Progress on M3D-C1 Disruption-Mitigation Modeling

by

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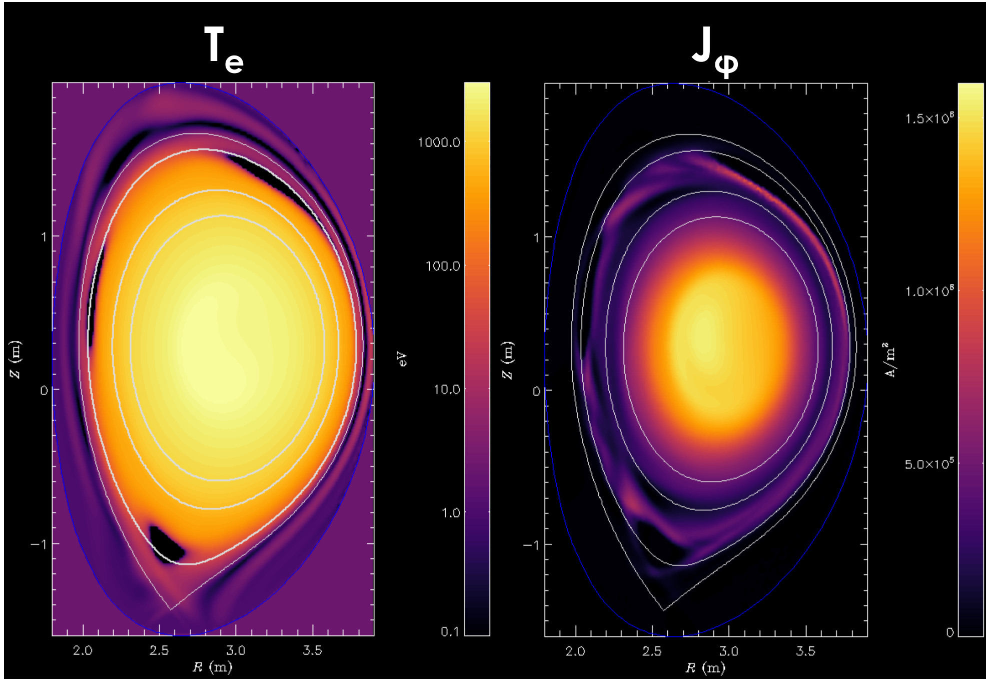
Recent Improvements to Impurity Coupling Have Increased Numerical Stability, Allowing Simulations Through Current Quench

- **Past M3D-C1 runs often crashed due to numerical instability at the onset of physical instability**
  - Negative-temperature islands form on rational surfaces
  - Current diffuses into thin sheets
  - Ultimately noise in density causes crash
- **New coding prevents spurious impurity and radiation evaluations at low T_e**
- **M3D-C1 runs now routinely run through thermal (TQ) & current quenches (CQ)**
  - Full-CQ simulations completed for DIII-D, JET, and KSTAR plasmas
  - Code can be run at lower diffusivities
  - MHD instabilities can cause global stochasticization and complete TQ
  - Current spikes observed in some runs

Anatomy of past failed runs

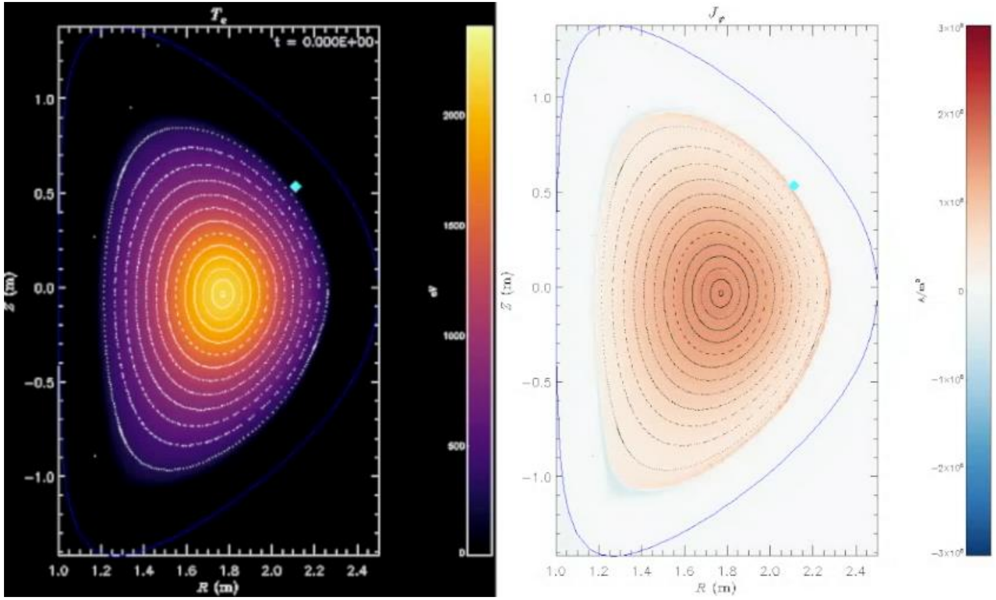


DIII-D Benchmark with NIMROD

3D Benchmark between M3D-C1 & NIMROD with Realistic, Injected Pellet is Underway (Lyons, Kim)

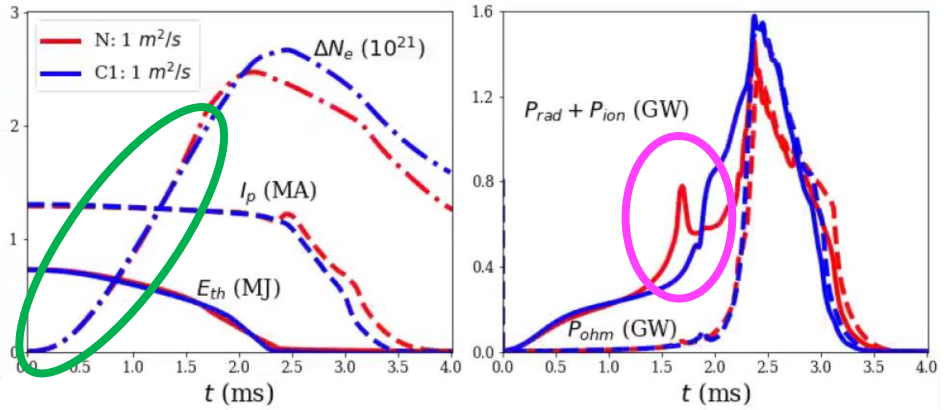
- **DIII-D 160606 @ 2990 ms: 0.7 MJ, 1.28 MA**
- **3D nonlinear MHD**
  - Fixed boundary
  - Single-temperature equation
- **Pellet/deposition parameters**
  - 3 mm radius, pure neon
  - 5 cm poloidal and 2.4 m toroidal half-width
  - 200 m/s with realistic trajectory
- **Ongoing work has motivated code development and bug fixes**
- **Both codes are able to run benchmark case stably for a range of parameters**

Example M3D-C1 Benchmark



Benchmark Performed for a Range of Density Diffusivities

- **Decent agreement at low D**
  - Similar thermal & current quenches
  - Early agreement in N_e shows matching ablation & ionization
  - NIMROD see extra, earlier instability
- Diverge more as D increases
- M3D-C1 is more stable with increasing D, while NIMROD is less



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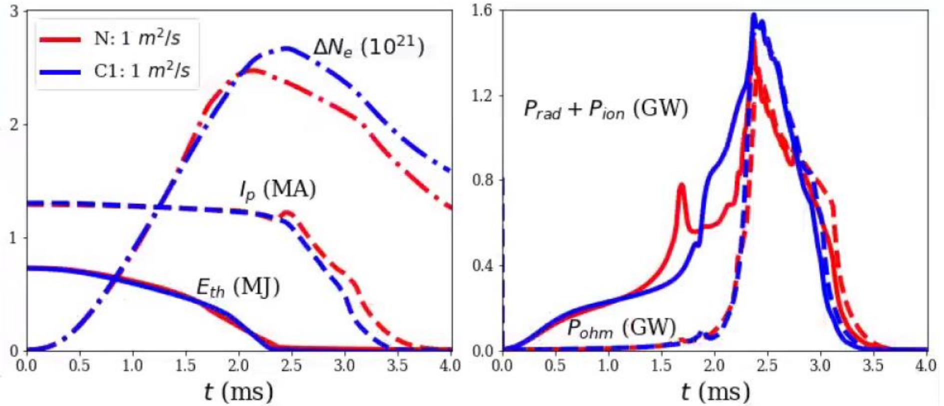

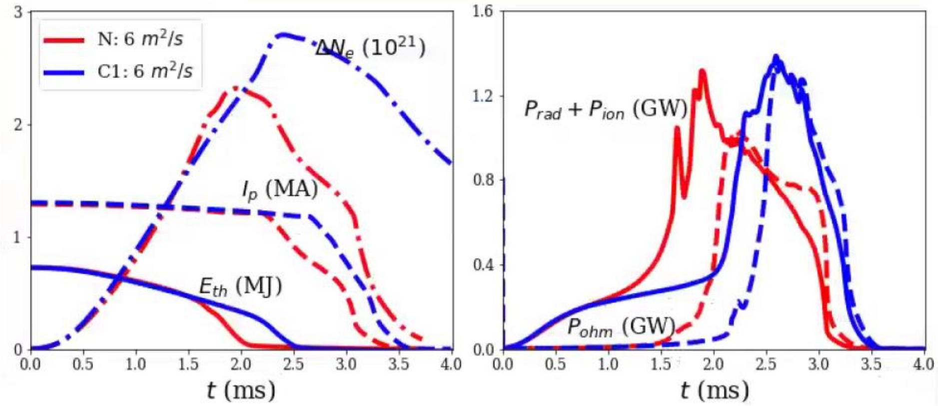

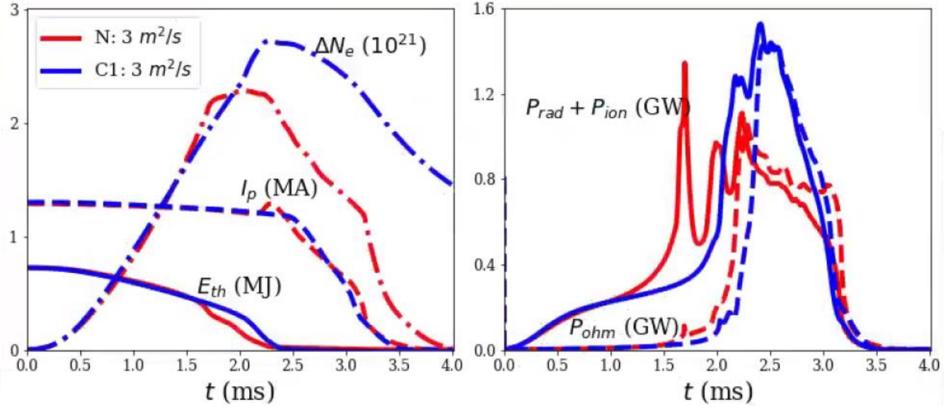

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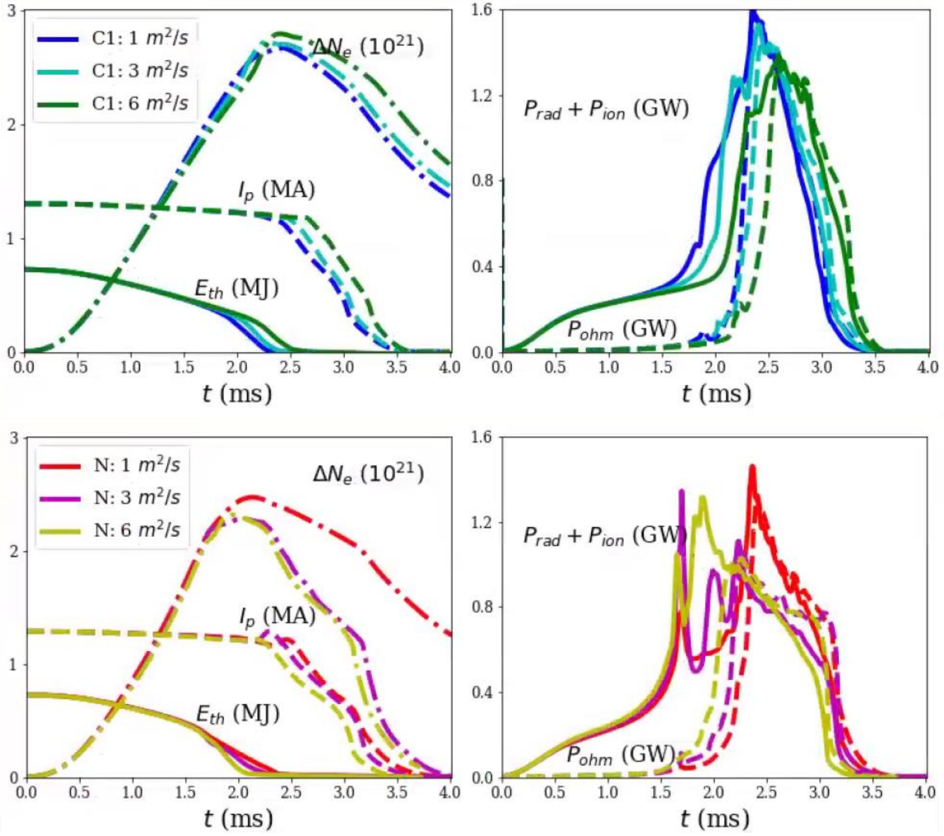

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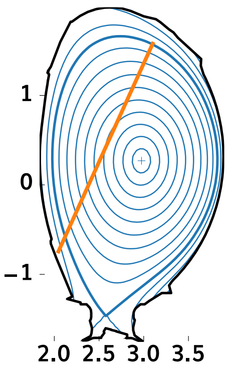
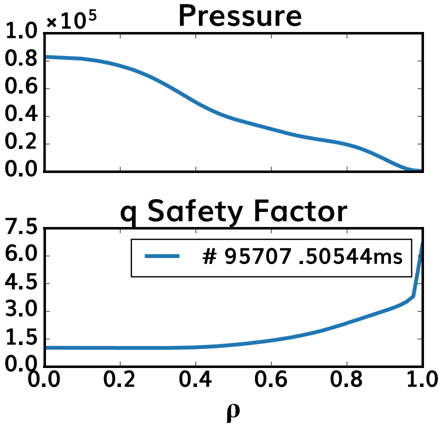
JET & KSTAR Single-Pellet Modeling

DOE International-Collaboration will Validate M3D-C1 and NIMROD against Recent JET and KSTAR SPI Experiments

- **Modeling component of grant has several objectives**
  - Interpret recent mitigation experiments
    - JET, particular high thermal energy and radiation fraction/asymmetry
    - KSTAR, particularly dual, symmetric shattered-pellet injection
  - Develop cross-machine database to inform ITER disruption-mitigation system
  - Make predictions for additional experiments
- **Equilibria reconstructed with kinetic profiles acquired for recent experiments**

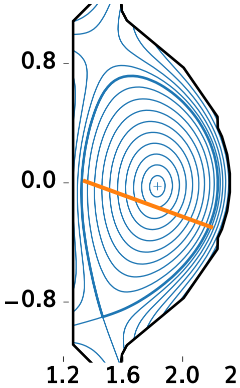
JET 95707
I_p = 2.4 MA
W_{th} = 3.4 MJ
(Scenario 1 High W_{th})

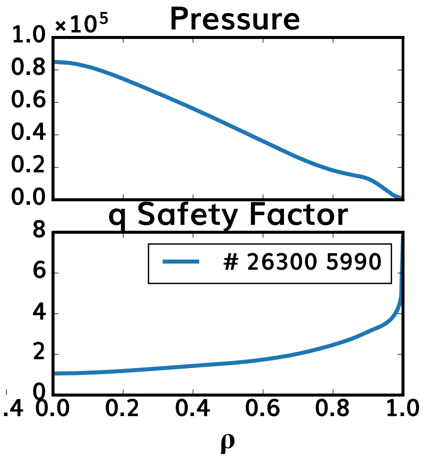




KSTAR 26300
I_p = 0.76 MA
W_{th} = 0.56 MJ

R0 = 2.63818
Z0 = -0.45954
θ = 20°





EUROfusion
JOINT EUROPEAN TORUS (JET)

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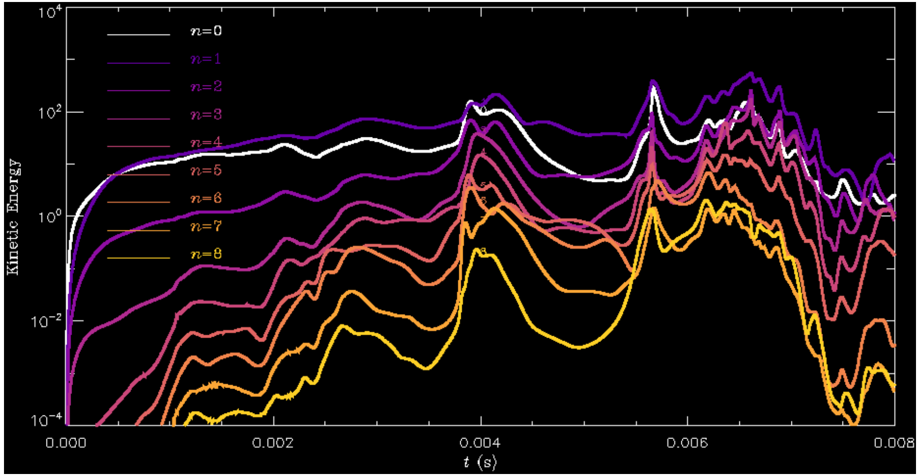
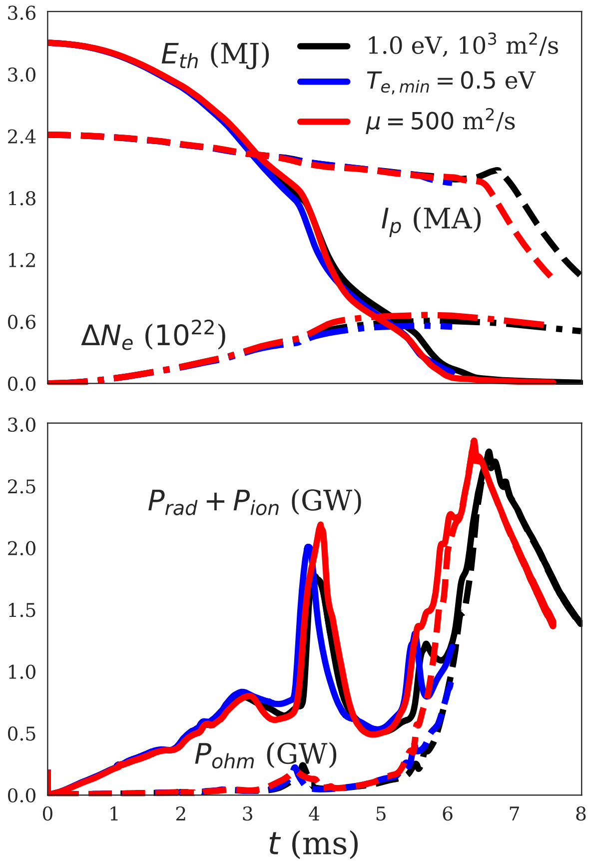
Single-Pellet JET Modeling Shows Complete TQ & CQ

- **Single-pellet simulations done for 95707 at 50.5448 s (150 m/s, D=8.1 mm, pure-neon)**
- **Typical characteristics of SPI disruption**
  - Radiative decay of thermal energy
  - MHD event(s) cause radiation spike and rapid TQ
  - Slight current spike before CQ





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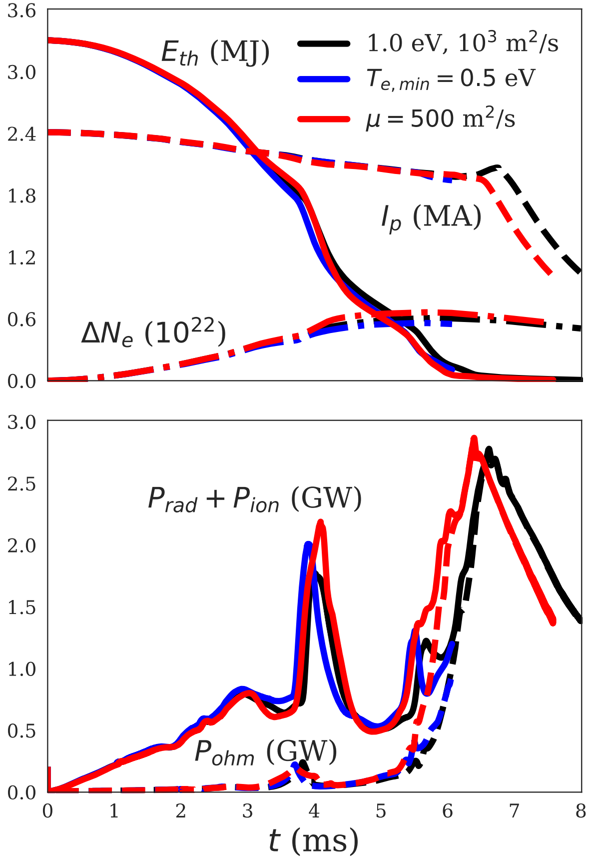
- **Typical characteristics of SPI disruption**
  - Radiative decay of thermal energy
  - MHD event(s) cause radiation spike and rapid TQ
  - Slight current spike before CQ
- **Results qualitatively insensitive to KPRAD cutoff temperature and viscosity**
  - Slightly more radiation when either lowered
  - Earlier CQ with less viscosity
- **Future work**
  - Toroidal localization of pellet
  - Convergence with toroidal planes
  - Shattered pellet plume



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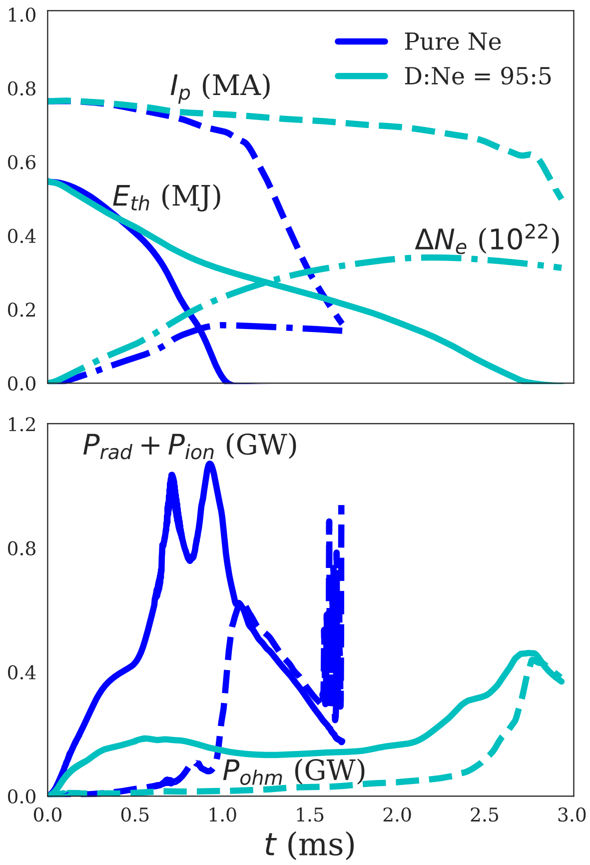
Single-Pellet KSTAR Modeling Well-Underway

- **Single-pellet simulations done for 26300 at 5990 ms**
  - 300 m/s along realistic trajectory
  - Pure neon and 95% deuterium considered
- **Complete TQ relatively rapid**
  - Radiation driven due to low W_{th}, high velocity, and large (4.6 mm) pellet
  - Maybe some MHD in pure-Ne but relatively benign
- **Future work**
  - Pure-deuterium?
  - Dual injection
  - Shattered pellet plume



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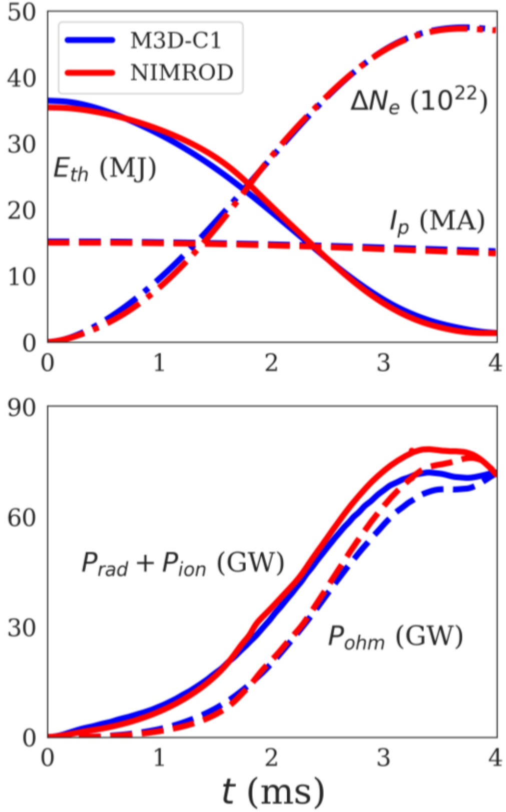
SPI Characteristics Benchmarked in 2D Simulations of ITER L-mode

- **ITER Case H26: 15 MA L-mode plasma**
- **Initial simulations consider pencil-beam model (line of uniform pellet fragments)**
  - 95/5 D/Ne pellet
  - Different fragment sizes
  - Different velocities
- **2D benchmark successfully performed with NIMROD**
  - Confidence in both codes to explore optimization of pellet and shatter parameters
  - Helped identify bugs and numerical challenges
- **To consider**
  - Poloidal/toroidal spread
  - Non-uniform fragment sizes
  - 3D
  - H-mode scenarios

512 2.5-mm fragments



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Plans for Future Work

- **Complete 3D nonlinear benchmark with NIMROD**
  - What are metrics for success?
  - Strong nonlinearity makes exact agreement difficult
  - Chaotic evolution: small discrepancies early cause exponential deviation
  - Perhaps need to benchmark qualitative behavior of physics-based scans?
- **Validation with DIII-D**
- **Validation with JET & KSTAR**
- **What are the areas to focus on?**
  - Eidietis: pure-deuterium as timely
  - Nardon & KSTAR: Vary impurity content and dual vs single injection

Acknowledgments

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Additional slides

M3D-C1 and NIMROD Extended-MHD Solvers are Coupled to Impurity Ionization/Radiation Models

- **Both codes solve full, nonlinear, 3D extended MHD equations**
  - M3D-C1 uses a complete C^1 finite-element representation
  - NIMROD uses finite elements in poloidal plane and Fourier modes toroidally
- **Both have been coupled to the KPRAD[1] impurity model**
  - Low-density, coronal non-equilibrium model based on ADPAK rate coefficients
  - Impurity & electron densities 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 and radiation
  - NIMROD uses single-temperature, M3D-C1 uses single or two-temperature

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

$$n_{ti} \left[\frac{\partial T_i}{\partial t} + \mathbf{v} \cdot \nabla T_i + \Gamma T_i \nabla \cdot \mathbf{v} \right] = (\Gamma - 1) \left(-\nabla \cdot \mathbf{q}_i - Q_{ei} - \mathbf{\Pi} : \mathbf{v} \right) - T_i \left(\frac{\partial n_{ti}}{\partial t} + \mathbf{v} \cdot \nabla n_{ti} \right)$$

[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.