Verification and Validation of Extended-Magnetohydrodynamic Modeling of Disruption Mitigation

by

Brendan C. Lyons[1]

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*See the author list of E. Joffrin et al. 2019 Nucl. Fusion 59 112021

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GENERAL ATOMICS

EUROfusion
JOINT EUROPEAN TORUS (JET)

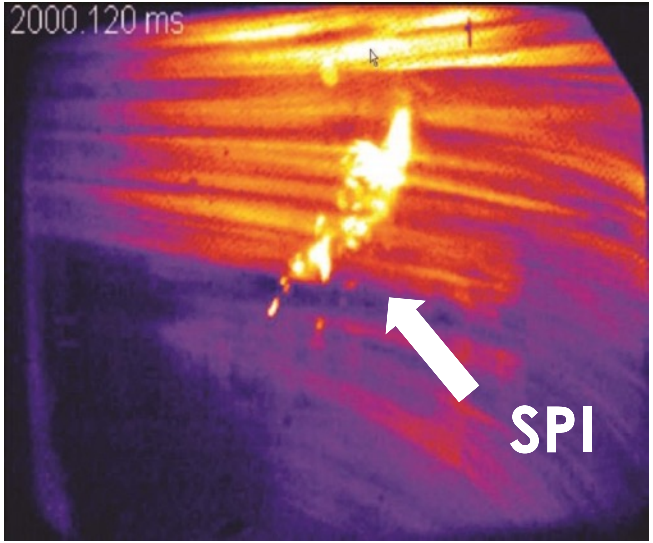
DIII-D
NATIONAL FUSION FACILITY

Many Grants Provide Opportunities of Synergistic Research

- **US DOE grants used for code validation & close collaboration with experiment**
  - GA Theory (DE-FG02-95ER54309) and DIII-D (DE-FC02-04ER54698)
  - CTTS SciDAC for MHD modeling (DE-SC0018109)
  - JET/KSTAR Disruption Mitigation Solution (DE-SC0020299)
- **EUROfusion Enabling Research project for JOREK code development and validation**
- **National Energy Research Scientific Computing Center for high-performance computing**

Studying of Disruption Dynamics and Mitigation Requires Multiphysics Models

- **Simulations validated against experiments are required to project mitigation techniques to future devices**
- **Integrated model is required to capture all relevant physics**
  - Magnetohydrodynamics (MHD) for macroscopic evolution of disruption dynamics
  - Atomic physics for impurity ionization/radiation
  - Drift-kinetics for runaway-electron (RE) evolution
- **Disparate spatial and temporal scales make numerical modeling particularly challenging**
- **M3D-C1[1], NIMROD[2,3], and JOREK[4,5] are rising to this challenge**
  - Different physics and numerical model provide robust verification opportunities
  - Multiple code permit parallel research efforts



DIII-D shattered pellet injection (SPI)
D. Shiraki, IAEA presentation 2016

[1]S. C. Jardin, et al., Comput. Sci. Discovery 5, 014002 (2012)
[2]C. R. Sovinec et al., J. Comput. Phys. 195, 355 (2[illegible])
[3]C. Sovinec & J. King, J. Comput. Phys. 229, 5803 (2[illegible]0)
[4]G.T.A. Huysmans & O. Czarny, Nucl. Fusion 47, 659 (2007)
[5]O. Czarny & G. Huysmans, J. Comput. Phys. 227, 7423 (2008)

GENERAL ATOMICS

Outline and Major Results

- **Overview of code models**
- **Verification studies**
  - M3D-C1 & NIMROD show quantitative agreement in 2D, nonlinear benchmark, JOREK differences likely due to its impurity model
  - M3D-C1 & NIMROD 3D nonlinear benchmarks
    - Axisymmetric, core deposition shows stable thermal quench, instability-induced current quench with large current spike
    - Injected, ablating pellet benchmark is underway
  - NIMROD viscosity & deposition scans show expected thermal-quench dependence
- **Validation studies**
  - Initial M3D-C1 pellet-composition study shows qualitative agreement with DIII-D data, NIMROD shows quantitative agreement with experiment
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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

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

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

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

GENERAL ATOMICS

JOREK Extended-MHD Solver Coupled to Coronal-Equilibrium Impurity Model

- **JOREK solves 3D nonlinear extended MHD equations**
  [Huysmans and Czarny, NF 2007; Overview article: Hoelzl et al., in preparation; https://www.jorek.eu/]
  - 2D C^1 finite elements poloidally & Fourier modes toroidally
  - Fully implicit [Czarny and Huysmans, JCP 2008]
  - Free-boundary simulations with JOREK-STARWALL [Hoelzl et al., JPCS 2012]
  - Typically run in reduced MHD (including all simulations here)
- **Various extensions permit disruption mitigation modeling**
  - Neutrals [Fil et al., PoP 2015]
  - Shattered-pellet injection [Hu et al., NF 2018]
  - Impurities under coronal equilibrium [Hu et al., in preparation]
  - Impurities beyond coronal equilibrium is under development [Wieschollek et al.]
  - Runaway Electrons
    - Fluid model [Bandaru et al., Phys. Rev. E 2019]
    - Test particles [Sommariva et al., NF 2017 & 2018]

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Axisymmetric Benchmark Between M3D-C1 and NIMROD was Highly Successful (Lyons, Kim)

- **2D, nonlinear modeling of argon injection in DIII-D core (See pub. for details [†])**
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  - Current quench caused by contact with boundary shows qualitative agreement
  - Quantitative differences likely caused by disparate boundary conditions
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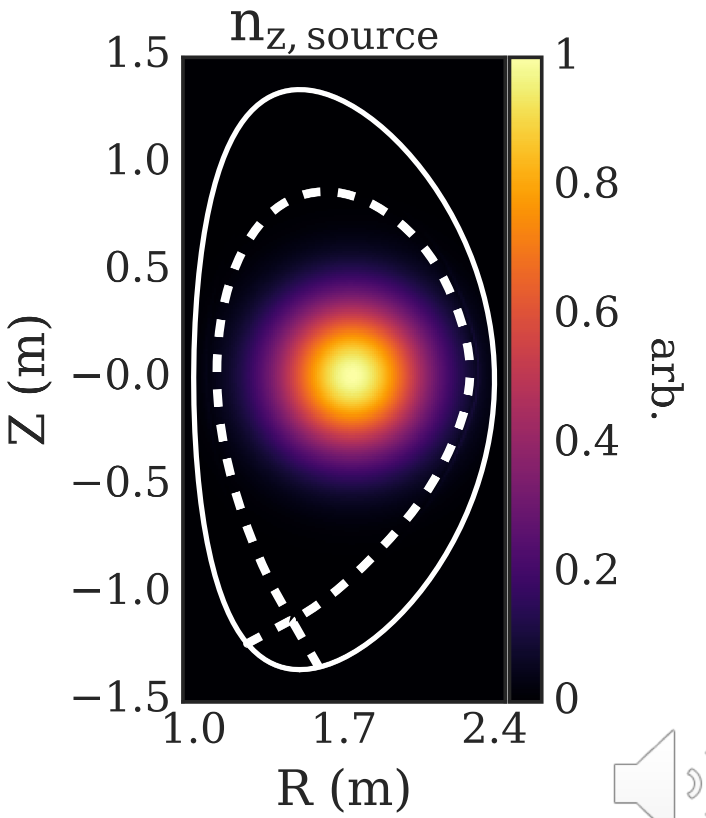
- **After thermal quench, plasma forms expanding shell with core turbulence**



[†] B.C. Lyons et al., PPCF **61**, 6 (2019). doi.org/10.1088/1361-6587/ab0e42

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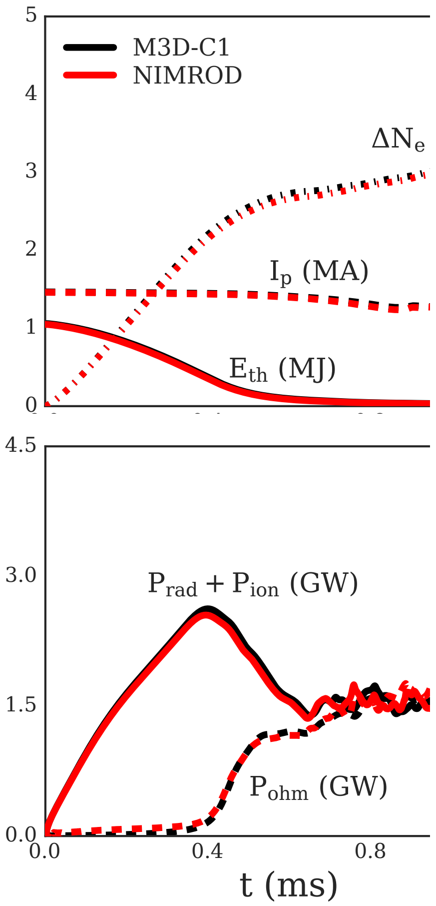

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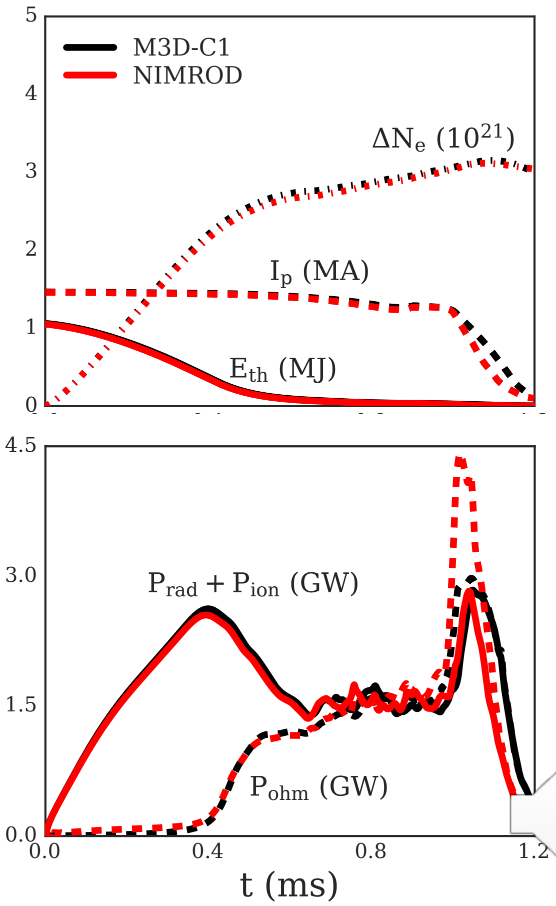

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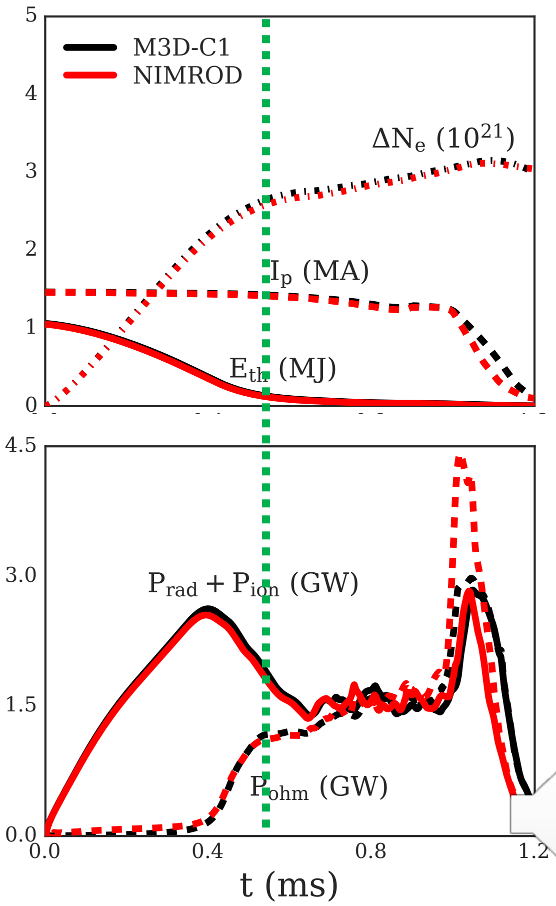

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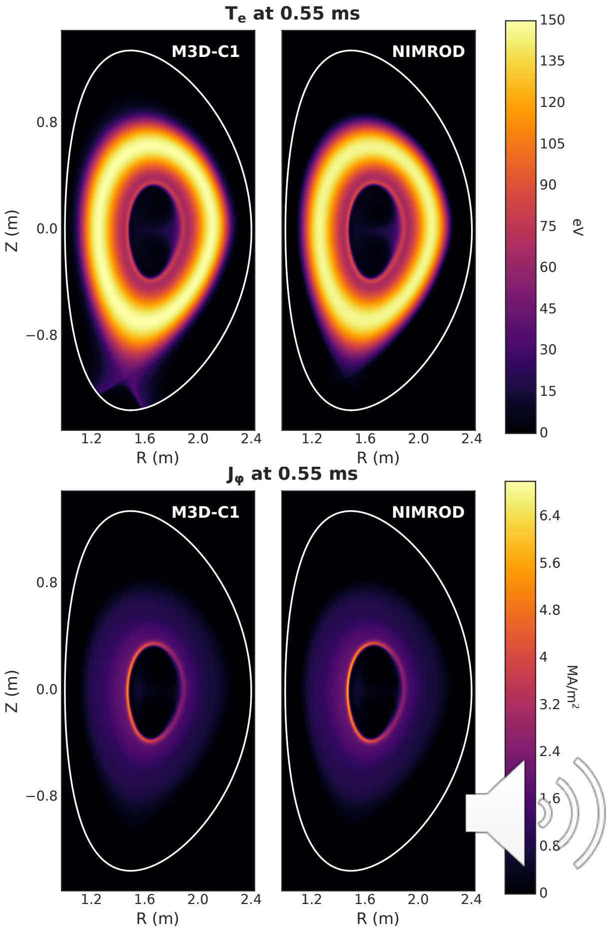
T_e

0.55 ms

J_ϕ



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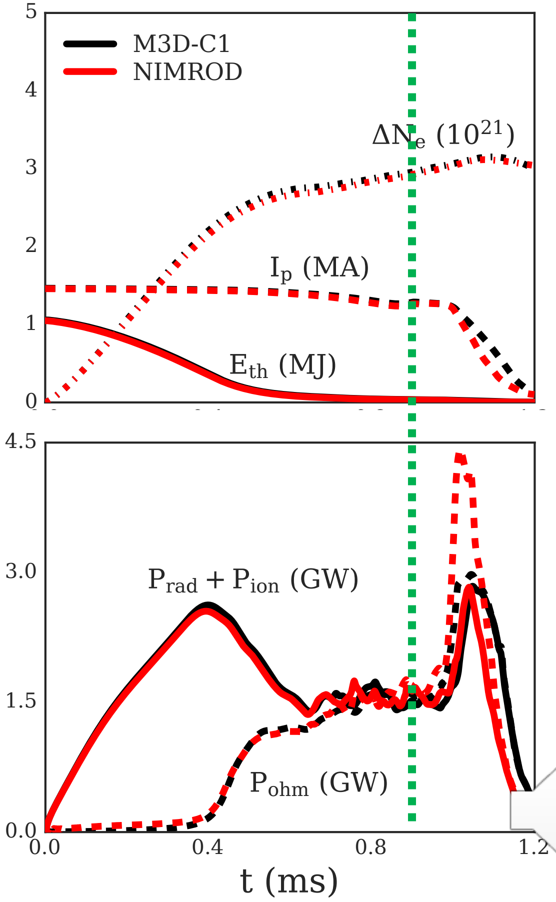

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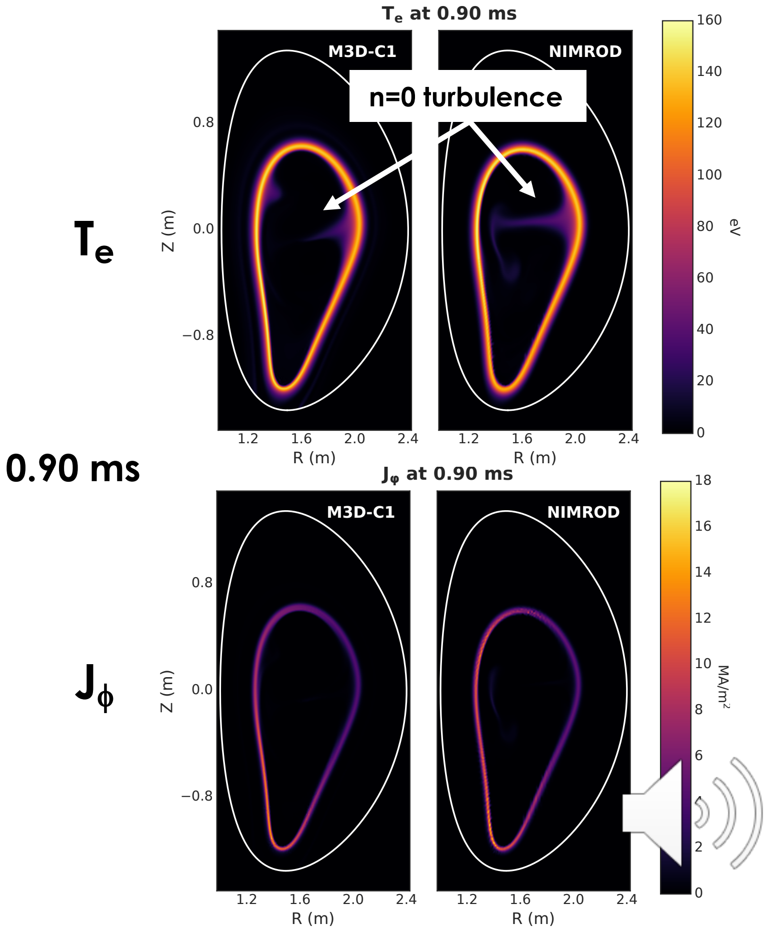

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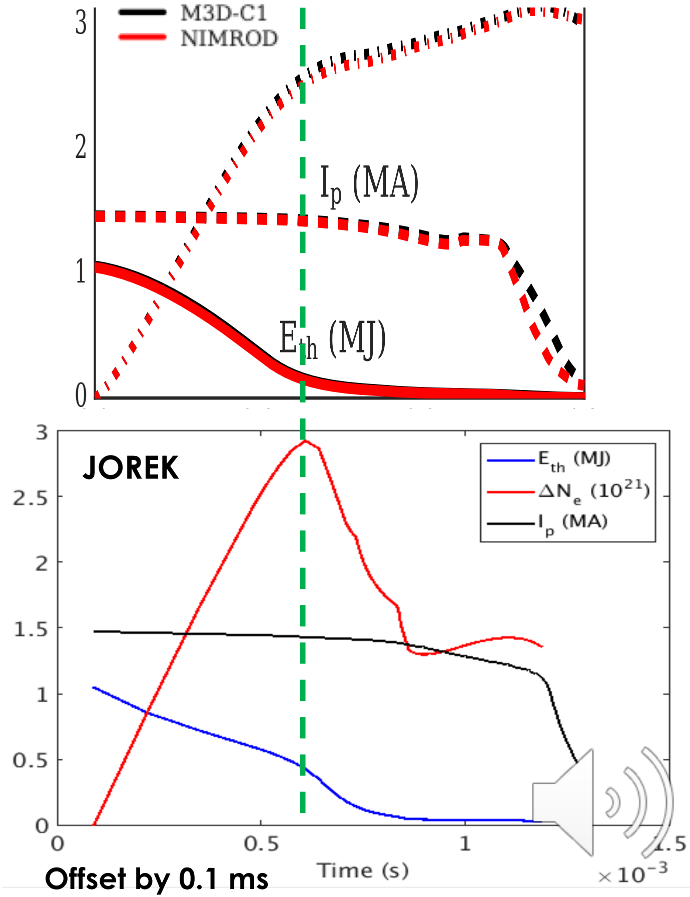
JOREK Modeling Shows Quantitative Differences Likely Due to Coronal-Equilibrium Impurity Model (Nardon)

- **JOREK reduced-MHD simulation shows similar thermal quench timescale, though a bit slower**
- **Similar initial rate of density increase, but decreases in JOREK after thermal collapse**
- **Loss power rises more slowly in JOREK initially**
- **Likely due to crucial difference in impurity models**
  - JOREK assume impurity charge states remain in coronal equilibrium
  - M3D-C1 & NIMROD use a coronal model, but allow each charge state to evolve in time
  - Motivates ongoing upgrade of JOREK impurity, and future work to move to collisional-radiative model in M3D-C1



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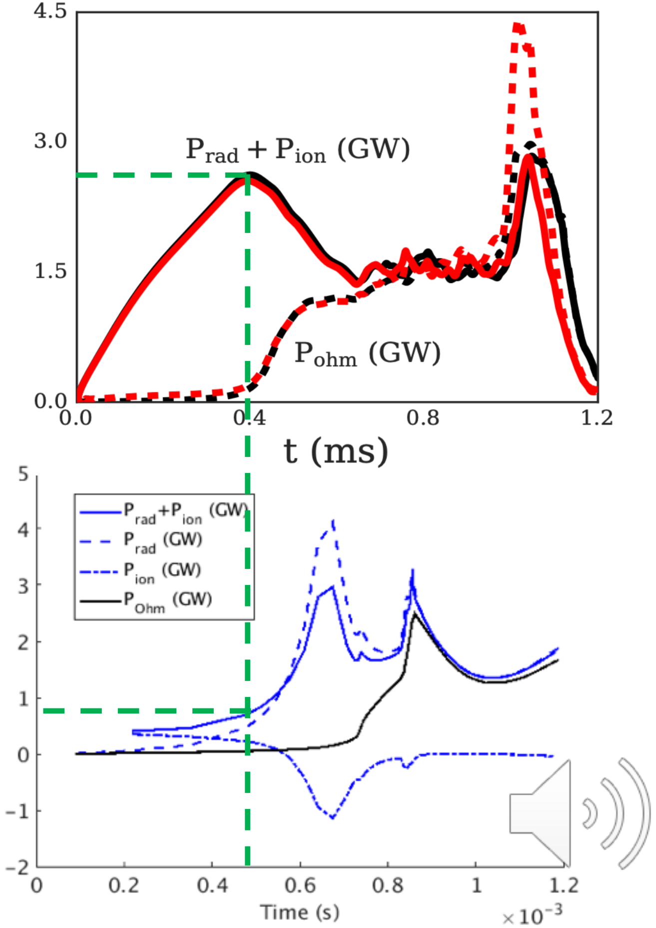

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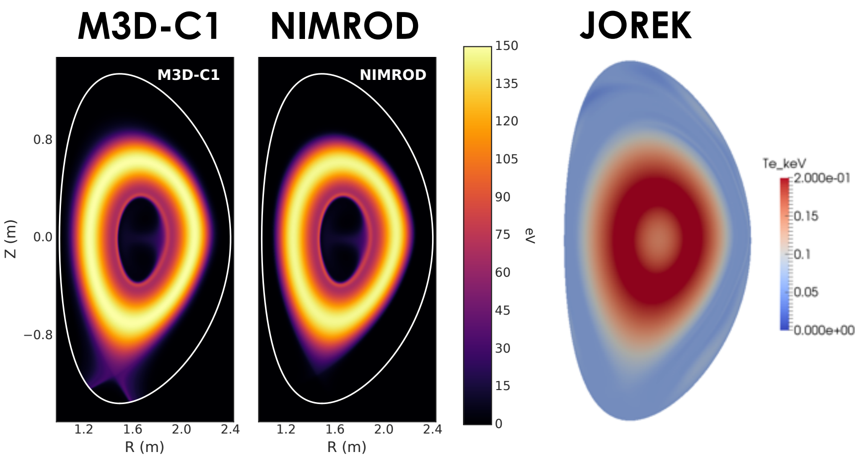
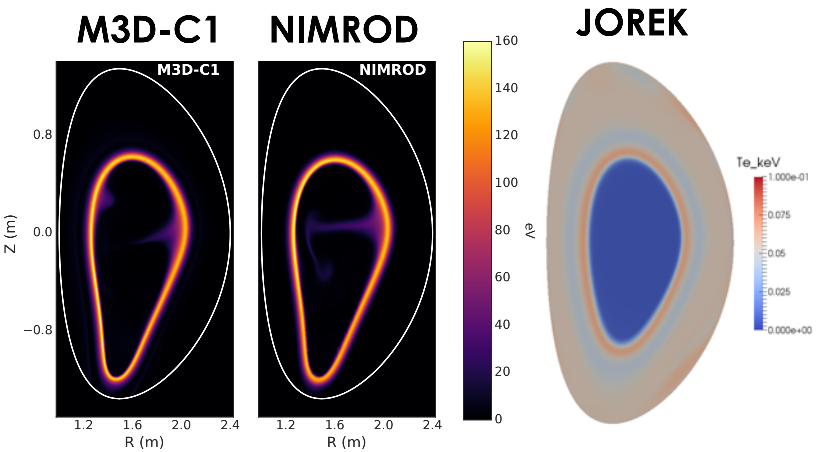
JOREK Also Shows Inside-Out Thermal Quench and Evolving Plasma Sheet, but Differs Qualitatively (Nardon)



- Te at ~0.55 ms after injection starts
- JOREK shows hollow profile, but less so



- Te at ~1.0 ms after injection starts
- Sheet has formed in JOREK, but less shaping and no core turbuelnce

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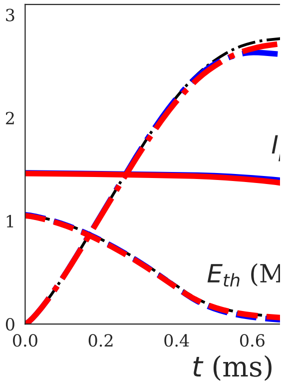
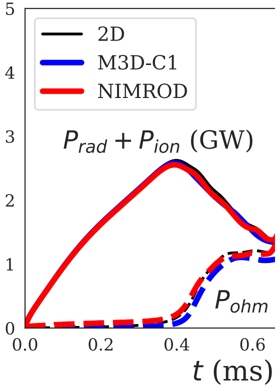
3D Modeling of Axisymmetric Benchmark Shows Stable Thermal Quench, Instability-Induced Current Quench (Lyons, Kim)

- **Plasma stays axisymmetric through 0.65 ms, identical to 2D benchmark**
- **Good qualitative agreement between codes during current quench**
  - Rapid current quench
  - Plasma sheet goes unstable after thermal quench
  - Mixing increases radiation & ohmic heating
- **Prominent current spike***
  - 120-150 kA among largest seen in 3D, nonlinear MHD simulations
  - NIMROD spike slightly delayed and current quench is faster
  - Sensitivity to resistivity and boundary temperature under investigation





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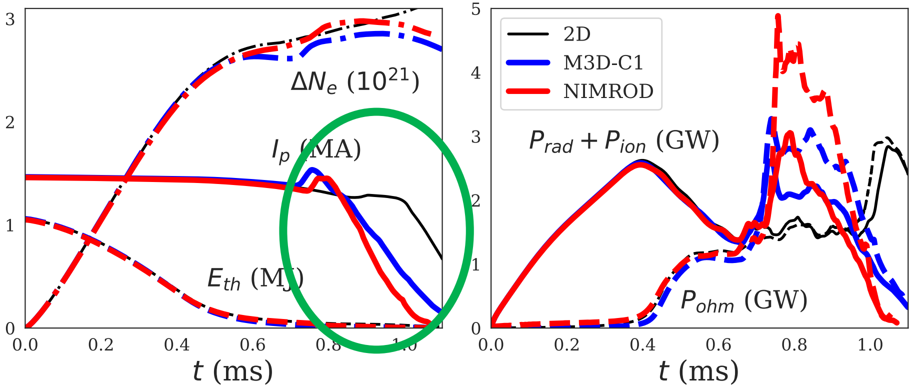

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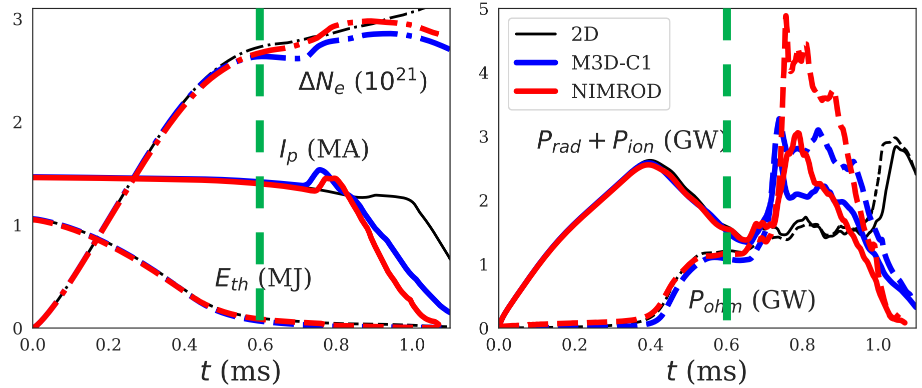

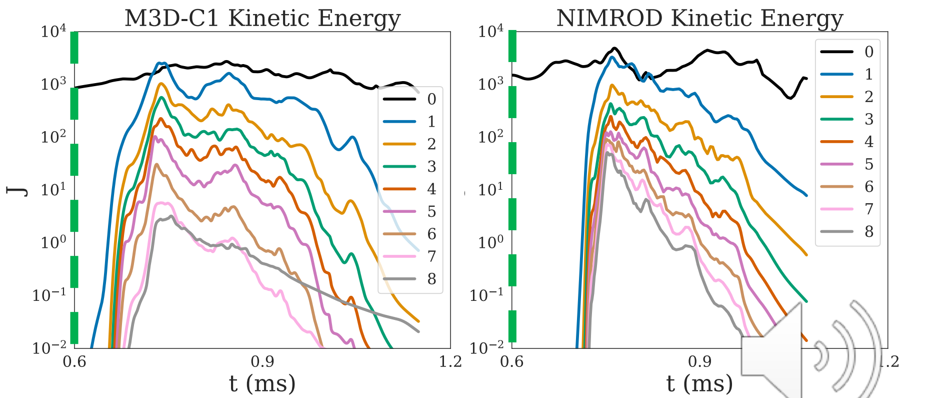

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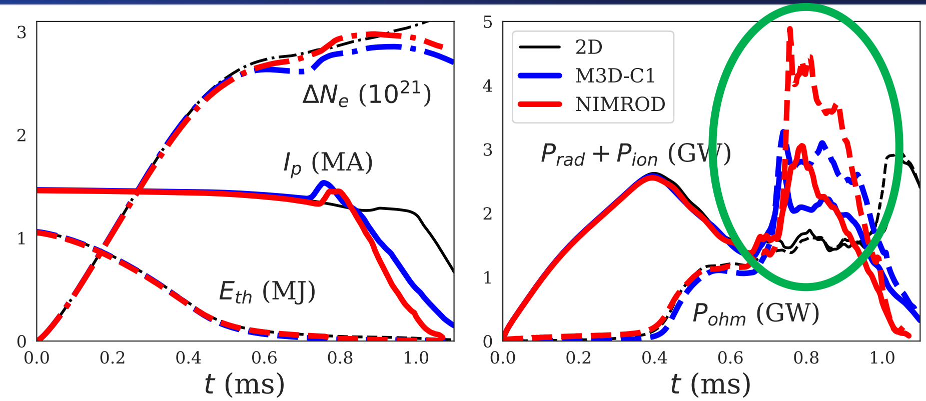

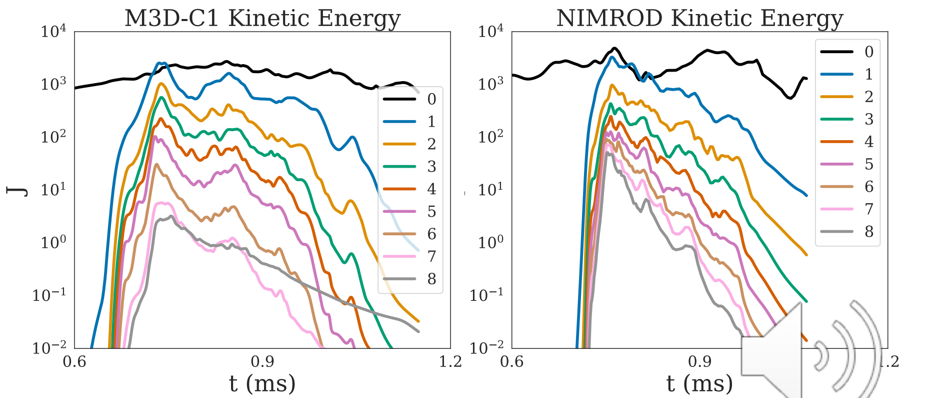

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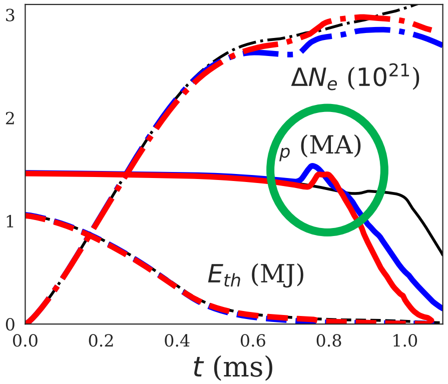
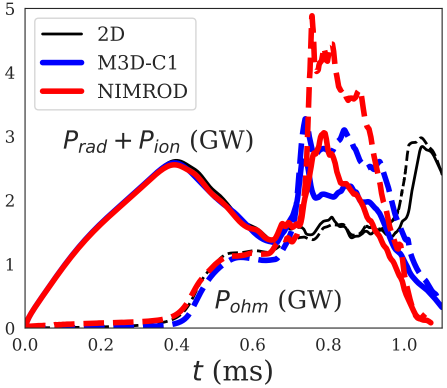
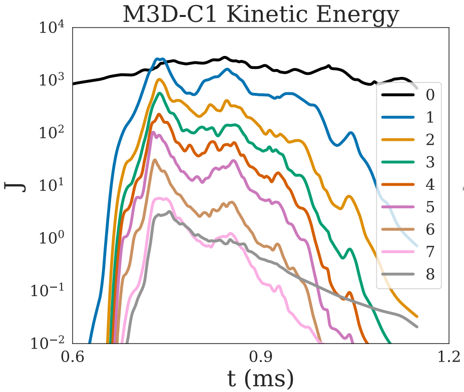
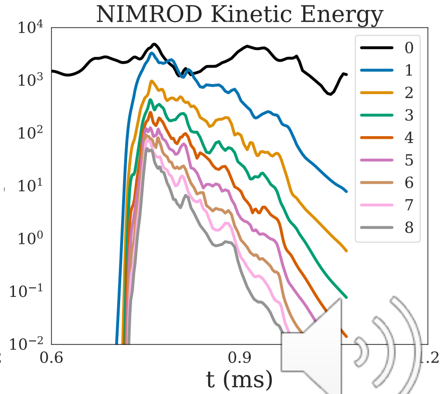
***Letter on M3D-C1 current spike in preparation**









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

- **DIII-D 160606 @ 2990 ms: 0.7 MJ, 1.28 MA**
- **3D nonlinear MHD with fixed boundary and single-temperature equation**
- **Pellet parameters**
  - 3 mm radius, pure neon
  - 5 cm poloidal and 2.4 m toroidal deposition half-width
  - 200 m/s with realistic trajectory
- **First results have obvious discrepancies**
  - Early, quantitative agreement in number of electrons (i.e., ablation and ionization)
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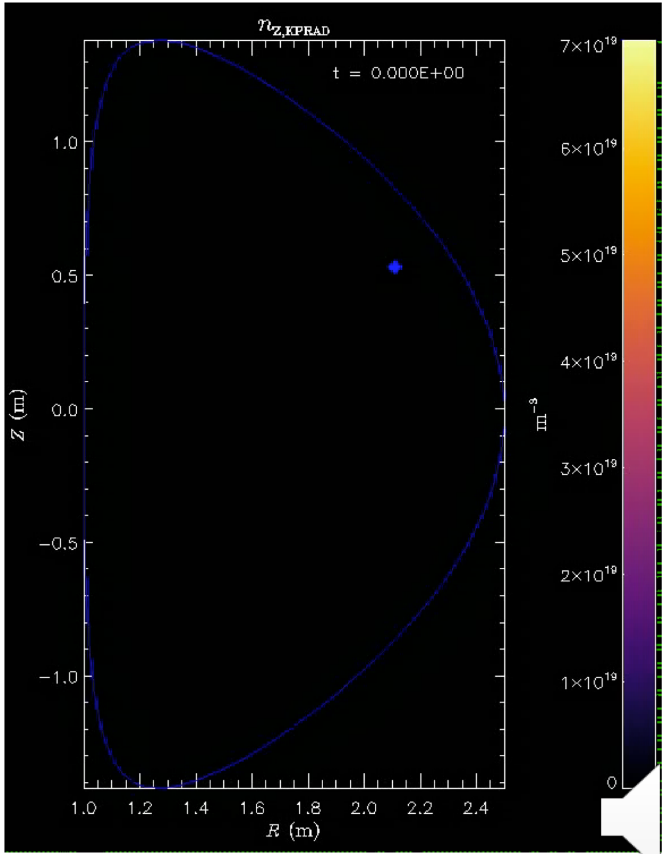

GENERAL ATOMICS

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

- **DIII-D 160606 @ 2990 ms: 0.7 MJ, 1.28 MA**
- **3D nonlinear MHD with fixed boundary and single-temperature equation**
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  - 3 mm radius, pure neon
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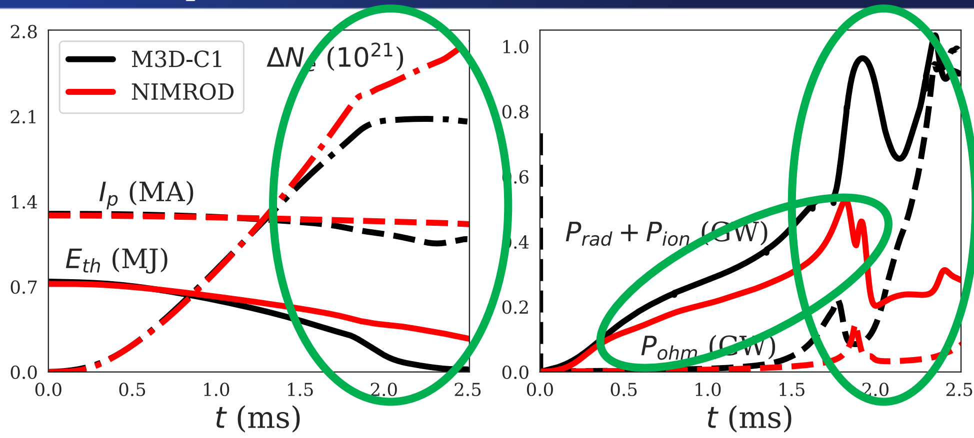

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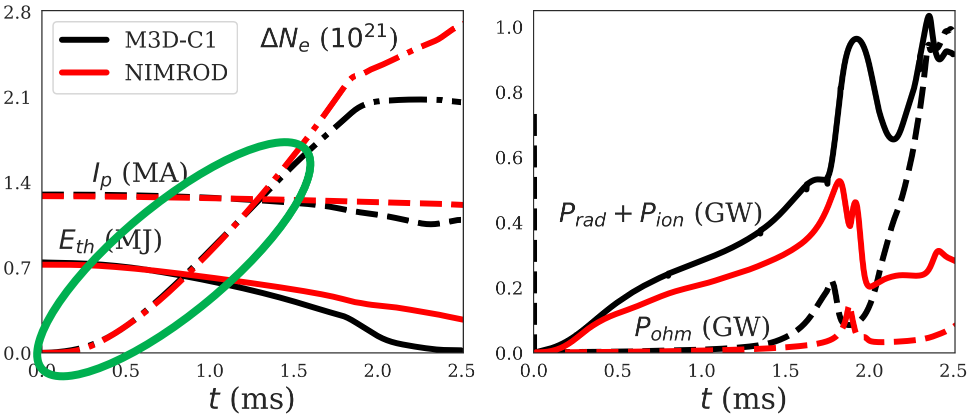

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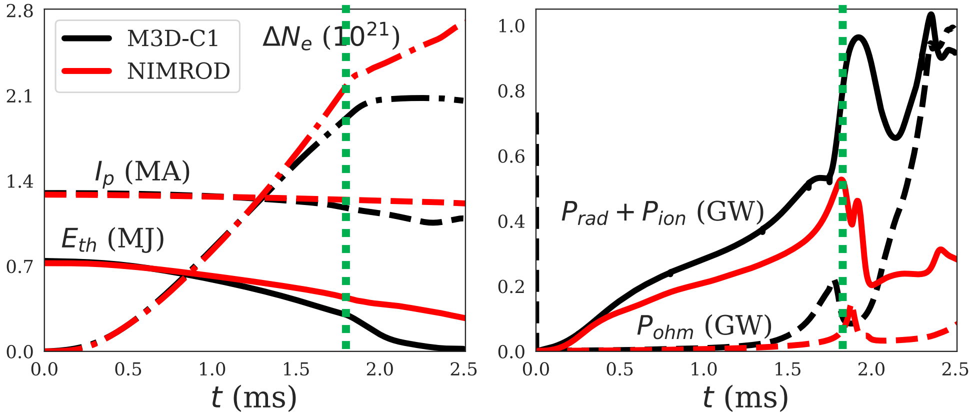

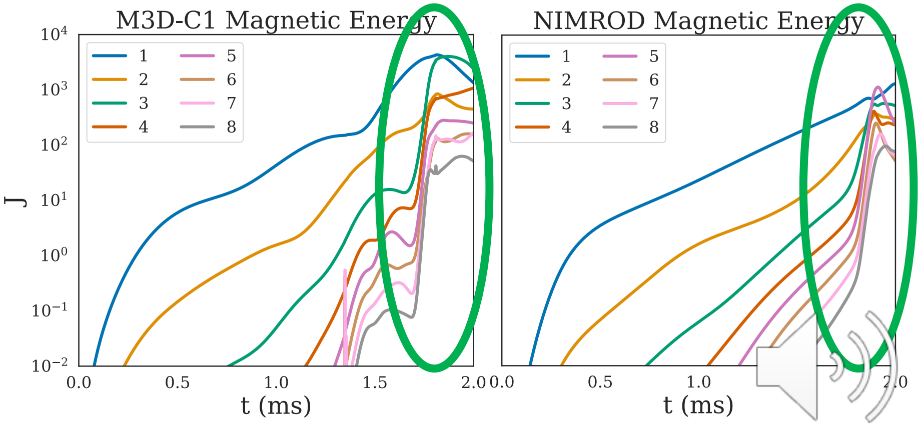

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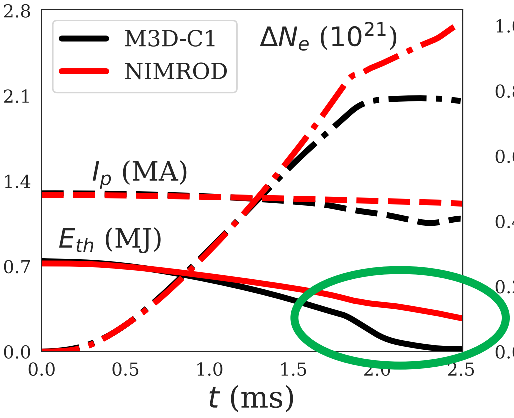

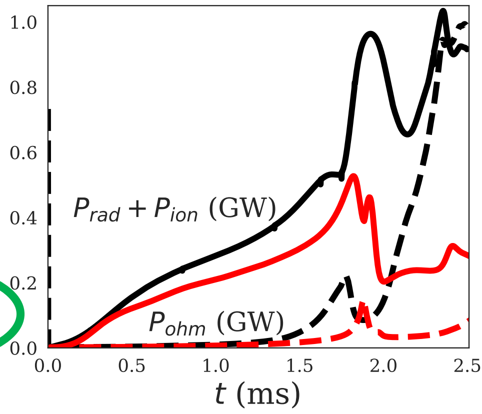

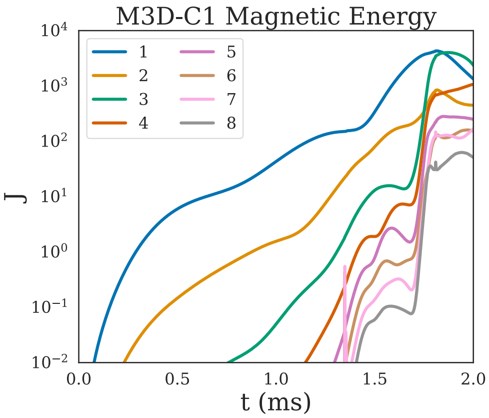

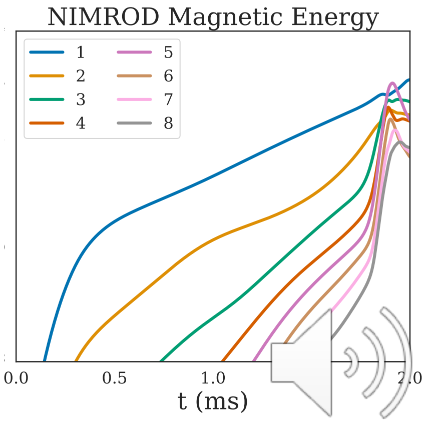

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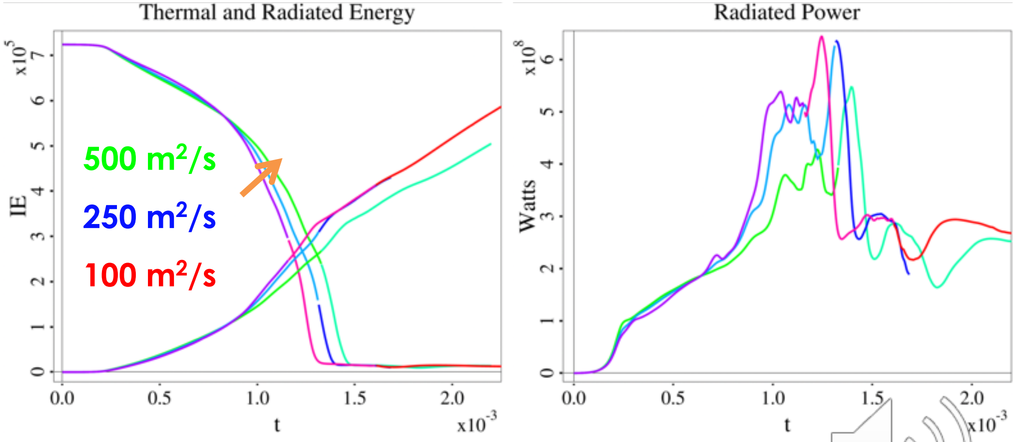
NIMROD Modeling Shows Lower Viscosity Leads to Shorter Thermal Quench due to Stronger Linear MHD Response (Kim)

viscosity	$d\phi/2\pi$	τ_{TQ} (ms)	P_{rad}^{peak} (GW)	E_{rad}/E_{th}	assim.
500 m^2/s	0.05	1.451	0.55	45%	34%
250 m^2/s	0.05	1.379	0.64	47%	38%
100 m^2/s	0.05	1.316	0.64	44%	41%

- **Decreasing viscosity accelerates dynamics**
  - Stronger linear response [(2,1),(3,2)] driven by ablating fragments
  - Earlier nonlinear saturation but not necessarily larger amplitude
- **Higher viscosity suppresses MHD activity, decreasing radiation**



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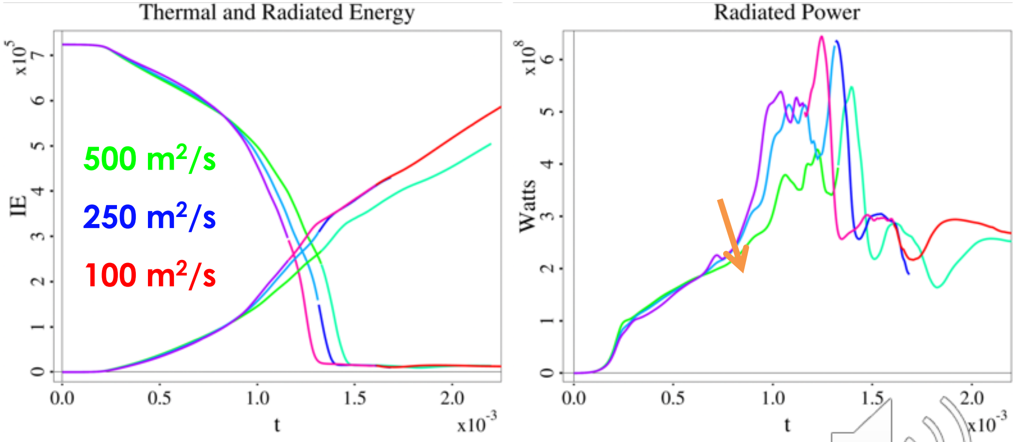

GENERAL ATOMICS

NIMROD Modeling Shows Broader Toroidal Deposition Causes Shallower Penetration but Higher Assimilation (Kim)

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100 m^2/s	0.05	1.316	0.64	44%	41%
500 m^2/s	0.10	1.478	0.50	40%	42%
250 m^2/s	0.10	1.268	1.46	58%	66%
100 m^2/s	0.10	1.227	0.93	45%	61%

- **Overall, broader deposition causes**
  - Shorter thermal quench
  - Larger fraction of pellet ablated
- **Trends within broader deposition cases are less consistent, possibly due to nonlinear mixing from crossing of more flux tubes**

GENERAL ATOMICS

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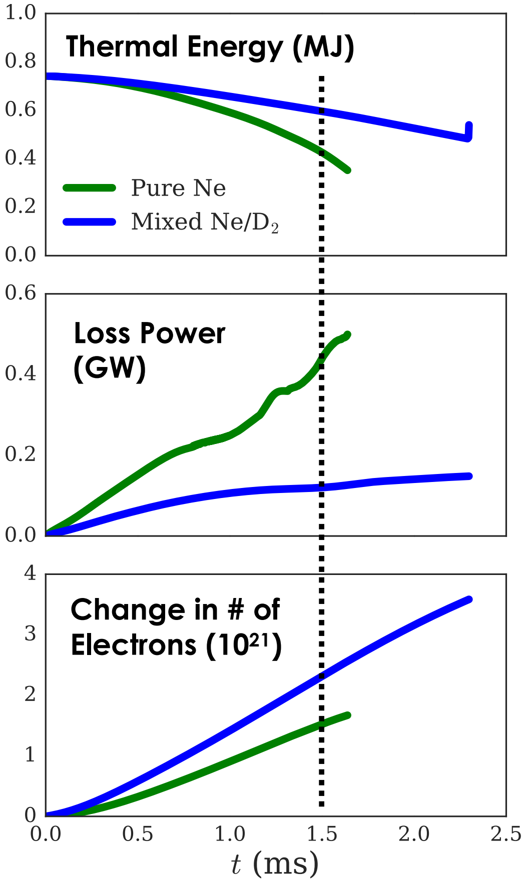
M3D-C1 Validation with DIII-D Pellet Composition Shows Thermal Quench for Pure Neon Pellet Faster than Mixed Ne-D2 (Lyons)

- **Simulations**
  - DIII-D 160606
  - Single, monolithic pellet
  - Realistic velocity
  - Half-widths: 10 cm pol.
    3 m tor.
- **Radiative losses several times higher with pure neon than 10:1 D2:Ne**
- **Trends are consistent with NIMROD modeling and experiment**
  - NIMROD agrees well with experiment
  - Increased resolution improved results from publication*



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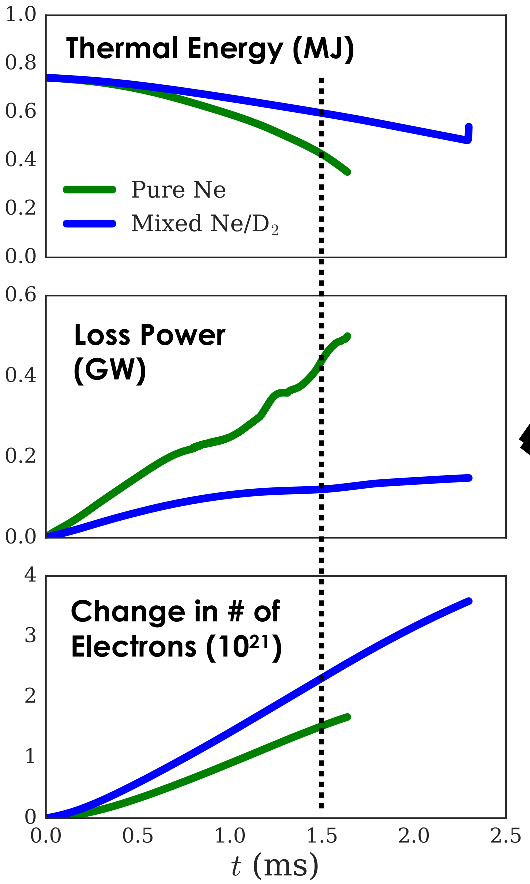

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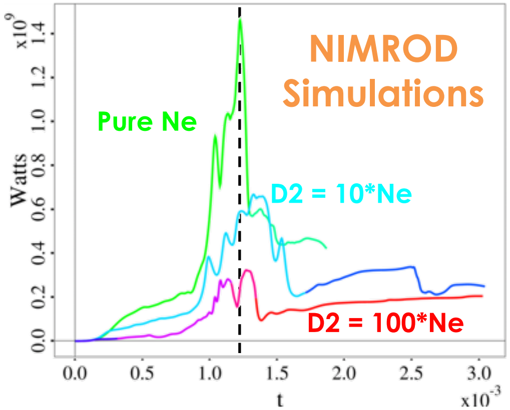
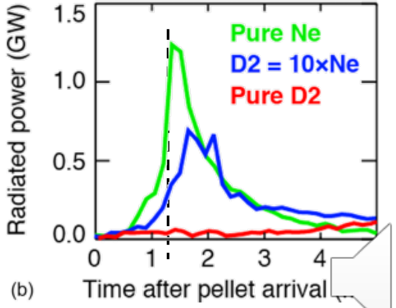


*Updated from C.C. Kim et al., Phys. Plasmas 26, 042510 (2019)



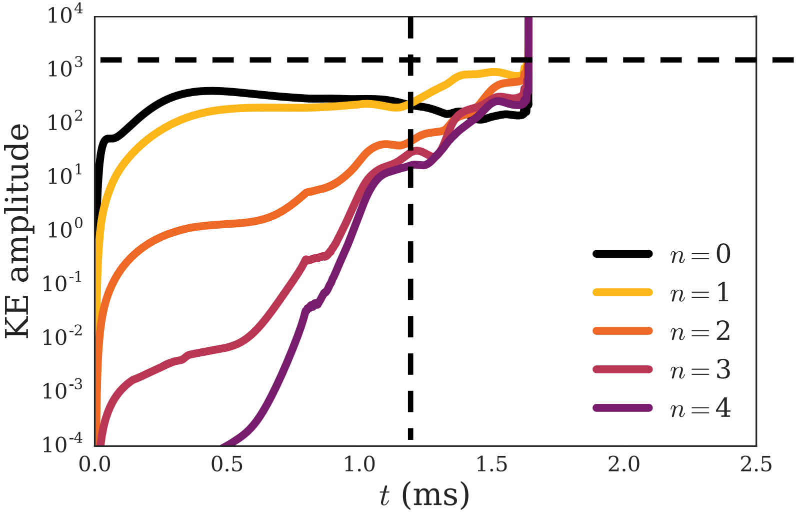
DIII-D Data

D. Shiraki et al., Phys. Plasmas 23 (6), 062516

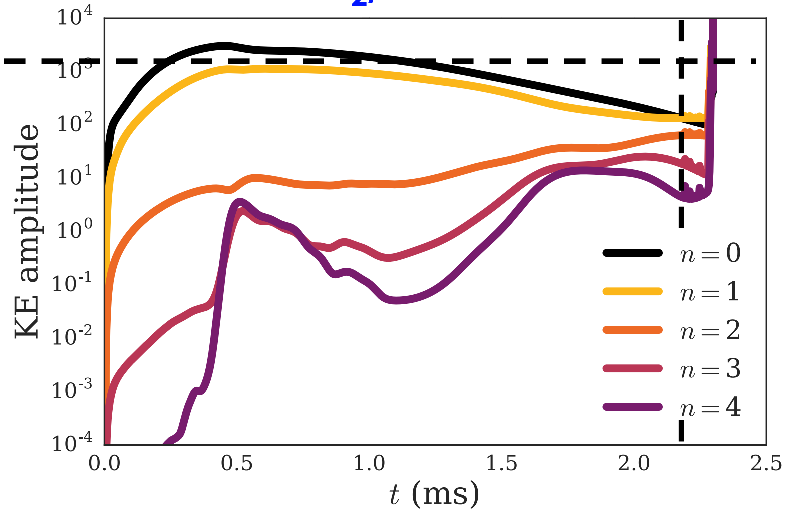
GENERAL ATOMICS

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

Pure Ne



D_2/Ne = 10



- **<u>Preliminary results</u>: to be rerun with**
  - Higher toroidal resolution
  - Newer, more stable code version
- **Pure neon pellet drives linear instability**
- **Both go numerically unstable when plasma highly non-axisymmetric**

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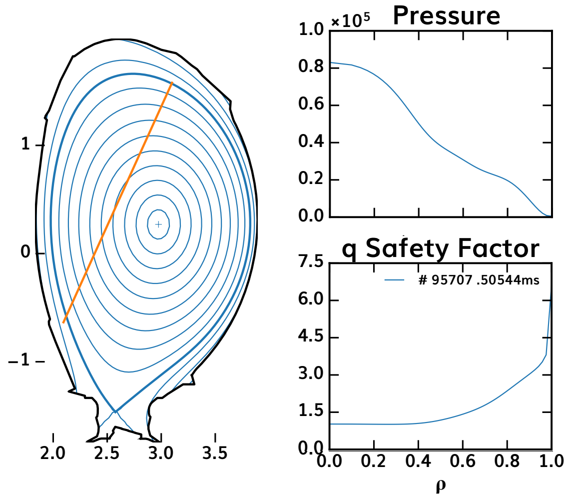
GENERAL ATOMICS

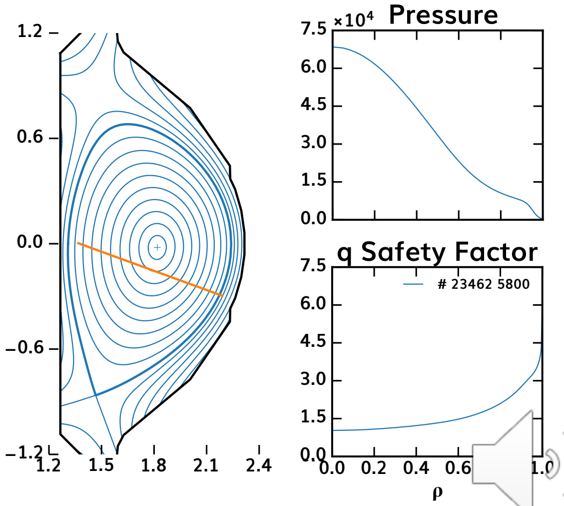
New International Collaboration will Validate M3D-C1 and NIMROD against Recent JET and KSTAR SPI Experiments

- **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 23462
I_p = 0.75 MA
W_{th} = 0.40 MJ



GENERAL ATOMICS

Initial Modeling of JET & KSTAR is Underway (McClenaghan, Lyons)

- **JET modeling of 95707**
  - Initial 2D NIMROD modeling shows outside-in thermal quench driven by line radiation
  - 3D M3D-C1 nonlinear modeling shows quiescent, radiation-driven thermal quench
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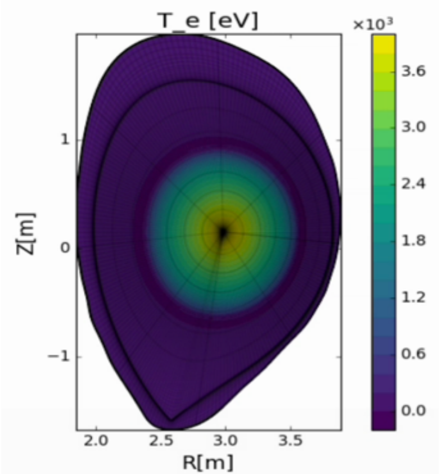

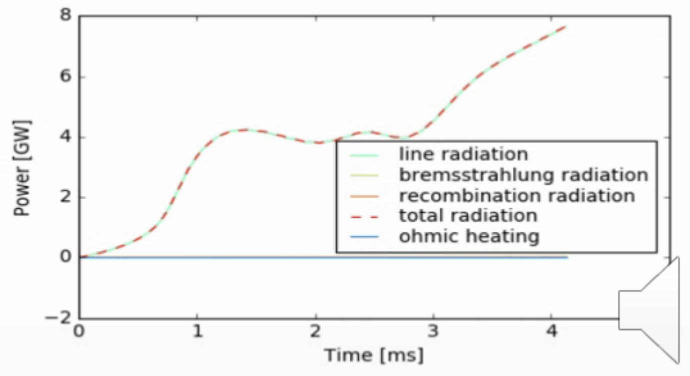

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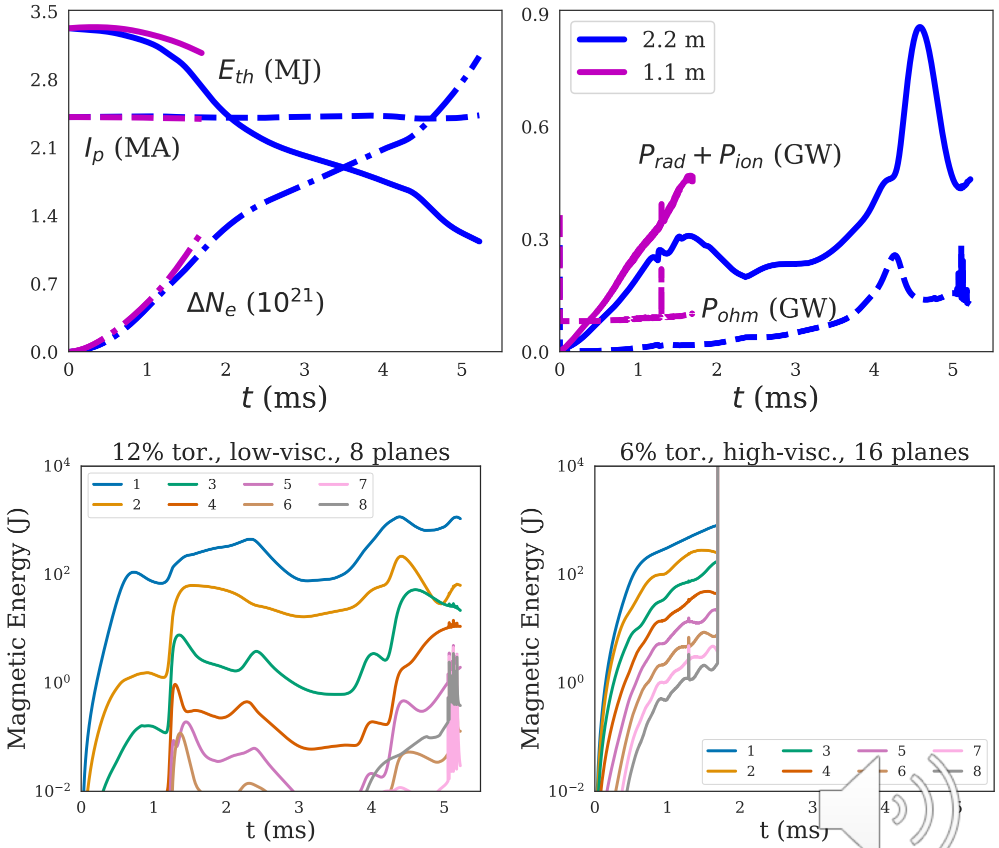

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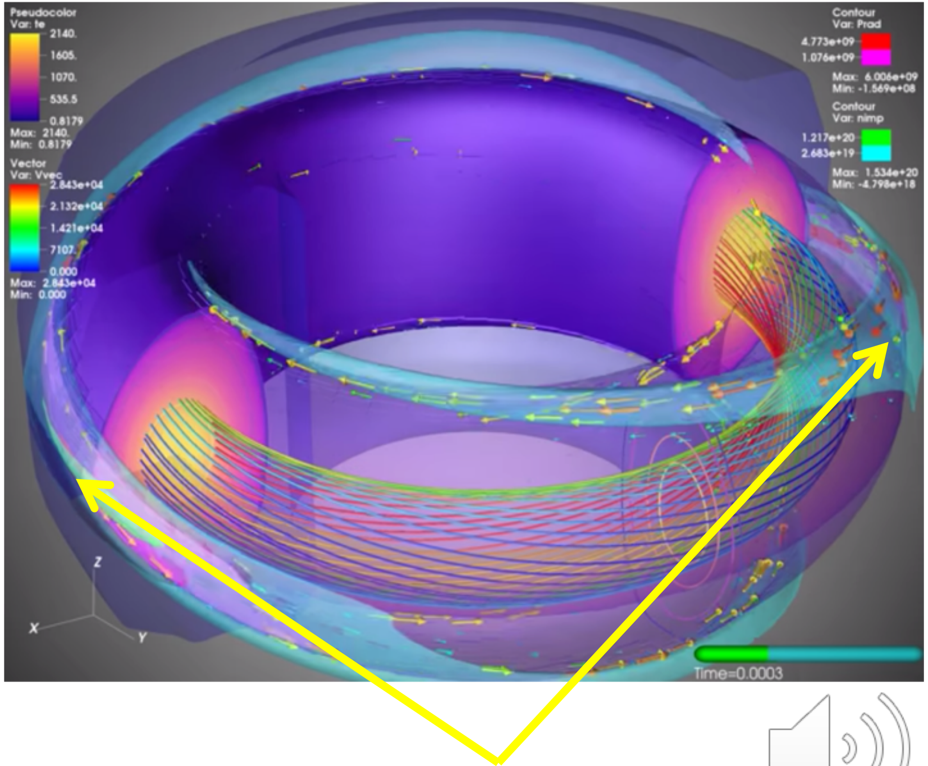

NIMROD Dual Injection in DIII-D

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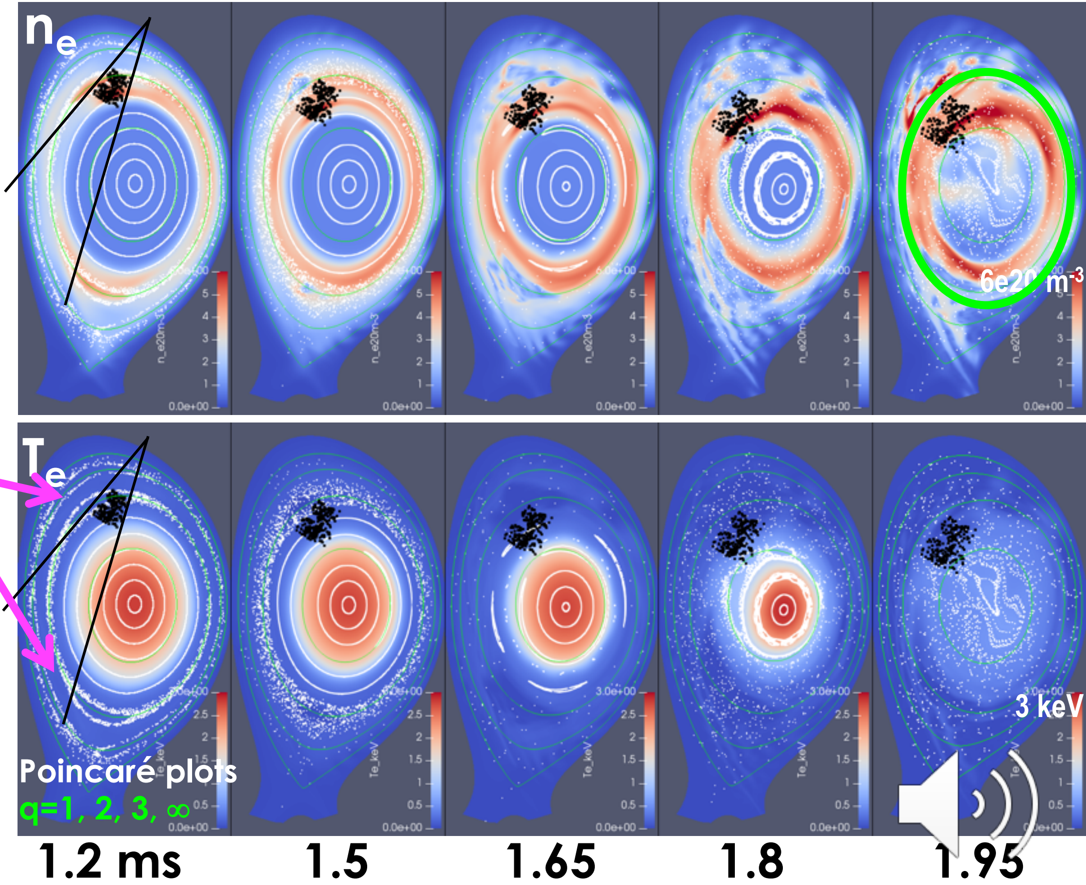
JOREK Modeling of JET Reference Scenario 1 Discharge Show MHD Driven Thermal Quench (Bonfiglio)

- **Shot 89800**
  - From earlier MGI experiment
  - Used for current Scenario 1
- **Pellet size and composition under active investigation**
  - 4.5 mm vs 8 mm
  - Pure Ne vs mixed Ne/D2
- **Example of 4.5 mm pure Ne**
  - MHD activity induced by n=0 current contraction and helical cooling on rational surfaces
  - Stochasticazation causes thermal quench, but core remains at low density (potentially bad for runaway suppression)
- **Synthetic diagnostics are being implemented for experimental validation**



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Verification, Validation, and Predictive Modeling Will Continue

- **M3D-C1 and NIMROD**
  - Complete 3D benchmark this year
  - Extensive validation with experiment
    - DIII-D: dual SPI, thermal & magnetic energy
    - JET: high thermal energy and radiation fraction/asymmetry
    - KSTAR: dual, symmetric SPI
  - Model upgrades
    - Collisional-radiative impurity model
    - Coupling to detailed pellet ablation code
- **JOREK**
  - Use synthetic diagnostics for JET validation
  - Upgrade to impurity model (ongoing) to complete 2D benchmark
- **All codes will make predictions for efficacy of ITER disruption-mitigation system**
  - Cross-machine, cross-code database will provide robust understanding of SPI dynamics
  - High-fidelity, 3D nonlinear modeling of relevant ITER scenarios

Acknowledgments and Disclaimers

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- This research used resources of the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility operated under Contract No. DE-AC02-05CH11231.

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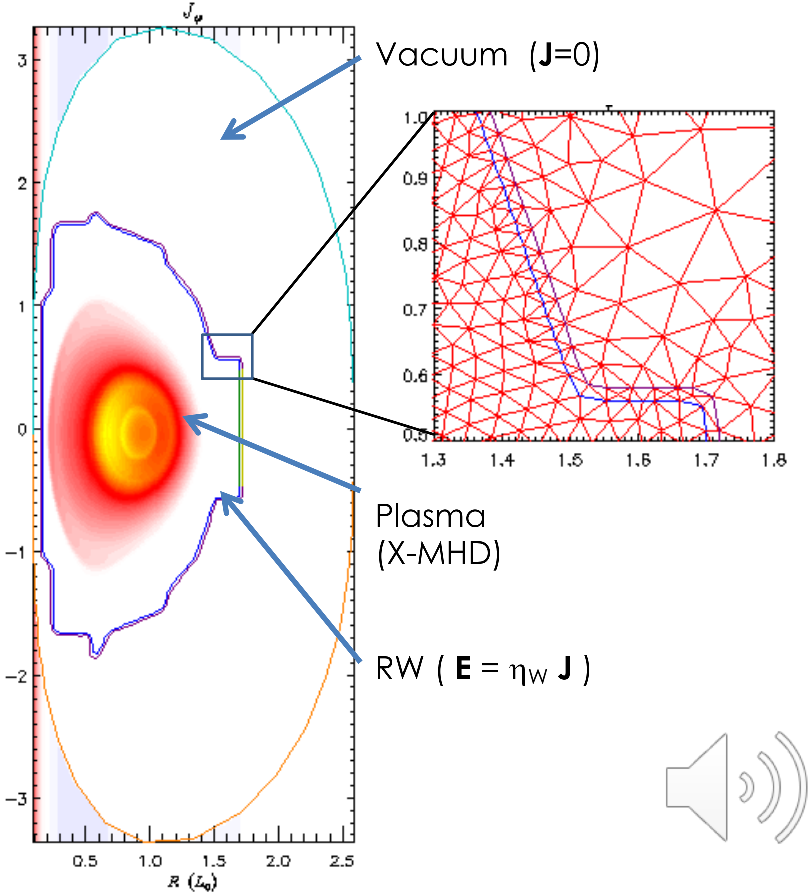
- This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training program 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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

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

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

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

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

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

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

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

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

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

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

GENERAL ATOMICS

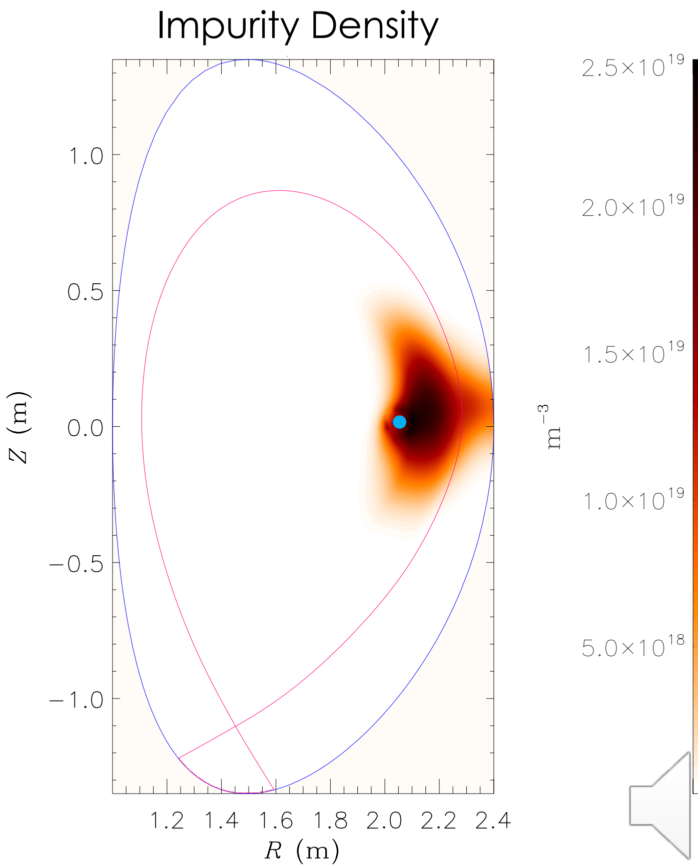
Ablation model for Ne-D2 pellets implemented in M3D-C1

- **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 fraction of D2, X

- **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)



GENERAL ATOMICS