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
  
  - 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 $E_\parallel$ during CQ is large enough, runaway electrons (REs) can form

- **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
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

\[
\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{u}) = \sigma_i \\
\rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \Pi \\
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B} - \eta \mathbf{J}) \\
\frac{\partial n_z}{\partial t} + \nabla \cdot (n_z \mathbf{u}) = \sigma_z \quad z = 1, \ldots, Z
\]

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

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)
   \[
   n_e \left( \frac{\partial T_e}{\partial t} + \mathbf{u} \cdot \nabla T_e + (\Gamma - 1)T_e \nabla \cdot \mathbf{u} \right) + \sigma_e T_e = (\Gamma - 1)(Q_e + Q_{rad} + Q_{\Delta} + \nabla \cdot \mathbf{q}_e + \eta J^2)
   \]
   \[
   n_i \left( \frac{\partial T_i}{\partial t} + \mathbf{u} \cdot \nabla T_i + (\Gamma - 1)T_i \nabla \cdot \mathbf{u} \right) + \sigma_i T_i = (\Gamma - 1)(Q_i - Q_{\Delta} + \nabla \cdot \mathbf{q}_i + \Pi_i : \nabla \mathbf{u} + \eta J^2)
   \]
KPRAD Model Implemented in M3D-C1

- Calculates ionization, recombination, and radiation from impurities
  \[ \sigma_z = I_{z-1}n_{z-1} - (I_z + R_z)n_z + R_{z+1}n_{z+1} \quad z = 0, 1, \ldots, Z \]
- Calculates electron energy sink \( Q_{\text{rad}} \) from Radiation, Bremsstrahlung, Ionization, and Recombination
- Does not assume coronal equilibrium
- Can take \( \sim \) ms to reach coronal equilibrium
“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

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 $n_{\text{Ar}} = 10^{19} / \text{m}^3$.

- 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 $\kappa_\parallel \hat{b} \hat{b} \cdot \nabla T$, 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
  \[ \eta \sim T^{-3/2} \Rightarrow \frac{d\eta}{dT} \sim -T^{-5/2} \]

- Current channel contracts, leading to skin currents and instability

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

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

$t = 10 \ \mu s$

$E_{\parallel}$

$t = 180 \ \mu s$

$E_{\parallel}$
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

• 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 $\rightarrow$ skin currents $\rightarrow$ instability $\rightarrow$ 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