Center for Tokamak Transients Simulation

M3D-C1 Code Development

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CTTS Meeting

Auburn, AL

April 22, 2018

M3D-C1 Code Development Is Focused on Modeling Disruptions

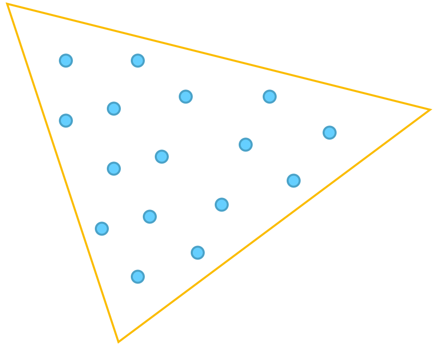
- Resistive wall model is crucial for modeling current quench and wall forces
  - Basic capability is implemented and tested
  - Future improvements will include more complicated wall
- Impurity model is necessary for modeling thermal quench
  - Now implemented in M3D-C1. Uses KPRAD to calculate ionization, recombination, and radiation
- Pellet model / coupling to FronTier
  - Parks ablation model implemented by A. Fil before impurity modeling was implemented (needs to be updated)

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



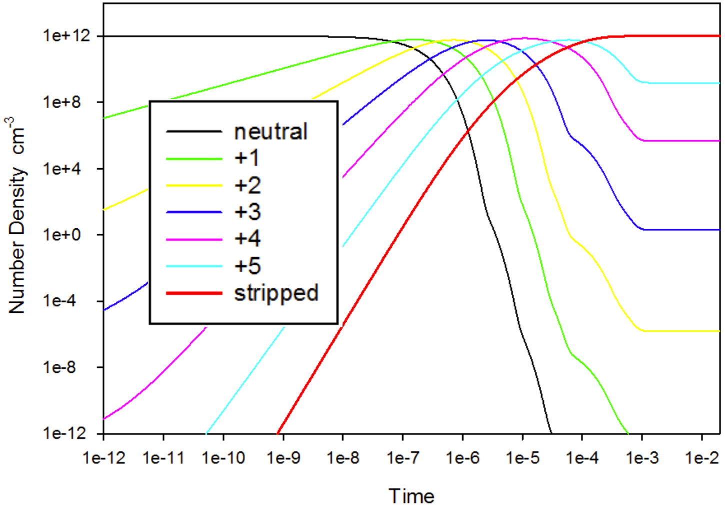
- Calculates losses from line radiation, bremsstrahlung, ionization, and recombination

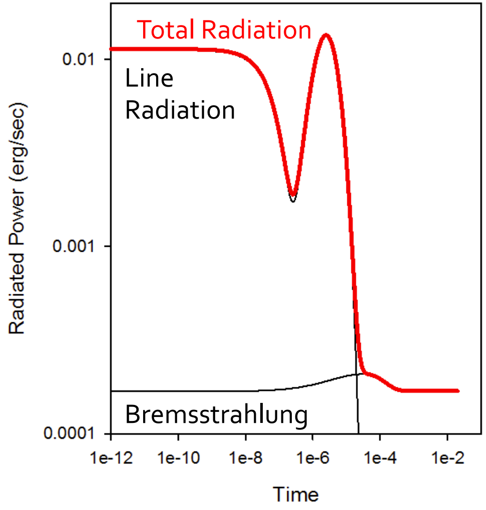
Charge States and Radiation Evolve on Comparable Timescale to Disruption Dynamics

- 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

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

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

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

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).

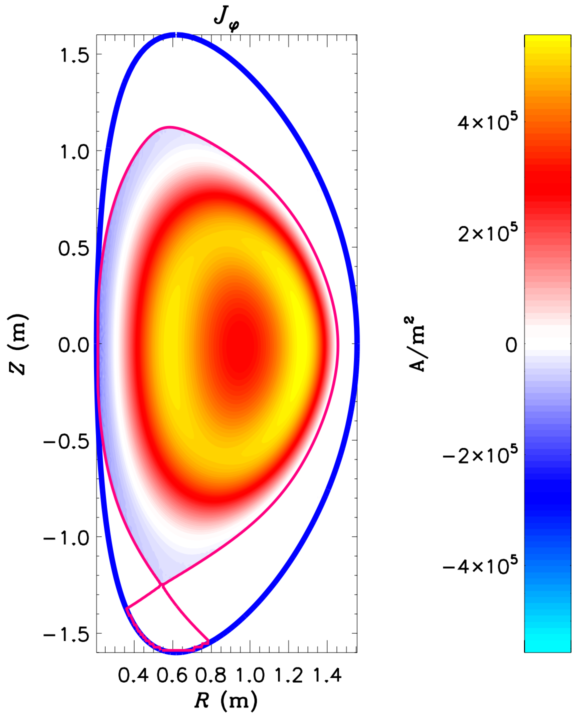
$$n_e\left(\frac{\partial T_e}{\partial t} + \mathbf{u}\cdot\nabla T_e + (\Gamma-1)T_e\nabla\cdot\mathbf{u}\right) + \sigma_e T_e = (\Gamma-1)\left(Q_e + Q_{rad} + Q_\Delta + \nabla\cdot\mathbf{q}_e + \eta J^2\right)$$

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

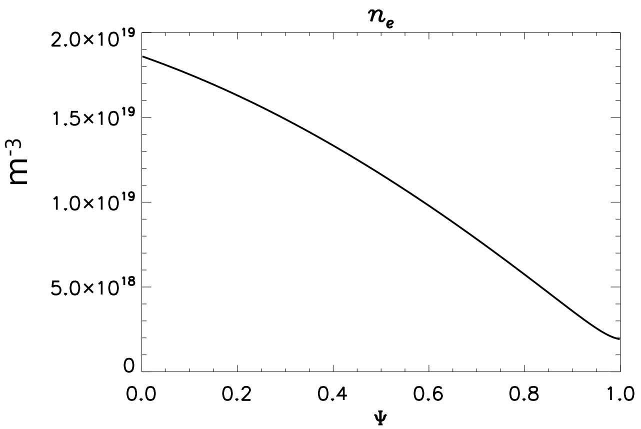
$$n_I = n_i + \sum_z n_z$$

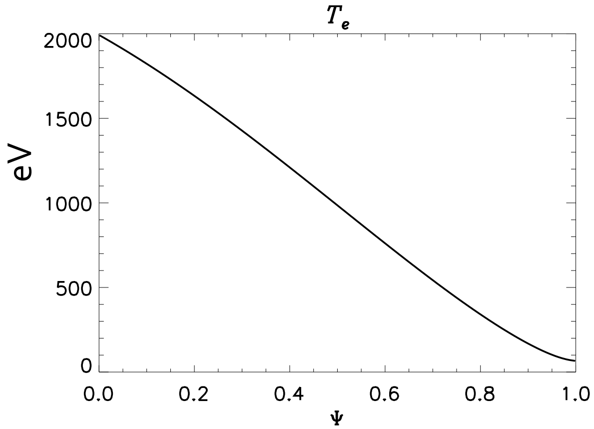
$$\sigma_I = \sigma_i + \sum_z \sigma_z$$

Simple Test Case:
Lots of Neutral Argon Introduced Globally



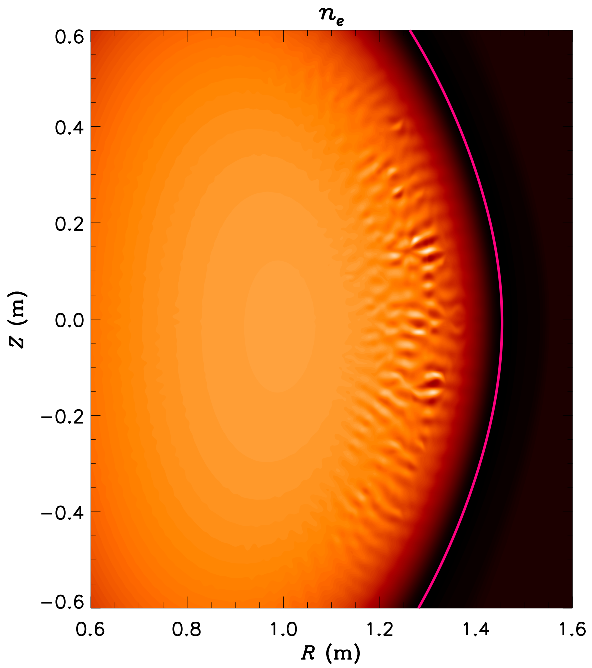
- Equilibrium is reconstruction of NSTX discharge 139536 at *t*=309 ms
- Neutral Argon is introduced globally at n_{Ar} = 0.1% n_D.
- Initial cooling is mainly due to dilution





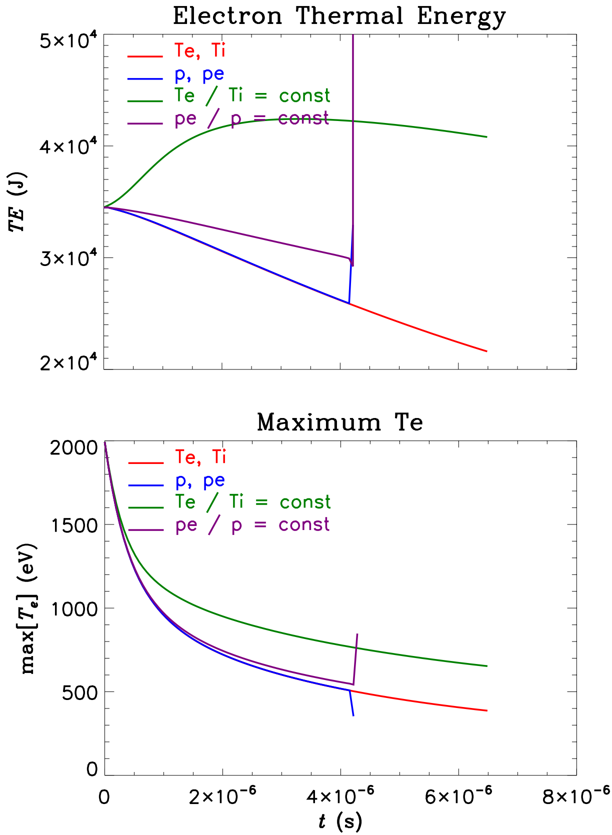
Split Pressure Advance is Numerically Unstable

- In "split" advance, $\mathbf{u}$, n, p (or T), and $\mathbf{B}$ are advanced separately (in that order)
  - $\mathbf{u}$ advance includes semi-implicit operator
- Split methods advancing p exhibit numerical instability
- "Unsplit" (Crank-Nicolson) pressure advance remains stable
  - Density, pressure, and magnetic field advanced together



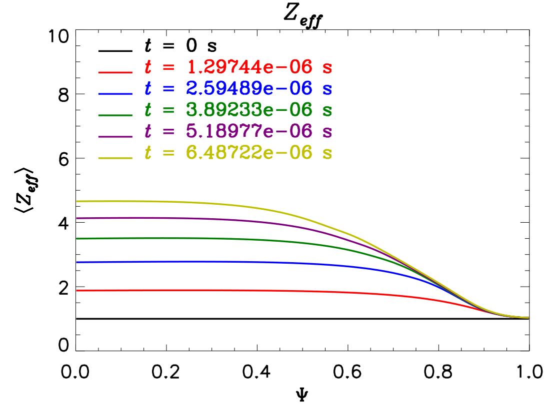
T_e / T_i = const is a Bad Assumption

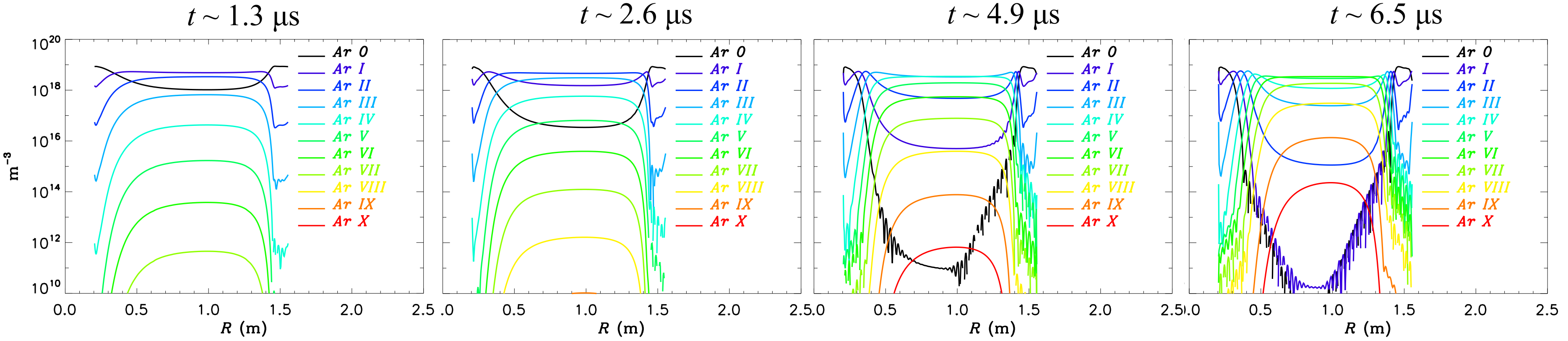
- Cooling mechanisms primarily affect electrons
  - Dilution from impurity electrons
  - Radiation
- This leads to T_e dropping much faster than T_i
  - T_e / T_i = const is bad assumption!
- Due to significant heat fluxes during disruptions, electrons and ions probably never reach equipartition
- When 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





Summary and Future Plans

- Detailed impurity model is now implemented in M3D-C1
  - Tracks all charge states of a single impurity species
  - Uses KPRAD for ionization, recombination, and radiation
  - Uses single-fluid velocity to advect impurities
  - Benchmarking is underway (Brendan's talk)
- Future plans:
  - Non-axisymmetric / non-contiguous conducting wall structures
  - More sophisticated impurity source models (e.g. FronTier)

Non-Axisymmetric / Non-Contiguous Wall Structures in M3D-C1

- "Resistive Wall" region in M3D-C1 is a logical region of the mesh
  - Must be axisymmetric and contiguous due

- Resistivity in this region does not have to be axisymmetric or contiguous
  - Conducting structures of arbitrary complexity can be modeled in this region
  - Only restriction is that plasma can't enter this region

- Simple rectangular "wall breaks" have already been implemented as a test of this concept