CENTER FOR TOKAMAK TRANSIENTS SIMULATION

Fast TQ with Impurities in M3D-C1

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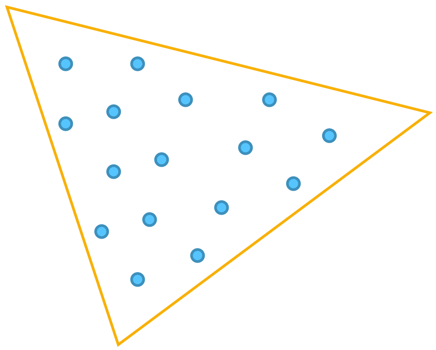
KPRAD Model Implemented in M3D-C1

- KPRAD calculates ionization, recombination, and radiation from impurities

$$\frac{\partial n_z}{\partial t} = I_{z-1} n_{z-1} - (I_z + R_z) n_z + R_{z+1} n_{z+1}$$

- All charge state densities for single impurity are evolved in time
  - Integration of master equation requires a few (variable) timesteps per MHD timestep. Done at each quadrature point independently.
  - FE representation of n_z fields calculated at each MHD timestep
  - All ionized states advected using fluid velocity
- Calculates losses from line radiation, bremsstrahlung, ionization, and recombination

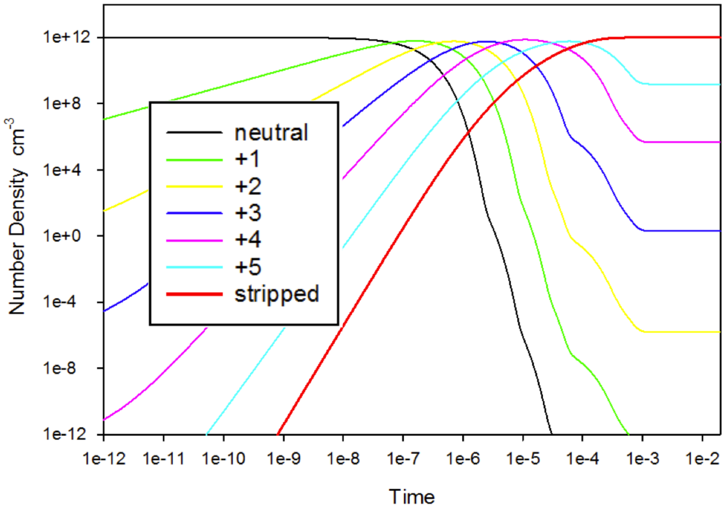


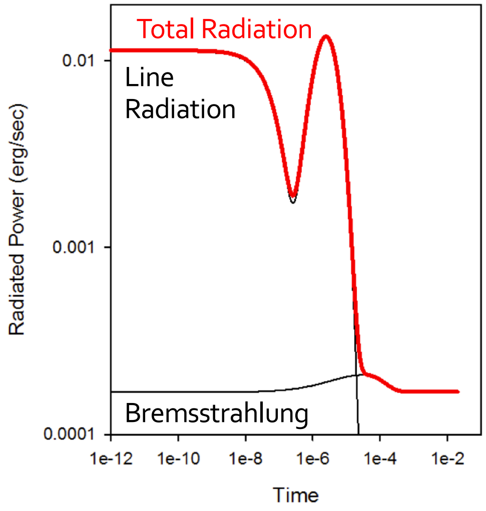
Charge States and Radiation Evolve on Comparable Timescale to Disruption Dynamics

- Distribution differs significantly from steady-state distribution on timescales less than ~1 ms
- Need to evolve charge state densities to get accurate electron source and radiation rates during disruption

0-D test of KPRAD model with C impurity

$n_C = 10^{12}$ cm^{-3}
$n_e = 10^{14}$ cm^{-3}
$T_e = 1$ keV





Single-Fluid Model with Single Impurity Species Now Implemented in M3D-C1

- Equations generalized to allow n_e / n_i to vary in space in time
- Single-fluid model implemented ($\mathbf{u}_e = \mathbf{u}_i = \mathbf{u}_z$)
- All ions (main & impurities) assumed to have same temperature T_i

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

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

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

$$\frac{\partial n_z}{\partial t} + \nabla \cdot (n_z \mathbf{u}) = \sigma_z$$

$$\rho = m_i n_i + \sum_z m_z n_z$$

$$n_e = Z_i n_i + \sum_z z n_z$$

$$\sigma_e = Z_i \sigma_i + \sum_z z \sigma_z$$

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

- Several models for pressure advance implemented

Collisional Terms Are Modified to Include Effects of Impurities

- Resistivity and equipartition terms include effect of electron—impurity collisions

$$\eta = \frac{m_e \nu_{eH}}{n_e e^2} \underbrace{\left(\frac{Z_i^2 n_i + \sum_z z^2 n_z}{n_e} \right)}_{Z_{\mathrm{eff}}}$$

$$Q_\Delta = 3\nu_{eH} \frac{m_e}{m_i} (T_i - T_e) \left(Z_i^2 n_i + \frac{m_i}{m_z} \sum_z z^2 n_z \right)$$

$$\nu_{eH} = \frac{4\sqrt{2\pi} e^4 n_e \ln \Lambda}{3\sqrt{m_e} T_e^{3/2}}$$

electron-ion collision frequency if plasma were purely hydrogenic

- Other collisional terms (viscosity, thermal diffusivity) are anomalous and are not modified by impurities (presently)

Four Models for Pressure Advance Implemented

1. Single equation for total pressure. Assumes $p_e / p = \text{const.}$

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

2. Single equation for temperature (from sum of all temp. equations). Assumes $T_e / T_i = \alpha$.

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

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

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

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

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

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

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

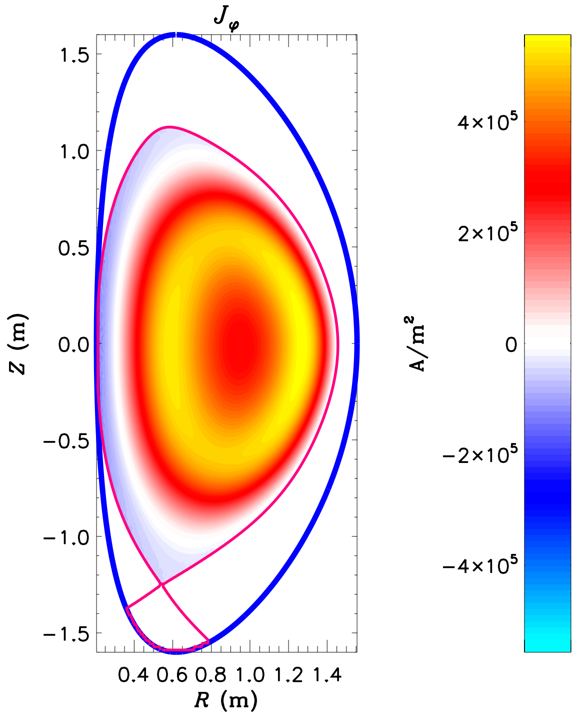
$$n_I\left(\frac{\partial T_i}{\partial t} + \mathbf{u}\cdot\nabla T_i + (\Gamma - 1) T_i \nabla\cdot\mathbf{u}\right) + \sigma_I T_i = (\Gamma - 1)\left(Q_I - Q_\Delta + \nabla\cdot\mathbf{q}_I + \Pi_I : \nabla\mathbf{u}\right)$$

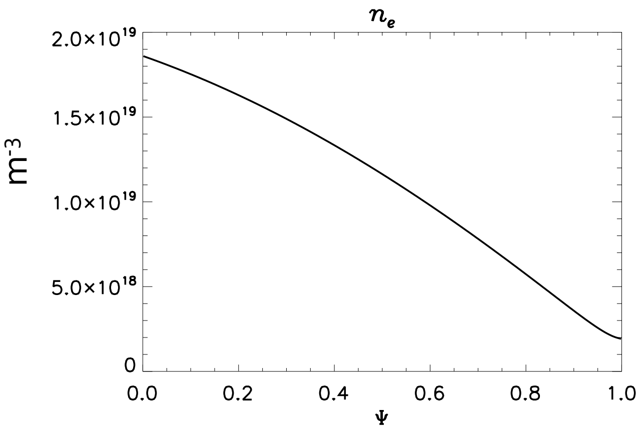
$$n_I = n_i + \sum_z n_z$$

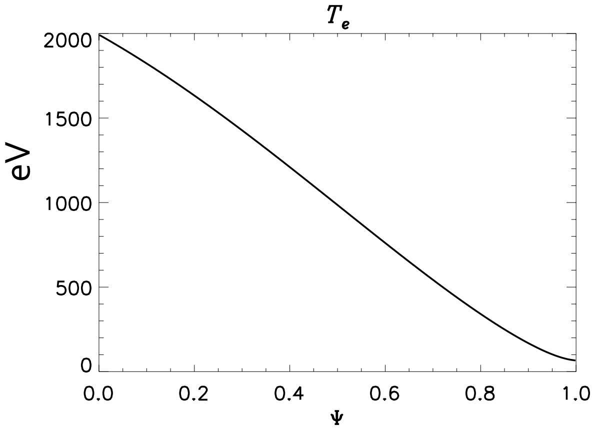
$$\sigma_I = \sigma_i + \sum_z \sigma_z$$

Simple Test Case:
Lots of Neutral Argon Introduced Globally

- Equilibrium is reconstruction of NSTX discharge 139536 at *t*=309 ms
- Neutral Argon is introduced globally at $n_{Ar} = 10^{19}$ / m^3
- Initial cooling is mainly due to dilution

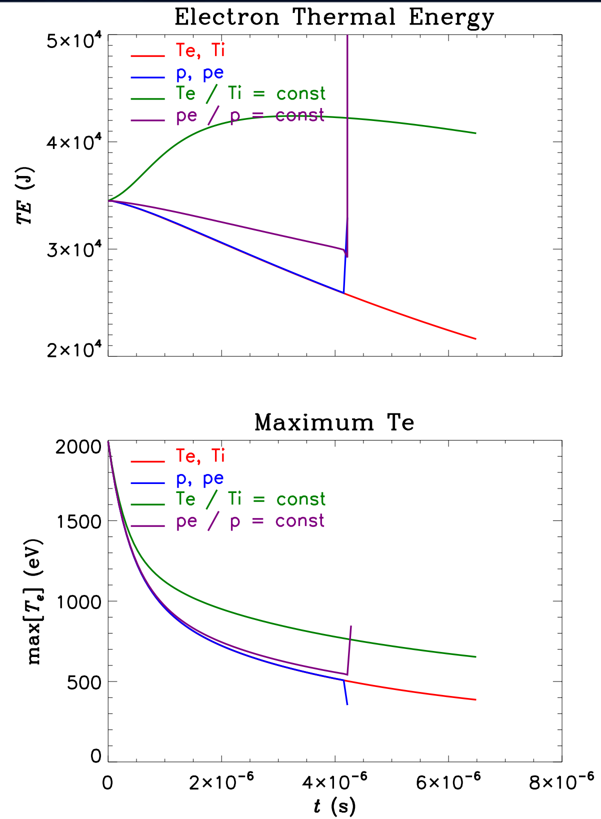






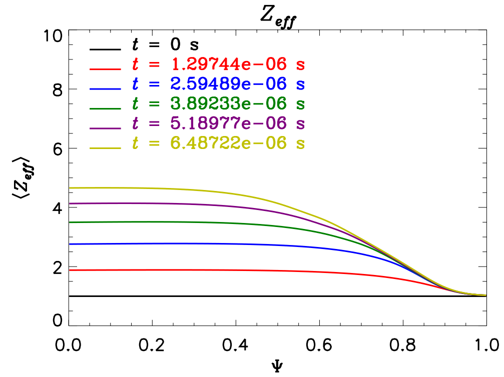
T_e / T_i = const is a Bad Assumption During Fast Quench

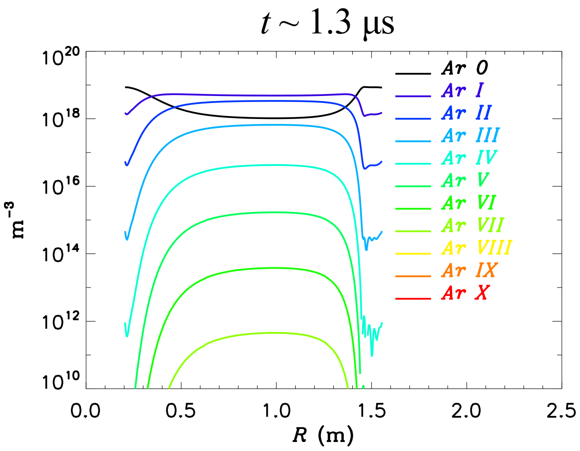
- Cooling mechanisms primarily affect electrons
  - Dilution from impurity electrons
  - Radiation
- This leads to T_e dropping much faster than T_i
  - T_e / T_i = const is bad assumption!
- Due to significant heat fluxes during disruptions, electrons and ions probably never reach equipartition
- When cooling is dominantly due to dilution, p_e / p = const is a much better assumption
  - Dilution does not remove thermal energy

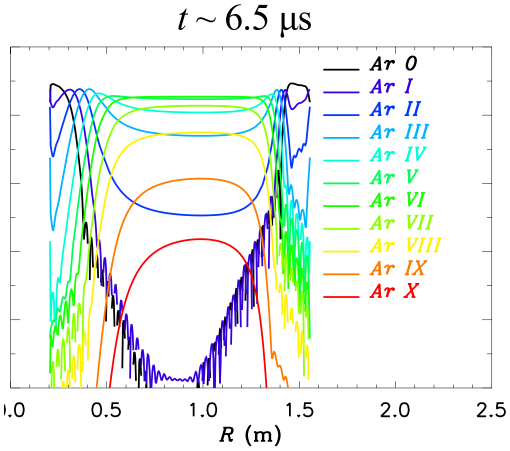


Edge Reaches Charge State Equilibrium Before Core

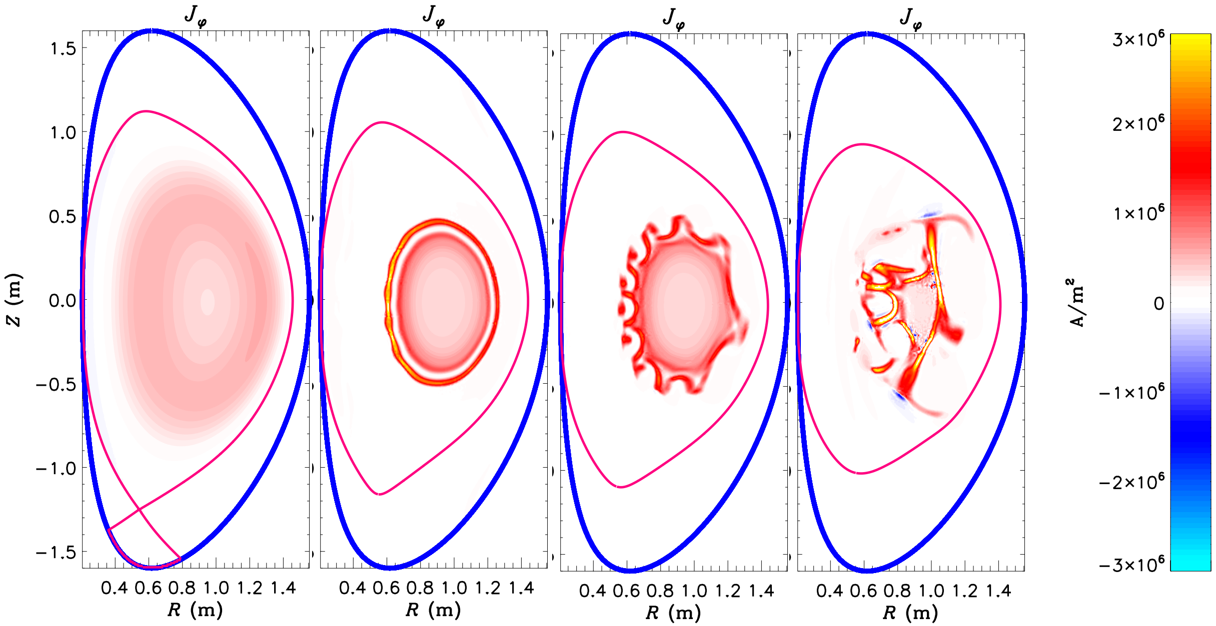
- Charge state densities in edge reach equilibrium before those in core
- Highly ionized states take ~ 100 μs to reach appreciable levels



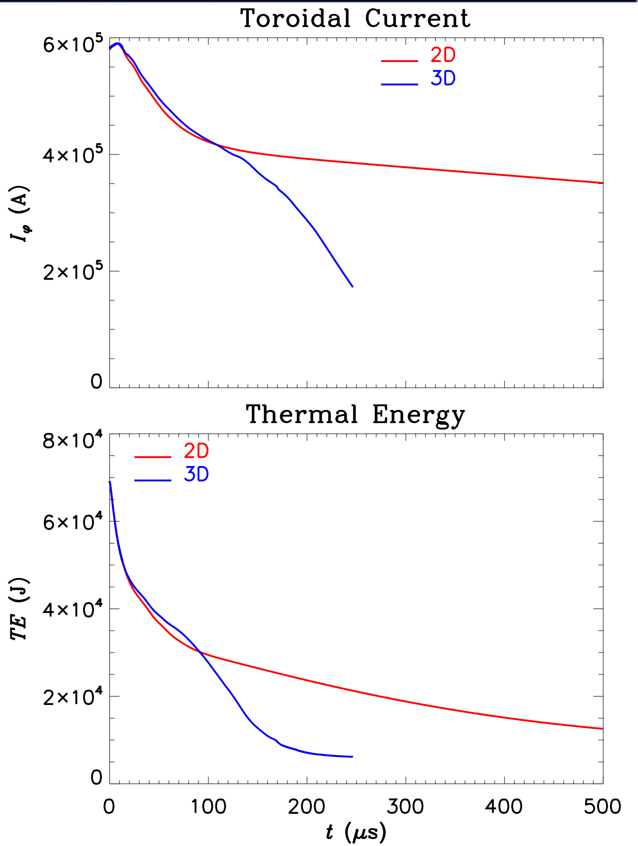




Current Channel Contracts Leading to Skin Currents and Secondary Instability



$t = 0$ $\quad$ $t = 52\ \mu s$ $\quad$ $t = 65\ \mu s$ $\quad$ $t = 117\ \mu s$

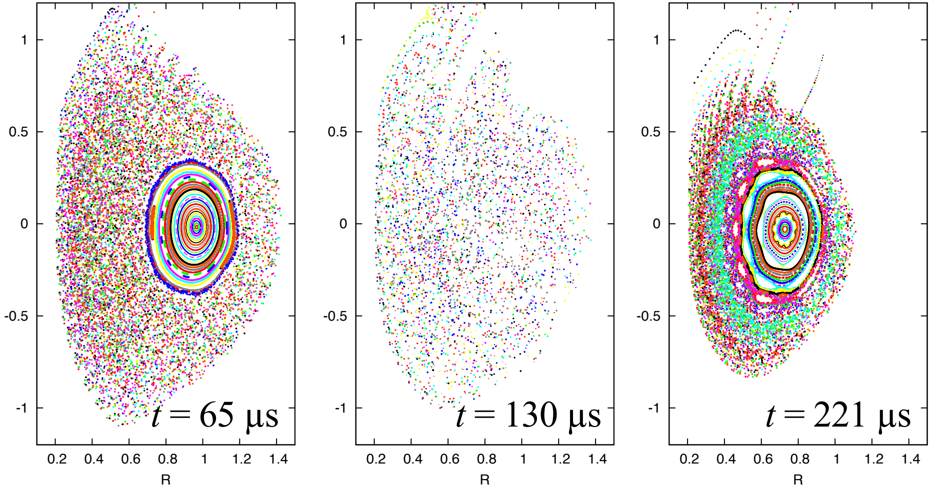


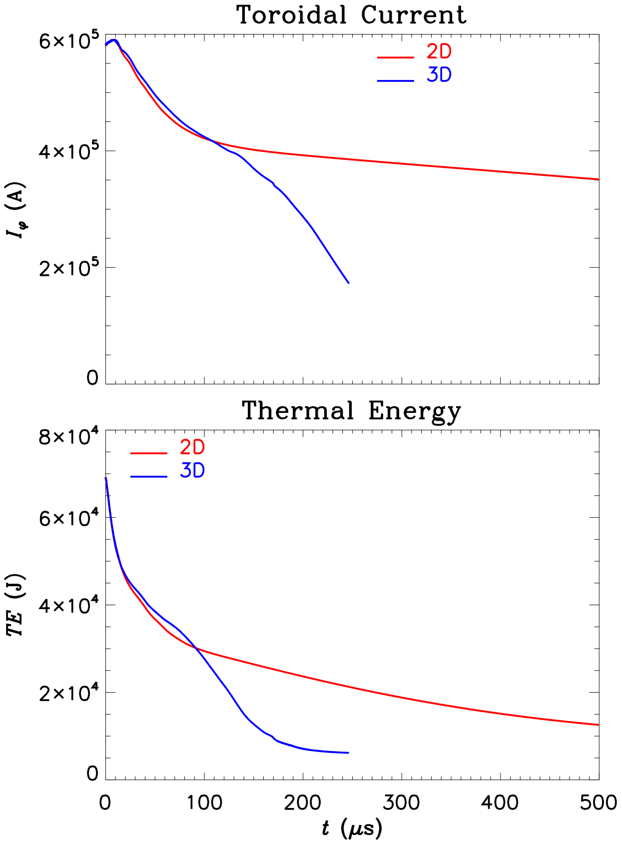
Current Channel Contracts Despite Well-Mixed Impurities

- Cooling is strongest near magnetic axis
  - Line radiation is initially strongest near axis
  - Dilution cooling from ionization is fastest near axis
- Despite this, resistivity rises faster at edge
  - Resistivity is much more sensitive to temperature in cooler regions
  - $\eta \sim T^{-3/2} \rightarrow d\eta/dT \sim -T^{-5/2}$
- Rapid rise in edge resistivity causes contraction of current channel, increase in l_i

Edge Instability Leads to Stochastization and Fast Thermal Quench

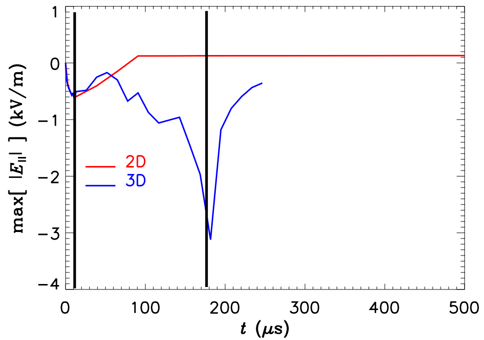
- Edge stochasticizes first due to edge-localized mid-n instabilities
- Lower-n modes grow later, stochasticizing core
- Surfaces re-heal after thermal quench

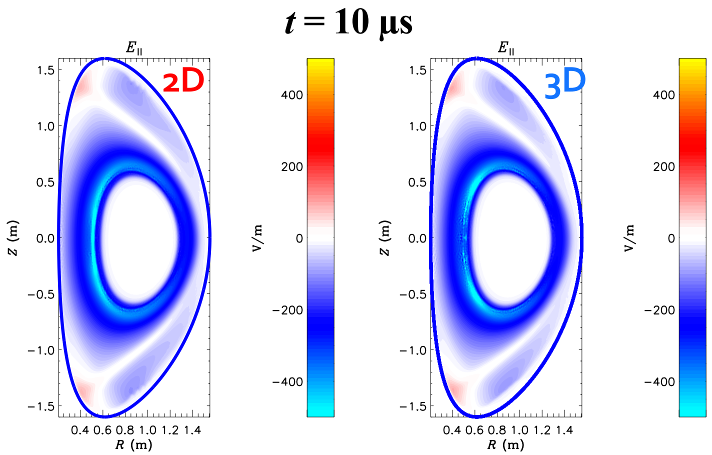


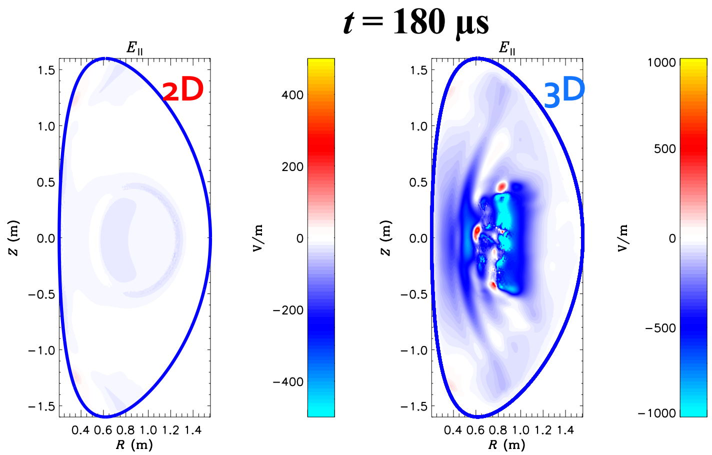


Local Spikes in $E_{||}$ Significantly Exceed Axisymmetric Values

- In 2D case, the largest $E_{||}$ is associated with skin currents
- In 3D case, local spikes in $E_{||}$ are much larger
- In both cases, $E_{||} >> E_{crit}$. Implications for runaways are TBD.







Summary

- M3D-C1 now has two-temperature coronal non-equilibrium model of impurity ionization, radiation, and transport
- Even well-mixed impurities lead to current channel contraction due to inverse dependence of resistivity on temperature
- Current channel contraction leads to skin currents, instability and fast thermal quench
- Large local parallel electric fields are generated by instability. Effect on runaways is TBD

Future Work Should Focus on Optimizing Mitigation

- Need to integrate a model of runaway electron generation
  - Added complication that E field is apparently turbulent during fast TQ
  - M3D-C1 has simple Connor-Hastie model implemented
  - More sophisticated modeling will be done as part of SCREAM

- Need to investigate whether core-localized impurity injection (e.g. shell pellets) can avoid instability
  - Preliminary indication is "yes" – see Brendan's talk

- Need validation and benchmarking