Disruption Mitigation and Impurity Radiation Modeling with M3D-C1

by

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with

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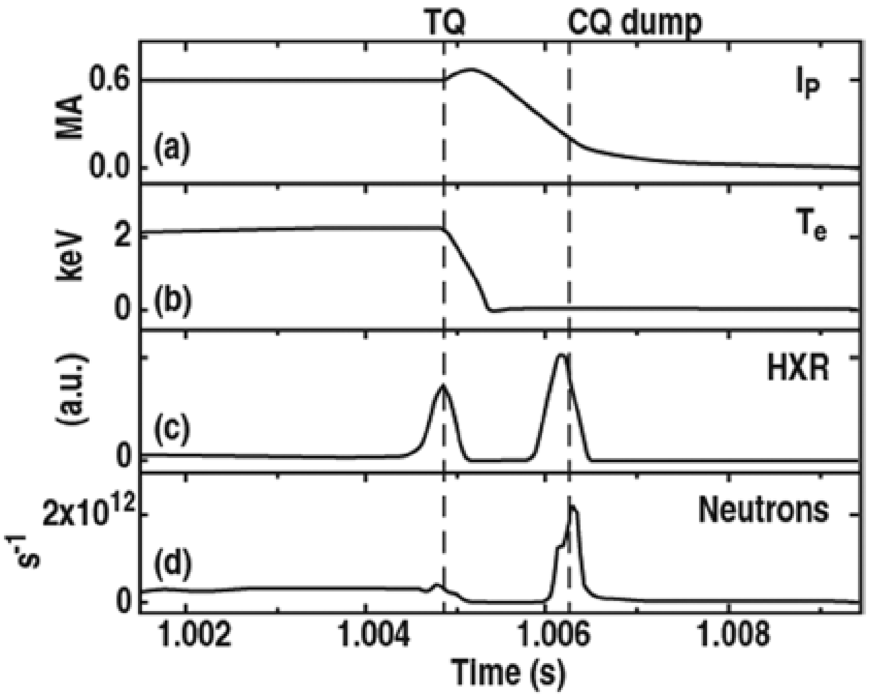
Future Tokamaks will Require Disruption Mitigation

- **Disruptions result in rapid loss of stored plasma energy**
  - Thermal quench can melt of plasma-facing components
  - Current quench
    - Can induce damaging wall forces
    - Can produce dangerous runaway electrons
- **Impurity injection can mitigate disruptions by radiating stored energy**
- **Two techniques under experimental and theoretical investigation**
  - Massive gas injection (MGI)
  - Pellet injection



MGI-triggered disruption in C-Mod
(a) Current quench
(b) Thermal quench
Runaway electrons detected by hard X-ray (c) and photo-neutron measurements(d)

Izzo Nucl. Fusion **51** (2011) 063032

Modeling of Disruption Dynamics and Mitigation Requires a Multiphysics Model

- **Simulations, validated against mitigation experiments, are required to project techniques to future devices**
- **Integrated model is required to capture all relevant physics**
  - Magnetohydrodynamics (MHD) for macroscopic evolution of disruption dynamics
  - Atomic physics for ionization and radiation from injected impurities
  - Drift-kinetics for phase-space evolution of runaway electron population
- **Here we present progress on coupled MHD-impurity physics simulations with M3D-C1**

Coupling M3D-C1 to KPRAD

M3D-C1 [1] is an Extended-MHD Solver

- **Three-dimensional**
- **Includes resistivity, density diffusivity, viscosity, & thermal conductivity**
- **Two-fluid effects (optional)**
- **Linear and nonlinear modes**
- **High-order, C^1 continuous finite element representation**
- **Mesh adapted to input equilibrium**

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \vec{v}) = 0$$

$$m_i n_i \left[\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} \right] = \vec{J} \times \vec{B} - \nabla p - \nabla \cdot \Pi_i$$

$$\frac{\partial \vec{B}^p}{\partial t} = -\nabla \times \vec{E}$$

$$\vec{E} = \eta \vec{J} - \vec{v} \times \vec{B} + \frac{1}{n_e e} \left(\vec{J} \times \vec{B} - \nabla p_e \right)$$

$$\Pi = -\mu (\nabla \vec{v} + \nabla \vec{v}^t) + \Pi_i^{\parallel} + \Pi_i^{\wedge}$$

$$\begin{aligned} \frac{\partial p}{\partial t} + \vec{v} \cdot \nabla p + \Gamma p \nabla \cdot \vec{v} &= (\Gamma - 1) \left(\eta J^2 - \nabla \cdot \vec{q} - \Pi_i : \vec{v} \right) \\ &\quad + \frac{1}{n_e e} \vec{J} \cdot \left(\nabla p_e - \Gamma \frac{\nabla n_i}{n_i} p_e \right) \end{aligned}$$

$$\begin{aligned} \frac{\partial p_e}{\partial t} + \vec{v} \cdot \nabla p_e + \Gamma p_e \nabla \cdot \vec{v} &= (\Gamma - 1) \left(\eta J^2 - \nabla \cdot \vec{q}_e \right) \\ &\quad + \frac{1}{n_e e} \vec{J} \cdot \left(\nabla p_e - \Gamma \frac{\nabla n_i}{n_i} p_e \right) \end{aligned}$$

[2]

$$\vec{q}_{e,i} = -\kappa \nabla T_e - \kappa_{\parallel} \frac{\vec{B}\vec{B}}{B^2} \cdot \nabla T_e \qquad \vec{q} = -\kappa \nabla (T_e + T_i)$$

[1] S. C. Jardin, et al., Comput. Sci. Discovery 5, 014002 (2012).
[2] N.M. Ferraro et al., Phys. Plasmas 23, 056114 (2016)

KPRAD Provides Needed Atomic Physics Information

- **KPRAD [1] solves for impurity-plasma interaction in low-density, coronal model**
  - Based on ADPAK rate coefficients
  - Impurity charge states and electron density evolve according to ionization and recombination

$$\frac{\partial n_s}{\partial t} + \nabla \cdot (n_s \mathbf{v}) = \nabla \cdot (D \nabla n_s) + \mathcal{I}_{z-1} n_{z-1} - (\mathcal{I}_z + \mathcal{R}_z) n_z + \mathcal{R}_{z+1} n_{z+1} + \mathcal{S}_z$$

  - Thermal energy lost from plasma due to
    - Ionization
    - Line radiation
    - Bremsstrahlung radiation
    - Recombination radiation
- **Subcycled much faster than typical MHD time steps**

[1] D.G. Whyte, et al., Proc. of the 24th Euro. Conf. on Controlled Fusion and Plasma Physics, Berchtesgaden, Germany, 1997, Vol. 21A, p. 1137.

KPRAD Couples to the M3D-C1 Pressure Equation(s)

- **Total and electron pressure equations**
  - Electrons lose energy to ionization and radiation
  - Main ions lose energy only through cooling on electrons

$$\frac{\partial p}{\partial t} + \mathbf{v}\cdot\nabla p + \Gamma p \nabla\cdot\mathbf{v} = (\Gamma - 1)\left[\eta J^2 - \nabla\cdot\mathbf{q}_{tot} - \mathcal{P}_{rad} - \Pi_{tot} : \nabla\mathbf{v} + \frac{1}{2}\varpi v^2\right]$$

$$\frac{\partial p_e}{\partial t} + \mathbf{v}\cdot\nabla p_e + \Gamma p_e \nabla\cdot\mathbf{v} = (\Gamma - 1)\left[\eta J^2 - \nabla\cdot\mathbf{q}_e - \mathcal{P}_{rad} + Q_{ei} - \Pi_e : \nabla\mathbf{v}\right]$$

- **Single pressure equation**
  - Evolve only total pressure equation (above)
  - p_e/p constant throughout time, implicitly assuming
    - No thermal equilibration
    - Losses split between ions and electrons by same fraction

KPRAD Couples to the M3D-C1 Temperature Equation(s)

- **Electron and all-ions temperature equations**
  - Dilution cooling of ions and electrons
  - Electrons lose energy to ionization and radiation
  - Main ions cool on electrons

$$n_e\left[\frac{\partial T_e}{\partial t}+\mathbf{v}\cdot\nabla T_e+(\Gamma-1)\,T_e\nabla\cdot\mathbf{v}\right]+\sigma_e T_e=(\Gamma-1)\left[\eta J^2-\nabla\cdot\mathbf{q}_e-\mathcal{P}_{rad}+Q_{ei}-\Pi_e:\nabla\mathbf{v}\right]$$

$$n_*\left[\frac{\partial T_i}{\partial t}+\mathbf{v}\cdot\nabla T_i+(\Gamma-1)\,T_i\nabla\cdot\mathbf{v}\right]+\sigma_* T_i=(\Gamma-1)\left[-\nabla\cdot\mathbf{q}_*-Q_{ei}-\Pi_*:\nabla\mathbf{v}+\frac{1}{2}\varpi_* v^2\right]$$

- **Single temperature equation**
  - Evolves sum over all species
  - T_e/T_i constant throughout time, implicitly assuming
    - Instantaneous thermal equilibration
    - Split of losses between species evolves as pressure ratio changes

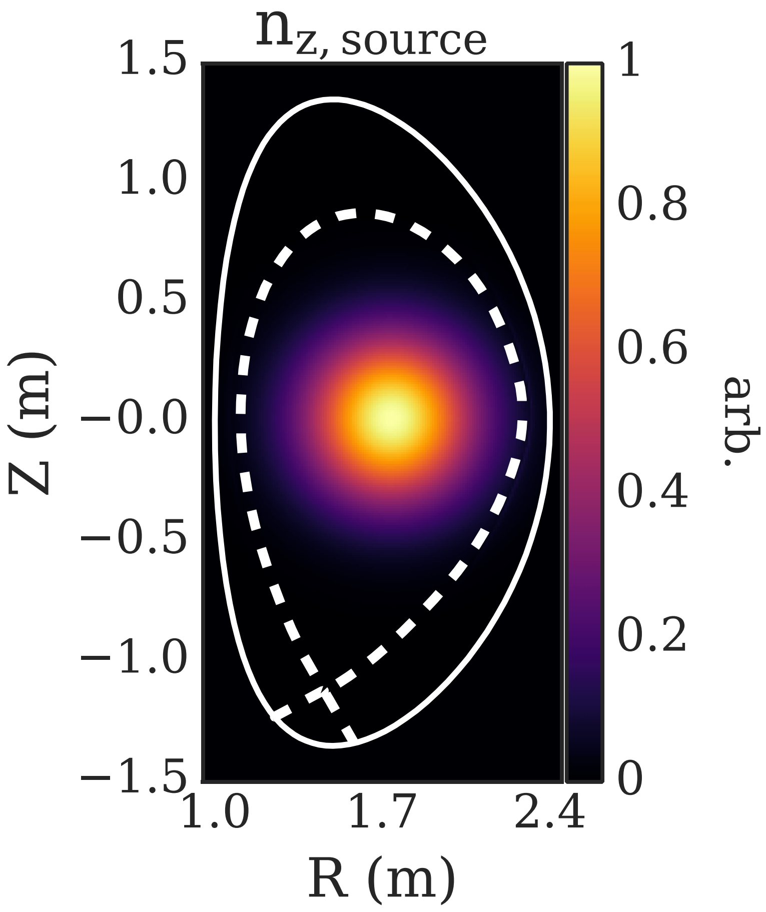
Verification Benchmark of NIMROD & M3D-C1

Fast Impurity Injection in DIII-D Core Used for Cross-Code Benchmark

- **Four cases solved by both M3D-C1 and NIMROD [1] (another extended-MHD code coupled to KPRAD)**
  - Argon or neon injection
  - Constant or Spitzer resistivity
- **Simulation setup**
  - DIII-D shot 137611 @ 1950 ms
  - 2D, nonlinear, single-fluid
  - Fixed boundary
- **Continuous neutral impurity deposition**
  - No impurities to start
  - Gaussian source

$$\frac{dn_z}{dt} = \nu \frac{R_0}{R} \exp\left[-\frac{(R-R_0)^2 + (Z-Z_0)^2}{2\delta^2}\right]$$

  - Injection rate: 4.37×10^{20} atoms/ms

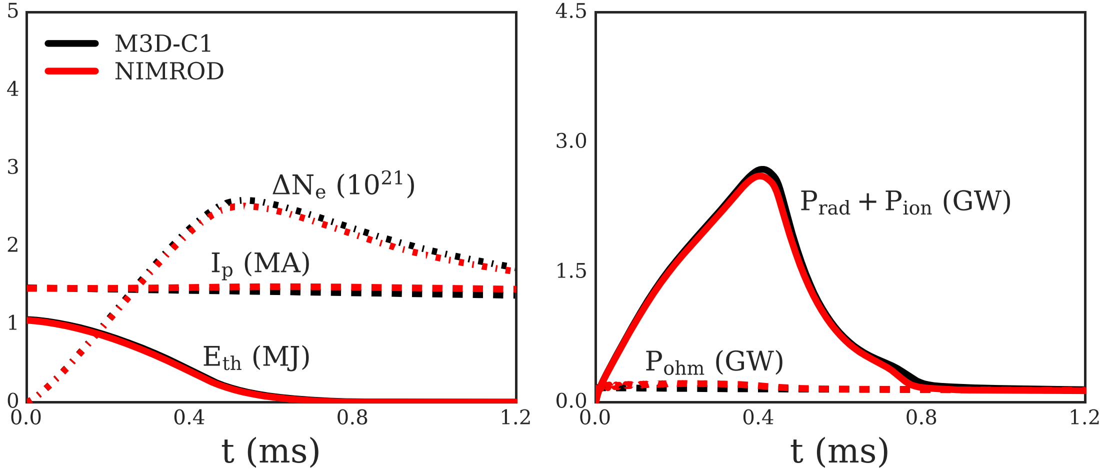


[1] C. R. Sovinec et al., J. Comput. Phys. 195, 355 (2004).
C. Sovinec & J. King, J. Comput. Phys. 229, 5803 (2010).

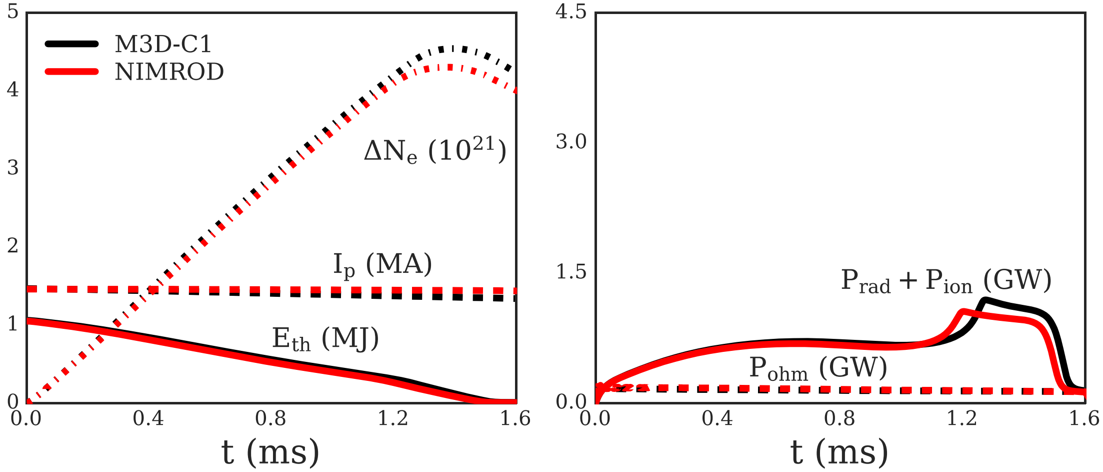
Successful Benchmark with Constant Resistivity (10^{-5} Ωm)

- **Excellent, quantitative agreement between the codes**
- **Peak of loss power and electron number correspond to temperature on-axis falling to near-zero**
- **Neon quench roughly 3x slower than argon due to lower atomic number**

Argon injection



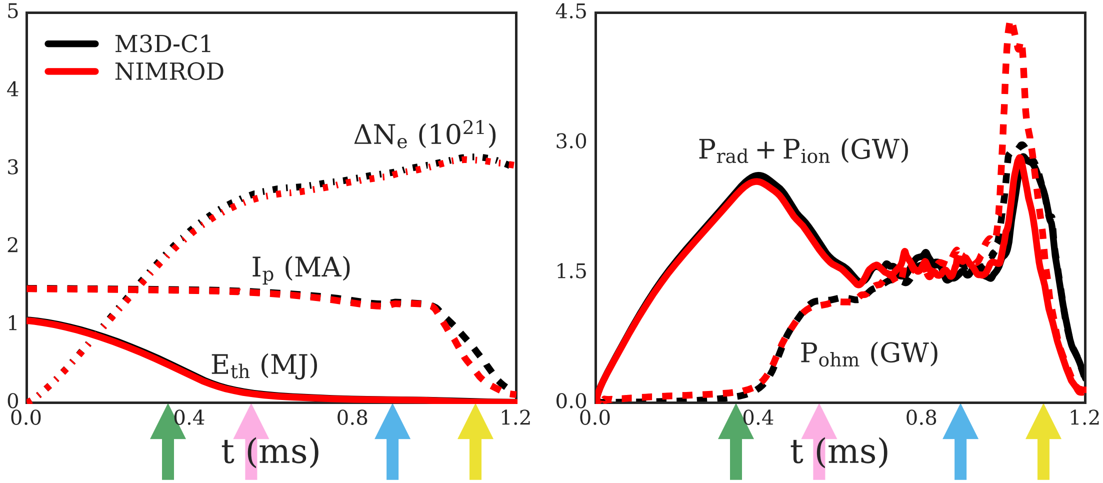
Neon injection



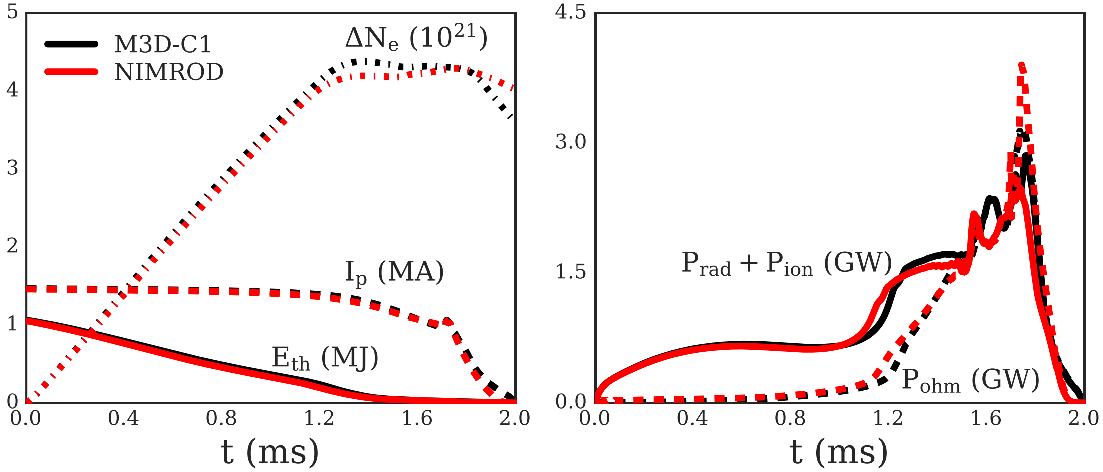
Successful Benchmark with Spitzer Resistivity ($\eta \propto T_e^{-3/2}$)

- **Excellent agreement between codes**
    - Quantitative during thermal quench
    - Qualitative during current quench
- **Low temperature in core causes resistivity to rise**
    - Ohmic power balances loss power
    - Current begins to drop more rapidly
    - Onset of turbulent dynamics in core
- **Rapid current quench caused by plasma making contact with boundary**

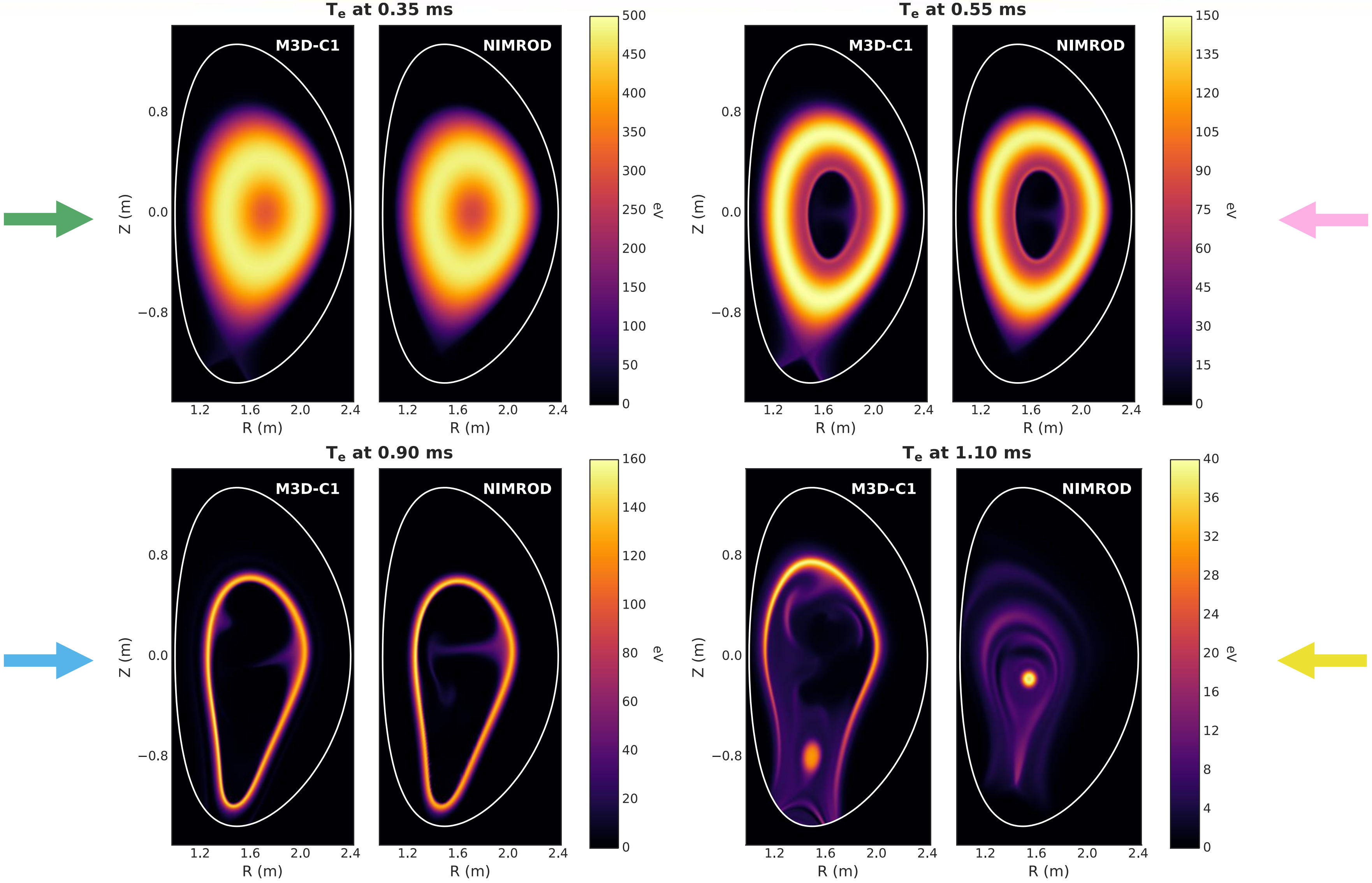
Argon injection



Neon injection



Ar + η_{Sptz}: Impurities Induce Inside-Out Thermal Quench with Core Turbulence



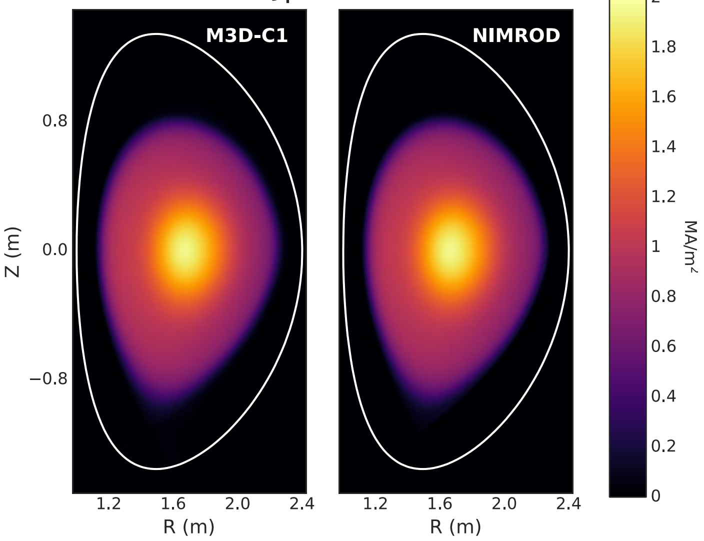
T_e at 0.35 ms

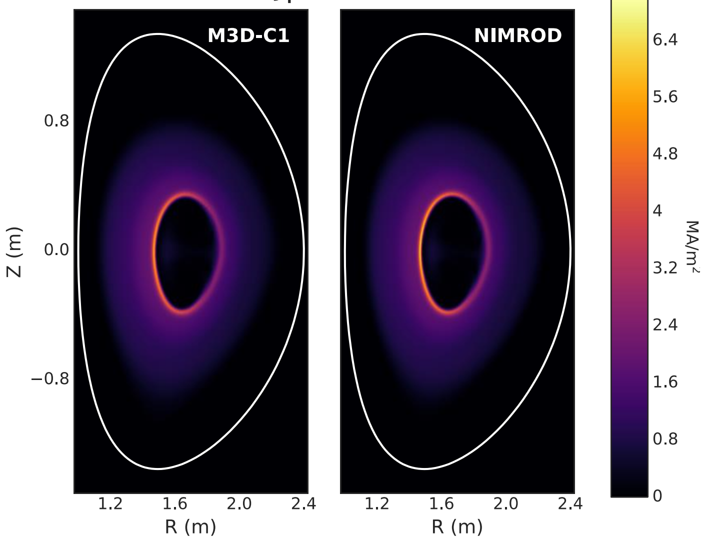
T_e at 0.55 ms

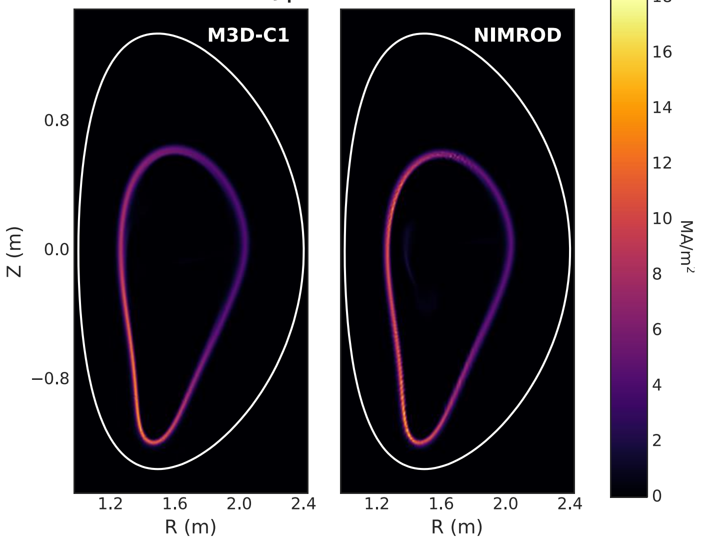
T_e at 0.90 ms

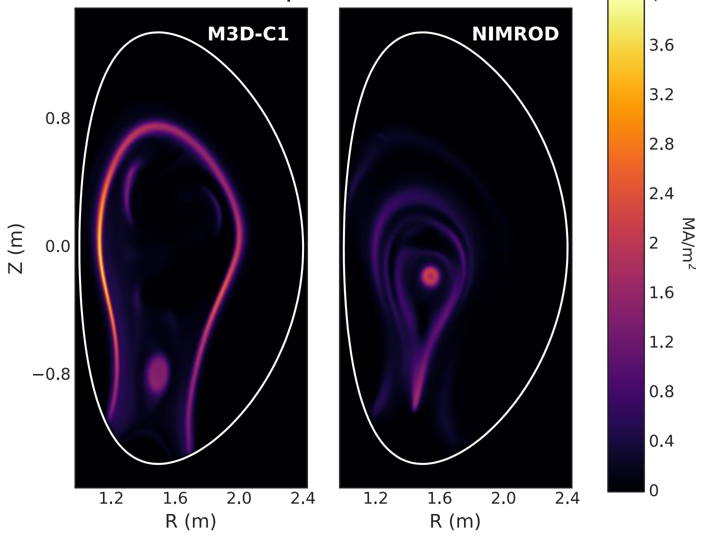
T_e at 1.10 ms

Ar + η_{Sptz}: Current Localizes to Thin, Expanding Shell that Contacts Domain Boundary


J_φ at 0.35 ms


J_φ at 0.55 ms


J_φ at 0.90 ms


J_φ at 1.10 ms

More Realistic Benchmarks Planned for Near-Future

- **Non-axisymmetry**
  - Strong gradients in thin temperature/current shell likely unstable
  - Should result in interchange or kink modes
- **Resistive-wall boundary**
  - Idealized, conducting boundary leads to unphysical behavior when plasma touches wall
  - Resistive wall should allow more physical thermal and current conduction
- **Pellet source**
  - Toroidally localized
  - Function of time and plasma parameters

Pellet-Ablation Modeling in M3D-C1

Ablation Model for Ne-D2 Pellets Implemented in M3D-C1

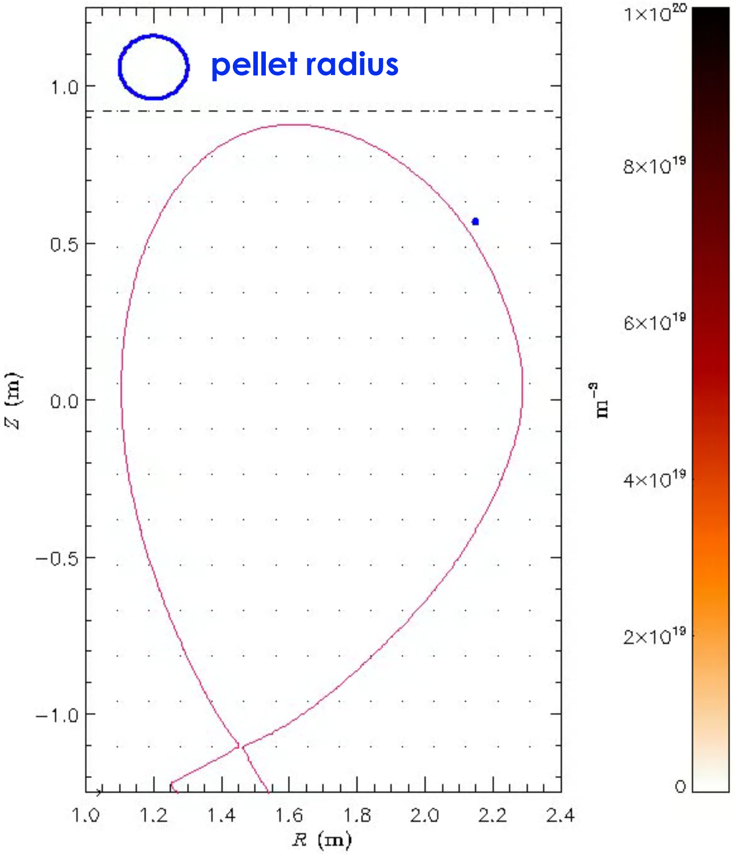
- **Practical, analytic expression fit to more complex ablation model (Parks)**

$$G\,(\mathrm{g/s}) = \lambda\,(X)\left(\frac{T_e}{2000\ \mathrm{eV}}\right)^{5/3}\left(\frac{r_p}{0.2\ \mathrm{cm}}\right)^{4/3}\left(\frac{n_e}{10^{14}\ \mathrm{cm}^{-3}}\right)^{1/3}$$

λ is fitting function, depending on molar X fraction of D2,

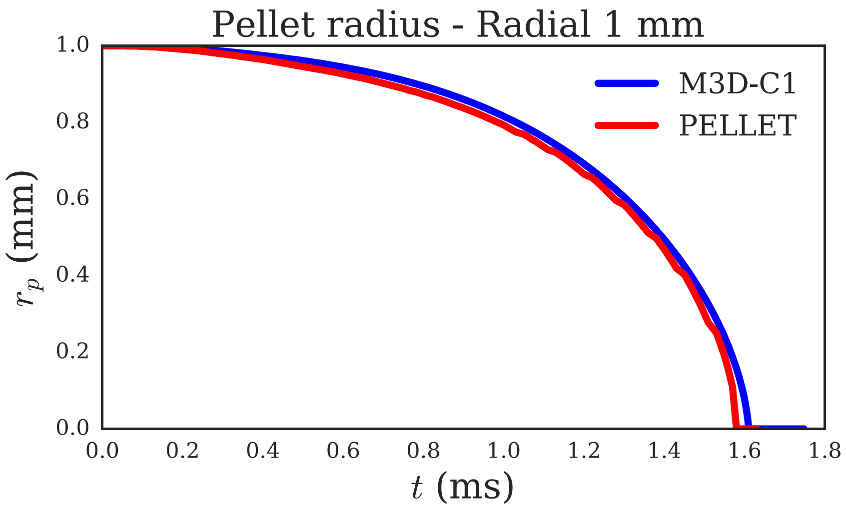
- **M3D-C1 implementation**
  - Advance pellet location in time
  - Calculate number of particles ablated and pellet-surface recession at each time step
  - Deposit main ion and/or impurities onto arbitrary spatial distribution (e.g. 2D or 3D Gaussian)

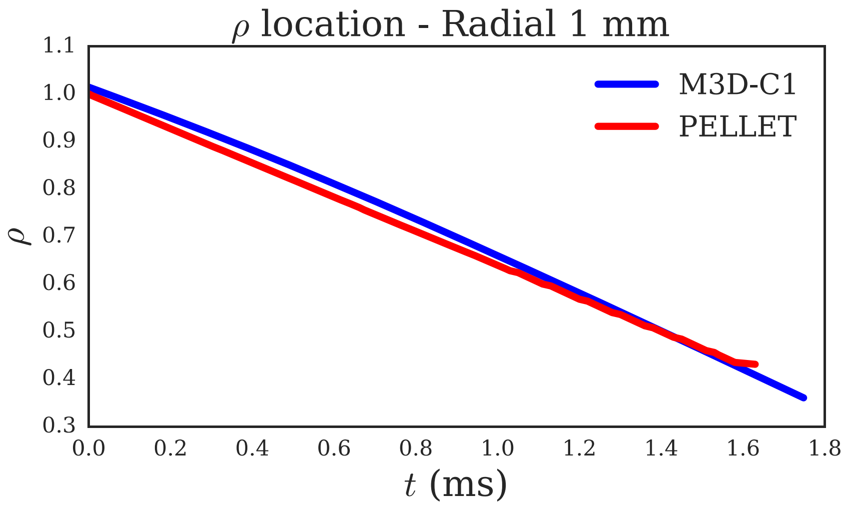
Impurity density



Ablation Benchmark Underway Between Several Codes

- **Ablation rate with fixed profiles being compared between**
  - M3D-C1
  - PELLET (ORNL)
  - Lagrangian-particle code (Stonybrook)
  - NIMROD
  - Pellet Ablation Module (GA)
- **Initial M3D-C1 & PELLET results**
  - Promising quantitative agreement
  - Some discrepancy in equilibrium mapping





Conclusions

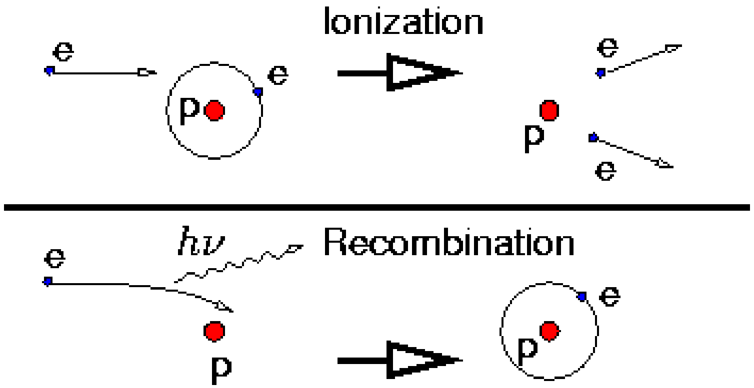
- **KPRAD has been coupled to M3D-C1, providing ionization and radiation loss model**
- **Axisymmetric benchmark with NIMROD show quantitative agreement**
  - 0D time-histories
  - 2D contours of temperature and current
- **Pellet-ablation model implemented in M3D-C1 with benchmarks underway**
- **Future work**
  - Perform 3D nonlinear benchmark, allowing for MHD instabilities
  - Validate M3D-C1 against DIII-D pellet-mitigation experiments
  - Perform predictive simulations for JET & ITER pellet mitigation

Additional Slides

Most Recombination Radiation Comes from Ionization/Potential Energy, not Thermal/Kinetic

- **Ionization process**
  - Thermal energy converted to potential energy
  - Electrons equilibrate causing dilution cooling
- **Recombination process**
  - Thermal electron trapped by ion
  - Thermal (kinetic) and potential energy released as radiation
  - Potential (~10^1-10^3 eV) greatly exceeds kinetic in cold plasma (~10^0 eV)
  - Only kinetic part of recombination radiation should be subtracted from plasma thermal energy
- **We have updated KPRAD to split kinetic and potential recombination energy**

Kinetic energy to potential energy



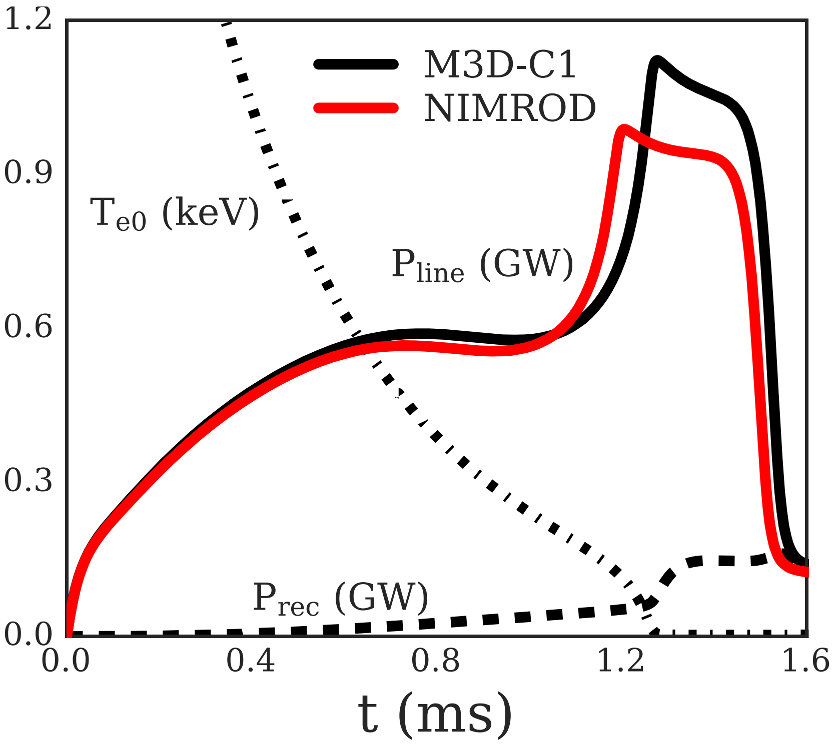
Kinetic & potential to radiation

Figure from Ahmadi & Ahmadi,
MSE Vol.119,159 - 166 (2016)

For Neon, Rapid Increase in Loss-Power due to Line Resonances at Low Temperature

- **Line radiation increases dramatically after ~1 ms**
  - Temperature falls from O(100) to O(1) eV
  - Indicates strong line resonances at those temperatures
- **Recombination radiation jumps when temperature falls below ~10 eV**
  - Recombination becomes dominant process in core
  - Causes N_e to begin falling

Neon with constant η



Initial 3D simulations with M3D-C1

- Currently running on NERSC
- Will include if successful before APS