Enabling Multiscale, Multiphysics Disruption Modeling with M3D-C1

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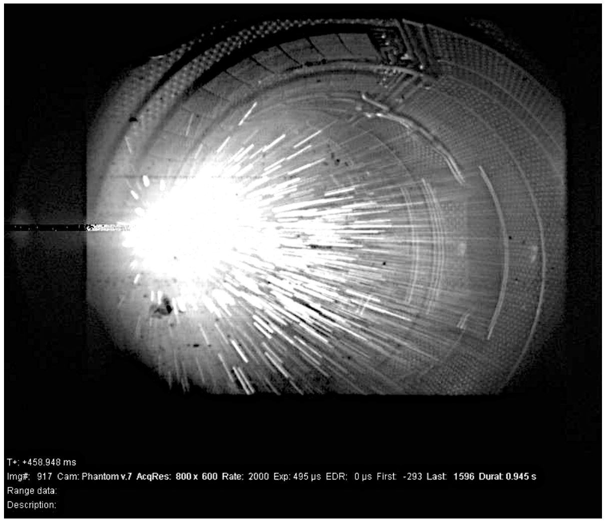
CTTS: Center for Tokamak Transients Simulations

- **Disruption**: uncontrolled loss of plasma current and confinement



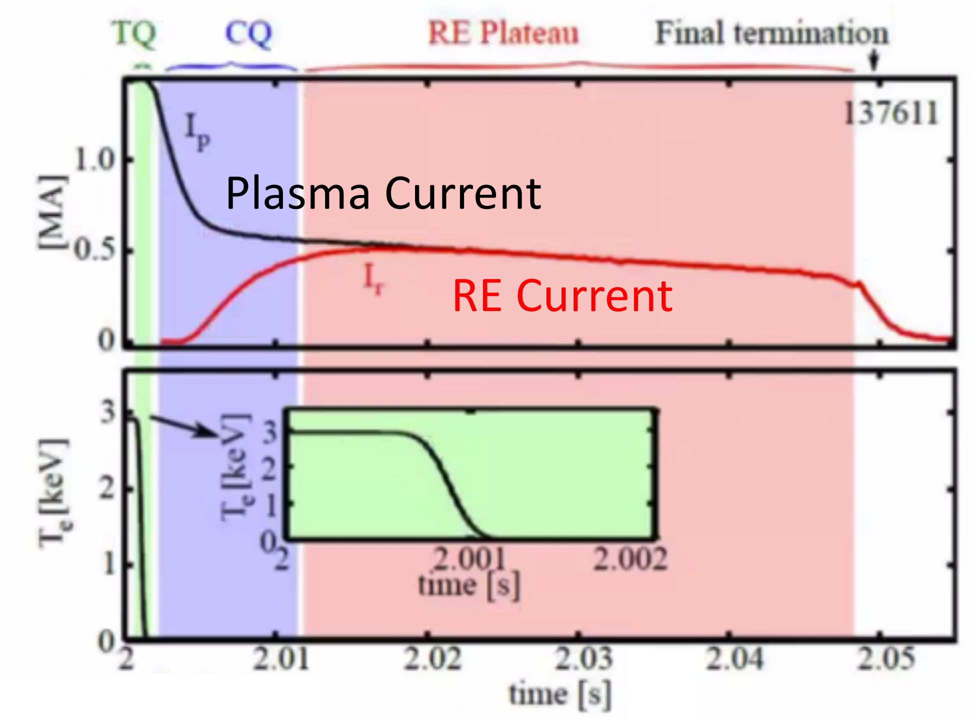
Tore-Supra, CEA
https://www.iter.org/newsline/106/1463

- Can cause serious damage
  - Huge forces and thermal fluxes in ITER
- Many different causes
  - Locked modes
  - Vertical displacement event
  - Radiative collapse
  - Density limit

- **Understanding disruptions and disruption mitigation is a primary goal of the domestic and international MFE program**

Phases of a Disruption

- **Thermal quench (TQ):** rapid cooling of plasma due to radiation or loss of confinement
- **Current Quench (CQ):** rapid loss of plasma current due to resistive decay
- **Runaway Plateau:** If $E_{||}$ during CQ is large enough, runaway electrons (REs) can form



Nick Bogatu

- We want to simulate these phases self-consistently
  - **Multi-physics, multi-scale problem**

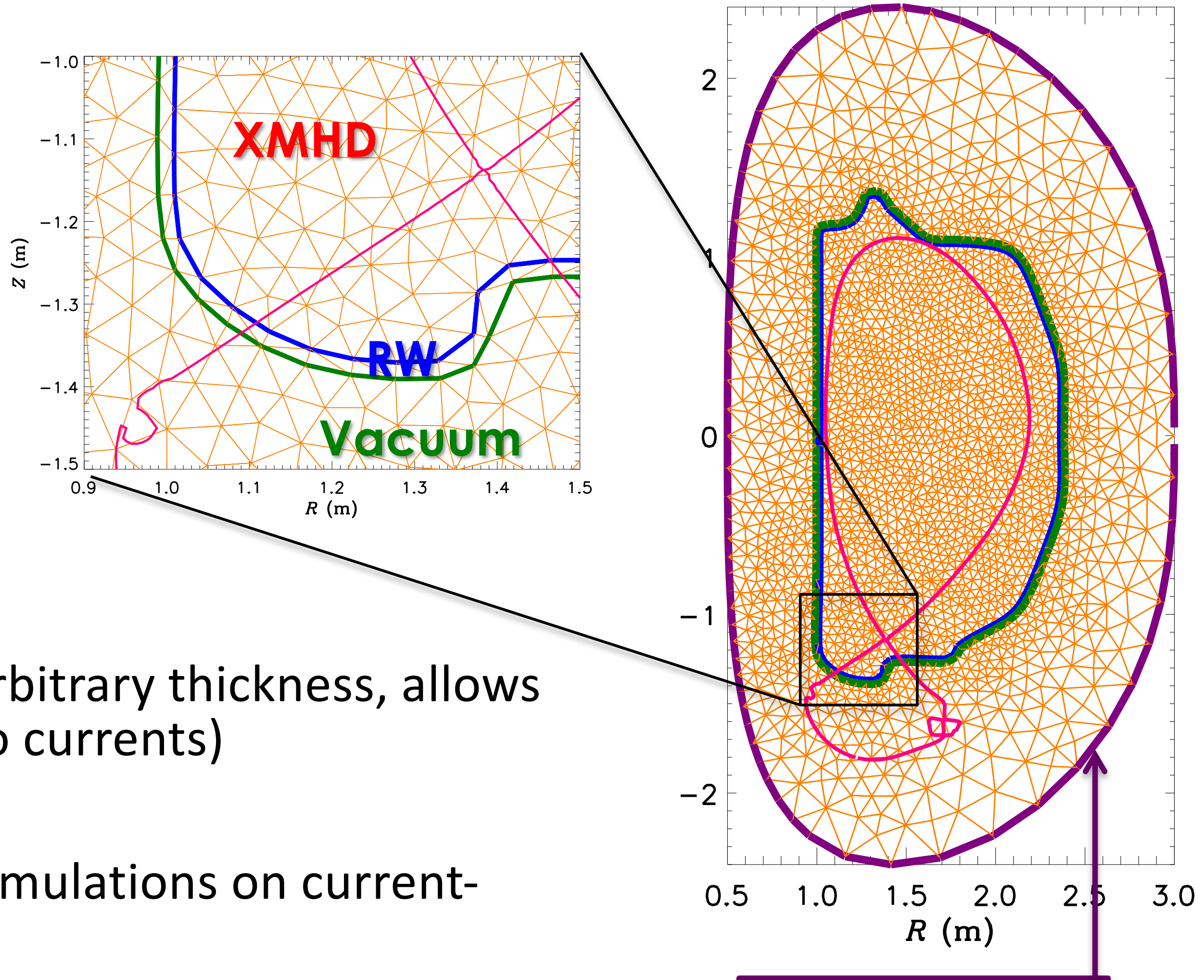
CTTS is Making Significant Progress in Capability to Model Disruptions

- Resistive wall models allow calculations of large-scale plasma displacement, wall forces, and halo currents
- High-fidelity models of pellet / gas injection and MHD evolution
  - Significant new developments in CTTS SciDAC
- Self-consistent evolution of thermal ions, electrons, and impurities
- Self-consistent evolution of runaway electrons and MHD
  - Ongoing work in SCREAM SciDAC

M3D-C1

Resistive Wall is a Region in M3D-C1's Unstructured Finite Element Mesh

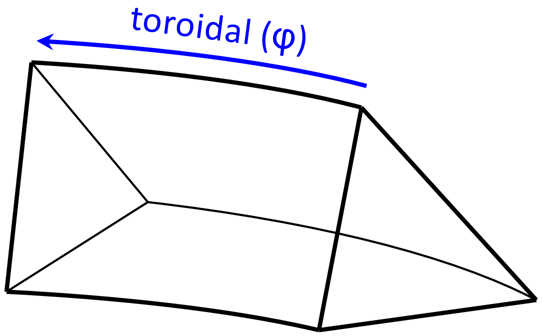
- C^1 triangular finite elements
- 3 regions inside domain:
  - XMHD (Extended MHD)
  - RW: $\mathbf{E} = \eta_W \mathbf{J}$
  - Vacuum: $\mathbf{J} = 0$
- Resistive wall region has arbitrary thickness, allows currents into the wall (halo currents)
- Implicit time step allows simulations on current-diffusion timescales



Domain Boundary (superconducting)

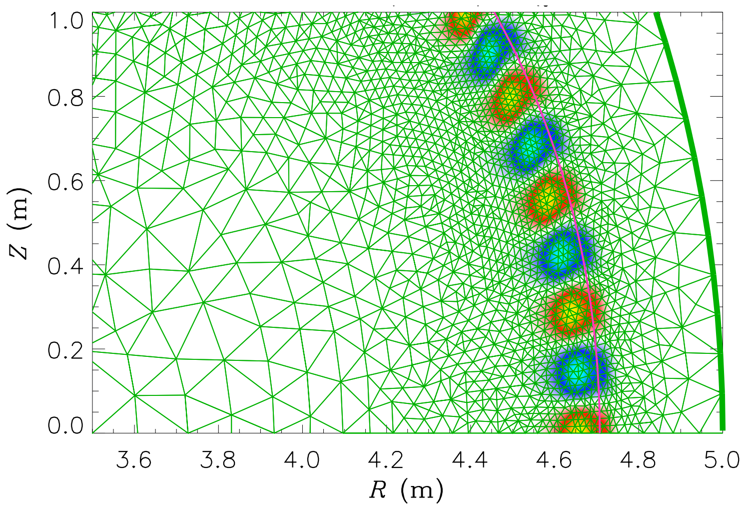
Unstructured Mesh Allows Complex Geometries and Refinement Capabilities

- High-order C^1 elements
  - Reduced quintic triangular elements (poloidal plane)
  - Cubic Hermite elements (toroidal direction)
  - Allow efficient use of vector-potential formulation of magnetic field
  - Compact matrices – vectorizes and scales well



- Uses PUMI mesh software developed by RPI SCOREC

- Multi-region, unstructured mesh allows scalable, implicit implementation of resistive wall model



Model Implemented in M3D-C1

$$\frac{\partial n_i}{\partial t} + \nabla\cdot(n_i\mathbf{u}) = \sigma_i$$

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = \mathbf{J}\times\mathbf{B} - \nabla p - \nabla\cdot\Pi$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{u}\times\mathbf{B} - \eta\mathbf{J})$$

$$\frac{\partial n_z}{\partial t} + \nabla\cdot(n_z\mathbf{u}) = \sigma_z \qquad z = 1,..,Z$$

$$\rho = m_i n_i + \sum_{z=1}^{Z} m_Z n_z$$

$$n_e = Z_i n_i + \sum_{z=1}^{Z} z\, n_z$$

$$\sigma_e = Z_i\sigma_i + \sum_{z=1}^{Z} z\,\sigma_z$$

$$\mathbf{J} = \nabla\times\mathbf{B}$$

- Compressible, resistive MHD with single impurity species

- All charge state densities for single impurity species are evolved separately
  - All charged species advected using same fluid velocity ($\mathbf{u}_e = \mathbf{u}_i = \mathbf{u}_z$)
  - Neutral impurities are not advected

- All ions (main & impurities) assumed to have same temperature T_i

- Several models for pressure advance implemented

Four Models for Temperature Evolution

1. Single equation for total pressure (sum of all pressure equations). Assumes $p_e \,/\, p \;=\; const.$

$$\frac{\partial p}{\partial t} + \mathbf{u}\cdot\nabla p + \Gamma p\nabla\cdot\mathbf{u} = (\Gamma - 1)(Q + Q_{rad} + \nabla\cdot\mathbf{q} + \Pi\!:\nabla\mathbf{u} + \eta J^2)$$

2. Single equation for temperature (sum of all temp. equations). Assumes $T_e \,/\, Ti \;_{=}\; \alpha.$

$$N\left(\frac{\partial T_e}{\partial t} + \mathbf{u}\cdot\nabla T_e + (\Gamma - 1)T_e\nabla\cdot\mathbf{u}\right) + \Sigma\, T_e = (\Gamma - 1)(Q + Q_{rad} + \nabla\cdot\mathbf{q} + \Pi\!:\nabla\mathbf{u} + \eta J^2)$$

$$N = n_e + \alpha\left(n_i + \sum\nolimits_z n_z\right)$$

$$\Sigma = \sigma_e + \alpha\left(\sigma_i + \sum\nolimits_z \sigma_z\right)$$

3. Two pressure equations: one for total pressure, one for electron pressure

$$\frac{\partial p_e}{\partial t} + \mathbf{u}\cdot\nabla p_e + \Gamma p_e\nabla\cdot\mathbf{u} = (\Gamma - 1)(Q_e + Q_{rad} + Q_\Delta + \nabla\cdot\mathbf{q}_e + \eta J^2)$$

4. Two temperature equations: one for electron temperature, one for ion temperature (sum of all ion temp. equations)

$$n_e\left(\frac{\partial T_e}{\partial t} + \mathbf{u}\cdot\nabla T_e + (\Gamma - 1)T_e\nabla\cdot\mathbf{u}\right) + \sigma_e\, T_e = (\Gamma - 1)(Q_e + Q_{rad} + Q_\Delta + \nabla\cdot\mathbf{q}_e + \eta J^2)$$

$$n_I\left(\frac{\partial T_i}{\partial t} + \mathbf{u}\cdot\nabla T_i + (\Gamma - 1)T_i\nabla\cdot\mathbf{u}\right) + \sigma_I\, T_i = (\Gamma - 1)(Q_I - Q_\Delta + \nabla\cdot\mathbf{q}_I + \Pi_I\!:\nabla\mathbf{u} + \eta J^2)$$

$$n_I = n_i + \sum\nolimits_z n_z$$

$$\sigma_I = \sigma_i + \sum\nolimits_z \sigma_z$$

KPRAD Model Implemented in M3D-C1

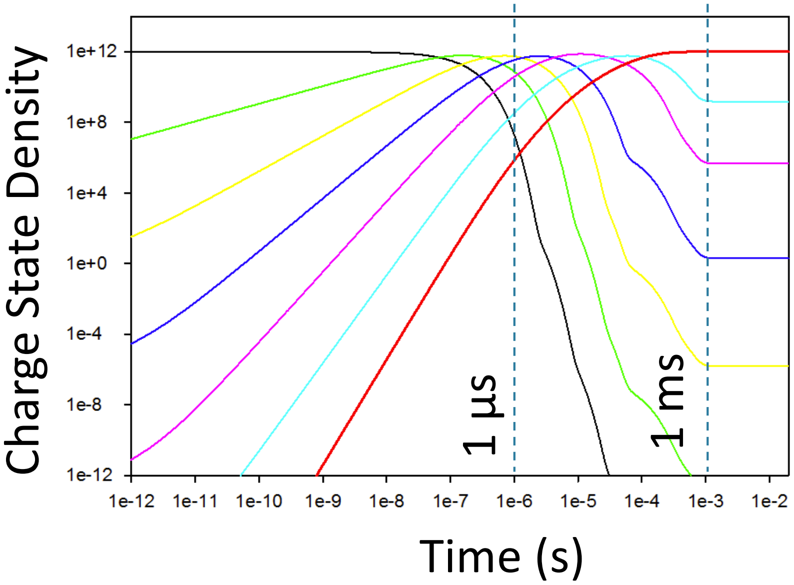
- Calculates ionization, recombination, and radiation from impurities

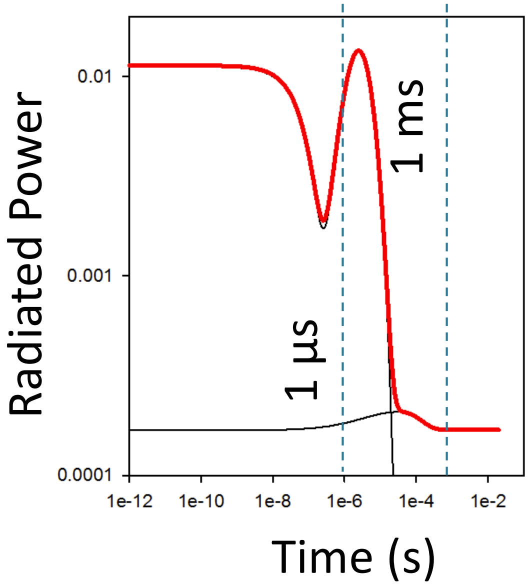
$$\sigma_z = I_{z-1}n_{z-1} - (I_z + R_z)n_z + R_{z+1}n_{z+1} \qquad z = 0, 1, \ldots, Z$$

- Calculates electron energy sink (Q_{rad}) from Radiation, Bremsstrahlung, Ionization, and Recombination

- Does not assume coronal equilibrium

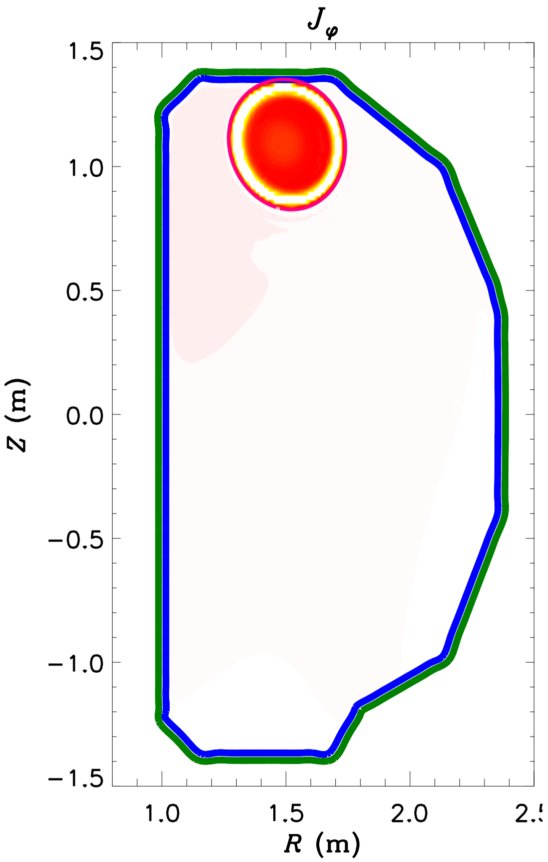
- Can take ~ms to reach coronal equilibrium





Fast Thermal Quench in VDEs

“Hot” VDEs are a Challenging Scenario for Large Tokamaks



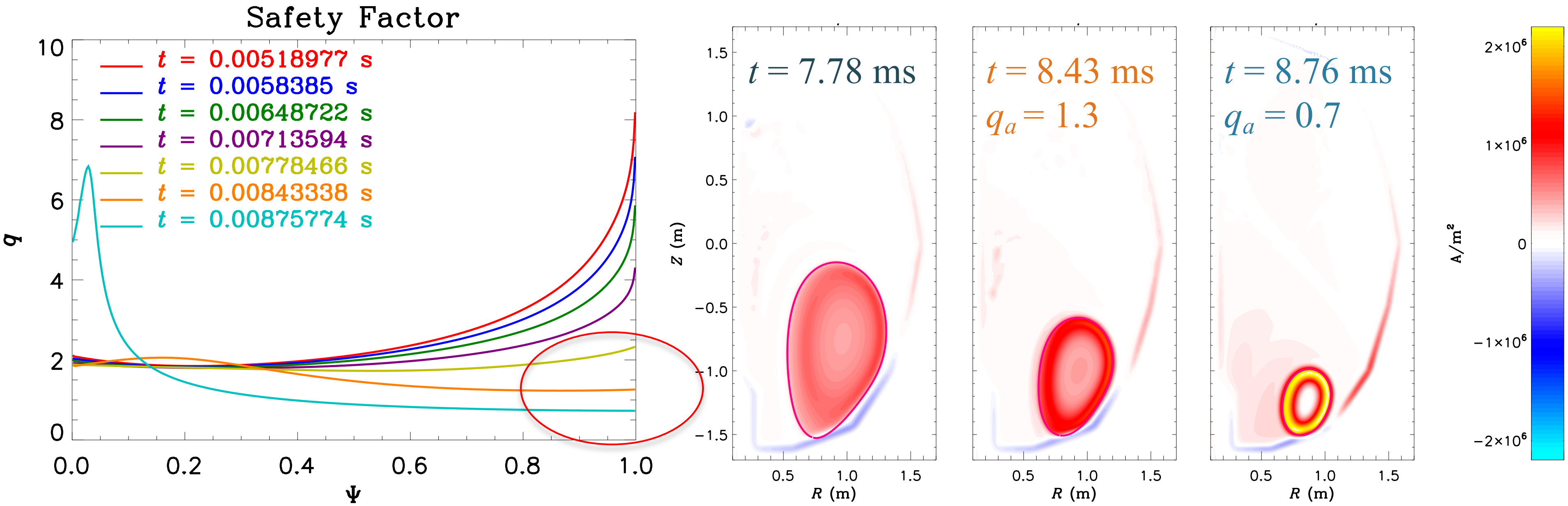
- Vertical displacement events (VDEs) are due to loss of vertical stability control

- 3D simulations of vertical displacement events are being carried out with M3D-C1 for ITER, NSTX(-U), DIII-D, and JET
  - Simulations use realistic wall and plasma resistivities
  - See poster by C Clauser for ITER results

- “Hot” VDEs are those that hit the wall before thermal quench is complete
  - No impurities – plasma stays hot
  - Large thermal fluxes
  - Large eddy and halo currents

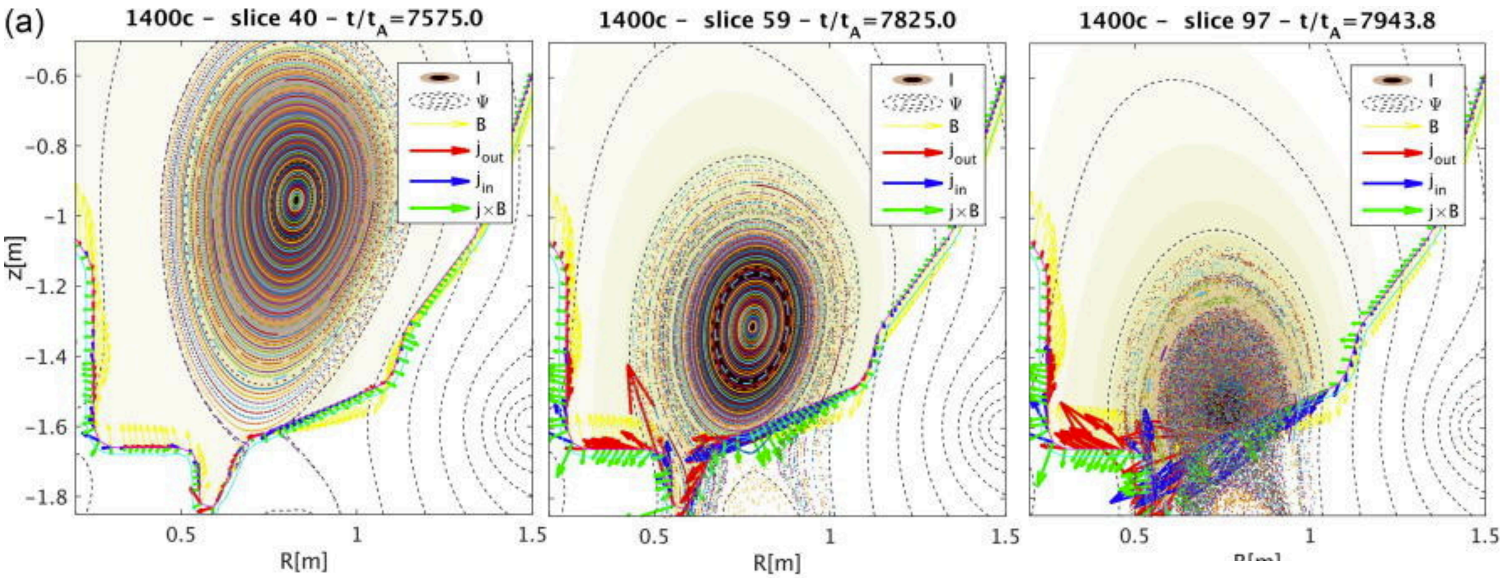
VDE Simulations Show Development of Current Sheets

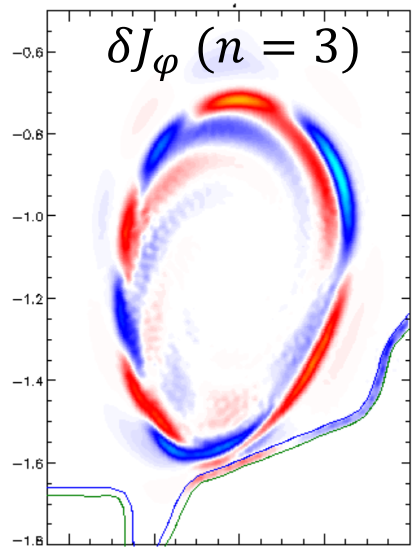
- Edge q drops as plasma is scraped off by wall
- Skin currents form to oppose contraction of current channel



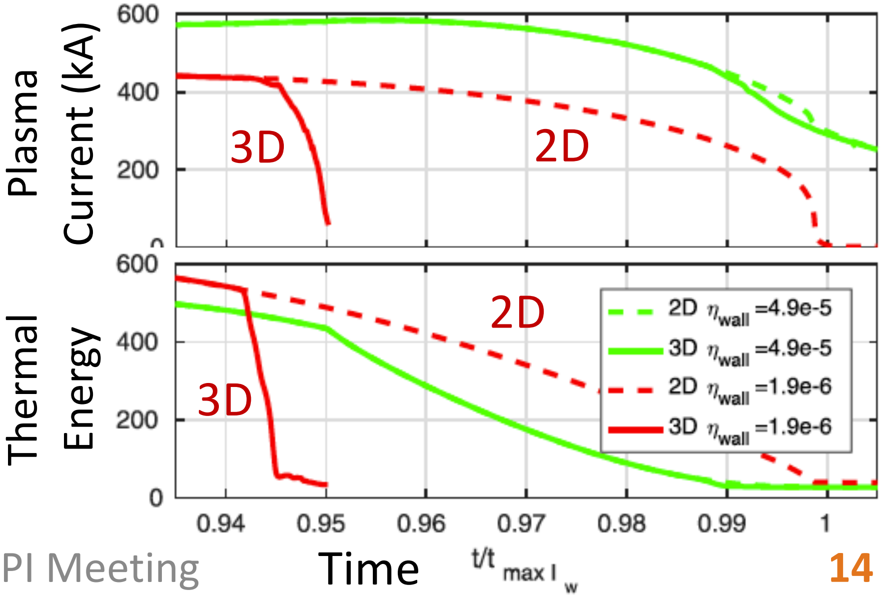
- Similar skin currents are seen during vertical displacement caused by CHI [Ebrahimi, *Phys. Plasmas* **24**, 056119 (2017)]

Current Sheet Instability Leads to Stochastization and Fast Thermal Quench





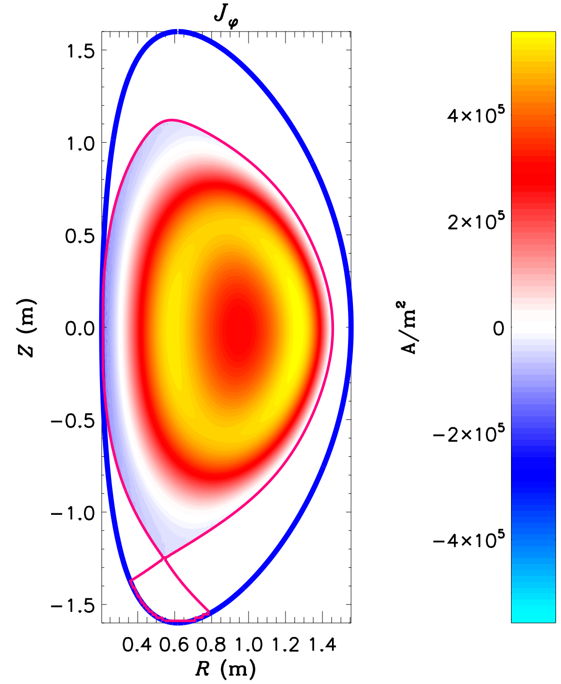
- Skin currents become unstable to mid-*n* instabilities
- Instabilities cause non-axisymmetric halo currents
- Instabilities stochasticize the magnetic field, leading to fast thermal quench

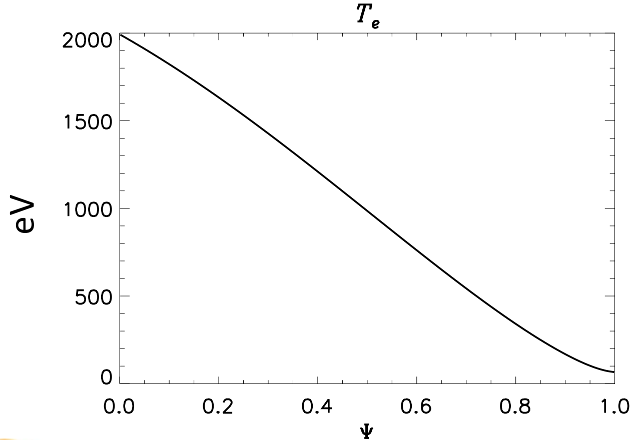


Pfefferlé *et al*, *Phys. Plasmas* **25**, 056106 (2018)

Fast Thermal Quench from Injected Impurities

Simulation of Well-Mixed Impurities: Lots of Neutral Argon Introduced Globally





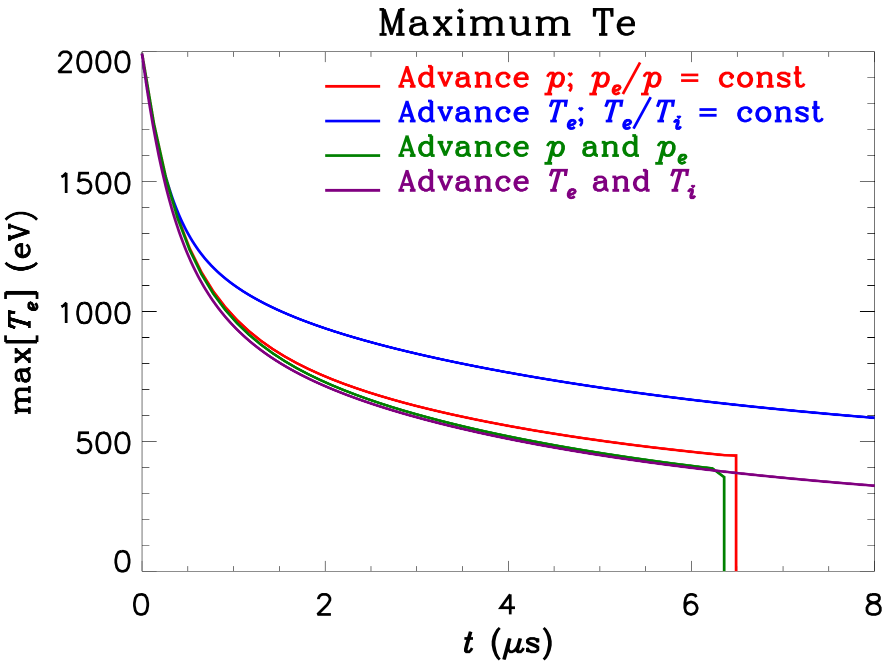
- Disruption mitigation aims for well-mixed impurities to efficiently radiate thermal energy quickly

- Here we simulate the instant introduction of uniformly distributed impurities
  - Equilibrium is reconstruction of NSTX discharge
  - Neutral Argon is introduced uniformly at $n_{Ar} = 10^{19} / m^3$.

- Initial cooling is rapid (~ 10 μs) and mainly due to dilution
  - Large new source of cold electrons

Constant T_e/T_i is a Poor Assumption During Fast Thermal Quench

- Models advancing pressure are not numerically stable
  - Dominant term in pressure equation is $\kappa_{\|}\hat{b}\hat{b}\cdot\nabla T$, which is not fully implicit in these cases
  - (Detail of implementation)

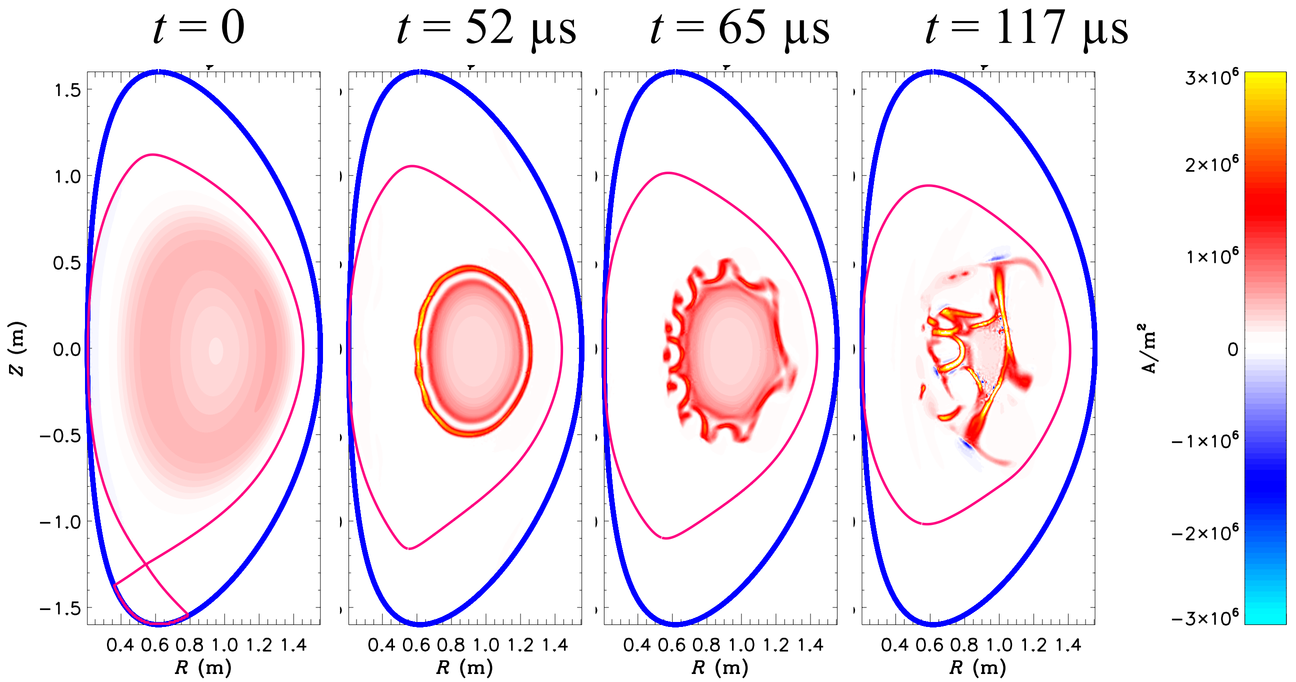


- Model that assumes $T_e/T_i = \text{const}$ is not very accurate
  - All cooling processes affect electrons, not ions
  - Quench time is faster than ion-electron thermal equilibration time
  - T_i is underestimated, T_e is overestimated

Current Channel Contracts Despite Faster Cooling in Core

- Edge resistivity drops fastest, despite strong core radiation
  - $\eta \sim T^{-3/2} \rightarrow d\eta/dT \sim -T^{-5/2}$
- Current channel contracts, leading to skin currents and instability

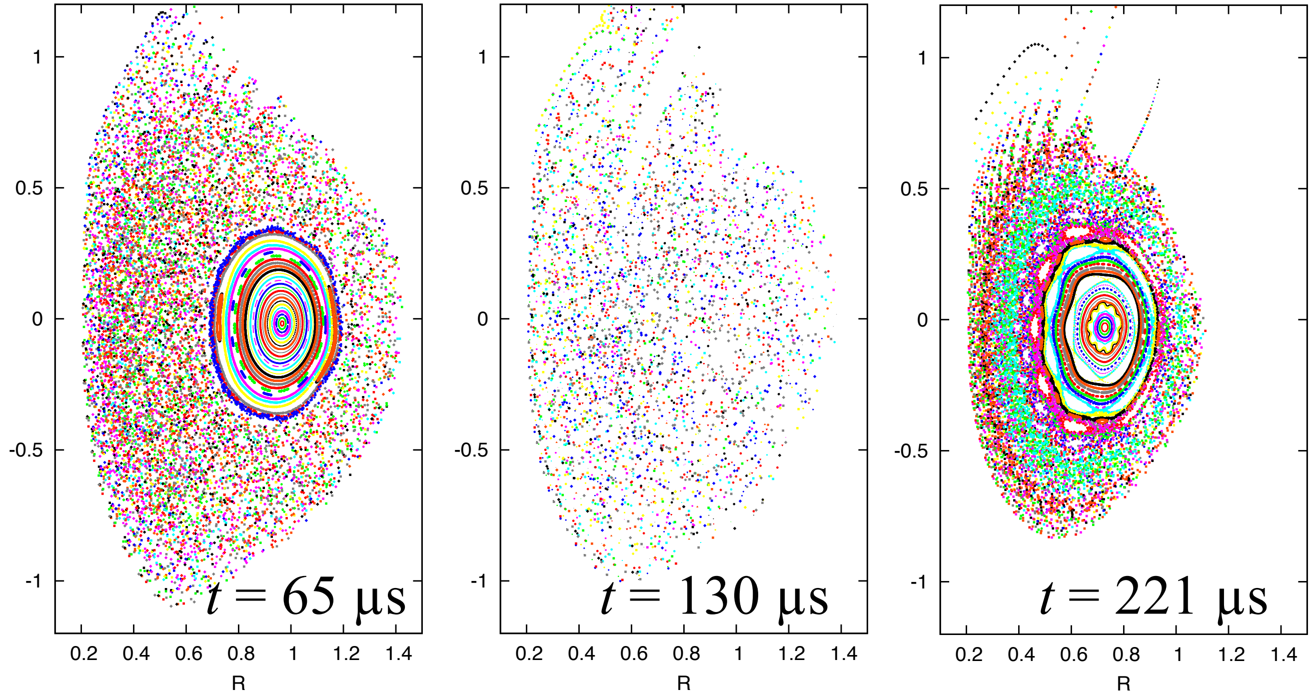
Toroidal Current Density:

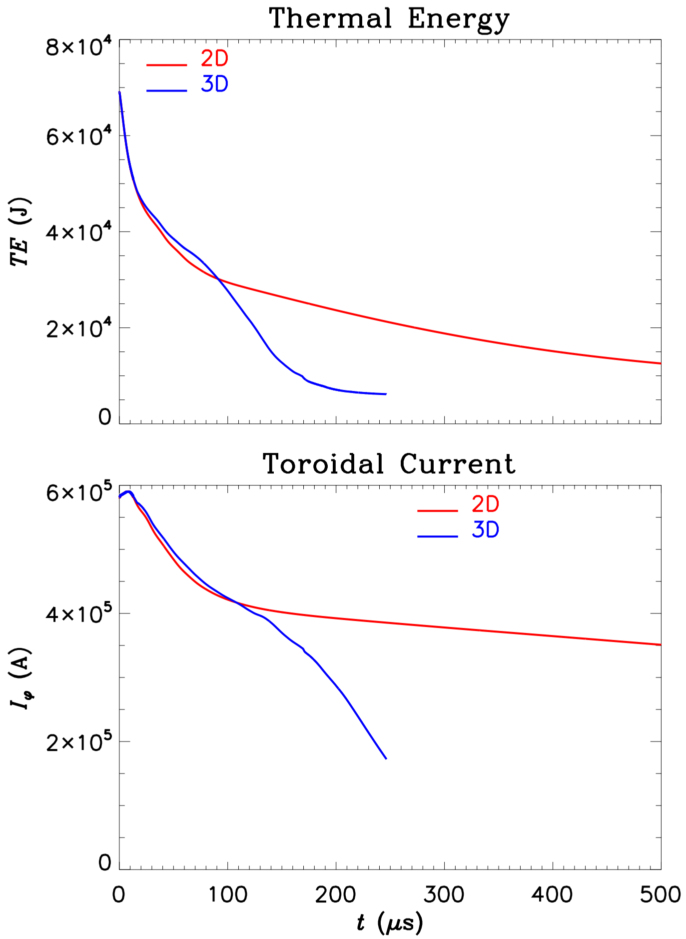


Ferraro *et al.* *Nucl. Fusion* **59** 016001 (2019)

Skin Current Instability Leads to Stochastization and Fast Thermal Quench

- Edge stochasticizes first due to edge-localized mid-n instabilities
- Lower-n modes grow later, stochasticizing core
- Surfaces re-heal after thermal quench

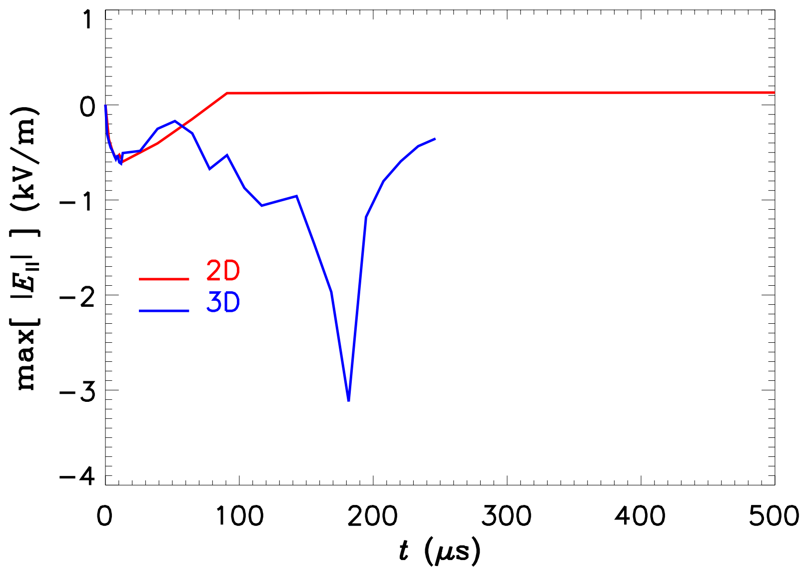


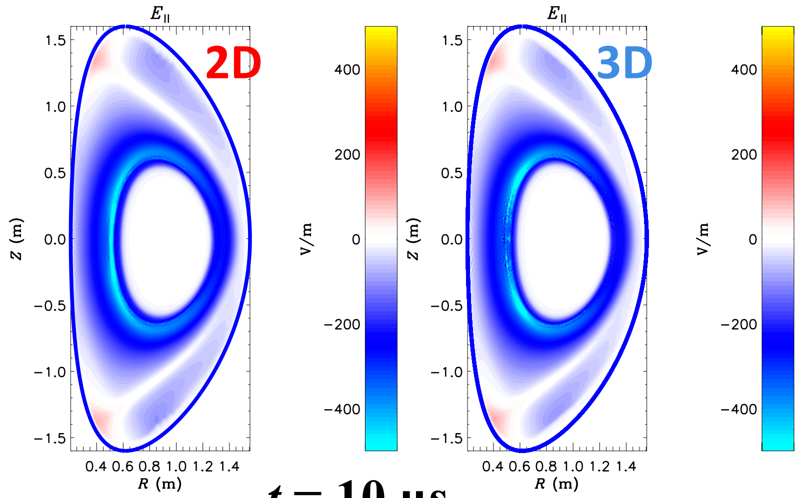


Ferraro *et al.* *Nucl. Fusion* **59** 016001 (2019)

Local Spikes in $E_\parallel$ Significantly Exceed Axisymmetric Values

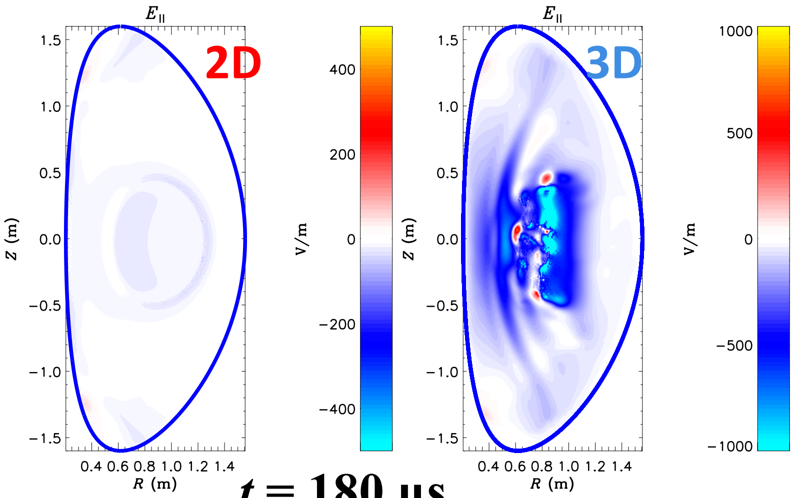
- In 2D case, the largest $E_\parallel$ is associated with skin currents
- In 3D case, local spikes in $E_\parallel$ are much larger
- In both cases, $E_\parallel >> E_{\text{crit}}$. Implications for runaways are TBD
  - Competing effects: large $E_\parallel$, but also rapid loss via stochastization
  - Surfaces appear to re-heal before end of CQ





$t = 10$ µs

$E_\parallel$



$t = 180$ µs

What are the Implications for Mitigation?

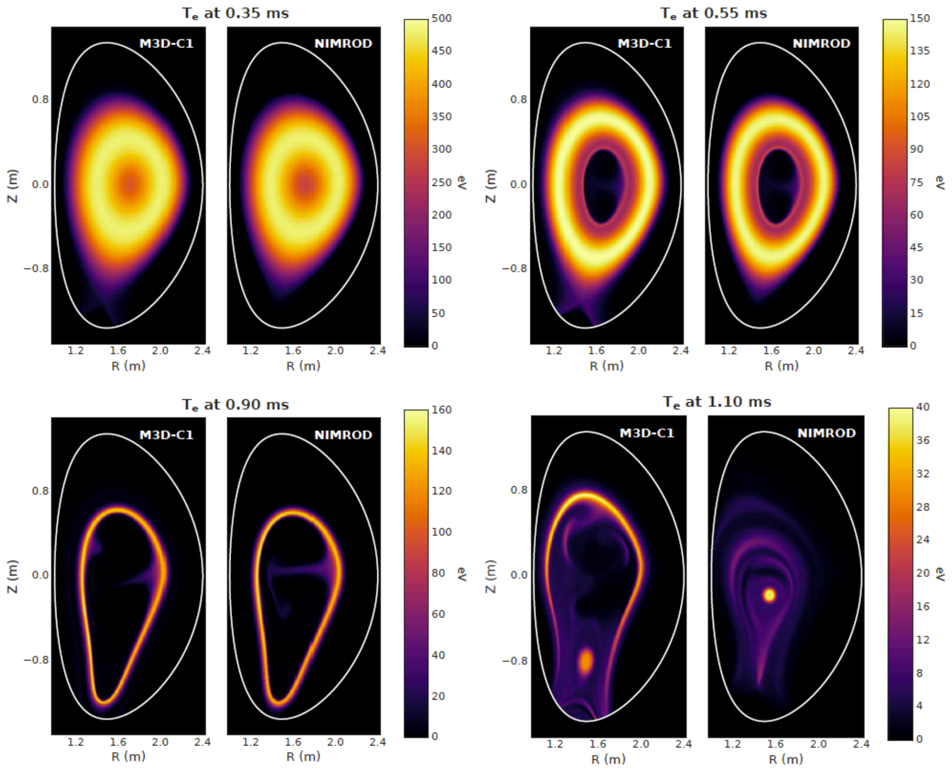
- Fast thermal quenches due to stochastization can be a challenge
  - Heat rapidly conducted to walls
  - Cold plasma causes fast drop in current, large $E_{\|}$
  - It would be better to radiate the heat away while maintaining MHD stability

- Well-mixed impurities are not enough to avoid current contraction and MHD instability
  - Core localized injection seems promising
    - Izzo, Parks. *Phys. Plasmas* **24**, 060705 (2017)
    - Hollmann, *et al. Phys. Rev. Lett.* **122**, 065001 (2019)

- How do we do this while avoiding runaway electrons?

Lots of Development is Underway

- Simulations of core-localized impurity deposition
  - Izzo, **Lyons**, Kim
- Coupling shattered pellet models with M3D-C1 and NIMROD
  - CTTS: Samulyak, Parks, Kim, **Lyons**
- Coupling runaway electron models with MHD
  - SCREAM: **C Liu**, **del-Castillo-Negrete**, **Cianciosa**



Lyons, et al. *PPCF* 2019

Summary: Significant New Disruption Modeling Capabilities and Results Enabled by CTTS SciDAC

- M3D-C1 implements a comprehensive integrated model for disruption simulation
  - Non-equilibrium impurity radiation, ionization, and transport
  - Resistive wall of arbitrary thickness that allows halo currents

- Separate equations for T_i and T_e are needed to accurately model fast cooling processes which dominantly affect electrons

- Disruptions due to well-mixed impurities and due to hot VDEs lead to similar sequence of events
  - Current channel contraction → skin currents → instability → fast thermal quench
  - Bad news for thermal flux; consequences for REs are uncertain
  - Core-localized injection might avoid this sequence

- Upcoming developments will allow self-consistent simulations of MHD, runaway electrons, and high-fidelity pellet models