3D Disruption Mitigation Modeling with M3D-C1

by

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Modeling of Disruption Dynamics and Mitigation Requires a Multiphysics Model

- **Disruptions pose a risk of damage to future tokamaks, necessitating robust mitigation techniques**
- **Most promising method uses pellet injection of impurities to radiate stored energy**
- **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

KPRAD* Provides Needed Atomic Physics Information

- **KPRAD solves for impurity-plasma interaction in low-density, coronal model**
  - N.B. *not* coronal equilibrium
  - Based on ADPAK rate coefficients
  - Impurity charge states and electron density evolve according to ionization and recombination

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

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

***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 Temperature Equation(s)

1) Electron and all-ions temperature equations

- Dilution cooling of ions and electrons
- Electrons lose energy to ionization and radiation
- Main ions cool on electrons

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

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

2) 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

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

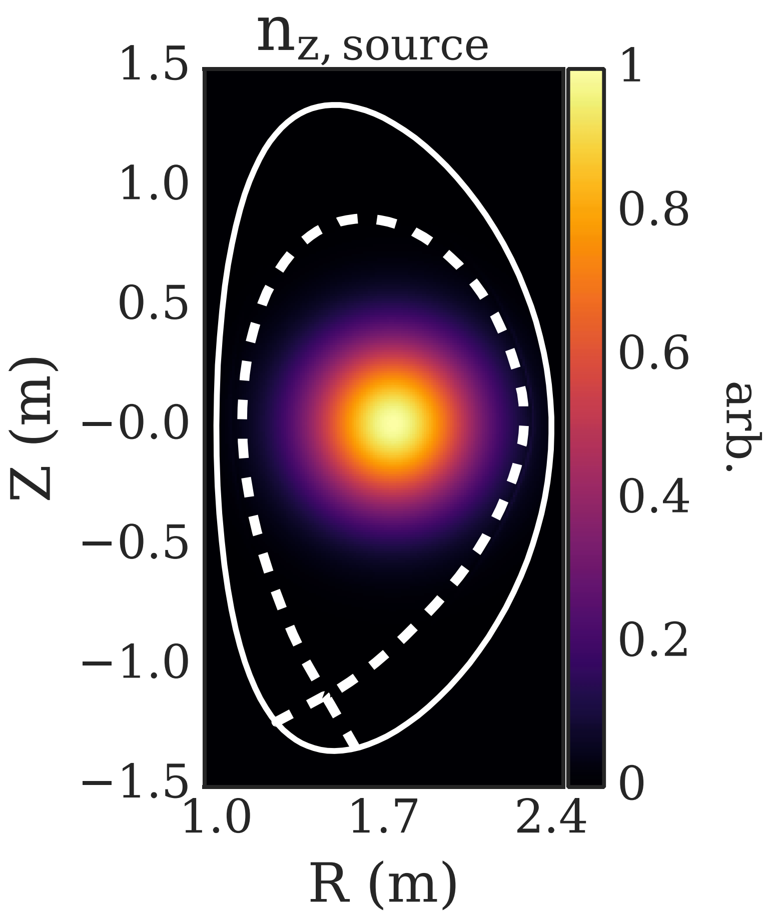
3D Nonlinear Modeling of Core Impurity Injection

Fast Impurity Injection in DIII-D Core Used for Cross-Code Benchmarking with NIMROD

- **Simulation setup**
  - DIII-D shot 137611 @ 1950 ms
  - Single-fluid, single temperature
  - Fixed boundary
- **Continuous neutral impurity deposition (Ar or Ne)**
  - No impurities to start
  - Gaussian source

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

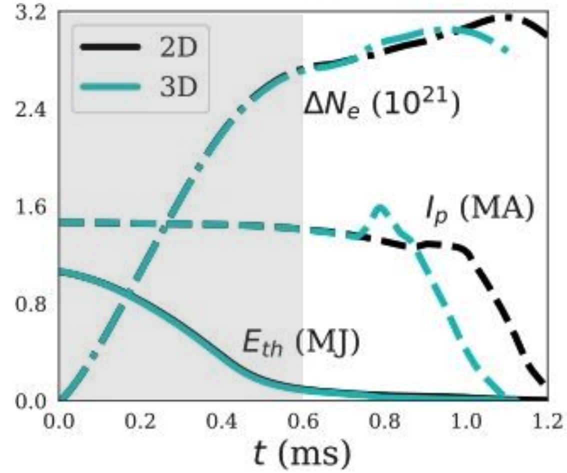
  - Injection rate ~1 mm Ne/Ar pellet per ms
- **Highly successful axisymmetric benchmark completed** †

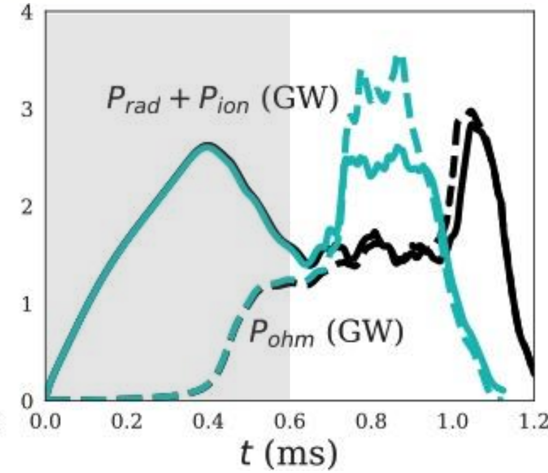


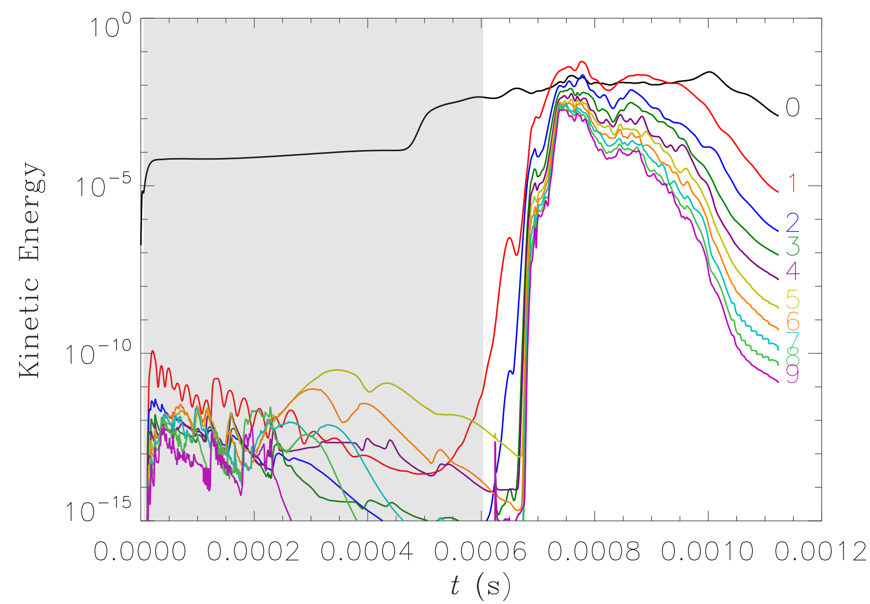
† B.C. Lyons et al., Plasma Phys. Control. Fusion, 61, 064001 (2019).

3D M3D-C1 Modeling Shows Stable Thermal Quench, Instability-Induced Current Quench with I_p Spike

- **3D, nonlinear simulation performed with M3D-C1 using argon benchmark initial conditions**
  - 3D run is linearly stable throughout thermal quench due to axisymmetric deposition
  - Plasma sheet goes unstable, quenching current
- **Instabilities cause current to spike**
  - Axisymmetric current broadens significantly
  - First spike of this magnitude in 3D MHD simulation







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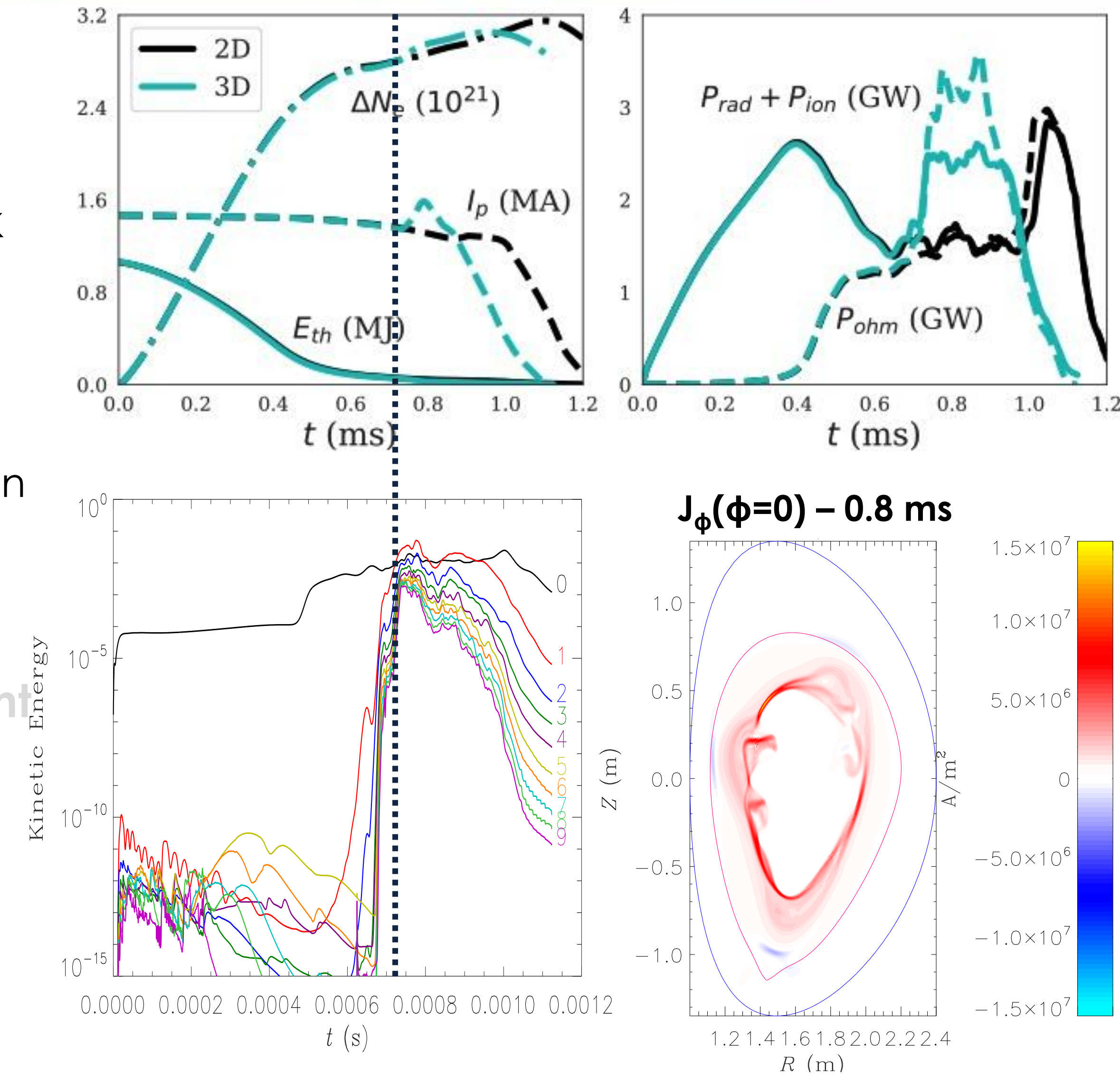

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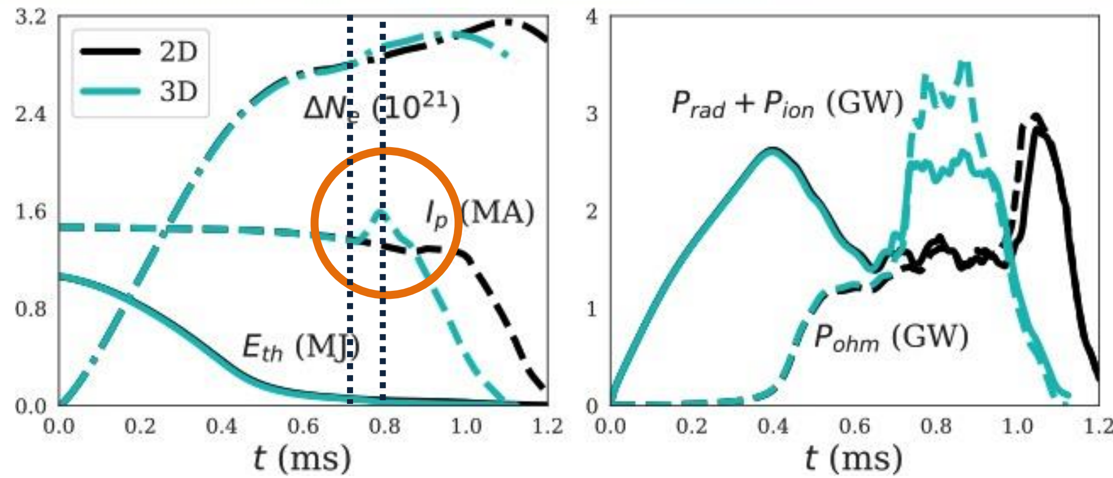
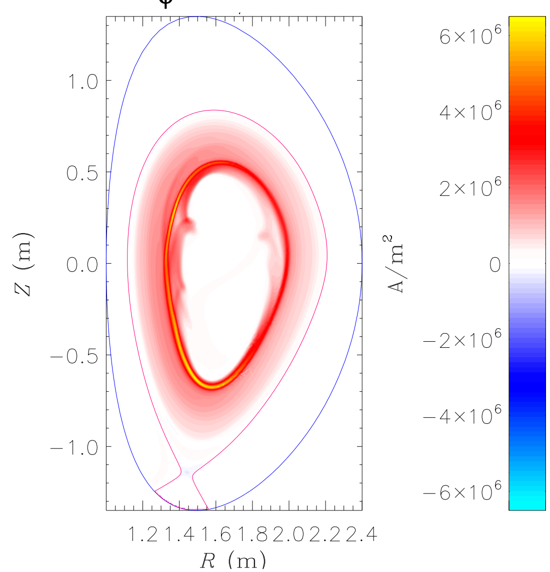
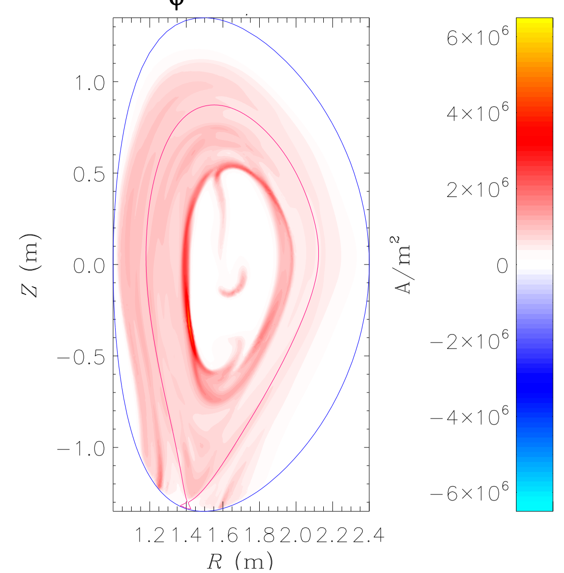


<J$_\varphi$> – 0.725 ms

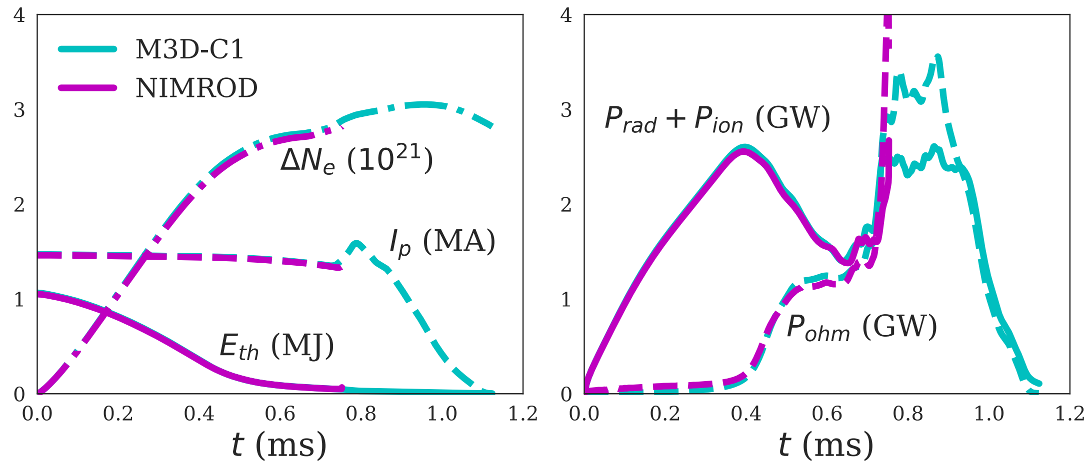


<J$_\varphi$> – 0.8 ms



3D Benchmark with NIMROD Has Begun

- **Shows axisymmetric behavior through ~0.75 ms, like M3D-C1**
- **Numerical instabilities hindering study of 3D crash**
- Beginning to see current spike, though slightly delayed
- Benchmark with edge-injected ablating pellet also underway



GENERAL ATOMICS

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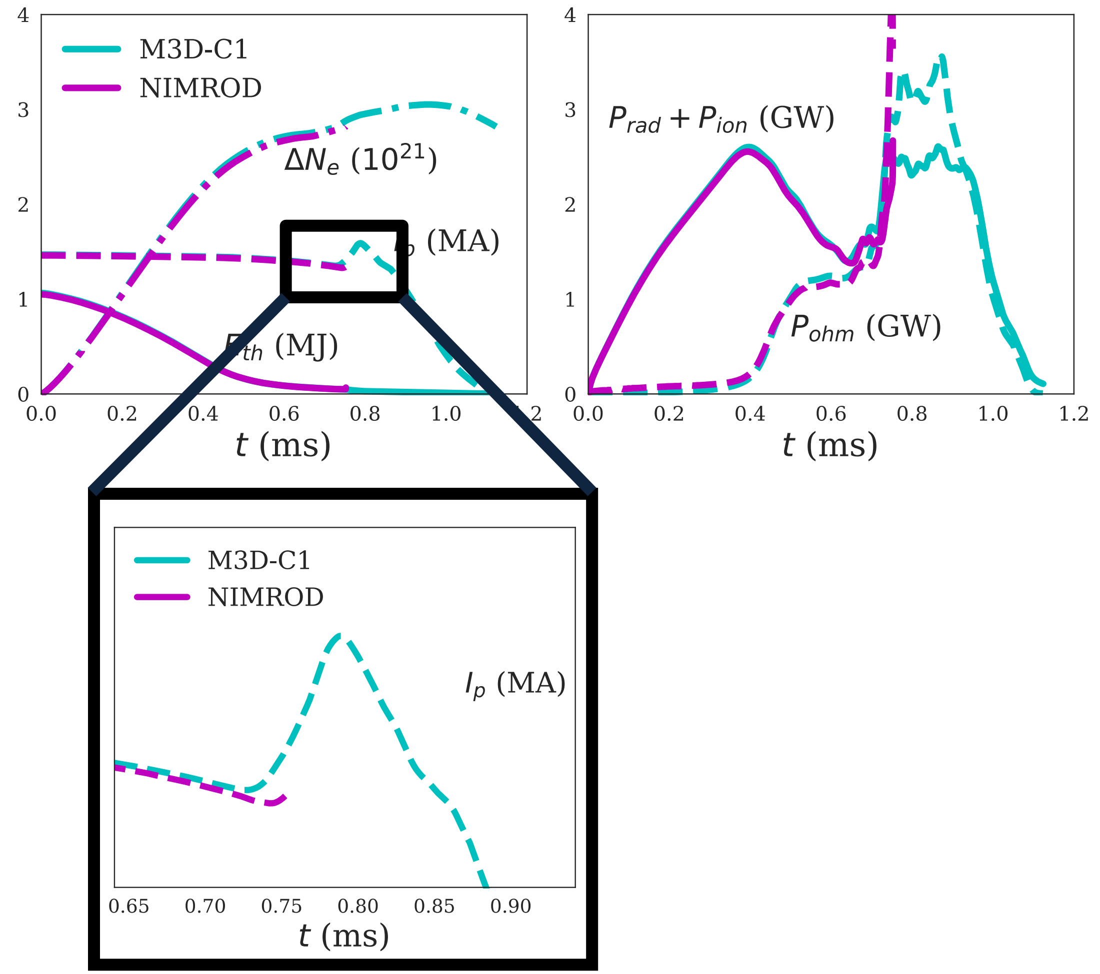

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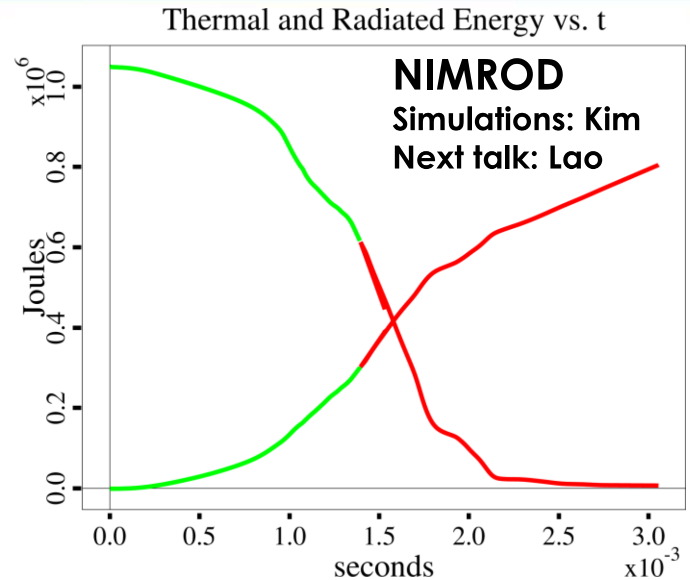
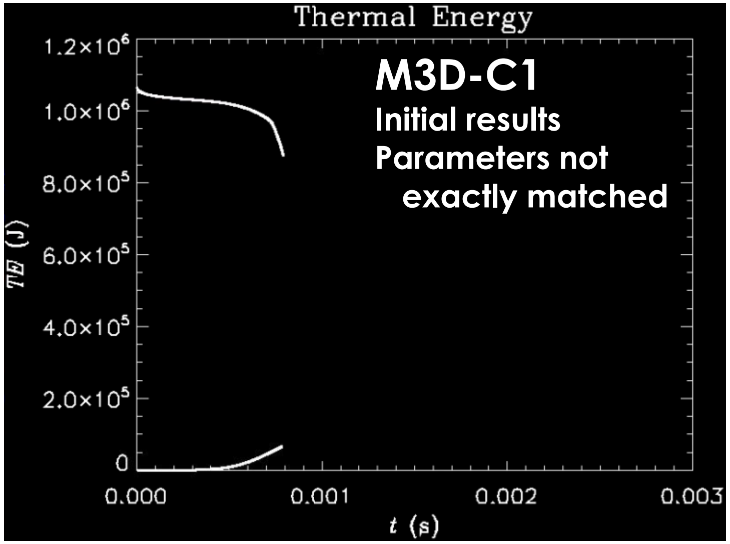




GENERAL ATOMICS

Pellet Mitigation Modeling

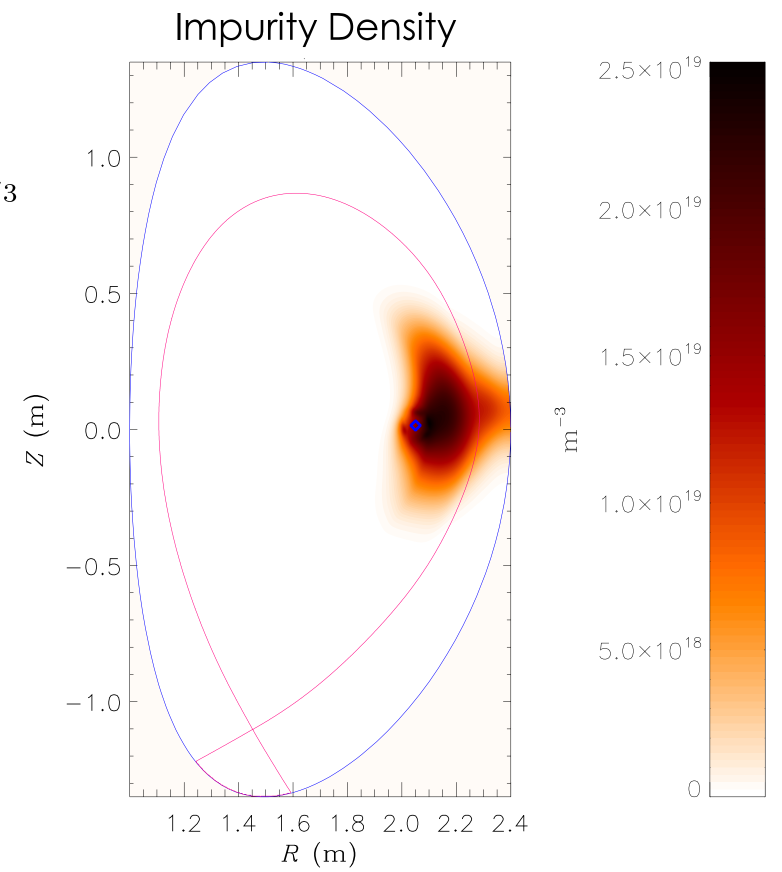
Ablation Model for Ne-D2 Pellets Implemented in M3D-C1

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

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

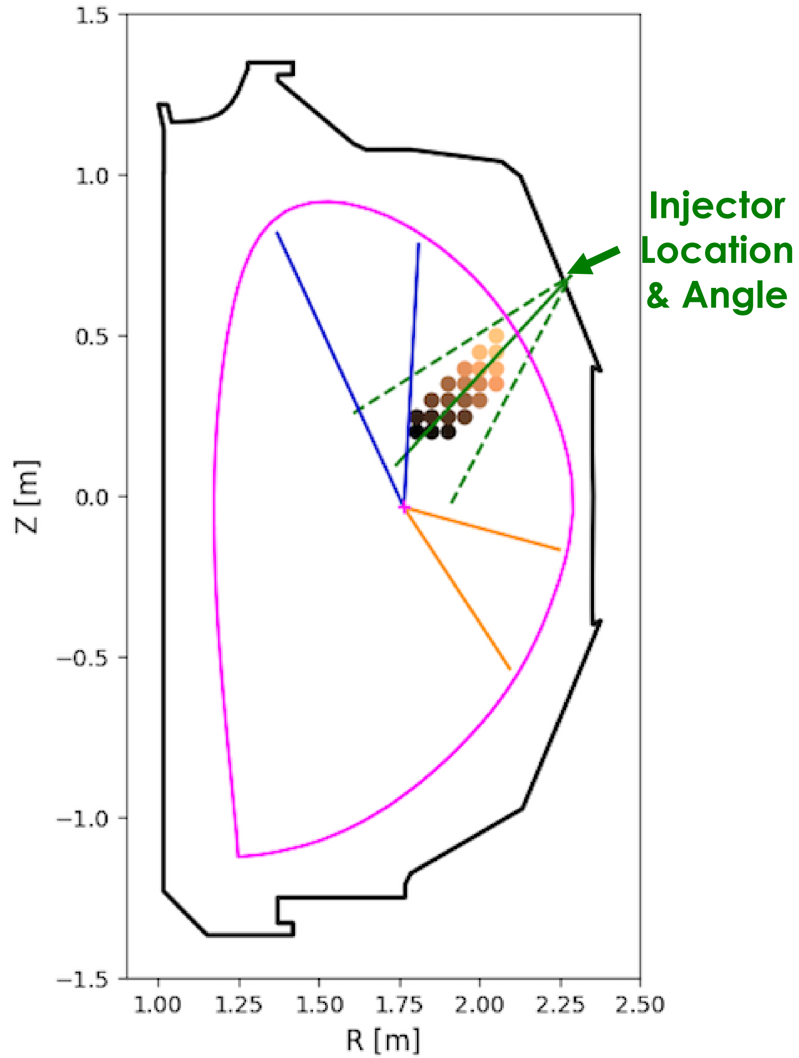
λ is fitting function, depending on molar X fraction of D2

- **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)



Initial M3D-C1 DIII-D SPI Validation

- **Single, unshattered pellet modeled**
  - 4 mm radius
  - 200 m/s @ 41° from horizontal
  - Two compositions
    - Pure Ne
    - 1:10 Ne:D_2
- **Impurity deposition**
  - (R,Z) Gaussian with 5 or 10 cm half-width
  - von Mises distribution toroidally with 1.5 or 3 m half-width
- **Realistic density, temperature, and pressure profiles**
- **Single fluid velocity but separate T_e and T_i evolution**

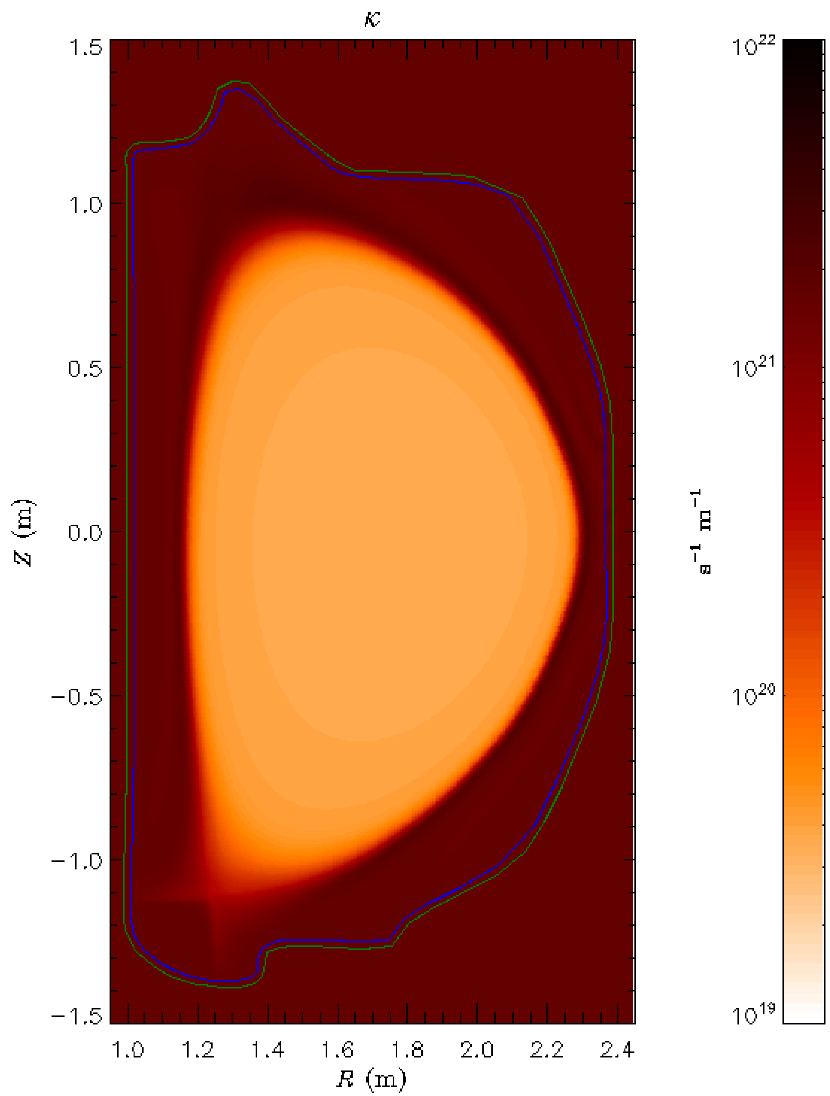


Simulations Often Limited by Negative Temperatures and Numerical Instabilities

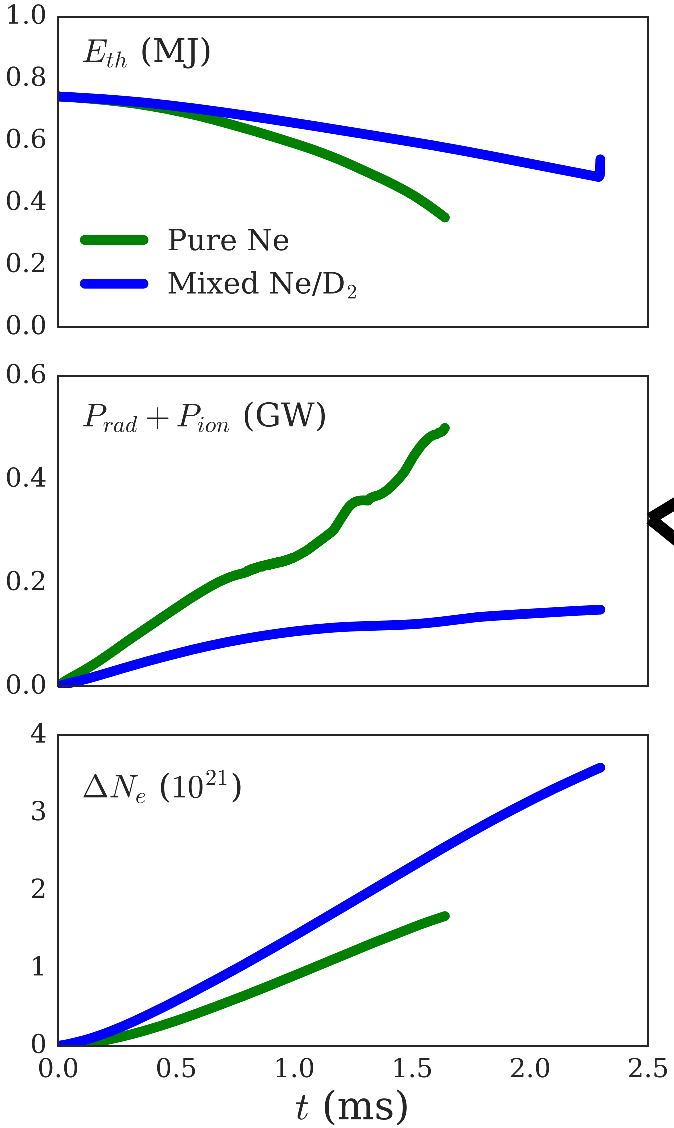
- **Negative temperatures can result due to competing desirable simulation parameters**
  - Low edge temperature to prevent heating of quenching plasma from the wall
  - Difficult to find good thermal conduction parameters
    - If $\kappa_{\|}/\kappa_{\Re}$ is large, steep edge gradients cause negative temperatures in SOL
    - If $\kappa_{\|}$ is small, get cold spots around pellet that are difficult to resolve
    - If $\kappa_{\Re}$ is large, significant thermal energy lost to diffusion
- **Temperature-evaluation floors improve stability, but runs still crash early**

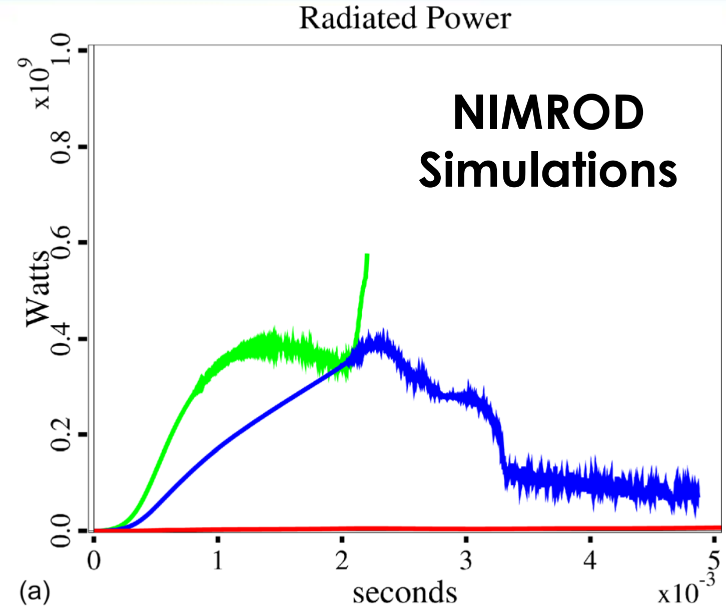
Temperature-Dependent Thermal Conductivity Improves Numerical Stability

- **Thermal conduction**
  - Low, constant $\kappa_{\Re}$ in core to maintain thermal energy during pellet injection $\kappa_{\Re} = 3.33 \times 10^{19}\ m^{-1}s^{-1}$
  - Rises at low T_e as $1/T_e$ to maintain positivity during quench
  - High, constant $\kappa_{\parallel}$ to prevent strong gradients near pellet $\kappa_{\parallel}/\kappa_{\Re} = 10^8$ in core
- **Other transport parameters**
  - Realistic Spitzer resistivity ($S \sim 10^8$)
  - Constant density diffusivity
  - Constant viscosity, though rises in open-field-line region for numerical stability

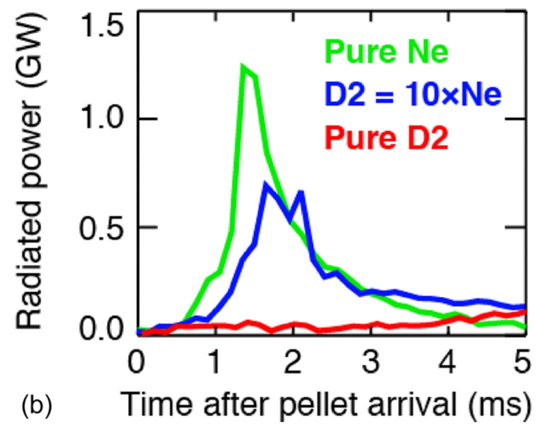


Pure Neon Pellet Radiates Thermal Energy Faster, Consistent with Experiment and NIMROD Modeling





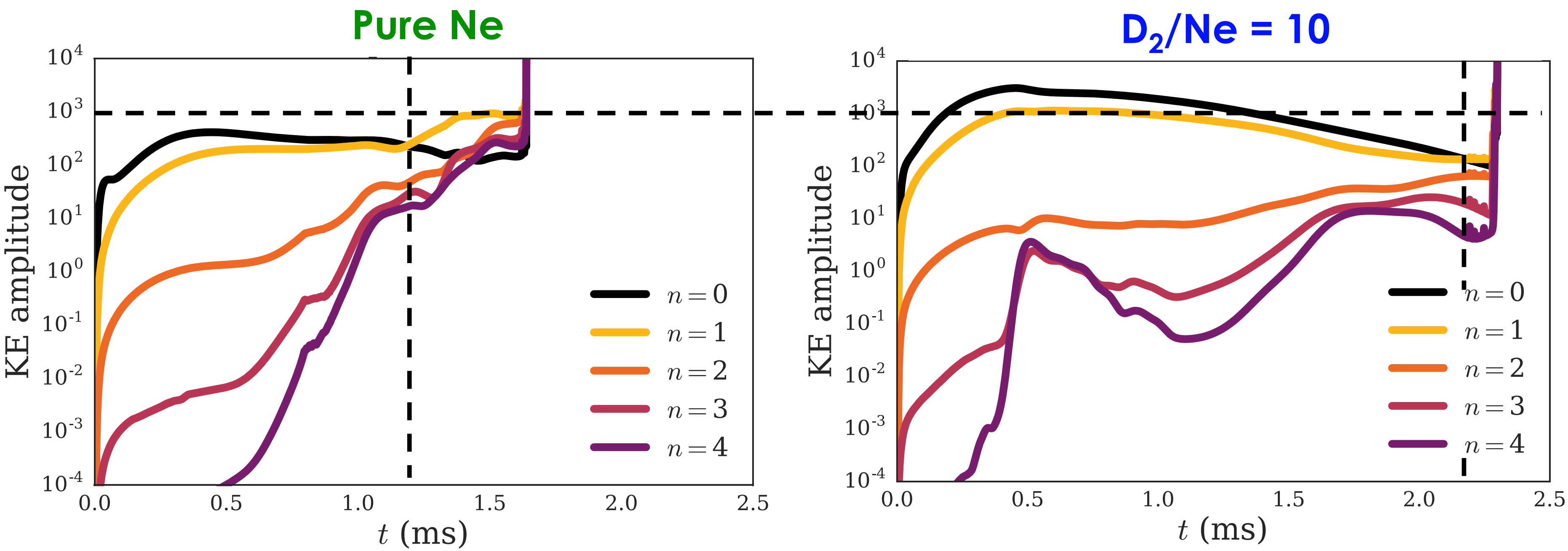
NIMROD Simulations



DIII-D Data

C.C. Kim et al., Phys. Plasmas 26, 042510 (2019)

Pure Neon Pellet Induces Dominant n=1 Mode, Mixed Pellet Remains More Quiescent



- **Late-time MHD appears marginally resolved toroidally**
- **Future work to extend simulations**
  - More planes
  - Smaller time step
  - More dissipation

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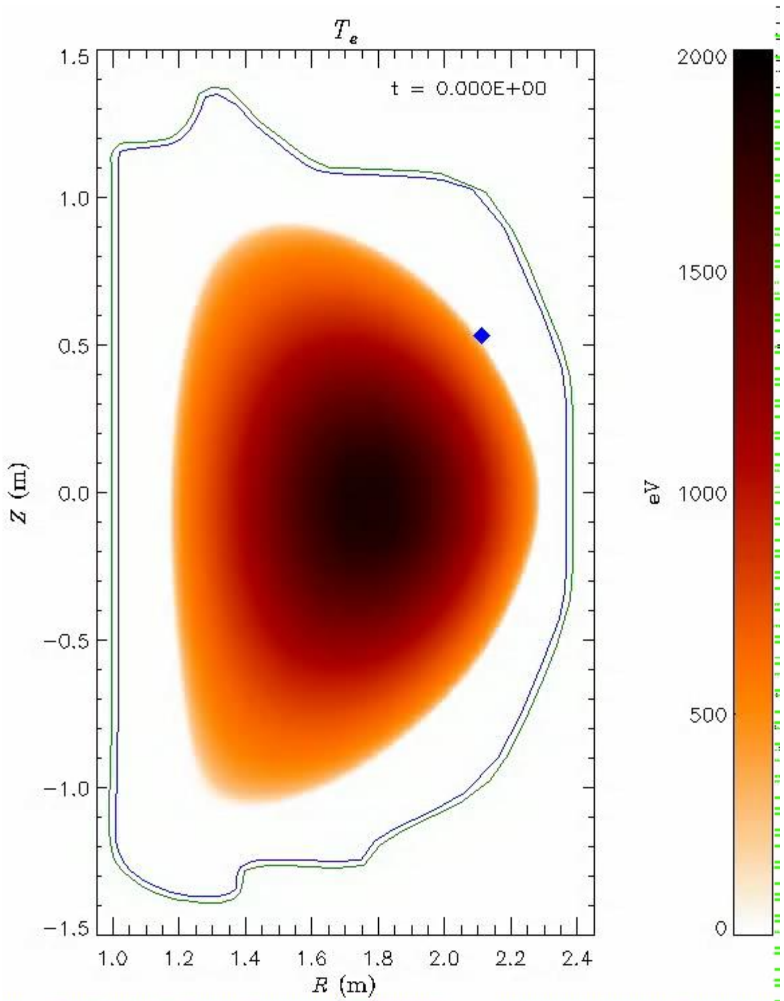
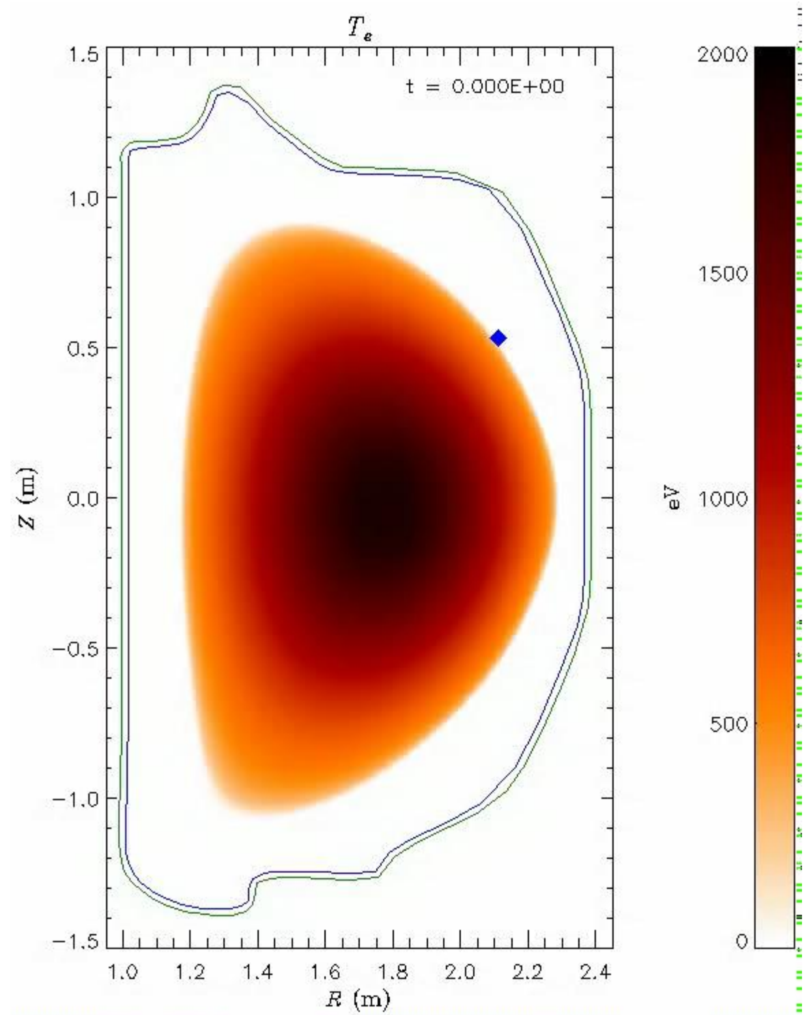
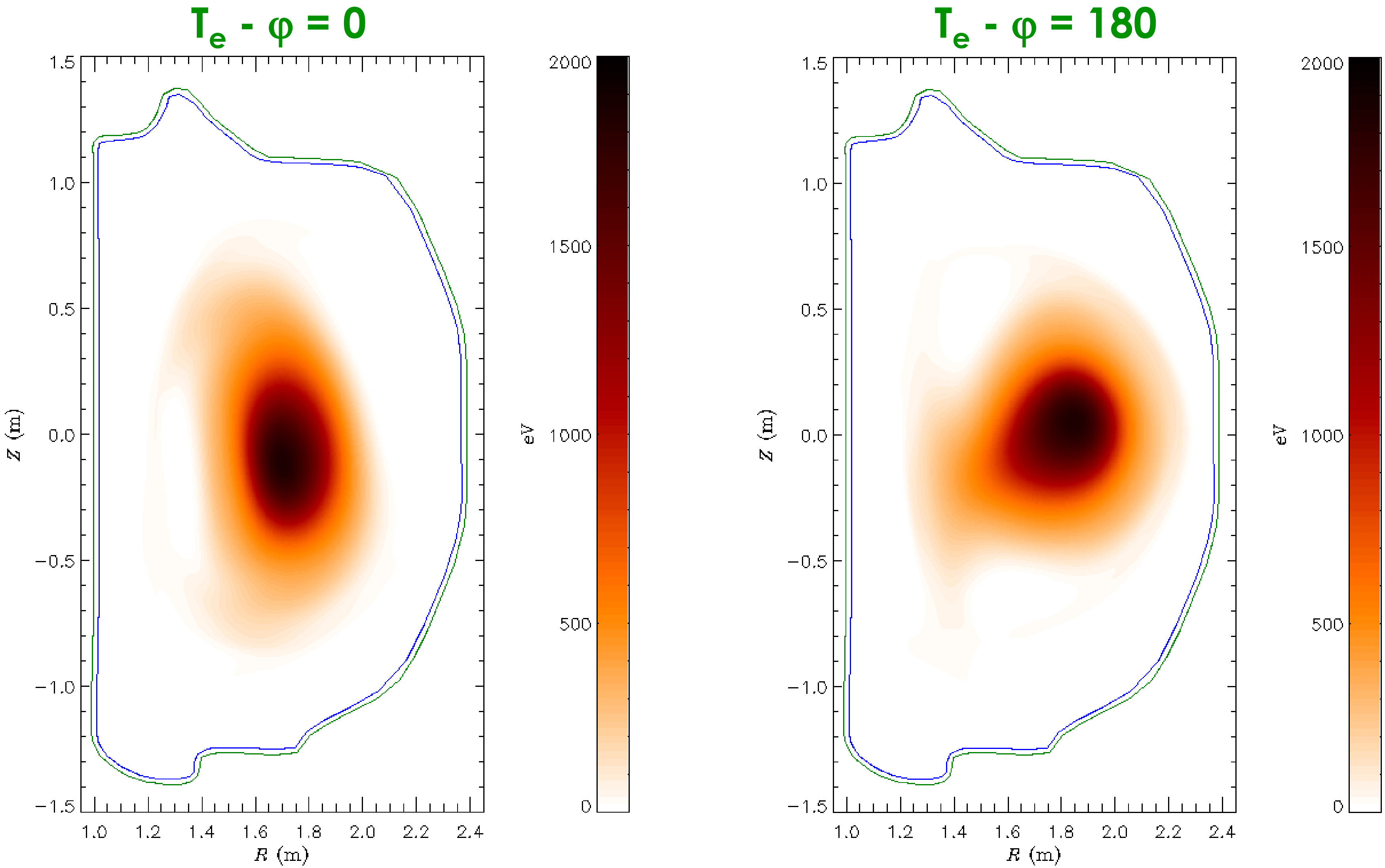
Pure Ne



D_2/Ne = 10

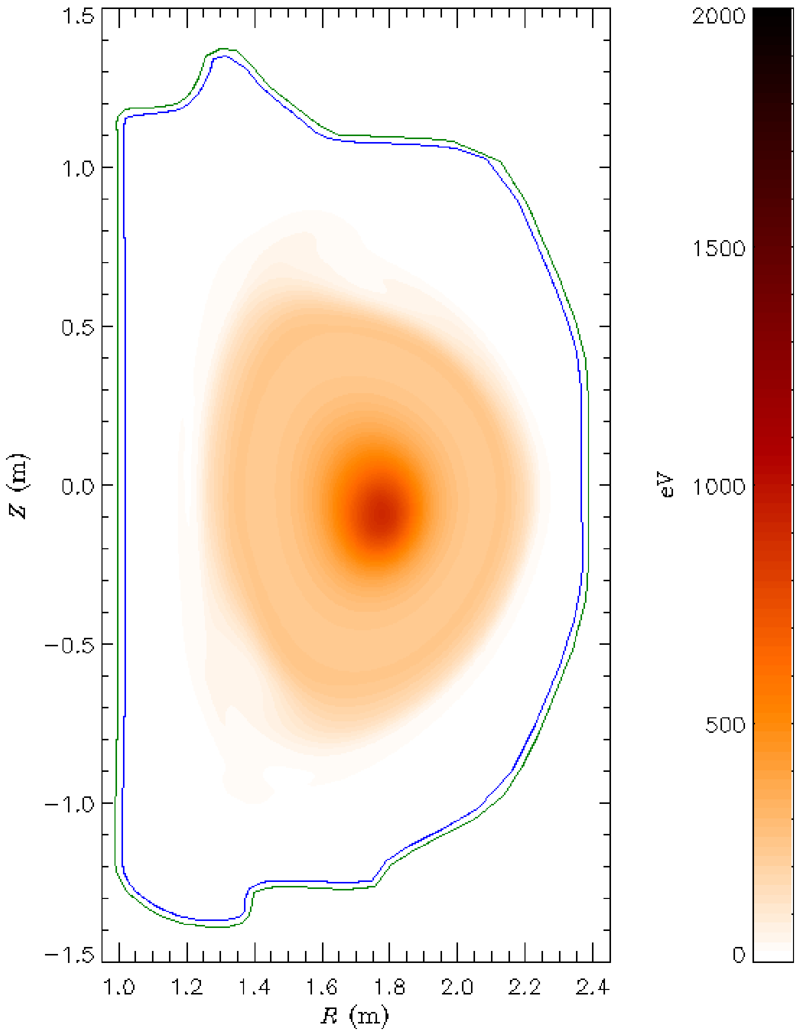


Pure Ne is Highly 3D at 1.5 ms

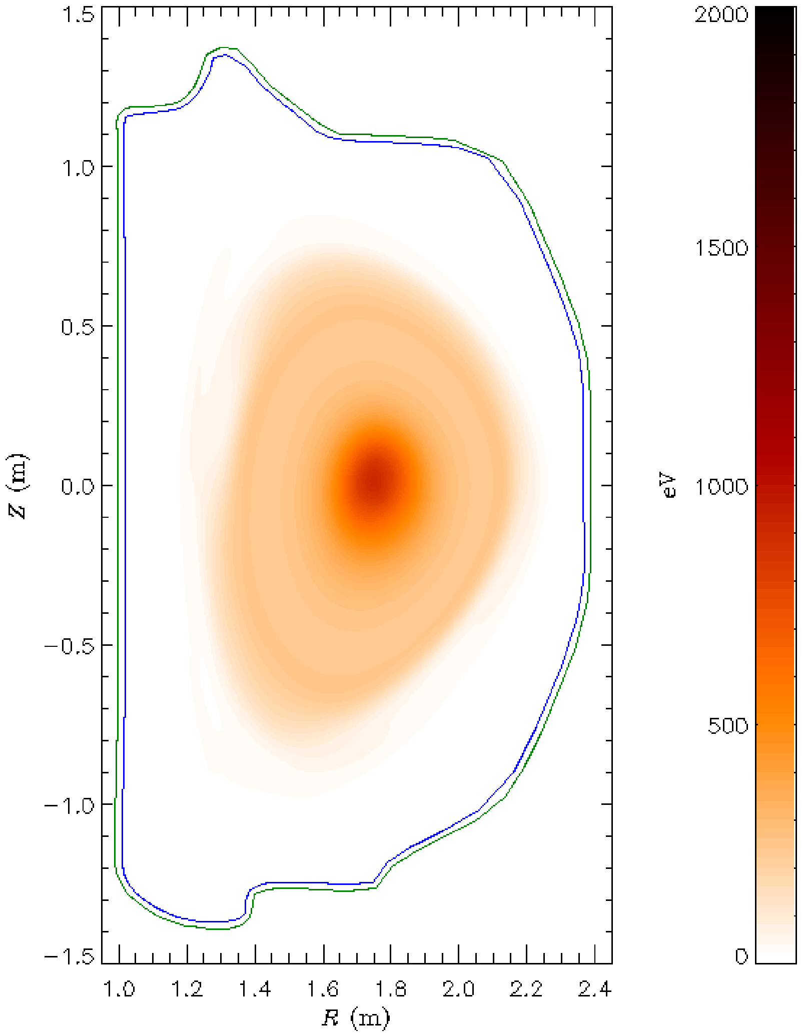


Mixed Ne/D_2 Remains More Axisymmetric through 2.25 ms

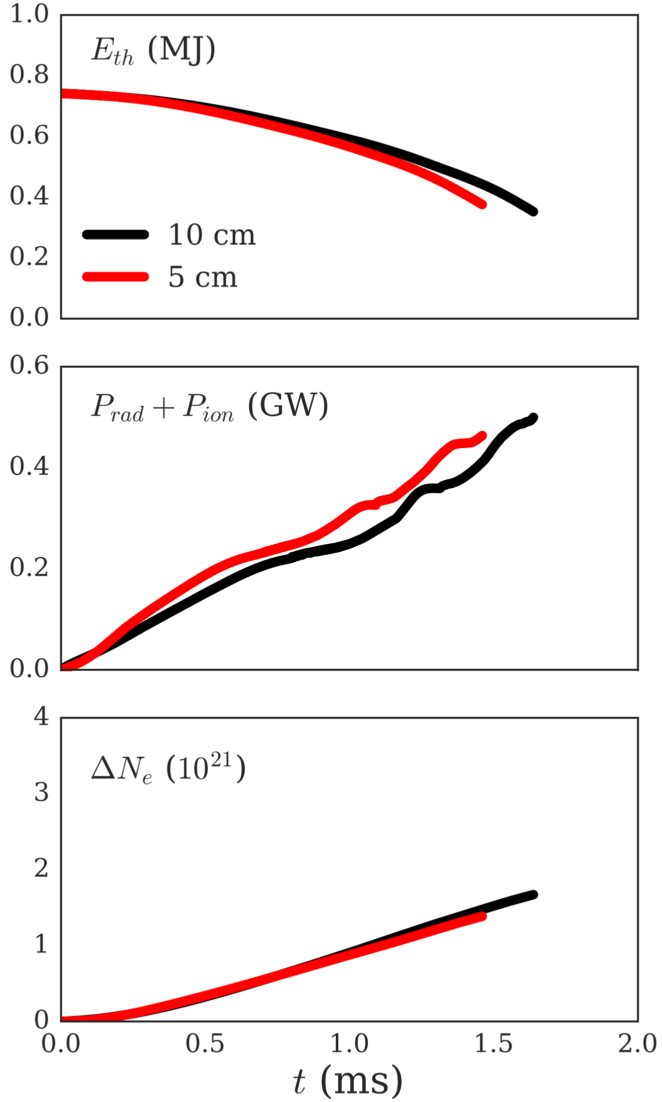
T_e - φ = 0

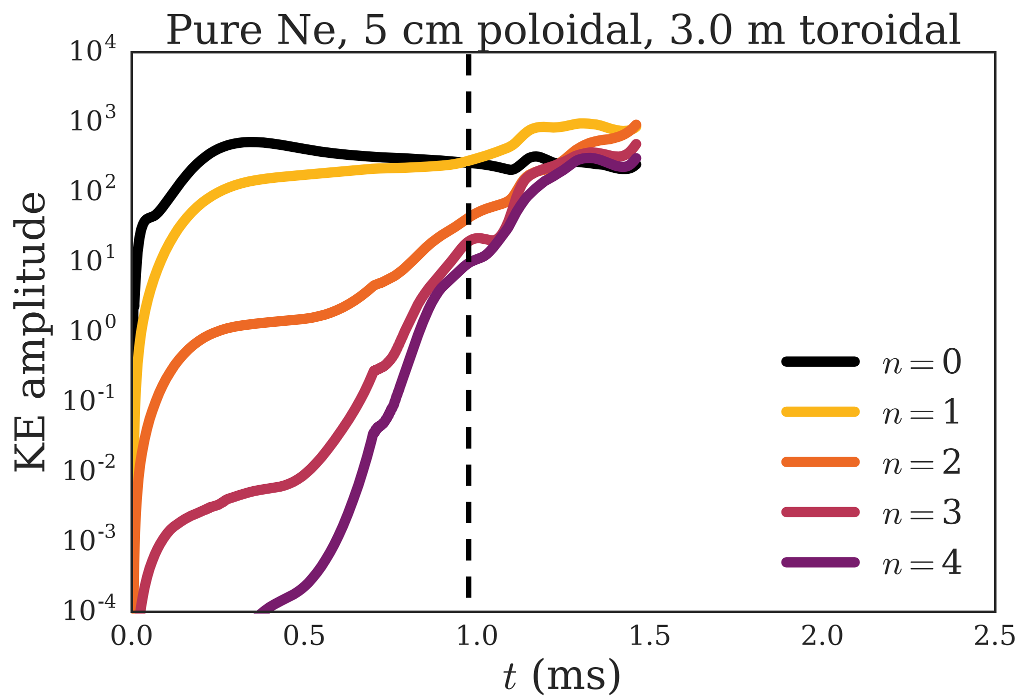


T_e - φ = 180

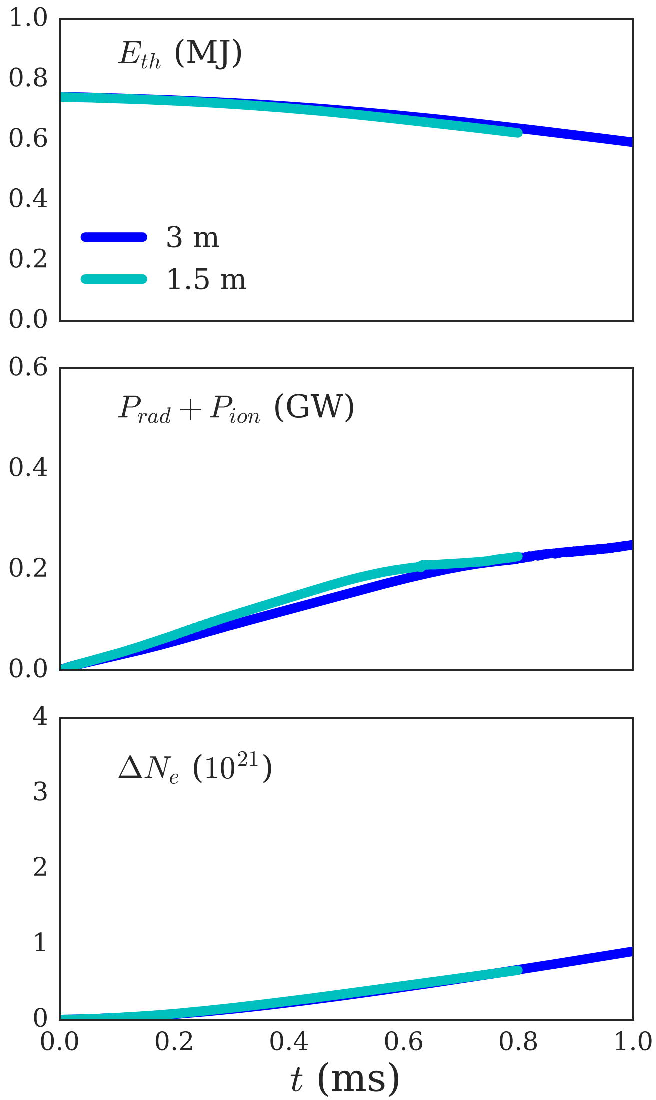


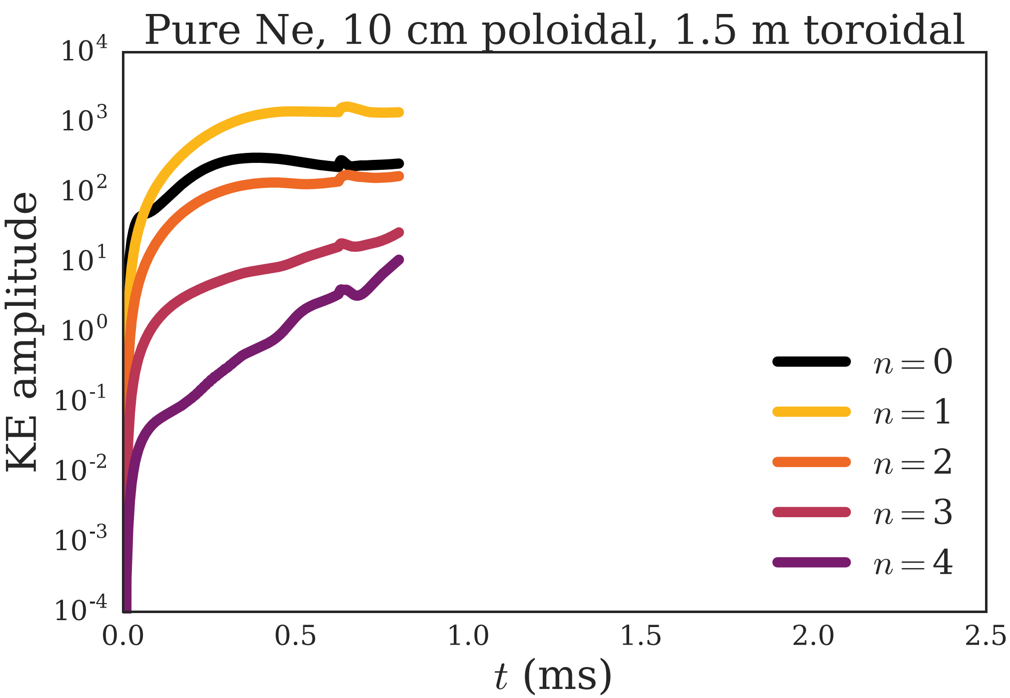
Poloidally Localized Pellet Drives Slightly Earlier MHD and More Radiation





Toroidal Localization Drives Early Non-Axisymmetry, but Not Instability or Radiation





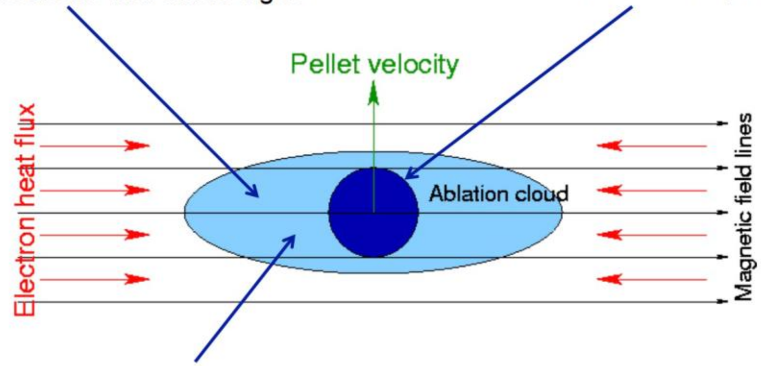
Coupling to Pellet Ablation Code

M3D-C1 is Coupling to Lagrangian-Particle Ablation Code is Underway

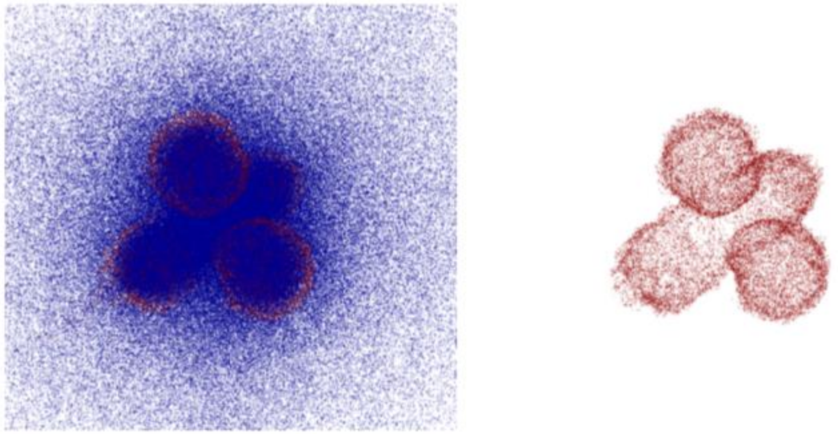
- **New Lagrangian particle code under development (Samulyak – Stonybrook)**
- **Resolves detailed physics**
  - MHD & atomic processes in ablation cloud
  - Phase transition at pellet/ablation surface
- **M3D-C1 and LP code exchange necessary information**
  - MHD code send upstream plasma parameters
  - Ablation code sends far-field ablated density

- Kinetic model for the interaction of hot electrons with ablated gas

- Explicitly tracked pellet surface
- Phase transition (ablation model)



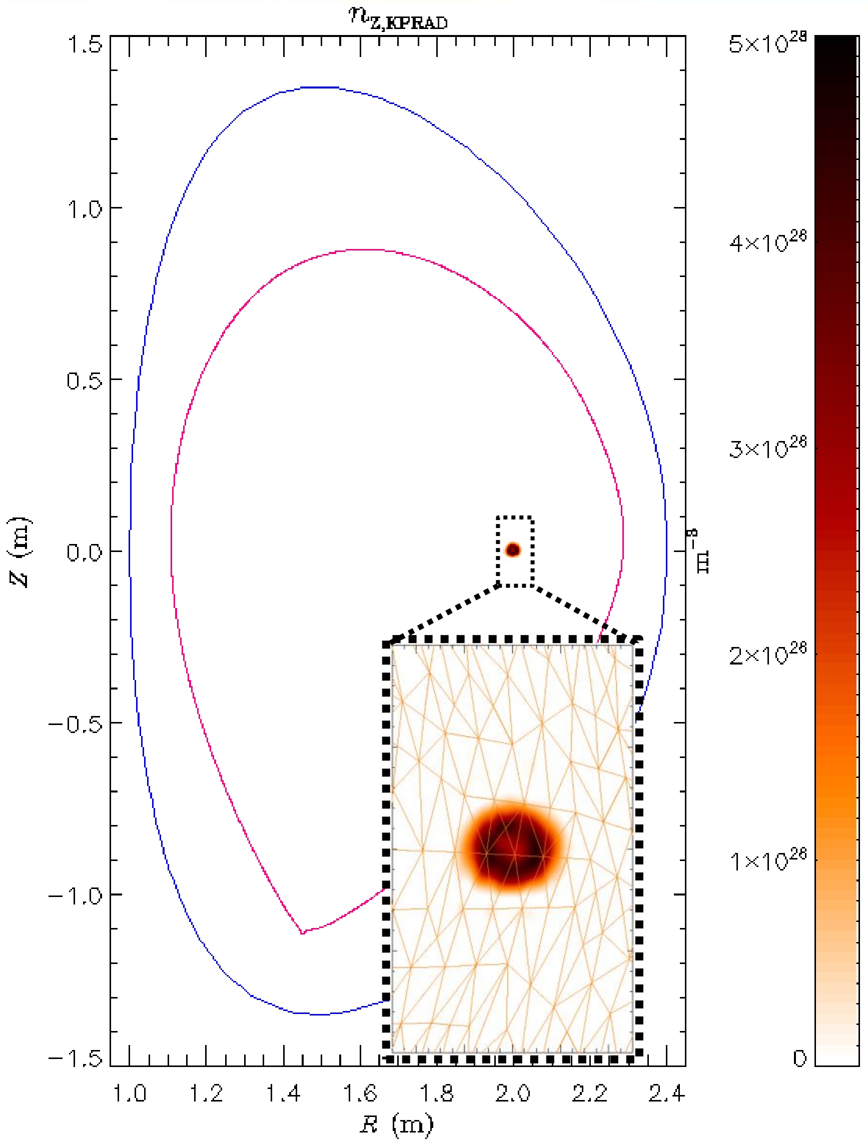
- Low Magnetic Re MHD equations
- Equation of state with atomic processes (Zeldovich average ionization model and tabular EOS based on solution of Saha equations)
- Radiation model
- Electric conductivity model



(a) SPI ablation cloud (b) Particles to be sent to tokamak code

M3D-C1 Successfully Deposits Lagrangian Particles

- **LP code run for stationary 2 mm Ne pellet**
  - Magnetic field: 2 T
  - Electron density: 10^{20} m^{-3}
  - Electron temperature: 2 keV
- **Each LP of ablated material written to text file**
- **Read into M3D-C1**
  - Each particle is delta-function source
  - Interpolated onto finite-element mesh



GENERAL ATOMICS

Summary

- **M3D-C1 is now being used to simulate disruption mitigation by pellet injection in DIII-D**
- **3D modeling of benchmark case showed significant current spike driven by instabilities**
- **Initial SPI validation shows proper trends with pellet composition**
- **Increased localization of impurity deposition**
  - Poloidal: more MHD and radiation
  - Toroidal: more non-axisymmetry, but not instability
  - More challenging but likely more accurate
- **Ablated material from LP code successful deposited in M3D-C1**

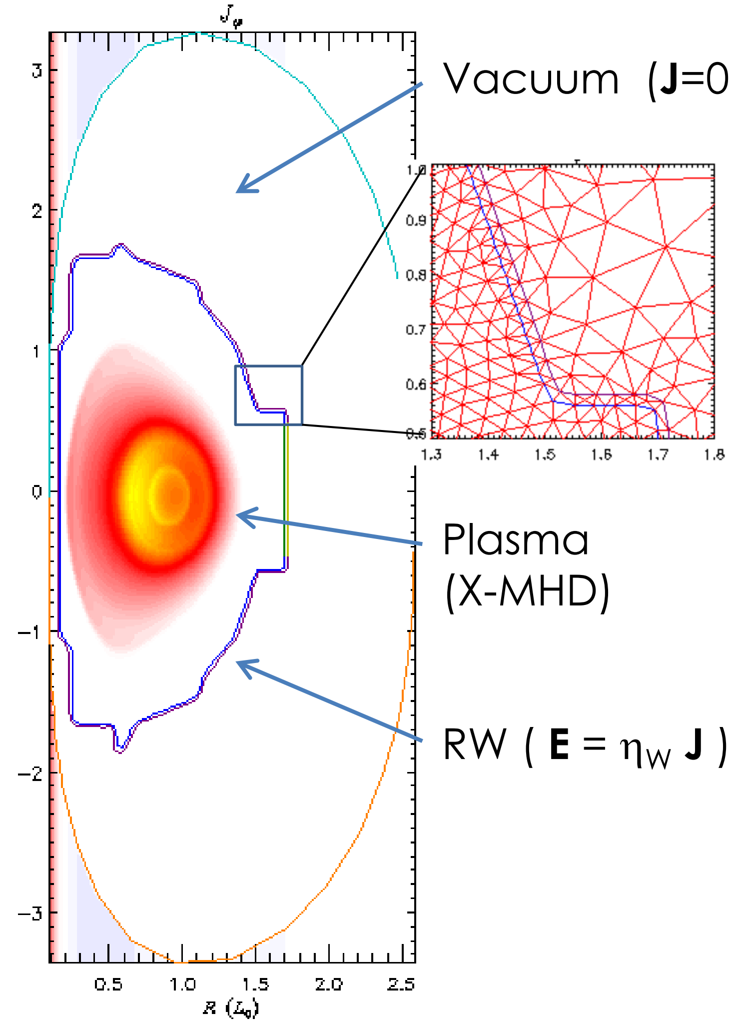
Future M3D-C1 Disruption Mitigation Work

- **Complete 3D nonlinear benchmark with NIMROD**
- **Continue validation against DIII-D experiments**
- **Continue study of toroidal localization of pellet source**
  - Axisymmetric vs. extended Gaussian vs. spherical
  - Make use of toroidal packing
- **Simulations with multiple pellet sources**
  - Shattered fragment cloud
  - Multiple toroidal injection (underway)
  - Couple to Lagrangian-particle/ablation code
- **Prediction and validation for JET, KSTAR, & ITER**
- **Dynamic simulations iterating between M3D-C1 and LP ablation code**

Additional Slides

M3D-C1* Solves the Extended-MHD Equations

- **Three-dimensional toroidal geometry**
- **Full (not reduced) MHD**
- **Solves for potential and stream-function fields for $\vec{A}$ & $\vec{v}$ ($\nabla \cdot \vec{B} = 0$ intrinsically)**
- **Includes resistivity, density diffusivity, viscosity, & thermal conductivity**
- **Two-fluid effects (optional)**
- **3D high-order finite elements**
  - Unstructured, triangular mesh in poloidal plane
  - Structured toroidally, but can pack planes
- **Can solve with finite-thickness resistive wall in domain****



***S. C. Jardin, et al., Comput. Sci. Discovery 5, 014002 (2012).**
****N.M. Ferraro, et al. ,Phys Plasma23 056114 (2016).**

M3D-C1 Solves the Extended-MHD Equations

Blue terms are 2-fluid

$$\frac{\partial n}{\partial t} + \nabla \bullet (n\mathbf{V}) = \nabla \bullet D_n \nabla n + S_n$$

$$\frac{\partial \mathbf{A}}{\partial t} = -\mathbf{E} - \nabla\Phi, \quad \mathbf{B} = \nabla \times \mathbf{A}, \quad \mathbf{J} = \nabla \times \mathbf{B}, \quad \nabla_\perp \bullet \frac{1}{R^2}\nabla\Phi = -\nabla_\perp \bullet \frac{1}{R^2}\mathbf{E}$$

$$nM_i\left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \bullet \nabla\mathbf{V}\right) + \nabla p = \mathbf{J} \times \mathbf{B} - \nabla \bullet \mathbf{\Pi}_i + \mathbf{S}_m$$

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \frac{1}{ne}\left(\mathbf{R}_c + \mathbf{J} \times \mathbf{B} - \nabla p_e - \nabla \bullet \mathbf{\Pi}_e\right) - \frac{m_e}{e}\left(\frac{\partial \mathbf{V}_e}{\partial t} + \mathbf{V}_e \bullet \nabla \mathbf{V}_e\right) + \mathbf{S}_{CD}$$

$$\frac{3}{2}\left[\frac{\partial p_e}{\partial t} + \nabla \bullet \left(p_e \mathbf{V}\right)\right] = -p_e \nabla \bullet \mathbf{V} + \frac{\mathbf{J}}{ne} \bullet \left[\frac{3}{2}\nabla p_e - \frac{5}{2}\frac{p_e}{n}\nabla n + \mathbf{R}_c\right] + \nabla\left(\frac{\mathbf{J}}{ne}\right) : \mathbf{\Pi}_e - \nabla \bullet \mathbf{q}_e + Q_\Delta + S_{eE}$$

$$\frac{3}{2}\left[\frac{\partial p_i}{\partial t} + \nabla \bullet \left(p_i \mathbf{V}\right)\right] = -p_i \nabla \bullet \mathbf{V} - \mathbf{\Pi}_i : \nabla \mathbf{V} - \nabla \bullet \mathbf{q}_i - Q_\Delta + S_{iE}$$

$$\mathbf{V}_e = \mathbf{V}_i - \mathbf{J}/ne$$

$$\mathbf{R}_c = \eta ne\mathbf{J}, \qquad \mathbf{\Pi}_i = -\mu\left[\nabla\mathbf{V} + \nabla\mathbf{V}^\dagger\right] - 2(\mu_c - \mu)(\nabla \bullet \mathbf{V})\mathbf{I} + \mathbf{\Pi}_i^{GV}$$

$$\mathbf{q}_{e,i} = -\kappa_{e,i}\nabla T_{e,i} - \kappa_\parallel \nabla_\parallel T_{e,i}$$

$$\mathbf{\Pi}_e = (\mathbf{B}/B^2)\nabla \bullet \left[\lambda_h \nabla\left(\mathbf{J} \bullet \mathbf{B}/B^2\right)\right], \qquad Q_\Delta = 3m_e(p_i - p_e)/\left(M_i \tau_e\right)$$

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

3) Total and electron pressure equations

- Electrons lose energy to ionization and radiation
- Main ions lose energy only through cooling on electrons

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

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

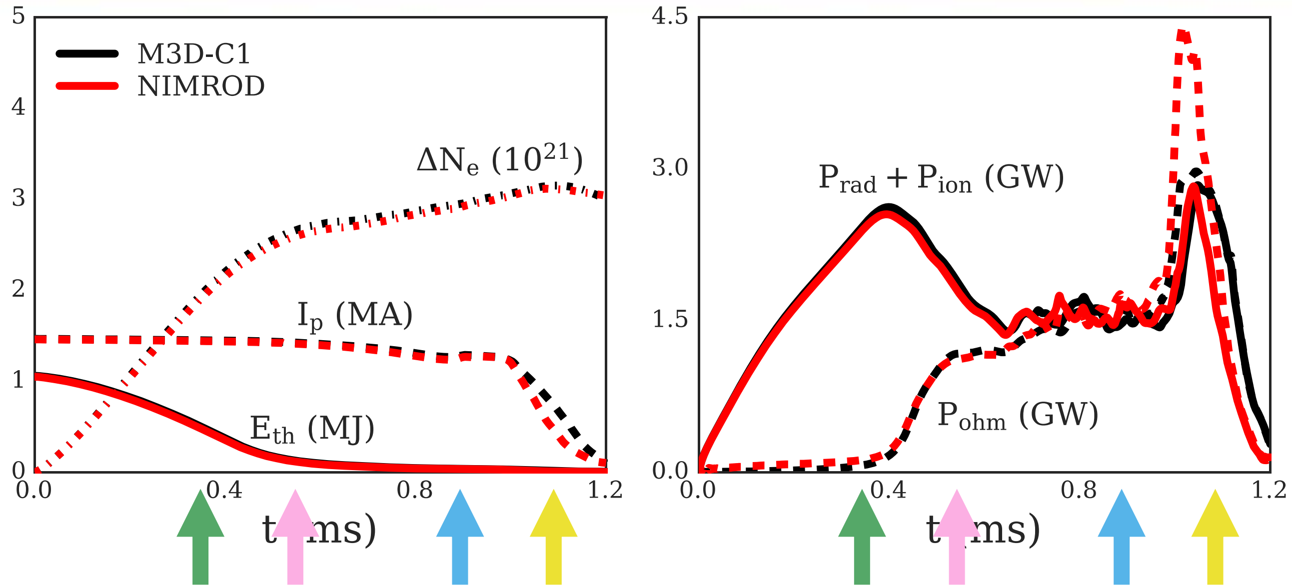
4) Single pressure equation

- 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

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

Successful Axisymmetric Benchmark between M3D-C1 and NIMROD*

Argon Injection



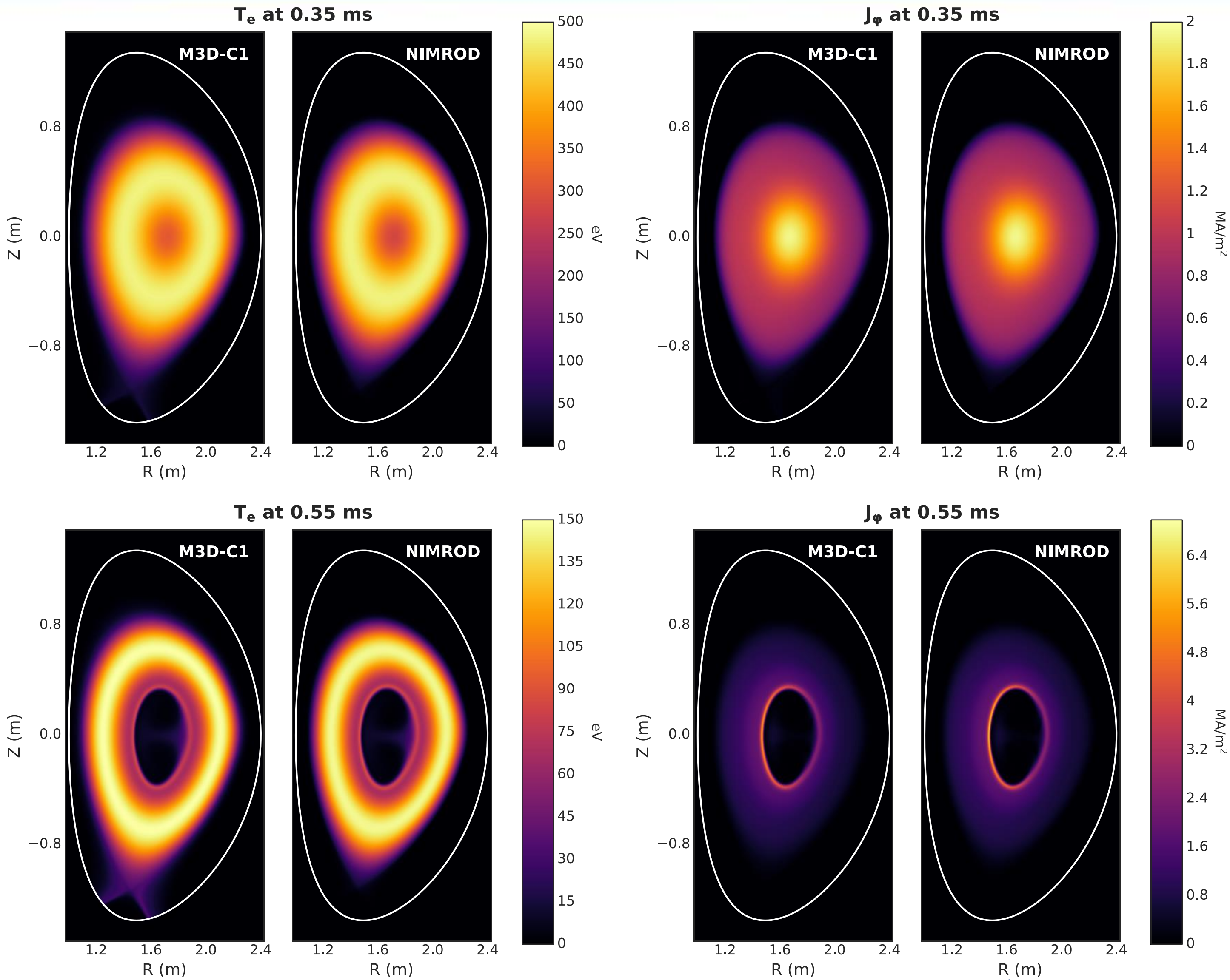
- **Excellent agreement between codes**
  - Quantitative during thermal quench
  - Qualitative during current quench
- **Neon quench roughly 3x slower than argon**
- **Peak loss power when temp. on-axis falls near-zero**
- **Low temperature in core causes resistivity to rise**
  - P_{ohm} balances P_{loss}
  - Current drops more rapidly
- **Current quench caused by contact with boundary**
- **JOREK[x] benchmark underway**

*C. R. Sovinec et al., J. Comput. Phys. 195, 355 (2004).
[x]G.T.A. Huysmans & O. Czarny. Nucl. Fusion 47, 659 (2007).

Early Times Show On-Axis Impurities Induce Inside-Out Thermal Quench and Hollowing of Current

Before peak radiation

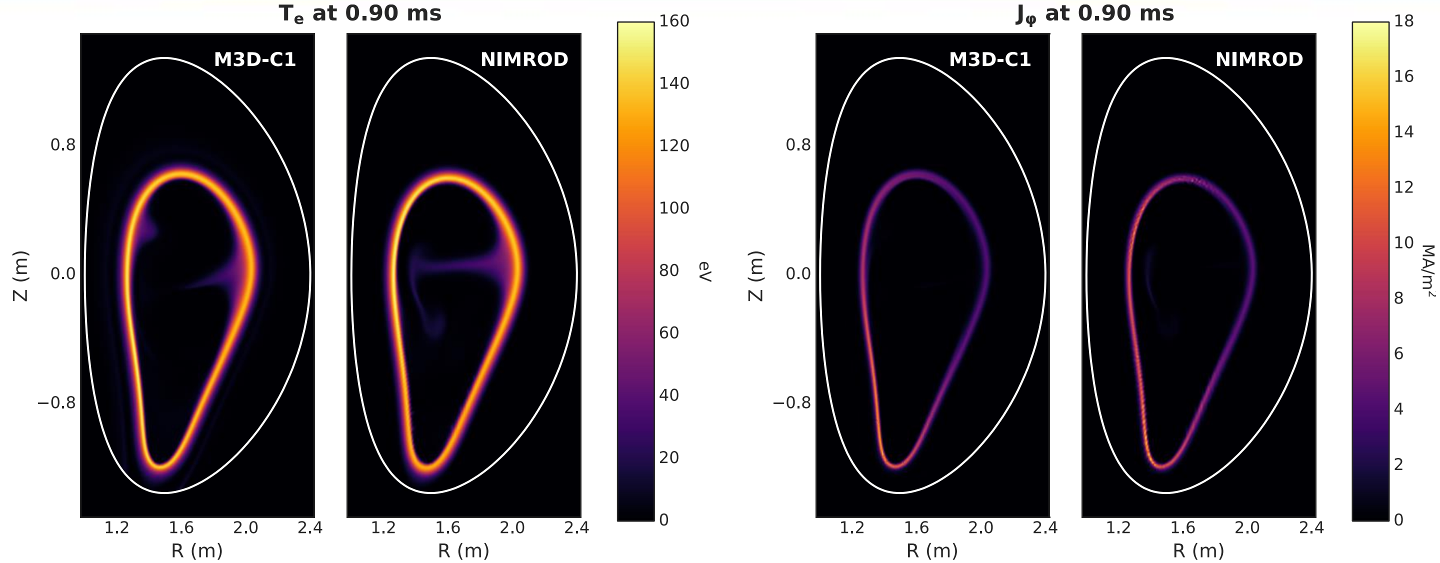
After ohmic heating rise



GENERAL ATOMICS

Late Times Show Core Turbulence and Expanding Shell of Warm Plasma

P_{ohm} = P_{loss}



Rapid current quench