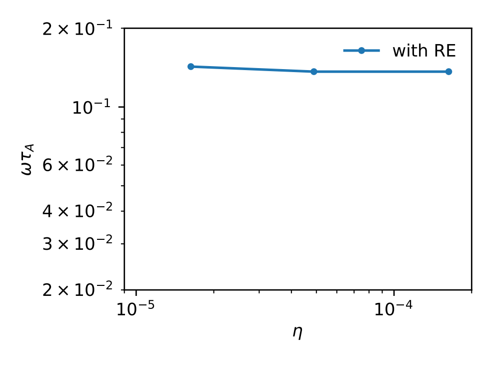


Mode structure of RE current



- The mode structure of ψ and ϕ are almost the same with and without RE.
- Perturbed RE current is strongly localized near $q = 2$ surface.

Real frequency in existence of RE current



Nonlinear simulation of MHD instabilities with RE current

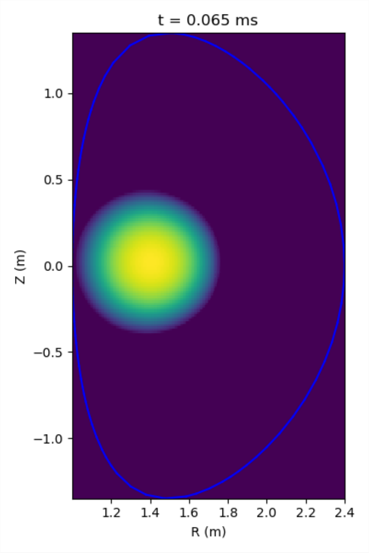
Extend the RE fluid model to 3D nonlinear simulation

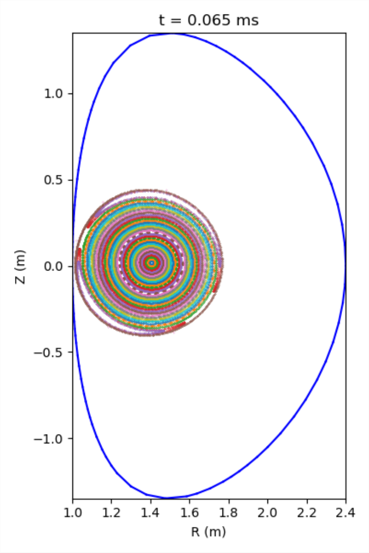
- In 3D meshes, solving the RE convection equation is more challenging because of numerical issues.
- We develop a characteristic method to solve the convection equation, by following the trajectories of runaway electrons (mostly along field lines).
  - Field tracing is done using the kinetic module of M3D-C1 for energetic ion simulation based on RK4, which has been accelerated using GPU.
  - It can help avoid numerical instabilities, and the calculation is much faster compared to solving convection equation matrix using block-Jacobi method.

Setup of nonlinear kink simulation with RE

- In nonlinear simulation, we use an equilibrium with ignorable pressure, so $\mathbf{j} \times \mathbf{B} = 0$. All the current is carried by REs.
- In equilibrium state $\mathbf{E} \times \mathbf{B}$ drift is ignored, so $\mathbf{j}_{RE} \parallel \mathbf{B}$, which is consistent with the equilibrium setup.
- Ohmic heating term $\eta(j - j_{RE})^2$ is used.
- Spitzer resistivity is calculated using local temperature. Initially the temperature is about 2 eV and no Ohmic heating ($j - j_{RE} = 0$).

Nonlinear evolution of RE current and Poincare plots during resistive kink excitation

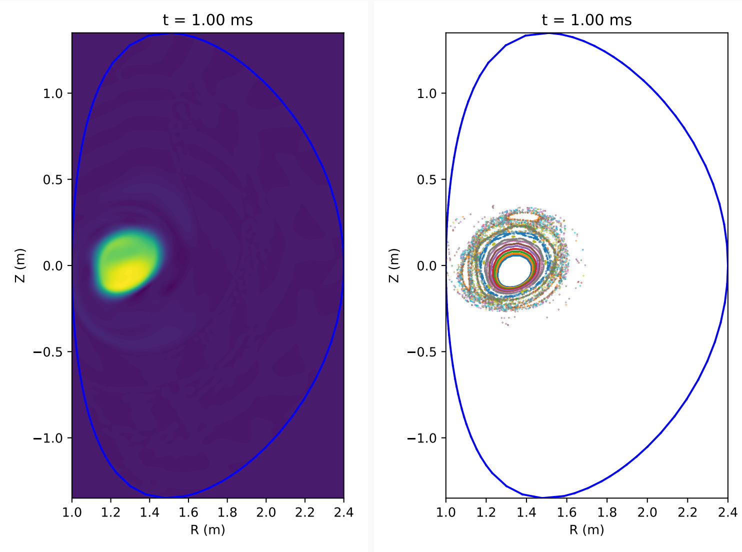




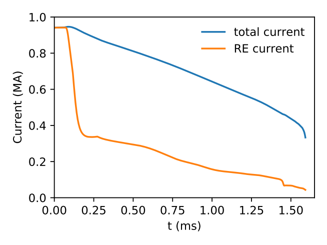
RE loss ratio is difference from MARS prediction

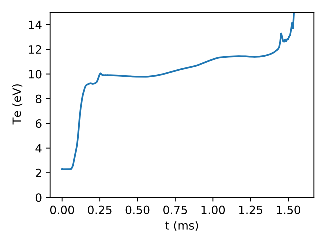
- At the saturation level of the mode growing, $\delta B \approx 710$G.
- According to MARS simulation, all the REs will get lost at this level of perturbation. However, we find that 35% of RE current will survive.
    - Note that in our fluid model of RE, no gradient or curvature drifts are taken into account. So the loss ratio has no dependence on RE momentum, pitch angle or streaming direction.
- RE current get peaked at the core when the loss at outer region happens. q_{min} drops below 1.

Nonlinear evolution after kink instability



Nonlinear evolution after kink instability





- After the initial kink mode, most of the current is replaced to be carried by thermal electrons especially in the outer region.
- Current decays due to resistive diffusion.
- RE keep getting lost due to other excited modes and stochastic field diffusion.
- Plasma temperature increases significantly due to Ohmic heating.
- Plasma and RE will shift towards high-field-side. There is a final loss after they hit the wall.
    - In our simulation the final loss happens at 1.5ms after kink instability, whereas in experiment this delay time is about 3ms.

Future work

- Study the linear behavior of the mode by using a high resistive vacuum model in M3D-C1 and try to match the results by MARS.
- Study the dependence of the linear growth rate and real frequency of kink mode with REs on resistivity and other quantities.
- Do a series of nonlinear simulation using different parameters and study the changes of saturation level.