NIMROD & KORC Computations of REs in MST and NIMROD Fluid RE Modeling

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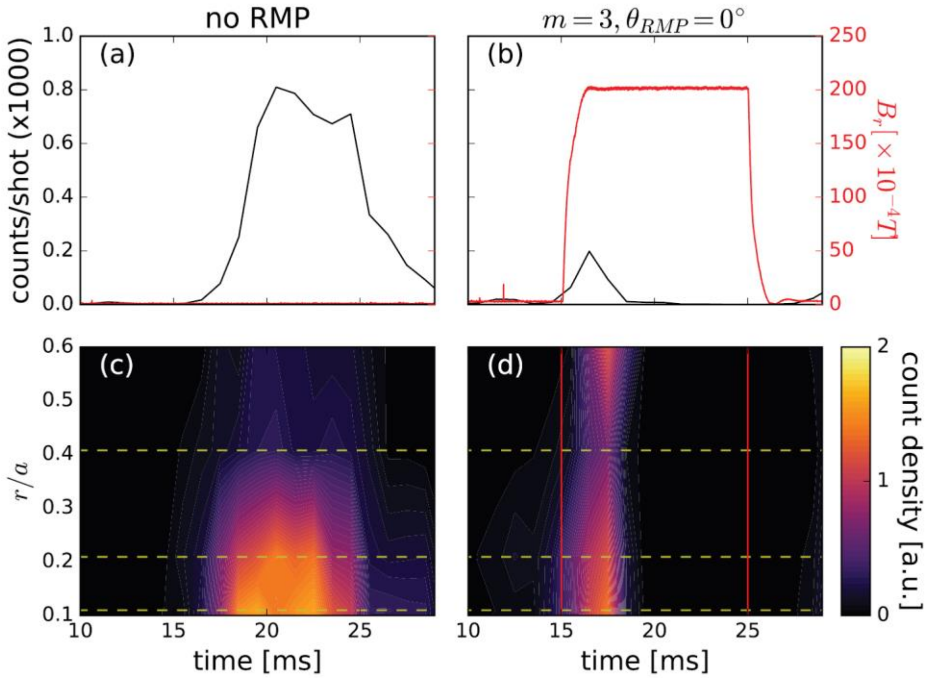
Outline

- NIMROD & KORC simulations applied to RMP studies of tokamak discharges in MST
  - Experimental summary
  - NIMROD simulations of macroscale
  - KORC computations of RE trajectories
- Fluid RE modeling
  - Equations and implementation
  - Large-R/a 2D benchmark
  - DIII-D - like case
- Conclusions

RMP deconfinement of REs is being studied in MST.

- The energetic electrons are measured through X-ray detectors.
- They are observed in low-density conditions, where E_{CH} is low.

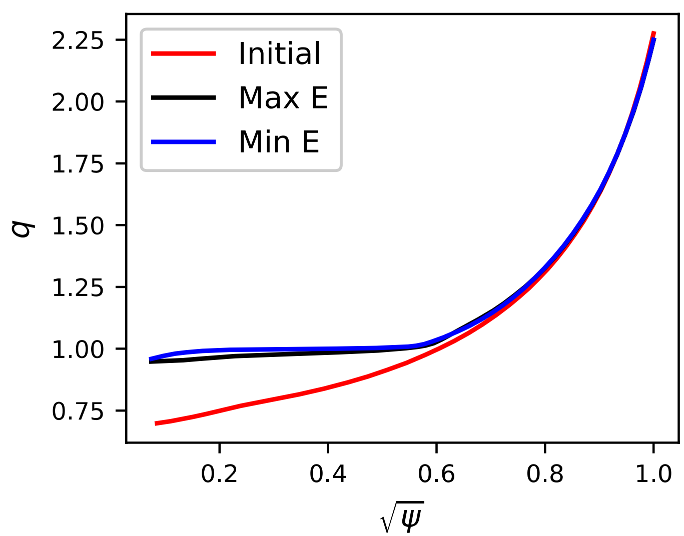


X-ray counts (black) and RMP amplitude (red) for shot with (a) and without RMP (b). Counts from an array of X-ray signals over *r* (c-d). [Munaretto, et al., NF 60, 046024]

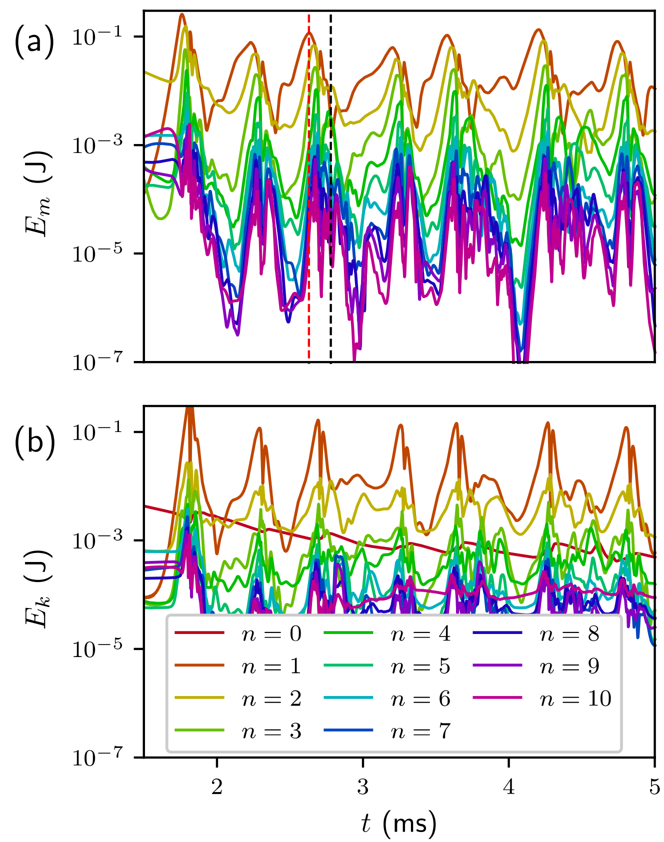
RMP of poloidal harmonic m=3 is effective at suppressing REs, m=1 is not.

Resistive-MHD NIMROD simulations of fitted profiles show sawtoothing.

- Brian Cornille used the zero-pressure model for the low-β_{pol} conditions.



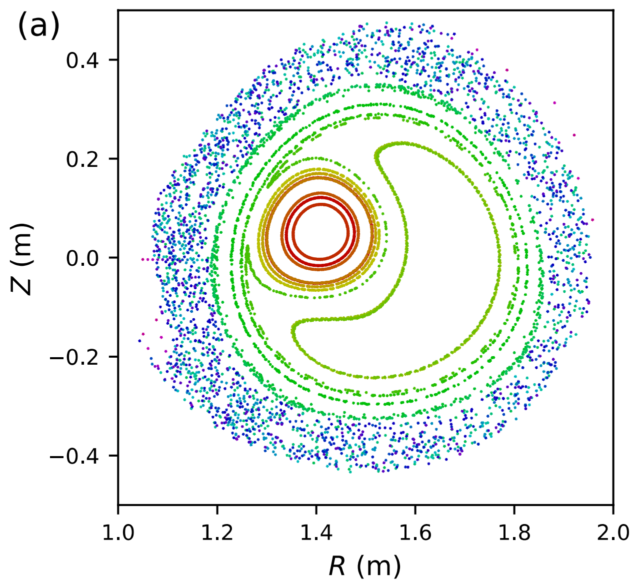
Central-q approaches unity during the initial transient, then varies only weakly over sawtoothing.



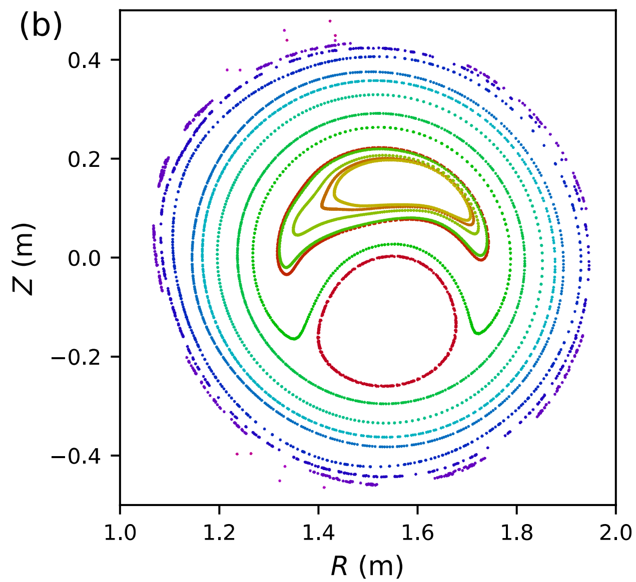
Simulated sawtooth cycle time is ~ 1/2 that in MST.

MHD simulation results suggests that sawtoothing enhances deconfinement.

- The m=3 RMP creates a stochastic edge, and sawtoothing reconnects the core.
- The m=1 RMP leaves nested flux surfaces in the edge.



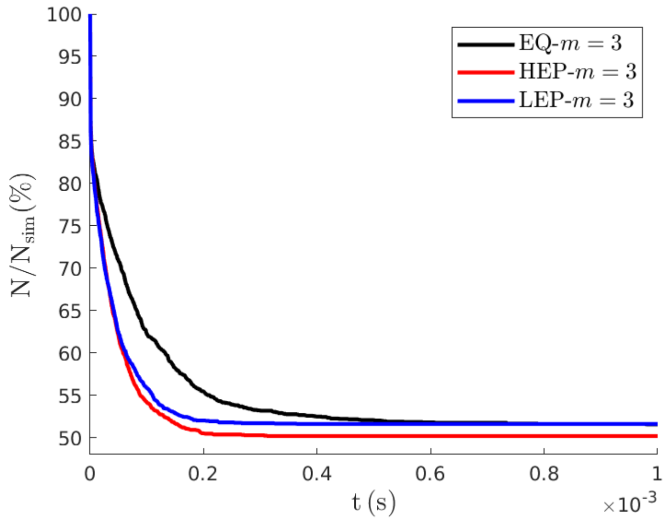
Poincare plot of magnetic topology with m=3 RMP.



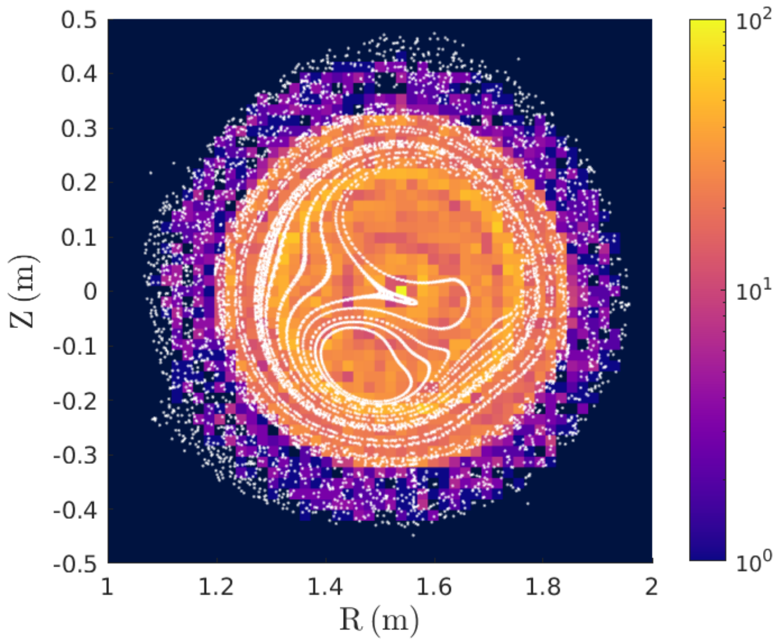
Poincare plot of magnetic topology with m=1 RMP.

KORC has been applied to check for sawtooth reconnection related/orbit-effect deconfinement.

- KORC was developed to investigate RE behavior. [Carbajal, et al., PoP **24**, 042512]
- Brian developed NIMROD interfacing through FusionIO.
- Matt Beidler of ORNL helped with running KORC.



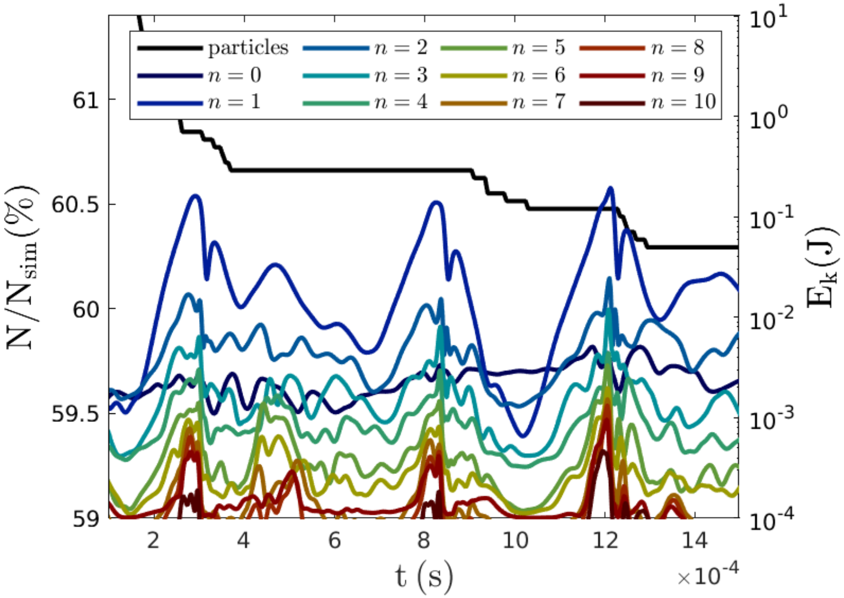
Fraction of particles (30 keV) that remain confined vs. time shows 50% loss with m=3 RMP; 85% for m=1.



Confined particles (full-orbit) remain in the core with m=3 RMP.

Relevant aspects have been checked to resolve the simulation/experiment discrepancy.

- Experiment finds total deconfinement with m=3.
- The following have been checked:
  - Numerical resolution
  - Initial particle energy and pitch-angle variation
  - *E*-field acceleration
  - Sawtoothing time-dependence
- Suspected causes are:
  - Simulated sawtoothing too weak due to equil. fitting
  - Non-modeled RMP transient



There is correlation between sawtoothing and (slight) particle deconfinement when KORC is run with time-dependent magnetic field.

B. S. Cornille PhD Thesis, UW-Madison, 2021; PoP article under review.

Fluid RE modeling in NIMROD captures interaction between RE current and B evolution.

- Model equations describe a fluid population of electrons flowing at the speed of light along magnetic field lines:

Continuity equation for runaway electron population:

$$\frac{\partial n_r}{\partial t} + \boldsymbol{\nabla} \cdot (n_r \boldsymbol{v_r}) = S_D(\mathcal{E}_{||}) + S_A(E_{||}) + D_r \nabla^2 n_r \qquad (1)$$

Where n_r is the number density of runaways, S_D, S_A are sources, D_r is a numerical diffusion coefficient and

$$\mathcal{E}_{||} \equiv \frac{E_{||}}{E_D}, \quad \boldsymbol{v_r} = c_r \hat{\mathbf{b}} + \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2}, \quad |c_r| = \text{const.} \ggg v_{th,e} \ggg v_A$$

$$E_D = \frac{n_e e^3 \ln \Lambda}{4\pi \epsilon_0 T_e}$$

RE sources are given by the Dreicer and Avalanche expressions

The model for the Dreicer source S_D is that presented by Connor and Hastie[4]

$$S_D = (n_e - n_r)^2 \frac{e^4 \ln \Lambda}{4\pi\epsilon_0^2 m_e^2 v_{th}^3} \mathcal{E}_{||}^{-\frac{3}{16}(1+Z_{eff})} \exp\left\{-\frac{1}{4\mathcal{E}_{||}} - \sqrt{\frac{1+Z_{eff}}{\mathcal{E}_{||}}}\right\}$$

$$\times \exp\left\{-\frac{T_e}{mc^2}\left(\frac{1}{8\mathcal{E}_{||}^2} + \frac{2}{3}\sqrt{\frac{1+Z_{eff}}{\mathcal{E}_{||}^3}}\right)\right\}$$

The avalanche source S_A is given by Rosenbluth and Putvinski[5]:

$$S_A = \frac{n_r}{\tau}\sqrt{\frac{\pi a}{3(Z+5)}}\left(\frac{E_{||}}{E_c} - 1\right)\left(1 - \frac{E_c}{E_{||}} + \frac{4\pi(Z+1)^2}{3a(Z+5)(E_{||}^2/E_c^2 + 4/a^2 - 1)}\right)^{-1/2}$$

$$E_c = \frac{n_e e^3 \ln \Lambda}{4\pi\epsilon_0^2 mc^2}, \quad a(\varepsilon) = (1 + 1.46\sqrt{\varepsilon} + 1.72\varepsilon)^{-1}, \quad \tau = \frac{mc \ln \Lambda}{eE_c}$$

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[4] J. W. Connor and R. J. Hastie, Nuclear Fusion **15**, 415–423 (1975)
[5] M. N. Rosenbluth and S. V. Putvinski, Nuclear Fusion **37**, 1355–1362 (1997)

RE interacts with MHD via the modified Ohms law.

In this Ohm's law, one assumes the parallel current carried by the runaways experiences no resistivity.

$$\mathbf{E} = -\boldsymbol{V} \times \boldsymbol{B} + \eta \left(\boldsymbol{J} - e n_r c \hat{\boldsymbol{b}} \right) \tag{2}$$

This model is valid for

$$\frac{n_r}{n_e} \ll 1, \qquad m_e n_r \partial_t \boldsymbol{v}_r \approx 0$$

- Note that the drift velocity contribution to the runaway current is neglected.
- This model is similar the model employed in Bandaru[6] and Matsuyama[7].

[6] V. Bandaru et al., Physical Review E **99**, 1–11 (2019)
[7] A. Matsuyama et al., Nuclear Fusion **57**, 10.1088/1741-4326/aa6867 (2017)

Least squares projection and time-split advance stabilizes runaway advection.

$$\Delta n_r = \Delta n_{r,\mathsf{adv}} + \Delta n_{r,\mathsf{src}}$$

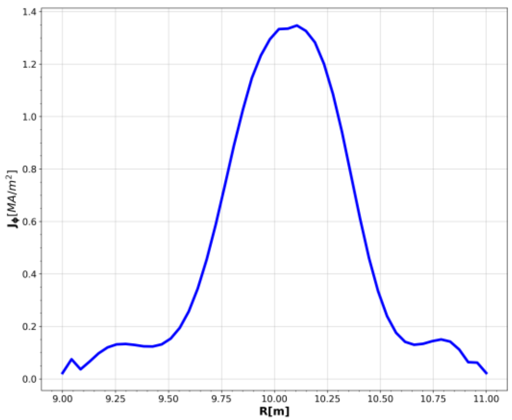
$$\int dV \left\{ \Delta n_{r,\mathsf{adv}} + \Delta t \boldsymbol{\nabla} \cdot \left(\boldsymbol{v}_r \frac{\Delta n_{r,\mathsf{adv}}}{2} \right) \right\} \times \left\{ g + \Delta t \boldsymbol{\nabla} \cdot \left(\boldsymbol{v}_r \frac{g}{2} \right) \right\}$$
$$= - \int dV \, \Delta t \boldsymbol{\nabla} \cdot \left(n_r^k \boldsymbol{v}_r \right) \times \left\{ g + \Delta t \boldsymbol{\nabla} \cdot \left(\boldsymbol{v}_r \frac{g}{2} \right) \right\}$$

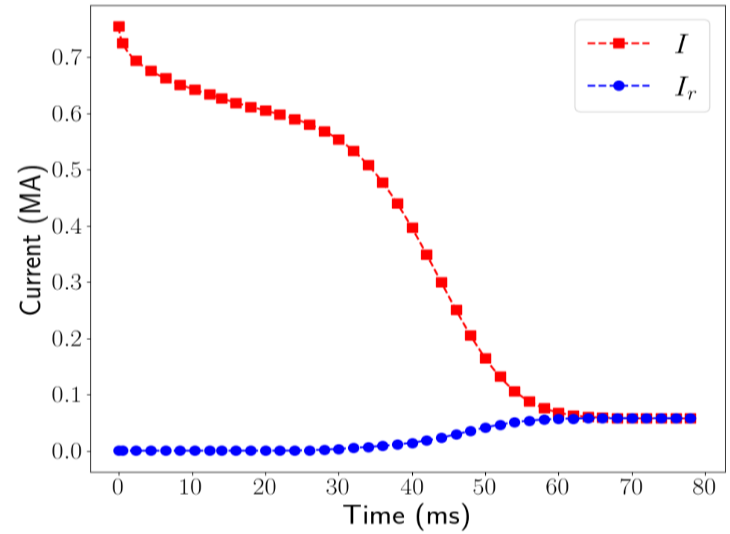
$$n_r^{k\prime} = n_r^k + \Delta n_{r,\mathsf{adv}}$$

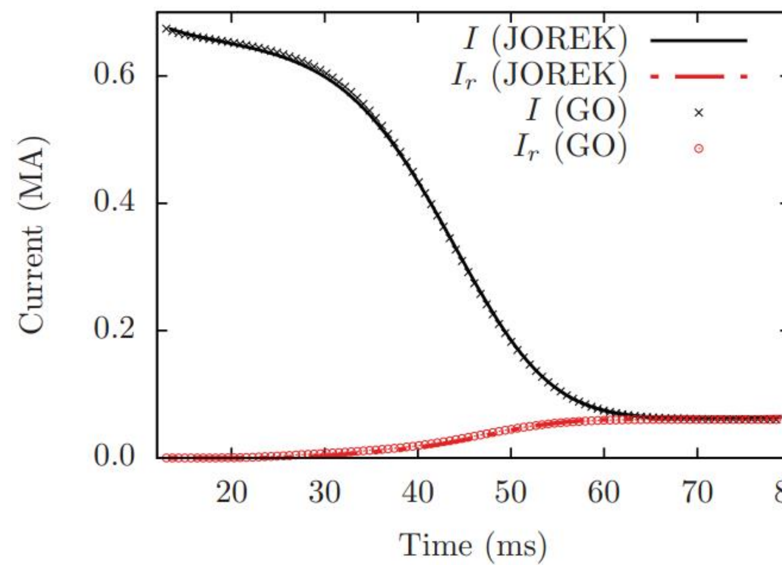
$$\int dV \left\{ \Delta n_{r,\mathsf{src}} g + \Delta t D_r \boldsymbol{\nabla} \left(\frac{\Delta n_{r,\mathsf{src}}}{2} \right) \cdot \boldsymbol{\nabla} g \right\}$$
$$= \Delta t \int dV \left\{ \left(S_D + S_A \right) g - \Delta t D_r \boldsymbol{\nabla} n_r^{k\prime} \cdot \boldsymbol{\nabla} g \right\}$$

$$n_r^{k+1} = n_r^{k\prime} + \Delta n_{r,\mathsf{src}}$$

Results from 2D, high R/a benchmark between NIMROD and JOREK predict the same current quench

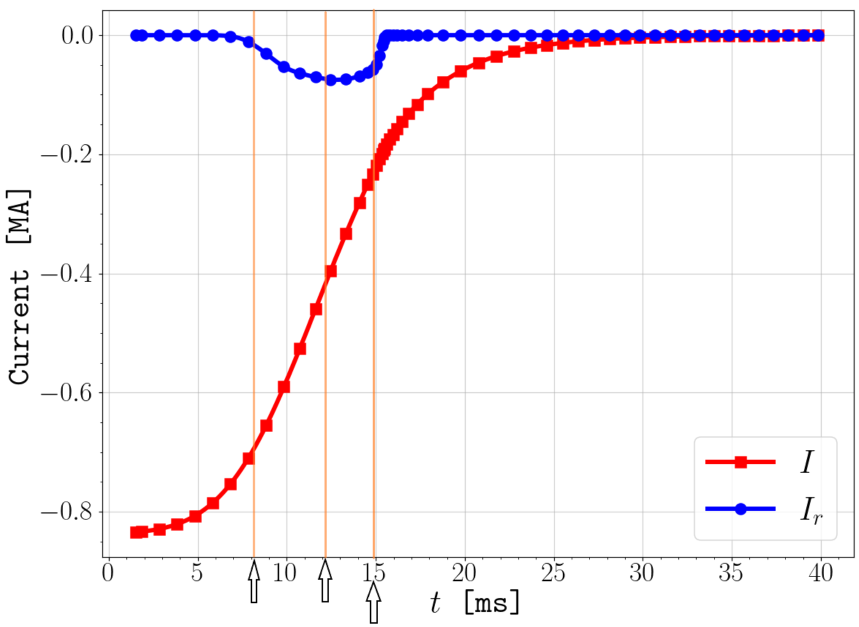


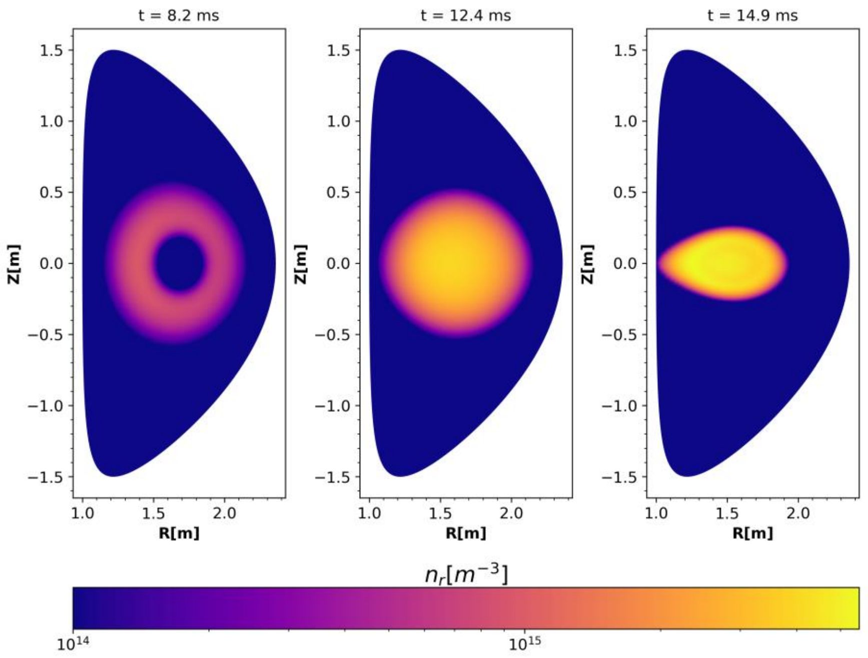




- Equilibrium toroidal current density profile for the benchmark case.
- Thermal quench imposed by raising the value of conductivity.
- Total current and runaway current computed in NIMROD agree with JOREK and GO [Bandaru, et al., Phys Rev E **99**, 063317]

2D results from DIII-D like case show loss to the wall disrupting formation of a current plateau.





- Contours on the right show runaway density at the three times indicated on the current traces on the left.
- The initially hollow distribution becomes more uniform and begins to be lost to the wall along open field-lines.

Conclusions

- NIMROD + KORC simulations MST find significant differences between the m=1 and m=3 RMP .
- The simulations do not predict total deconfinement of REs with the m=3 RMP.
- Suspected causes are:
  - Simulated sawtoothing too weak due to equil. fitting
  - Non-modeled RMP transient
- Fluid RE model in NIMROD reproduces JOREK results from 2D benchmark.
- Split-step runaway advance with least squares stabilizes the RE advection at larger time steps
- Results from DIII-D – like equilibrium case show that the model can capture the effect of RE loss to the wall along field lines.