

MHD simulations of high-pressure gas jet disruption mitigation

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Motivation

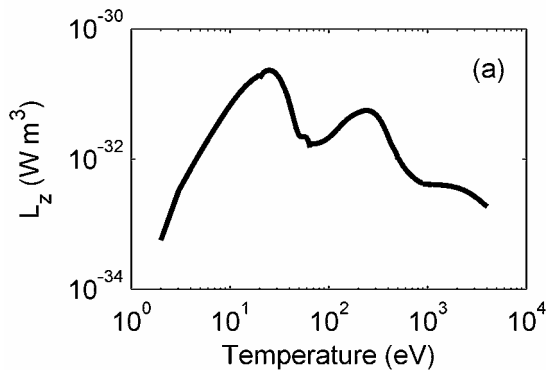
- In a high absolute pressure device like Alcator C-Mod, a gas jet is unlikely to penetrate significantly into the plasma
- Still, when high-pressure jets of noble gases are injected into C-Mod, a rapid thermal quench of the plasma is observed
- For higher Z gases, little or no electron density increase is observed before or during the thermal quench, suggesting little penetration of impurity atoms/ions
- Therefore, the cooling of the core plasma must not be directly caused by impurity radiation
- The critical role of MHD can be investigated numerically with the addition of an impurity radiation model into a 3D MHD code

Outline

- I. Simulations using a coronal equilibrium impurity model in NIMROD
 - A. MHD triggered thermal quench with shallow gas jet penetration
 - B. Faster quench with increasing penetration depth (significance of $q=2$)
 - C. Characteristics of the thermal quench
- II. Comparison of gas jet experiments on C-Mod with NIMROD simulations
 - A. Similarity to Krypton experiments
 - B. Differences between Krypton and Helium
- III. Improved impurity model

Simple radiation model is added to NIMROD

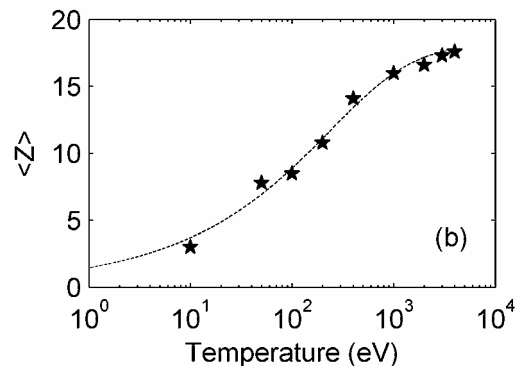
- Radiated power is computed based on cooling coefficients for Argon in coronal equilibrium
- Impurity fraction is specified on grid



$$P(T_e) = n_e n_Z L_Z(T_e)$$

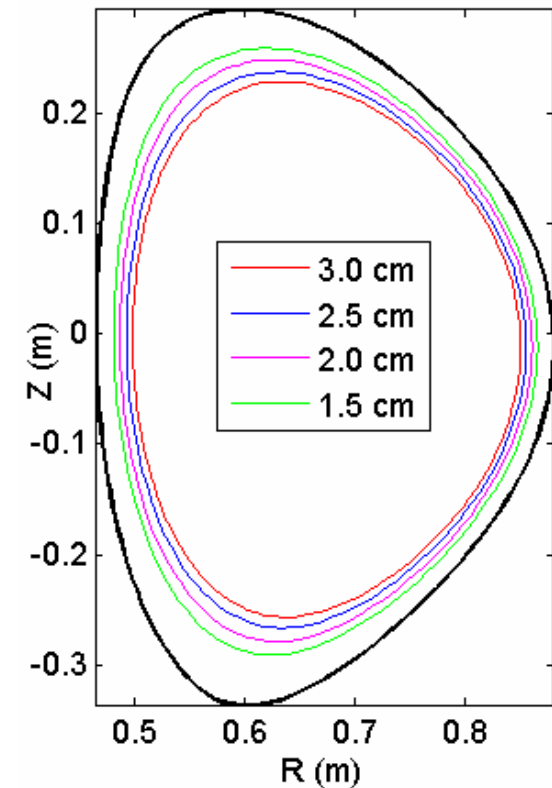
$$\Rightarrow P(T_i) = f_Z (1 + f_Z \langle Z \rangle) n^2 L_Z(T_i)$$

$$\langle Z \rangle = 18 \tanh[(T_i / 437)^{0.415}]$$



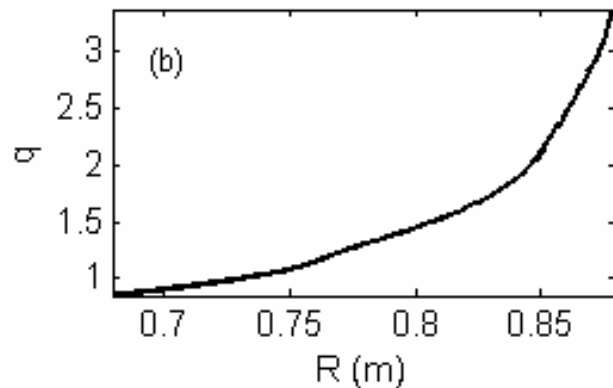
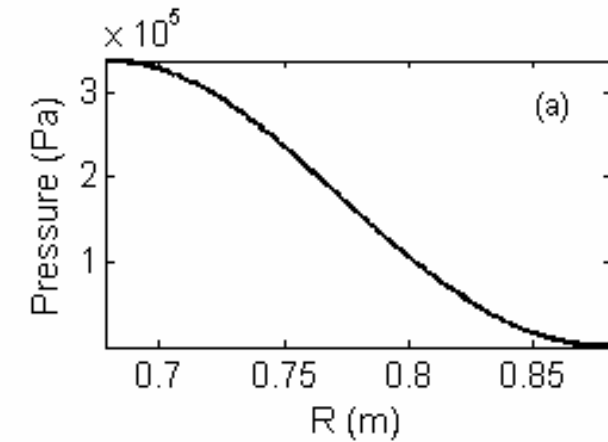
Temperature is modified at each time step :

$$T_i^{t+\Delta t} = T_i^t - P(T_i^t) \Delta t / nk$$



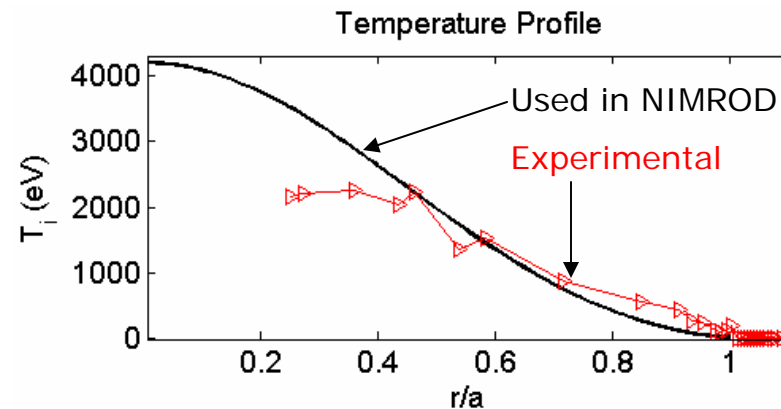
- In each simulation, impurities are located between the equilibrium boundary and a particular flux surface in a fixed fraction ($f_Z = 0.5$)

Initial condition is EFIT reconstructed C-Mod equilibrium



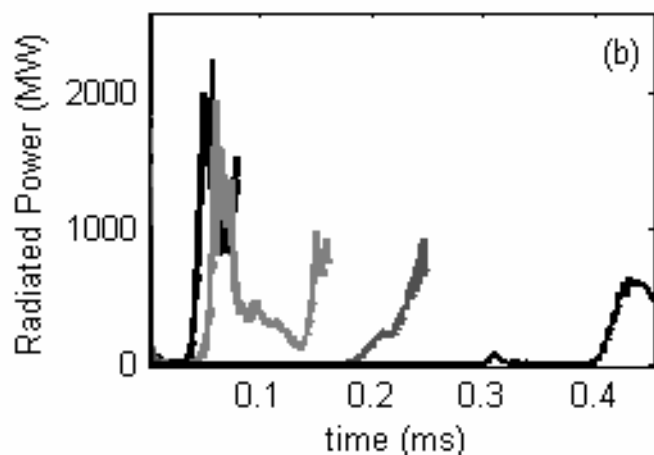
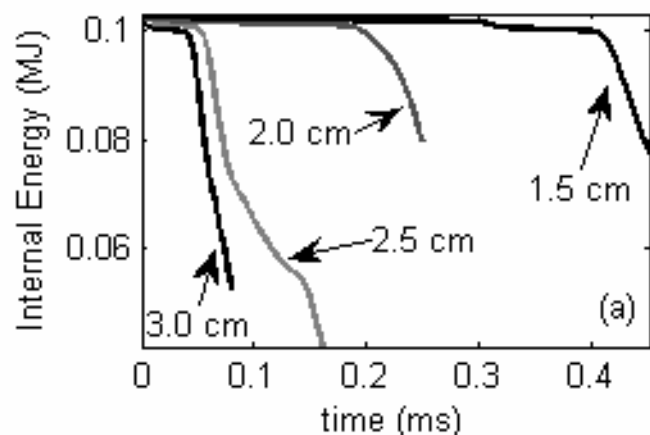
Shot 1040428007 at 900 ms

- High field, high current shot with $I_p = 1.7$ MA
- Temperature used in simulations is EFIT reconstructed pressure divided by measured density— considerably higher than measured temperature for this shot



Increasing penetration produces faster thermal quench

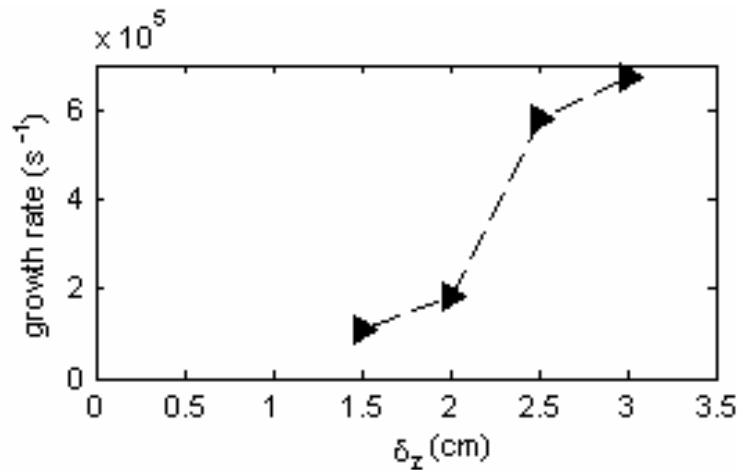
plasma thermal energy
and radiated power



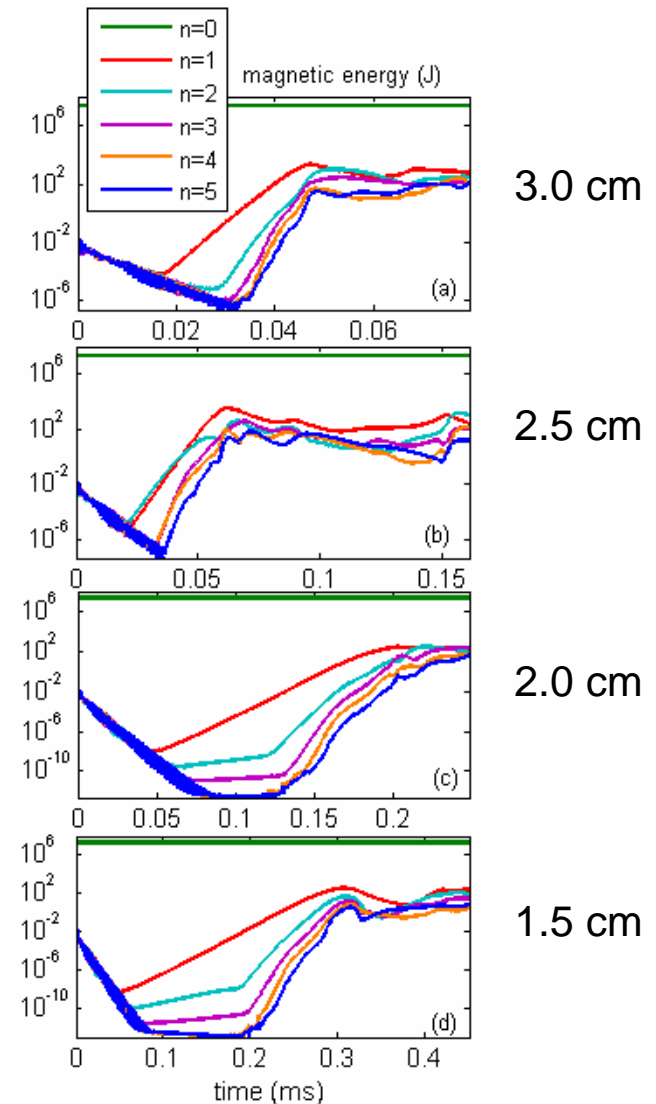
note: $S=10^5$,
experimental $S \sim \text{few } 10^7$

- Thermal quench is triggered in all cases
- In 3.0 cm case, cooling extends beyond the $q=2$ surface
- In the 2.5 cm case cooling boundary extends very close to $q=2$ surface, significant cooling at $q=2$ occurs due to perpendicular thermal transport
- In 2.0 cm and 1.5 cm cases, $q=2$ surface is not initially cooled by impurities, considerable delay occurs before thermal quench is triggered

Faster growth of $n=1$ instability when impurities cool $q=2$

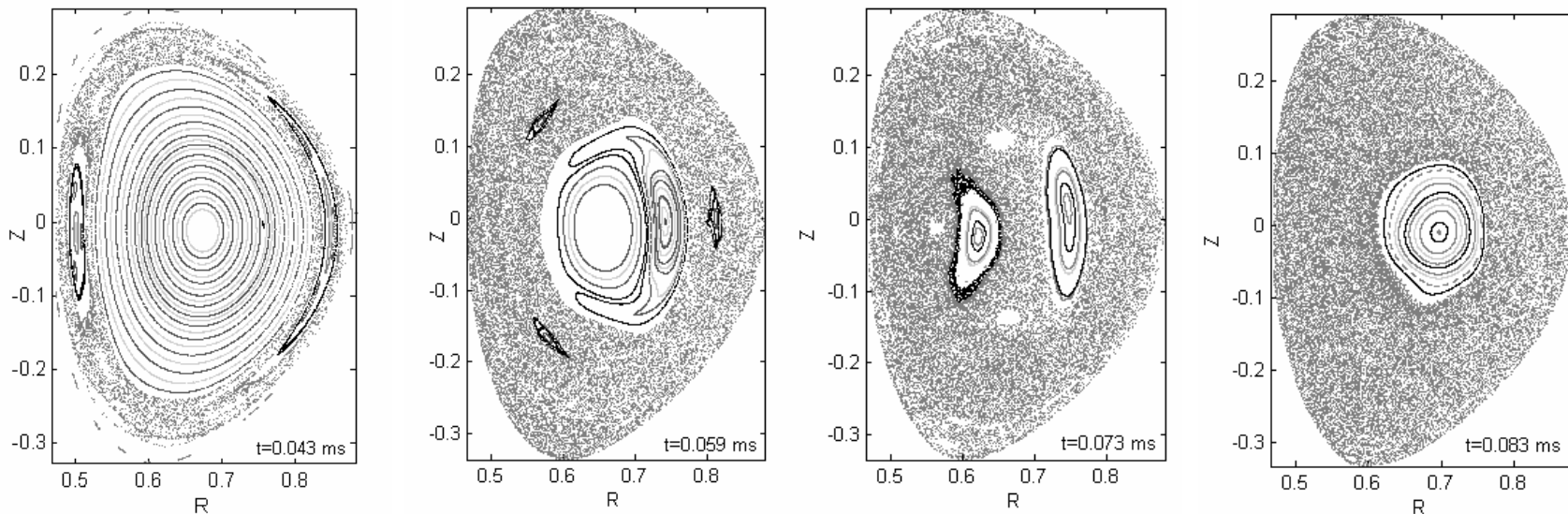


- ➔ $m=2/n=1$ is dominant mode at early times
- ➔ The growth rate of this mode increases with penetration depth
- ➔ Cooling at $q=2$ increases reconnection rate, producing largest change in growth rate between 2.0 and 2.5 cm cases



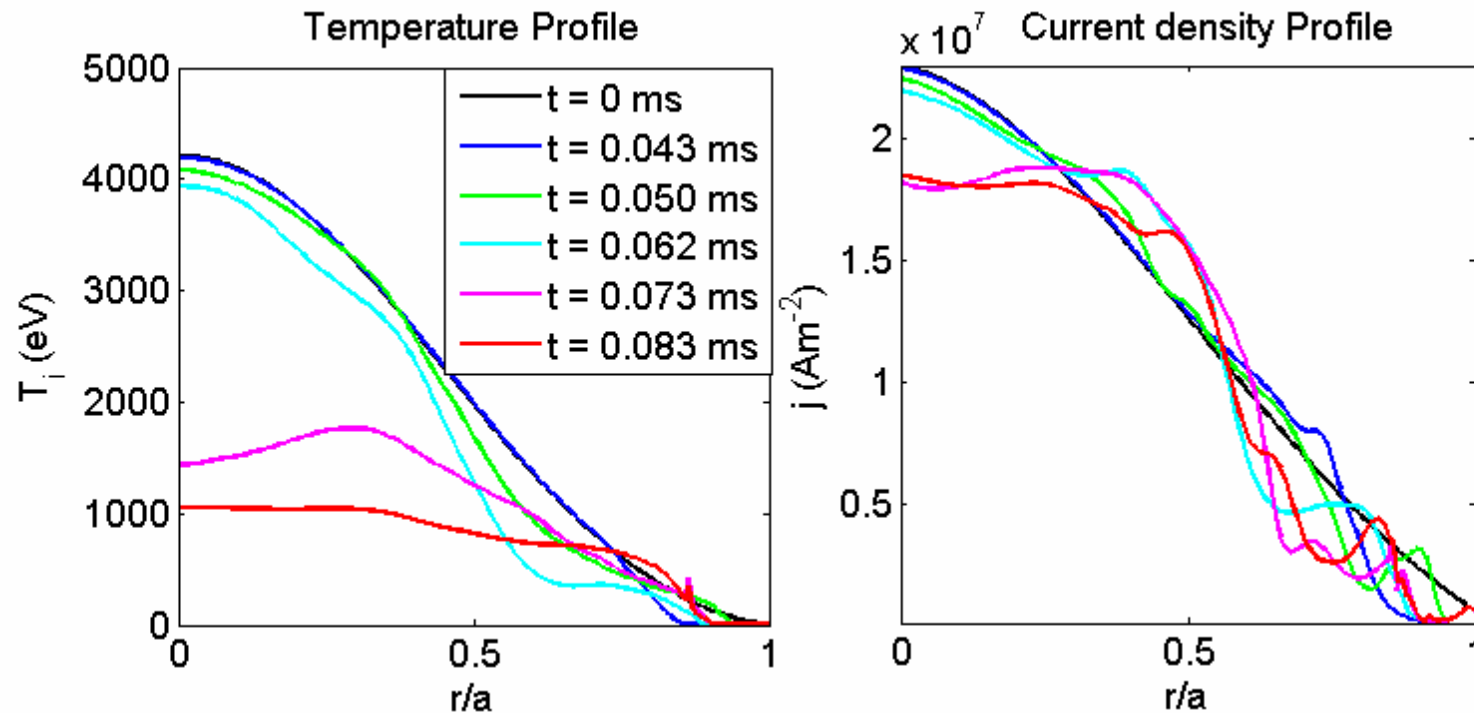
Flux surface evolution shows the role of 2 dominant $n=1$ modes

- ➔ $m=2/n=1$ island becomes large eventually all flux surfaces outside $q=1$ are destroyed
- ➔ $m=1/n=1$ mode swaps magnetic axis with island formed in the cold outer region



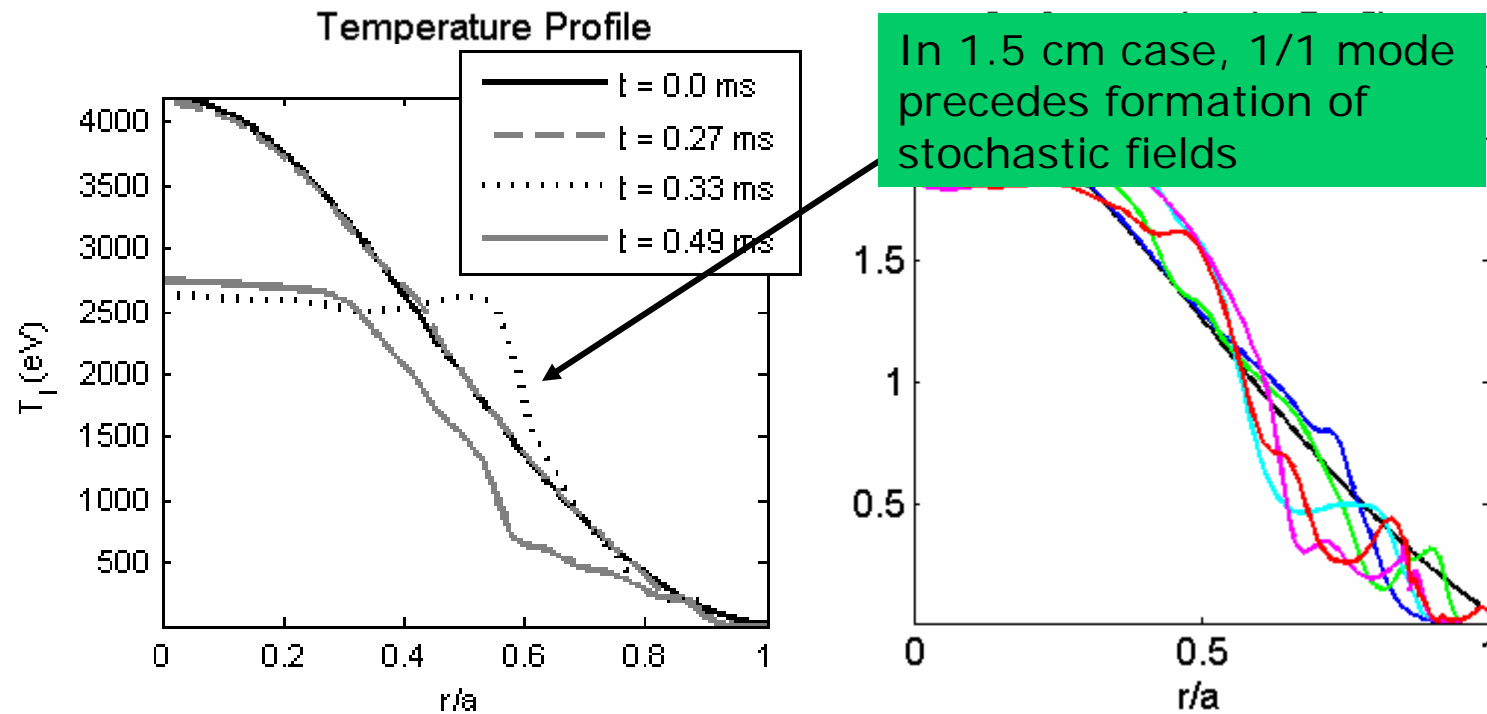
Signature of MHD events seen in characteristics of thermal quench

- Stochastization of outer flux surfaces produces heat loss mainly from outer 60% of minor radius
- Core temperature collapses all at once over a short period of time due to 1/1 mode



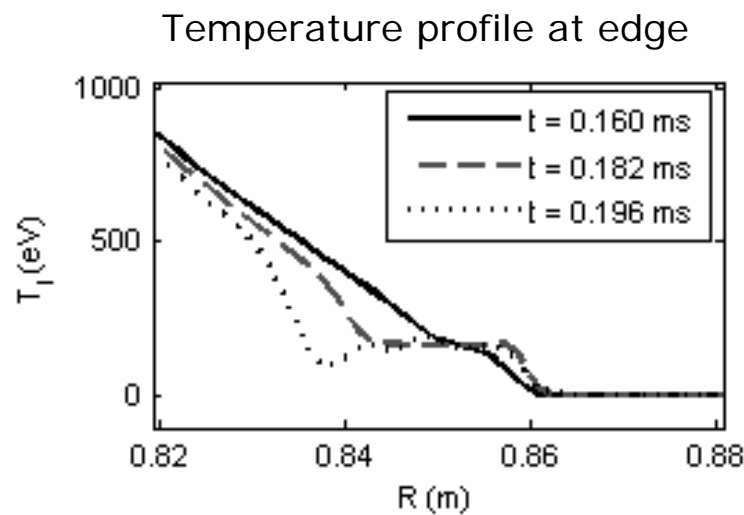
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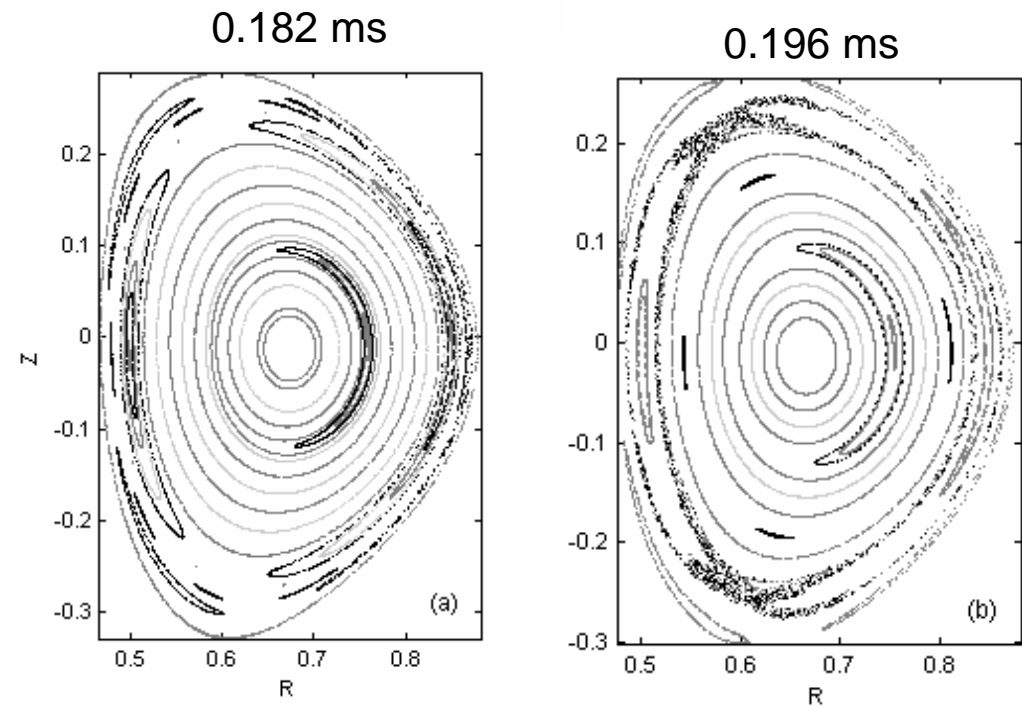


What triggers the thermal quench in the 1.5 and 2.0 cm cases?

- 2/1 island grows until it overlaps the cooling front (evidenced by cooling on low minor radius side of island).
- Overlap of island with cold edge coincides with initial appearance of stochastic fields.

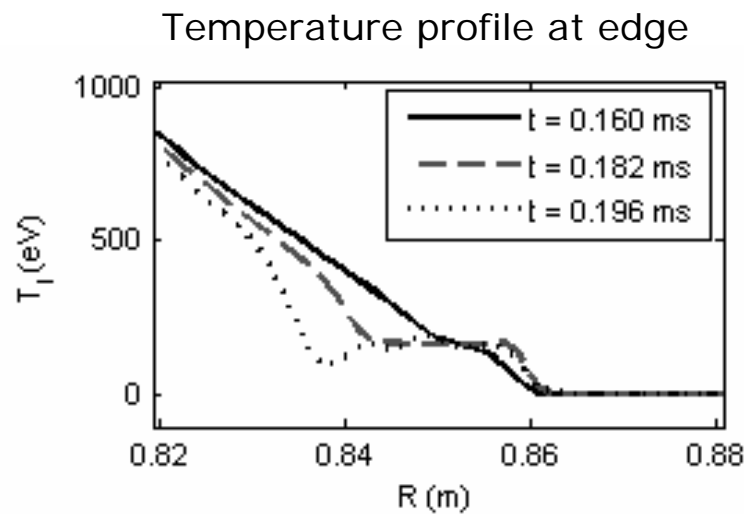


2.0 cm case

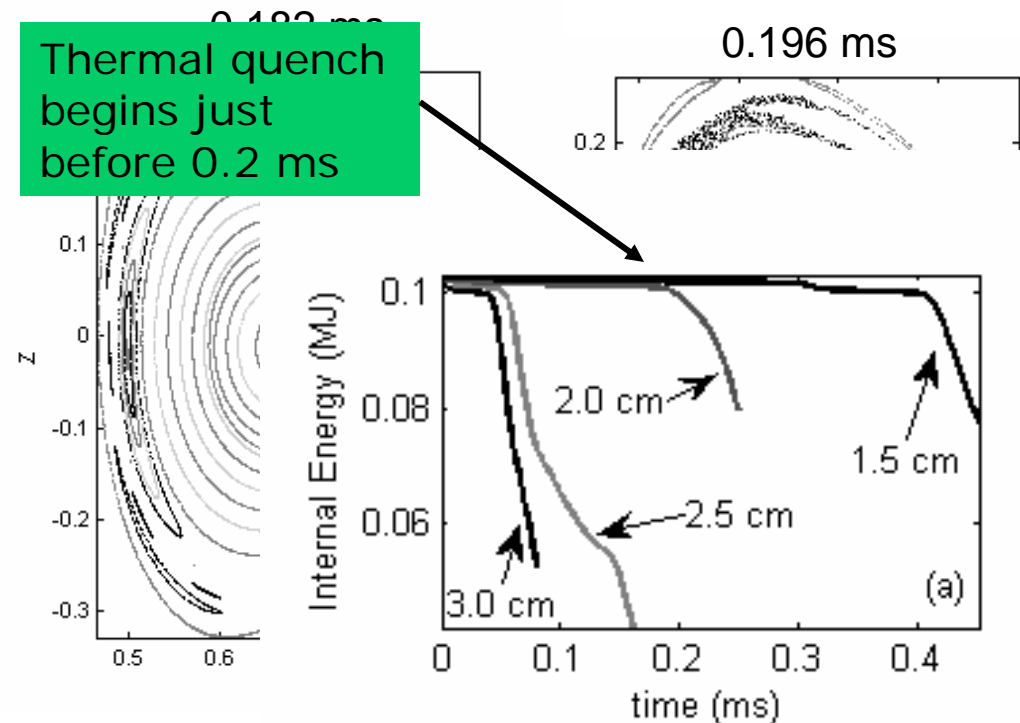


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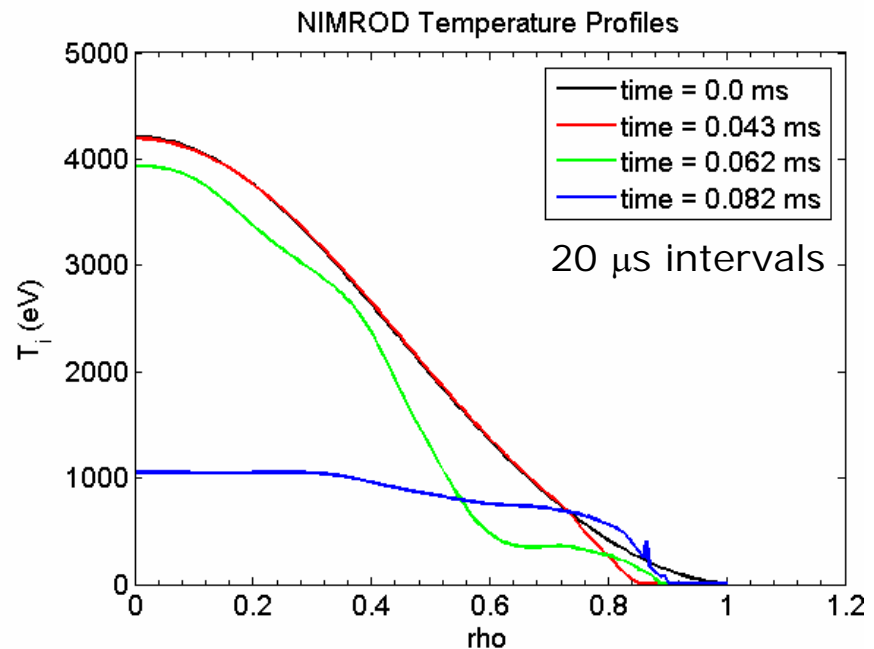
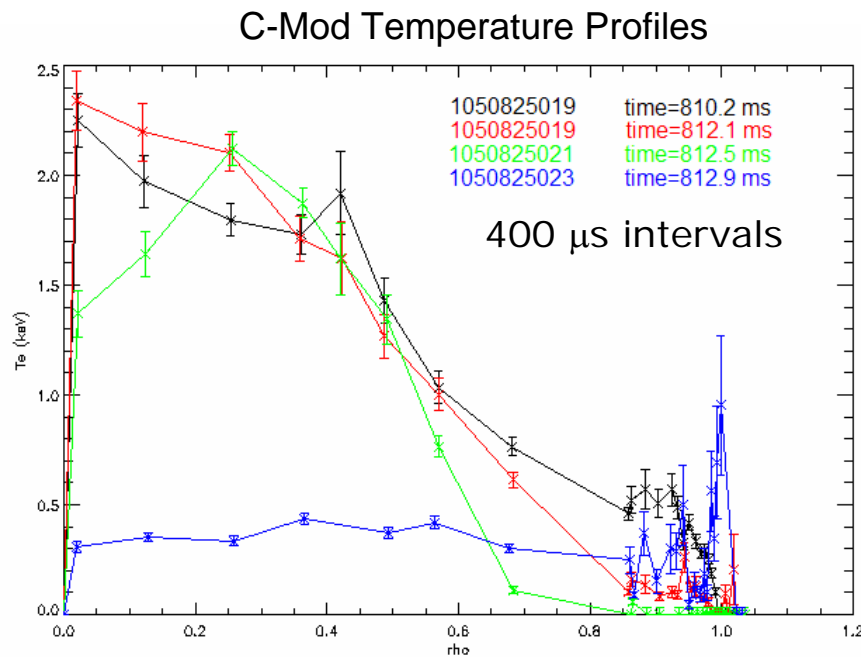


2.0 cm case



Thermal quench characteristics in simulation are very similar to Krypton shots on C-Mod

- ➡ Cooling outside $r/a=0.85$
- ➡ Outer 60 % begins to cool
- ➡ Sudden collapse of core temperature simultaneous with reheating of edge

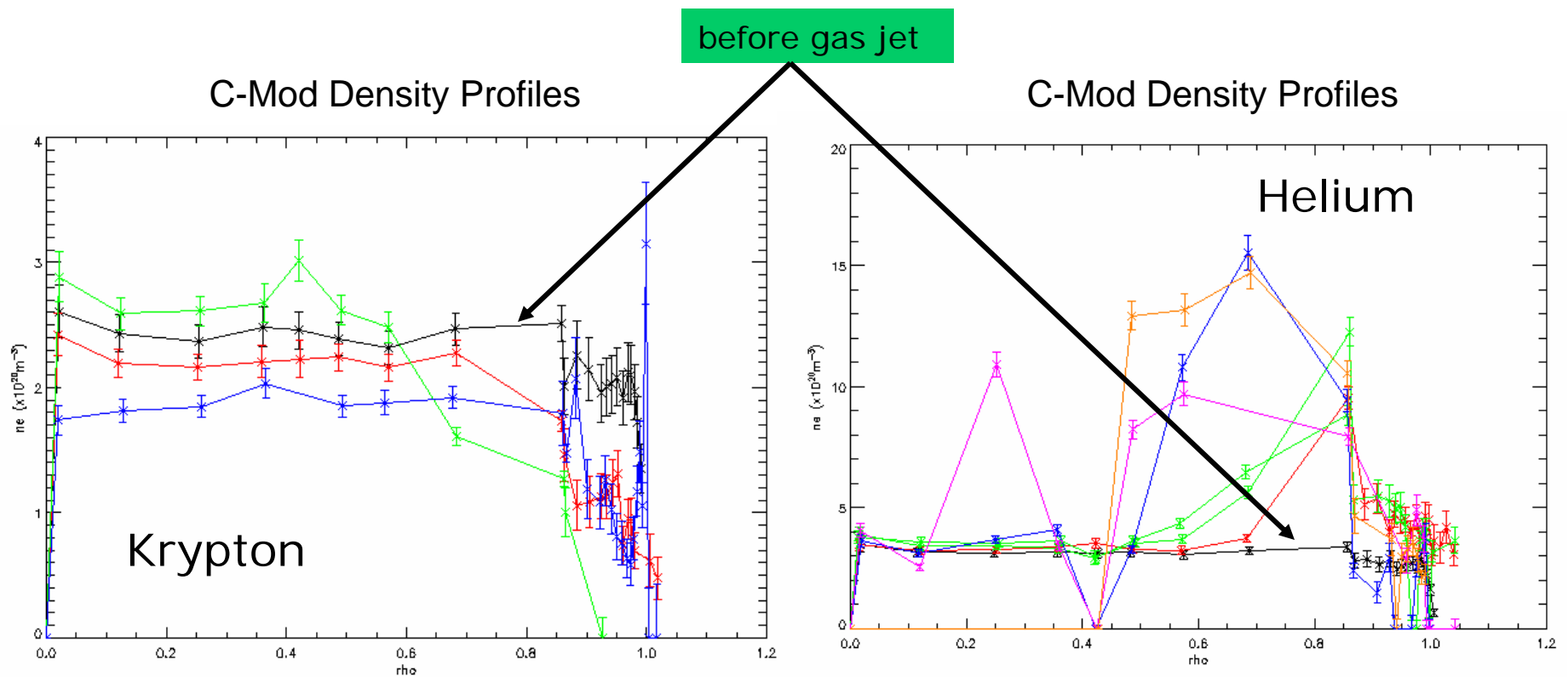


$S_{\text{experiment}}/S_{\text{simulation}} \sim 100 \Rightarrow$ Simulation has shorter MHD timescales

Krypton density profiles show no evidence of significant impurity penetration

➤ Edge density decreases after Krypton gas jet is fired

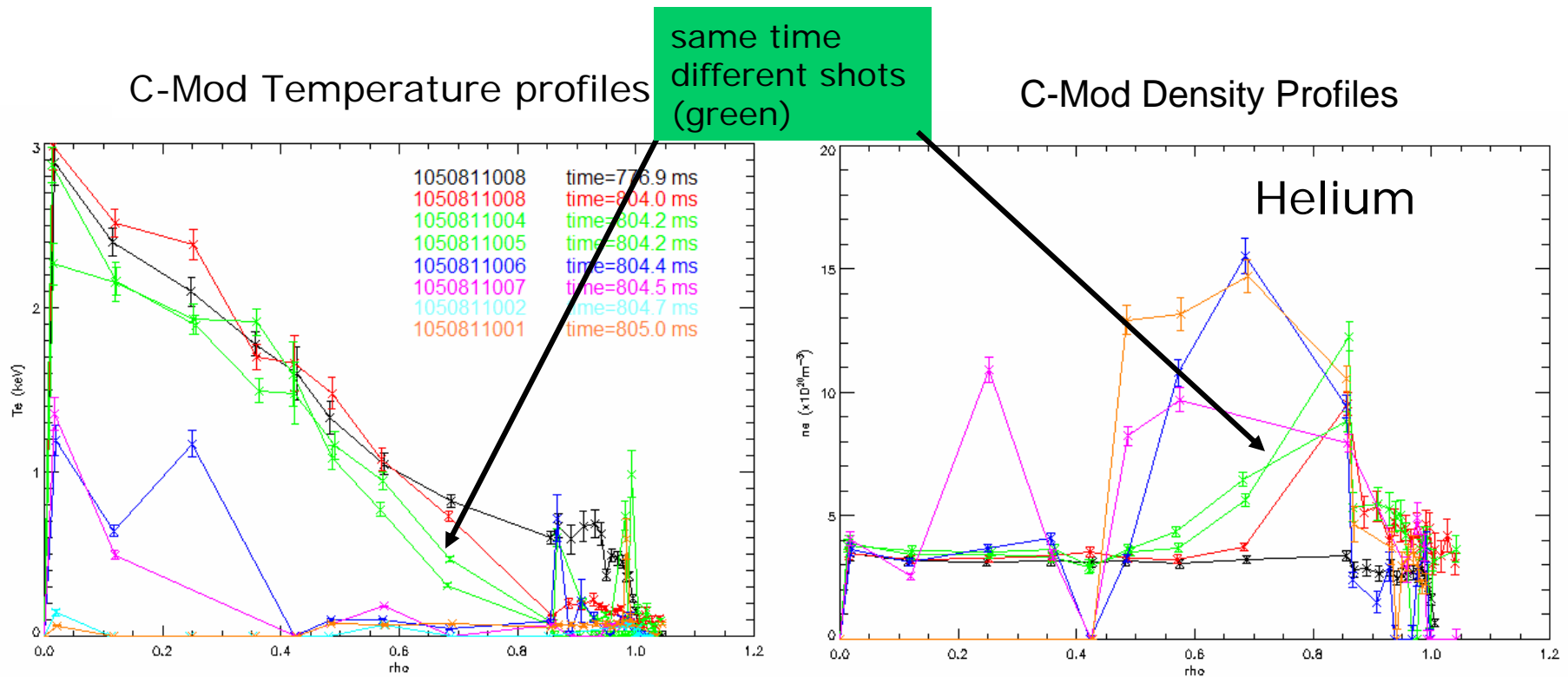
➤ Compare with Helium, for which significant density increases are observed



Krypton density profiles show no evidence of significant impurity penetration

➤ Helium thermal quench resembles cold front moving steadily in toward core

➤ Compare with Helium, for which significant density increases are observed



Improved impurity model will have accurate radiation rates, more physics

Subroutines from KPRAD radiation code are used to track all impurity charge states and calculate ionization, recombination, and radiation.

Ionization and recombination are computed for each charge state to produce electron source/sink

$$\frac{dn_e}{dt} + n_e \vec{\nabla} \cdot \vec{V} = \nabla \cdot D \nabla n_e + S_{ion} - S_{rec},$$

Impurity mass density and contribution to plasma pressure are accounted for

$$\rho \frac{d\vec{V}}{dt} = -\vec{\nabla} p + \vec{J} \times \vec{B} + \vec{\nabla} \cdot \mu \rho \vec{\nabla} \vec{V},$$

Z_{eff} dependence of resistivity is included

$$\vec{E} + \vec{V} \times \vec{B} = \eta \vec{J},$$

Thermal losses from ionization, recombination, line radiation and Bremsstrahlung are computed

$$n_e \frac{dT_e}{dt} = -(\gamma - 1) [n_e T_e \vec{\nabla} \cdot \vec{V} + \vec{\nabla} \cdot \vec{q}_e - Q_{loss}].$$

Improved impurity model (continued)

- User specifies rate and location of neutral deposition
- Impurities can be He, Be, C, Ne, and Ar
- Impurity ions are moved around the grid to track significant changes in electron density (ad-hoc impurity advection)
- Rate of neutral deposition will be determined by separate code computing gas flow down a pipe (M. Bakhtiari).
- Penetration depth of impurities is assumed to be the point at which the ablation pressure equals the pressure of the gas as it reaches the plasma—as the plasma cools the penetration depth increases
- This model has been implemented, but is still undergoing initial testing

Conclusions

- Very shallow penetration of impurities can lead to a thermal quench due to MHD activity
- Direct cooling of the $q=2$ surface by the impurities significantly hastens the onset of the quench
- When $q=2$ is not cooled, the quench is triggered when the $2/1$ island extends to overlap the impurity cooled edge
- Krypton gas jet experiments on C-Mod show a very similar thermal quench to the simulations
- Different cooling characteristics seen for Helium may require a more sophisticated model to simulate
- A model including more accurate radiation rates and more physics will be used for future simulations