MHD Modeling of SPI in JET

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With

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JET

GENERAL ATOMICS

Validation of shattered pellet injection disruption mitigation modeling is critical to accurately assess ITER predictions

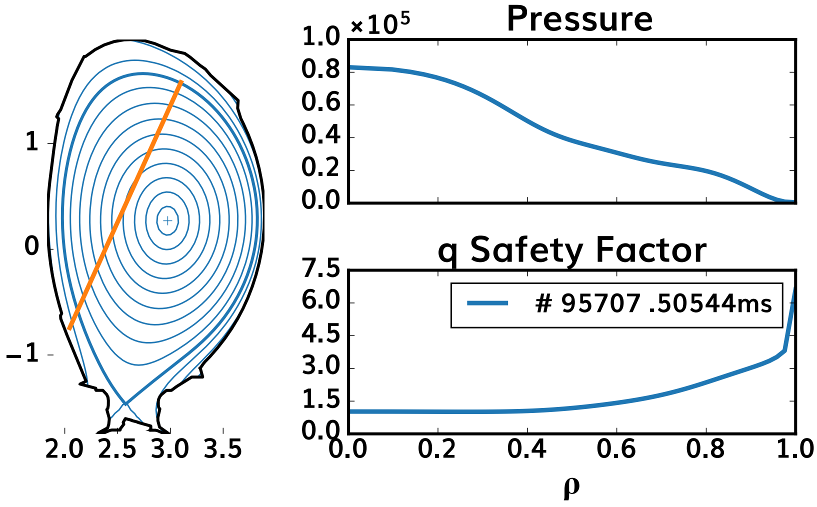
- Unmitigated disruptions can cause significant damage to ITER
- Validation of disruption mitigation models develop the necessary confidence in their predictive capabilities of the ITER Disruption Mitigation System
- Benchmarking models is critical in improving the models
- Validation varying of major radius and stored energy

DOE International-Collaboration will validate M3D-C1 and NIMROD against recent JET and KSTAR experiments

- **Objectives**
  - Interpret recent mitigation experiments
    - JET, particular high thermal energy and radiation fraction/asymmetry
  - Make predictions for additional experiments

- **Equilibria reconstructed with kinetic profiles of high W_{th} scenario 1 for recent experiments**

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



Impurity Modified Single Fluid Nonlinear 3D MHD Resistive Equations

$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha \mathbf{V}) = \mathbf{S}_\alpha + \nabla \cdot D \nabla n_\alpha$$

- α= ions(i) and impurities(Z) *including neutral ions and impurities*)
- S_α source and sink due to ionization and recombination from KRAD[1]
- electron(e) density from quasi-neutrality

$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = \mathbf{J} \times \mathbf{B} - \nabla p$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \qquad \nabla \times \mathbf{B} = \mu_0 \mathbf{J} \qquad \mathbf{E} = -\mathbf{V} \times \mathbf{B} + \eta \mathbf{J}$$

- $\eta(T)$ temperature dependent Spitzer resistivity

[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.

Impurity Modified Single Fluid Nonlinear 3D MHD Resistive Equations

- **NIMROD single temperature**

$$\frac{n_t}{\Gamma - 1}\left(\frac{\partial T}{\partial t} + \mathbf{V}\cdot\nabla T\right) = -p\nabla\cdot\mathbf{V} - \nabla\cdot\mathbf{q} + \mathbf{Q}$$

  - $T=T_i=T_e=T_Z$ assumes instant thermalization
  - heat flux **q** parameterized by temperature dependent $\chi_{\parallel}$ and $\chi_{\perp}$
  - **Q** includes Ohmic heating and loss due to ionization, recombination and radiation

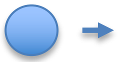
- **M3D-C1 two temperature model**

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

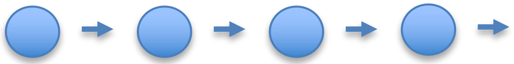
$$n_{ti}\left[\frac{\partial T_i}{\partial t} + \mathbf{v}\cdot\nabla T_i + \Gamma T_i\nabla\cdot\mathbf{v}\right] = (\Gamma - 1)\left(-\nabla\cdot\mathbf{q}_i - Q_{ei} - \mathbf{\Pi} : \mathbf{v}\right) - T_i\left(\frac{\partial n_{ti}}{\partial t} + \mathbf{v}\cdot\nabla n_{ti}\right)$$

Particle SPI Model Easy to Adjust Size, Trajectory and Composition

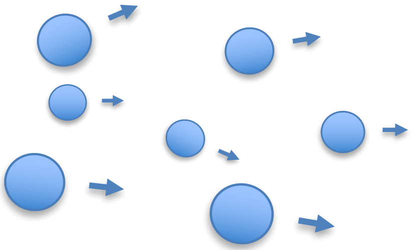
- **Single monolithic particle (ignore shatter)**



- **Pencil beam: plume is fixed length L_{pb} → fixed delay between particles**
  - uniform train of particles following single straight line trajectory

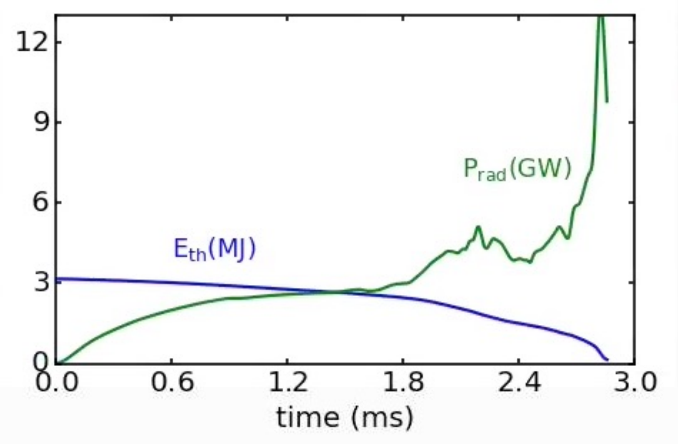


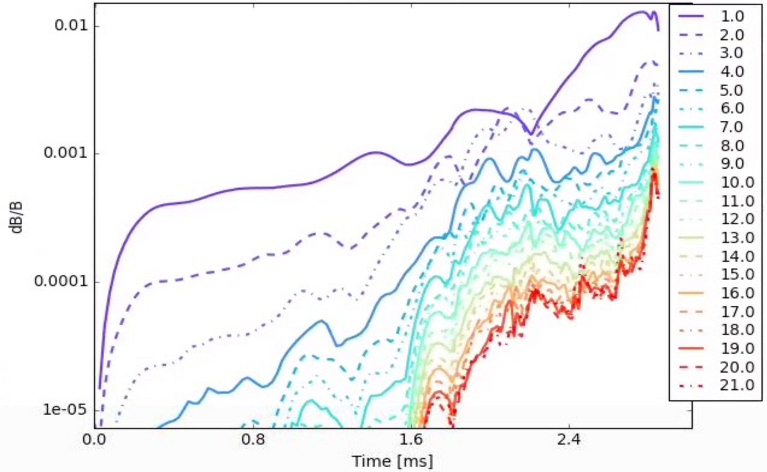
- **Cloud-of-fragments - may be important for multi-injector with finite time delay**
  - distribution of fragment sizes and trajectories (fracture-threshold theory)
  - adds additional time and space



NIMROD 3D single pellet simulation shows typical SPI disruption

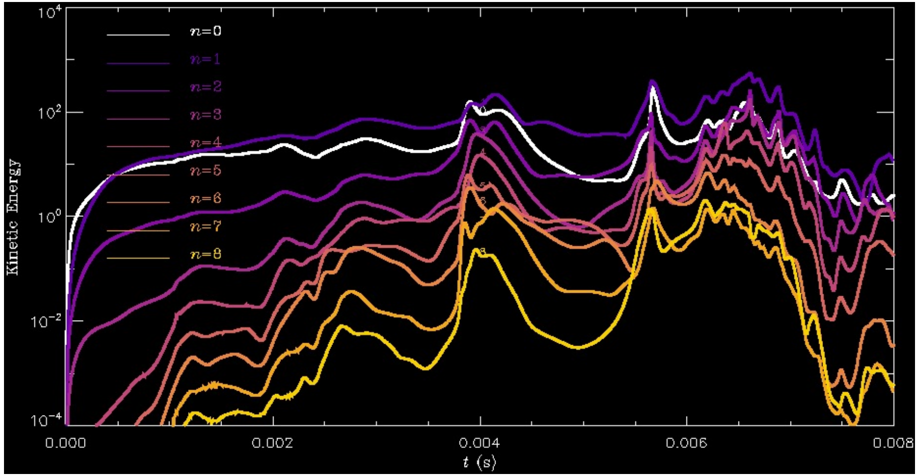
- **Single monolithic pellet representation simulation**
  - (v_p=200m/s, r_p=4mm, pure-neon)
- **Numerical viscosity of 1000 m^2/s**
- **Typical characteristics of SPI disruption**
  - Radiative decay of thermal energy
  - MHD event leads to radiation spike and rapid TQ

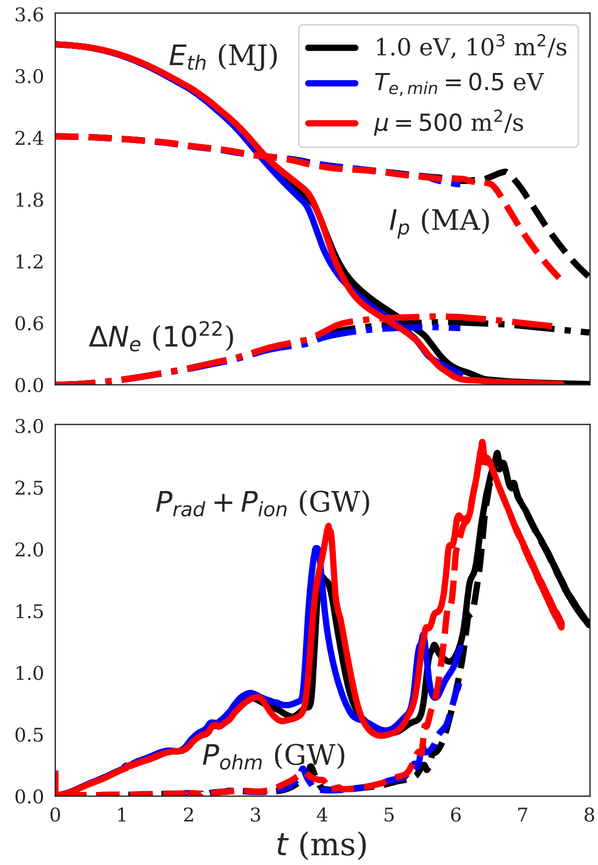




M3D-C1 Single-Pellet JET Modeling Shows Complete TQ & CQ

- **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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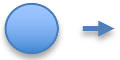

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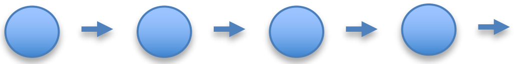

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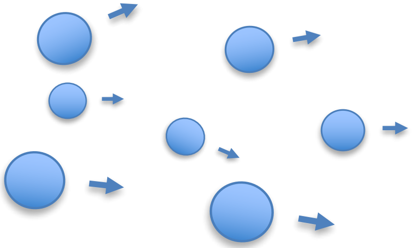
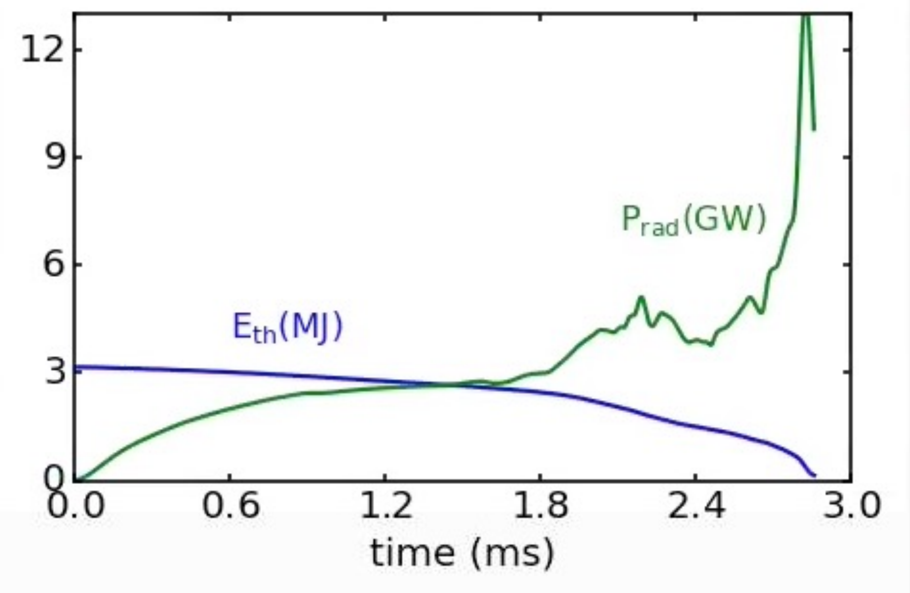
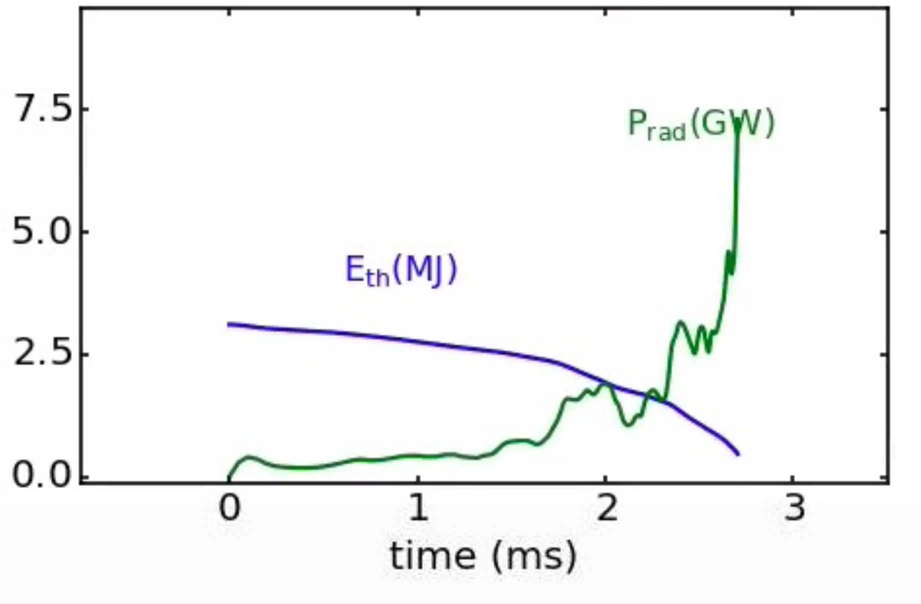


Switching to 10cm pellet beam representation show similar thermal quench with reduced MHD activity

- **NIMROD Single monolithic pellet**

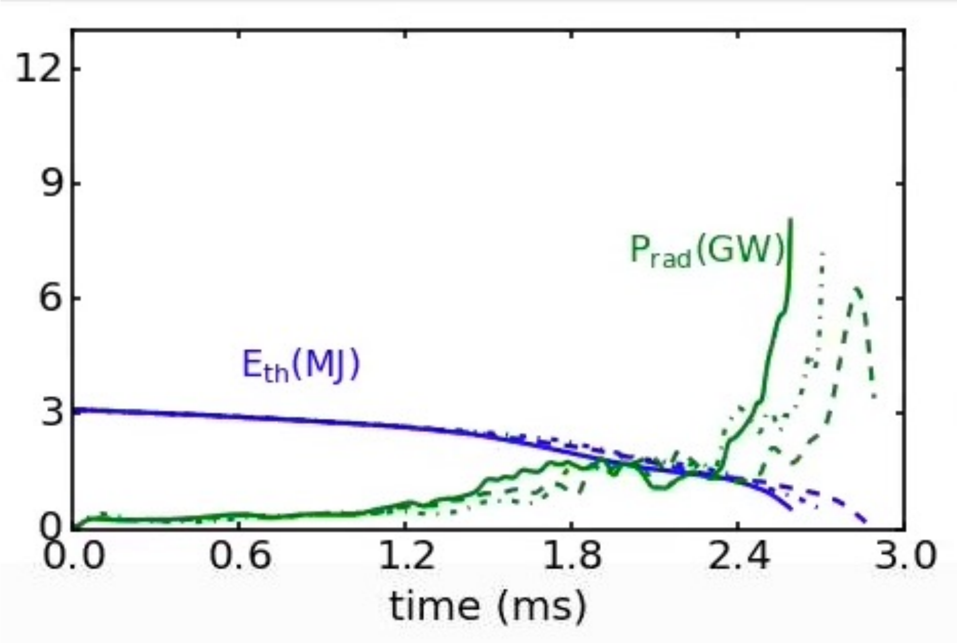


- **NIMROD 10 cm pencil beam**



Scan in viscosity shows reducing viscosity increases MHD and a more rapid thermal quench

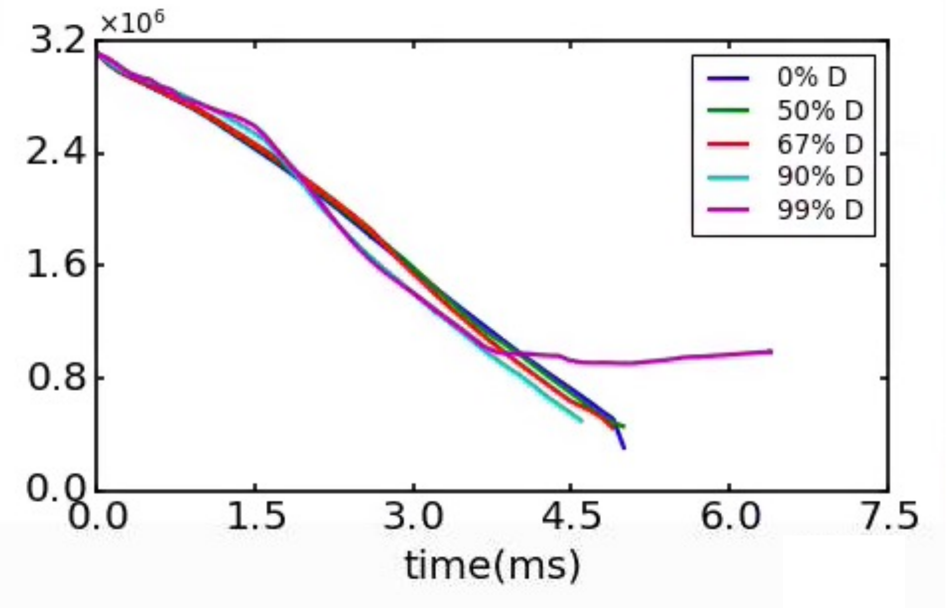
- **3 viscosities**
  - 2000 m^2/s (dashed)
  - 1000 m^2/s (dashdot)
  - 500 m^2/s (solid)



2D MHD simulation scanning deuterium content

- **0-67% Molar fraction Deuterium have similar predicted thermal quenches**

- **Behavior may not hold for 3D simulations which have quicker thermal quench.**



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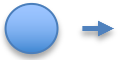

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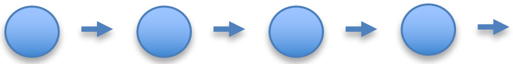

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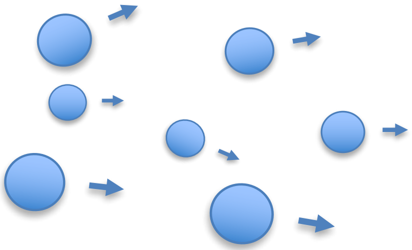
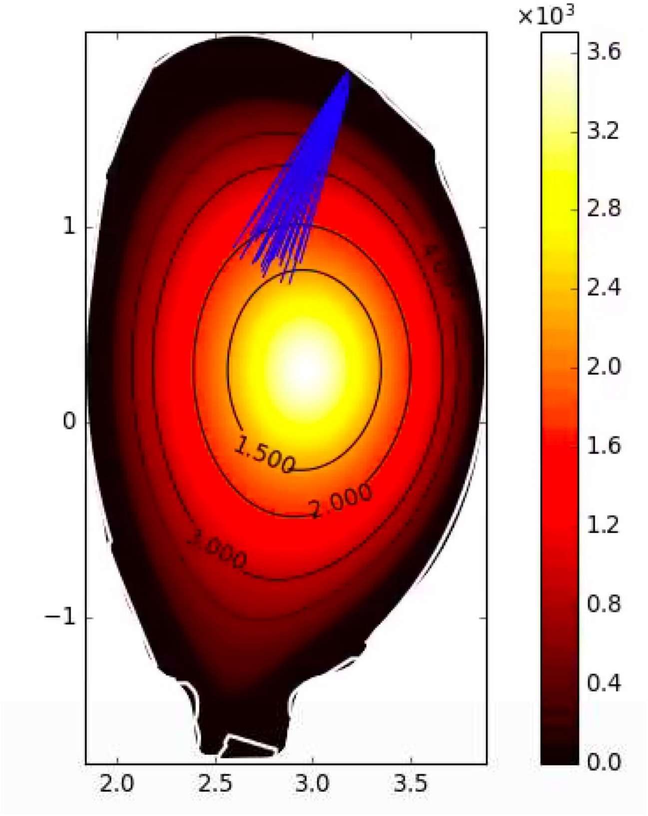


Future cloud-of-fragments simulations underway for both NIMROD & M3D-C1

- **Fracture threshold model for realistic pellets**
- **Pure Neon**
  - 30 fragments
  - r_p=1.71 mm
  - v_p=150 m/s

- **95% D, 5% Ne**
  - 85 fragments
  - r_p=1.21 mm
  - v_p=300 m/s



Conclusions

- **NIMROD & M3D-C1 3D single pellet simulation shows typical SPI disruption**
- **More realistic pencil beam simulation had similar thermal quench with reduced MHD activity**
- **Scan in viscosity shows reducing viscosity increases MHD and a more rapid thermal quench**
- **Future work:**
  - More realistic cloud of fragments modeling
  - assessment of radiation fraction and asymmetry as a function of pellet neon content and thermal-energy fraction