MHD Simulations of Disruption Mitigation on Alcator C-Mod and DIII-D, and Recent Experimental Highlights

By
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Motivation

- **Disruption mitigation is a serious problem for ITER, and is being investigated on present tokamaks. Runaway electron avalanching is a major concern given exponential scaling with plasma current.**
- **Massive gas injection (MGI) is one approach that has been studied on Alcator C-Mod and DIII-D**
- **MGI is a 3D process in which MHD plays an important role– physics of MGI needs to be better understood**
- **A model capable of extrapolating MGI results to ITER must be 3D and accurately account for both MHD and atomic physics– an extended version of NIMROD has been developed for this purpose**
- **Validation of the code against present experiments, along with improved understanding of results is the focus in the near term**

Outline

1) **The physics of MGI: experimental observations and present understanding**

2) **Experimental Highlights from Alcator C-Mod and DIII-D**

3) **The code: Atomic physics package for impurity modeling has been added to NIMROD**

   - Equations, neutral source model, adjustment of time scales

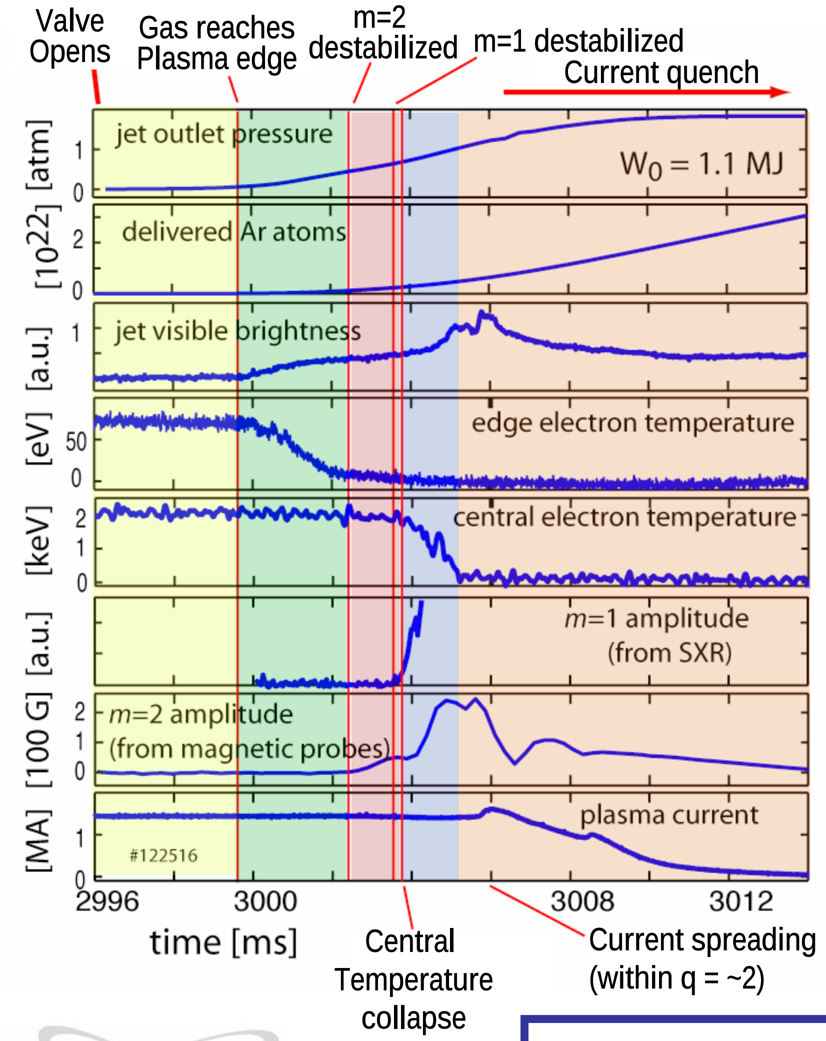
4) **Qualitative comparison: MGI sequence of events is captured by simulations**

5) **Quantitative comparisons:**

   - Thermal quench time agrees w/ C-Mod for neon jets
   - Helium jet simulations require background impurities

6) **Summary, Future work**

DIII-D Discharge 122516 Shows MGI Sequence of Events



1) Valve opens and gas travels down tube

2) Gas reaches plasma, edge begins to cool, current profile contracts

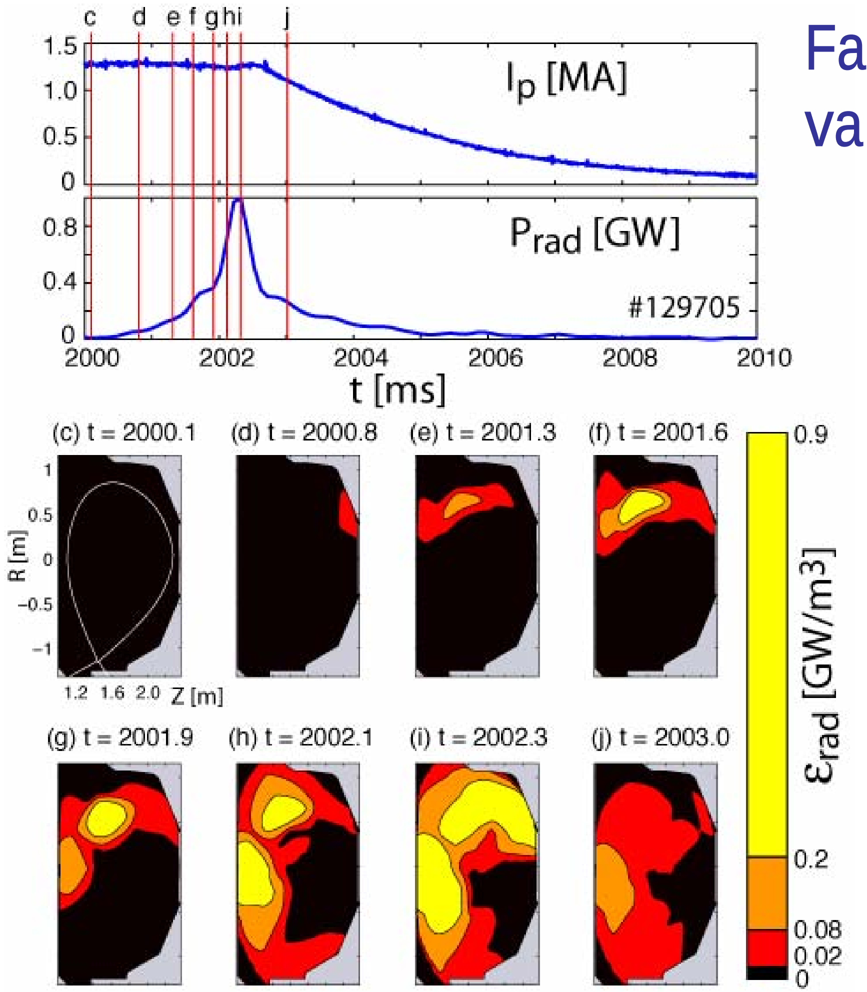
3) m=2 and m=1 modes are destabilized, flux surfaces are destroyed

4) Core thermal quench due to enhanced thermal transport and/or impurity mixing

5) Current quench

Simulations of stages 2-4 are presented

DIII-D research focuses on assimilation and mixing of impurities



Fast bolometry of Ne medusa valve MGI shutdown

- Impurity ions move around edge of plasma poloidally initially.
- Observed poloidal motion could be due to toroidal spreading along flux tube and/or due to edge poloidal drift.
- Ion mixing appears incomplete at TQ and even into CQ.

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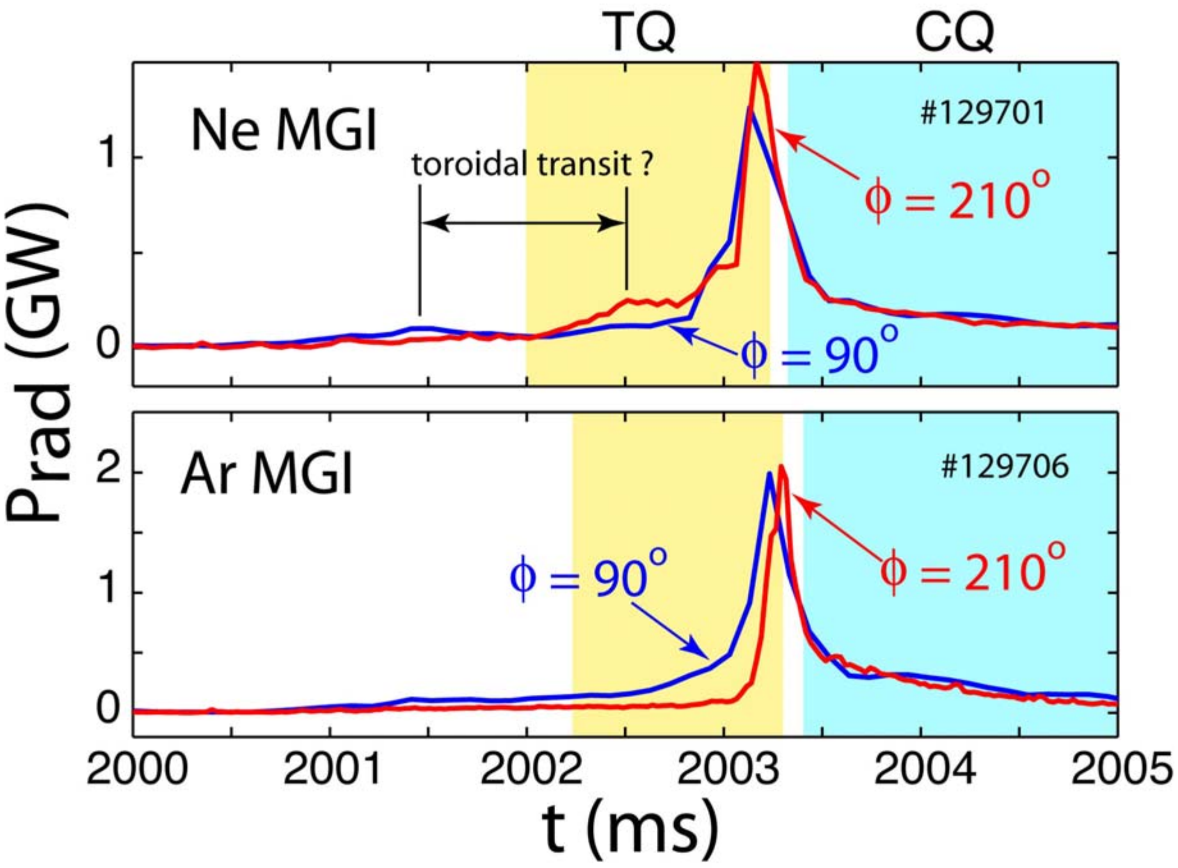
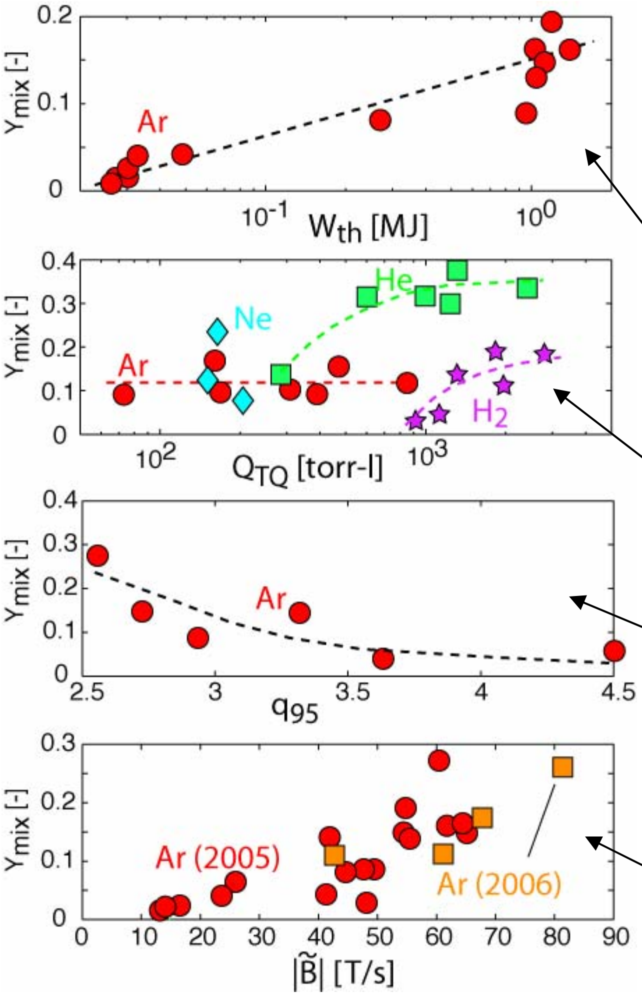
TQ radiation flash fairly uniform toroidally

P_{rad} at opposite sides of machine



- *Fast radiated power measurements show that ions take 1-2 ms to reach other side of machine.*
- *Main TQ radiation spike almost coincident on both side of machine - indicates fast heat transport from core.*

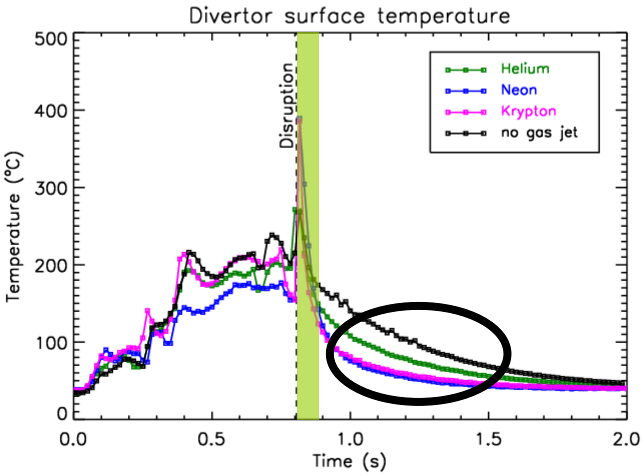
Mixing Efficiency Varies with Gas Species, q Profile, Plasma Thermal Energy

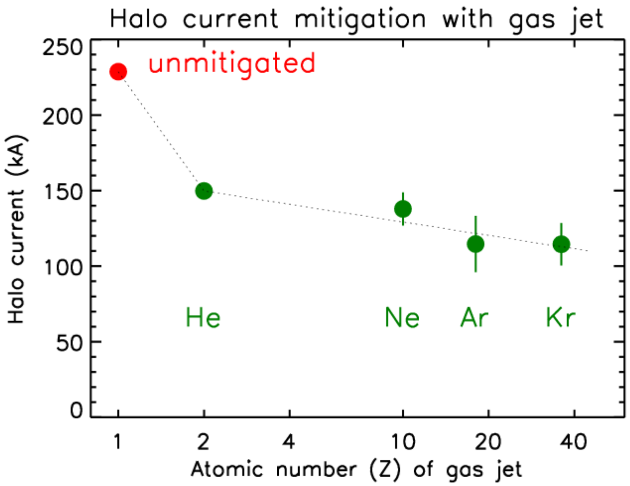


- Define jet impurity mixing efficiency $Y_{mix} = N_{assimilated}/N_{inject}$ in middle of CQ.
- Get $N_{assimilated}$ from measured n_e and use CQ measured T_e to estimate Z.
- Y_{mix} increases with increasing plasma thermal energy.
- Y_{mix} appears highest for He gas.
- Y_{mix} drops strongly with q_{95}, indicating that violent mixing during TQ MHD event dominates Y_{mix}.
- Y_{mix} increases with TQ magnetic fluctuation level.

C-Mod Shows Improved Mitigation with Higher Z Gases

- Experiments on C-Mod have been very successful at reducing heating of divertor and decreasing halo currents.

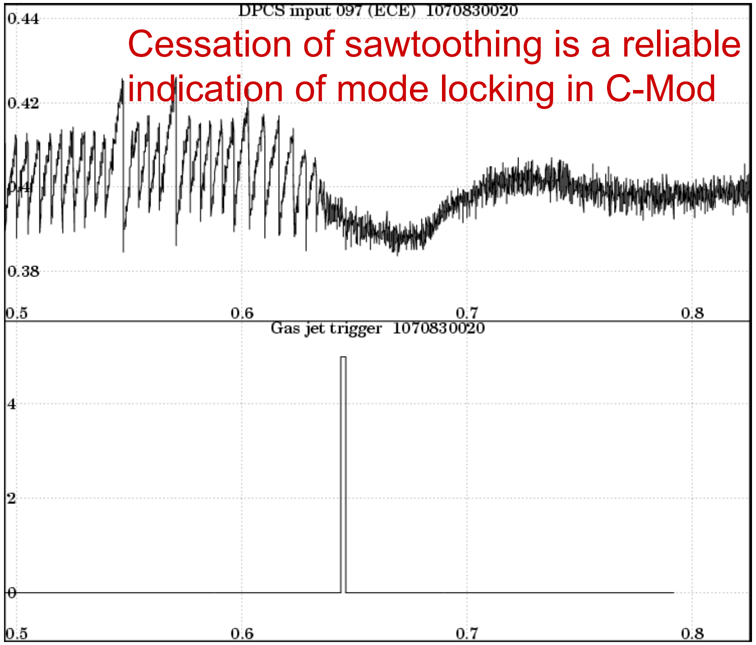




- Optimal mixture of 10-15% Ar in a helium jet has improved gas delivery time while maintaining good mitigation.
- Realtime detection of VDEs and triggering of the gas jet has been successfully carried out.

Future Focus of C-Mod Experiments is Real Time Detection

- Expand realtime detection with the digital plasma control system to include other types of disruptions (locked mode, density limit, high β, etc.)
    - Preliminary test of realtime locked mode detection shows promise (grad student: S. Angelini)



Cessation of sawtoothing is a reliable indication of mode locking in C-Mod

- The program uses a central ECE signal fed into the digital plasma control system (DPCS) every 10 μs.
- The primary check is that the normalized standard deviation of the ECE signal drops to less than 1.2% in a 0.6 ms time window.
- In preliminary tests, the program had an accuracy of 90% over the full set of shots from 2006.

Modeling of Impurity Species is Added to NIMROD

NIMROD is a 3D MHD code → nimrodteam.org

Atomic physics package computes ionization, recombination, radiation for all charge states of impurity species– source terms added to MHD equations

Energy

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

Q_{loss} includes ionization, line radiation, bremsstrahlung, and recombination losses, as well as dilution cooling

Heat Flux Vector

$$q = -n[\chi_{||} \hat{b}\hat{b} + \chi_{\perp}(I - \hat{b}\hat{b})] \cdot \nabla T$$

$\chi_{\perp} \sim 1\ m^2/s$; $\chi_{||} \sim 10^{10}\ m^2/s$

Ohm's Law

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

η proportional to local Z_{eff} as well as $T_e^{-3/2}$

Momentum

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

pressure and mass density include impurity contribution

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Alcator C-Mod

Separate Evolution of Three Densities Allows Impurity Mixing

Electron Continuity

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

Addition of source term due to ionization/recombination

Impurity Ion Continuity

$$\frac{dn_z}{dt} + n_z \vec{\nabla}\cdot\vec{V} = \nabla\cdot D\nabla n_z \left[+ S_{ion/rec}\right]$$

Source term is not part of the NIMROD advance– individual charge state populations are updated within atomic physics subroutines

Deuterium Ion Continuity

$$\frac{dn_i}{dt} + n_i \vec{\nabla}\cdot\vec{V} = \nabla\cdot D\nabla n_i + S_{ion/3-body}$$

Includes term for ionization and 3-body recombination (becomes significant at T~1eV)

Quasi-Neutrality

$$n_e = n_i + \langle Z\rangle n_z$$

After advancing 3 densities, specifies required $\langle Z\rangle$ for charge state distribution

Approximate Model for Neutral Gas Injection Neglects Jet Asymmetry for Simplicity

- Model assumes gas injection is poloidally and toroidally symmetric (although 3D capability exists)

- Assumed initial radial injection depth is 1 cm (limited by grid resolution); as edge temperature falls below species first ionization energy, neutral deposition extends in to that region

- Total impurity injection rate (vs. time) from gas dynamic code is divided by volume of the injection region to get neutral density deposition rate

Simulation Time Scales Are Artificially Reduced for Computational Expediency

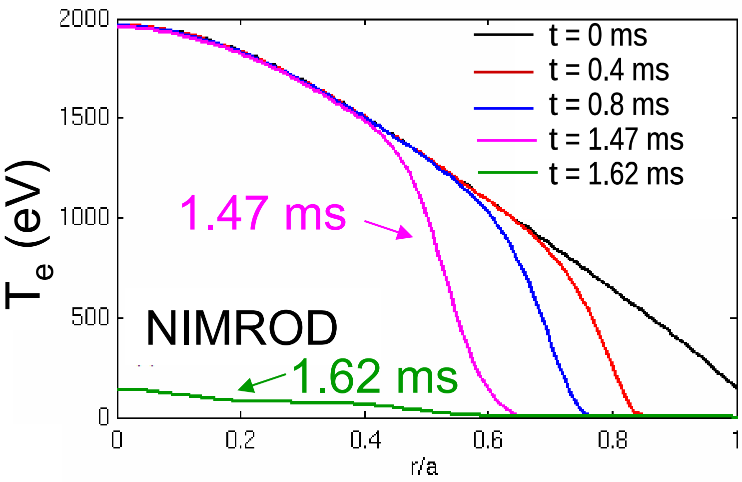
- Resistivity is enhanced by a large factor, E (100-900)
- **Assumption:** During the *thermal quench* phase of the mitigated disruptions, the important processes are heat loss by radiation and transport and reconnection
- Reconnection scales roughly as $\eta^{1/2}$ (~$E^{1/2}$)
- Therefore: Other rates including atomic physics rates, transport coefficients, gas injection rates, are increased by $E^{1/2}$
- Resistivity in Ohmic heating term is only enhanced by $E^{1/2}$ to achieve correct balance between radiation, Ohmic heating. Some magnetic energy vanishes.
- When compared with the experiment, time base is multiplied by $E^{1/2}$, radiated power is reduced by $E^{1/2}$

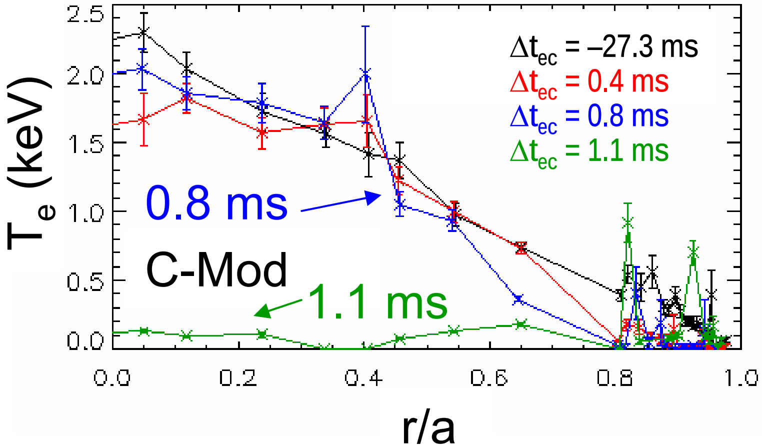
Simulated Lundquist Numbers Are Several Orders of Magnitude From ITER

	Lundquist number ($S \sim RBT_e^{3/2} n_e^{-1/2}$)
ITER	**$\sim 10^{10}$** ($R=6.2$ m, $B=5.3$ T, $T_e=15$ keV, $n_e=10^{20}$)
DIII-D	**$\sim 10^{8}$** ($R=1.7$ m, $B=2.1$ T, $T_e=3.5$ keV, $n_e=9\times10^{19}$)
Alcator C-Mod	**$\sim 10^{7}$** ($R=0.6$ m, $B=5.2$ T, $T_e=2$ keV, $n_e=2\times10^{20}$)
NIMROD	**$5\times10^{4} – 2\times10^{5}$** Each simulation takes ~ 4 days on 96 procs on Bassi (NERSC)

$S \sim 1/E$

C-mod Neon Jet Simulation Shows Experimental Sequence of Events





NIMROD results:

- **Inward propagating cold front to r/a~ 0.6 followed by sudden core T_e collapse**
- **Core thermal quench happens in ~0.15 ms**

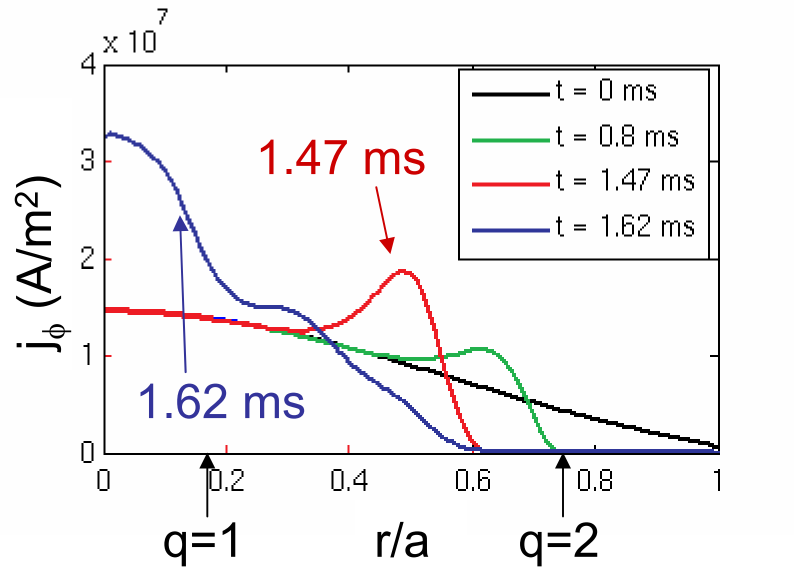
Experimental results:

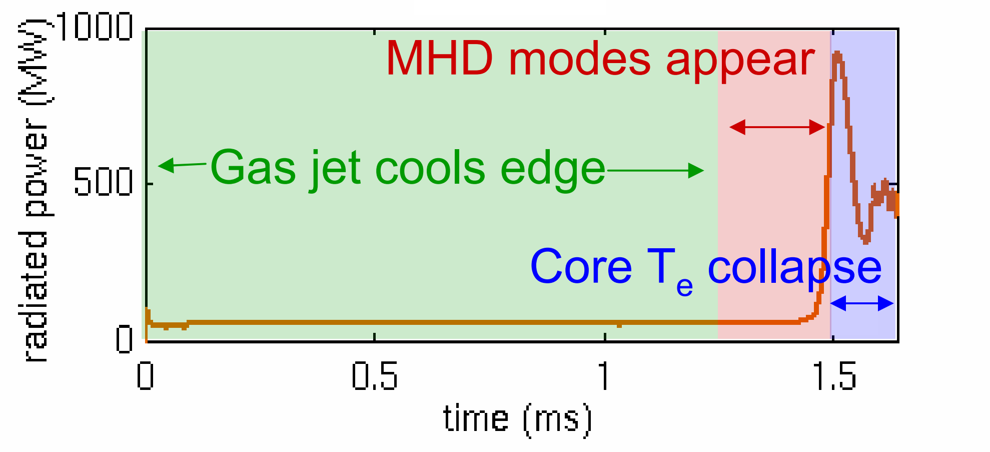
- **Penetration of cold front before thermal quench is slightly shallower**
- **C-Mod core thermal collapse ~0.2 ms**

Simulation with E=400

($S_{C\text{-}Mod}=2\text{x}10^7$, $S_{sim}=5\text{x}10^4$)

Large Pulse of Radiated Power Corresponds to Thermal Quench Onset



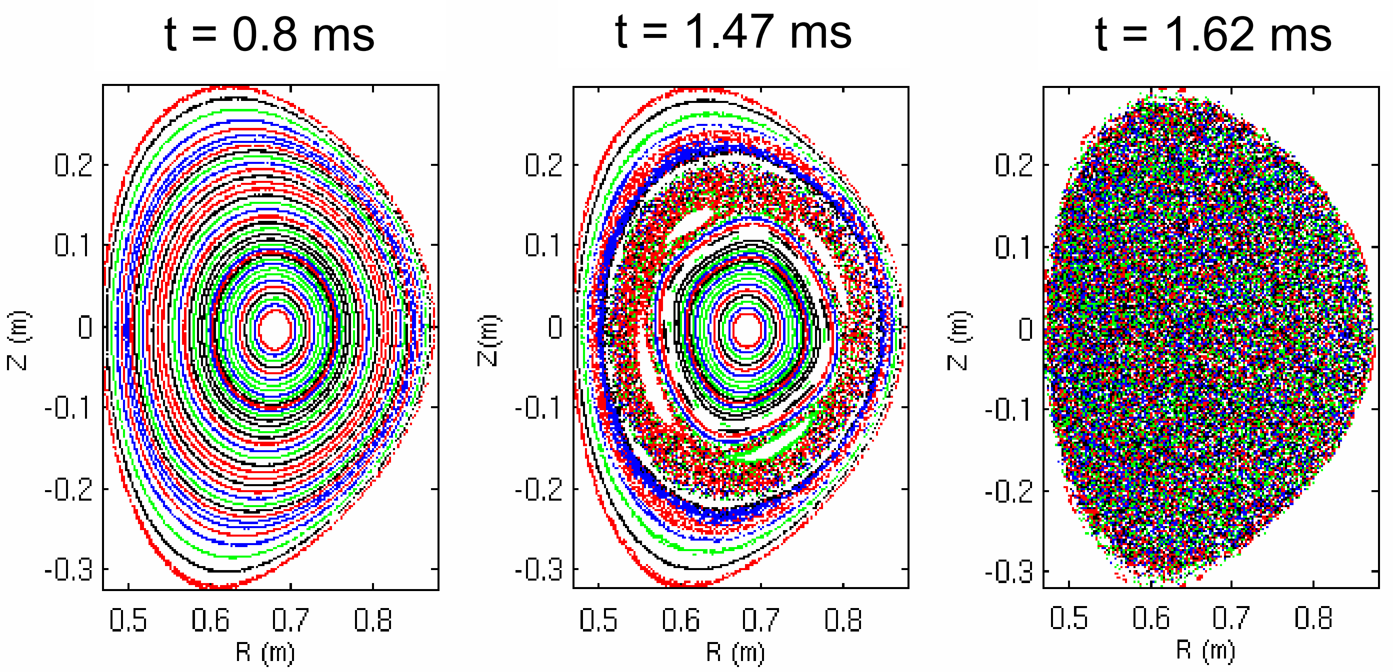


- **Current profile contracts as plasma edge cools**
- **Following thermal quench, peak current density is twice initial value**

- **Radiated power remains low as cold front propagates in plasma edge**
- **~GW radiated power when core temperature suddenly collapses**

Thermal Quench at 1.5 ms Corresponds to Destruction of Flux Surfaces

Parallel thermal transport from core to radiating edge drops core temperature rapidly



t = 0.8 ms

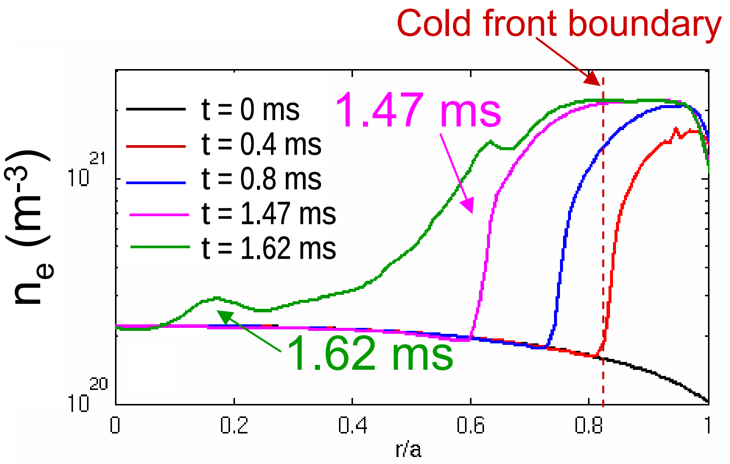
t = 1.47 ms

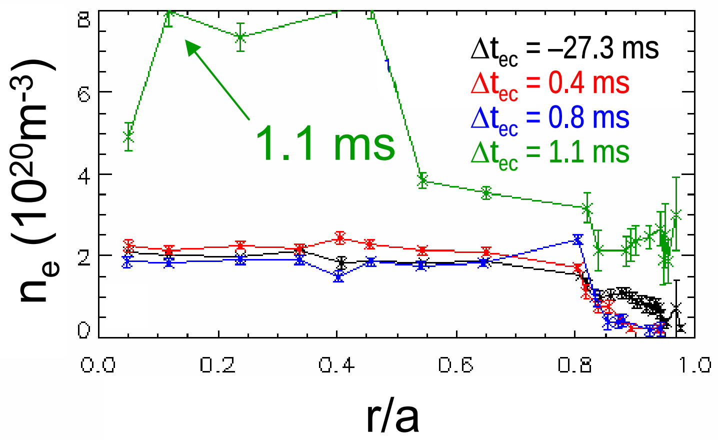
t = 1.62 ms

Flux surfaces are completely destroyed in this case; other simulations have shown good flux surfaces remaining inside q=1

Scaling of fluctuations with S will be important

Simulation's Large Edge Density is Not Measured by C-Mod Thomson Scattering





NIMROD results:

- **Large increase in edge density before thermal quench, no significant impurity mixing**
- **Small increase in core density after thermal quench**

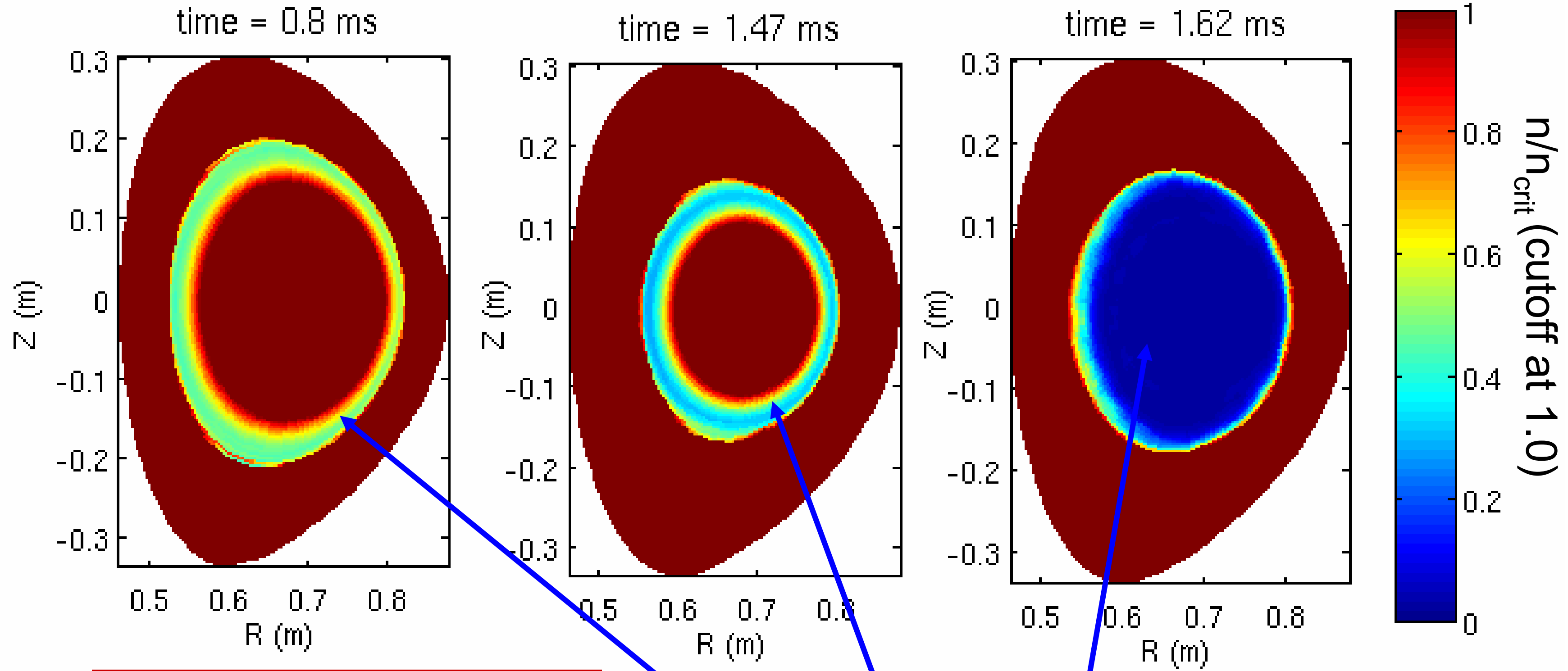
Experimental results:

- **No edge density increase before quench**
- **Moderate core density increase after quench**

⇒ Difference could be ionization fraction, confinement, gas injection rate or distribution

Runaway Electron Avalanching Criterion Is Satisfied in Large Regions of the Plasma

→ Ratio of electron density (free + bound) to critical density needed to stop runaway avalanching (color scale is cut off at 1.0; $n/n_{crit}<1 \Rightarrow$ avalanching)



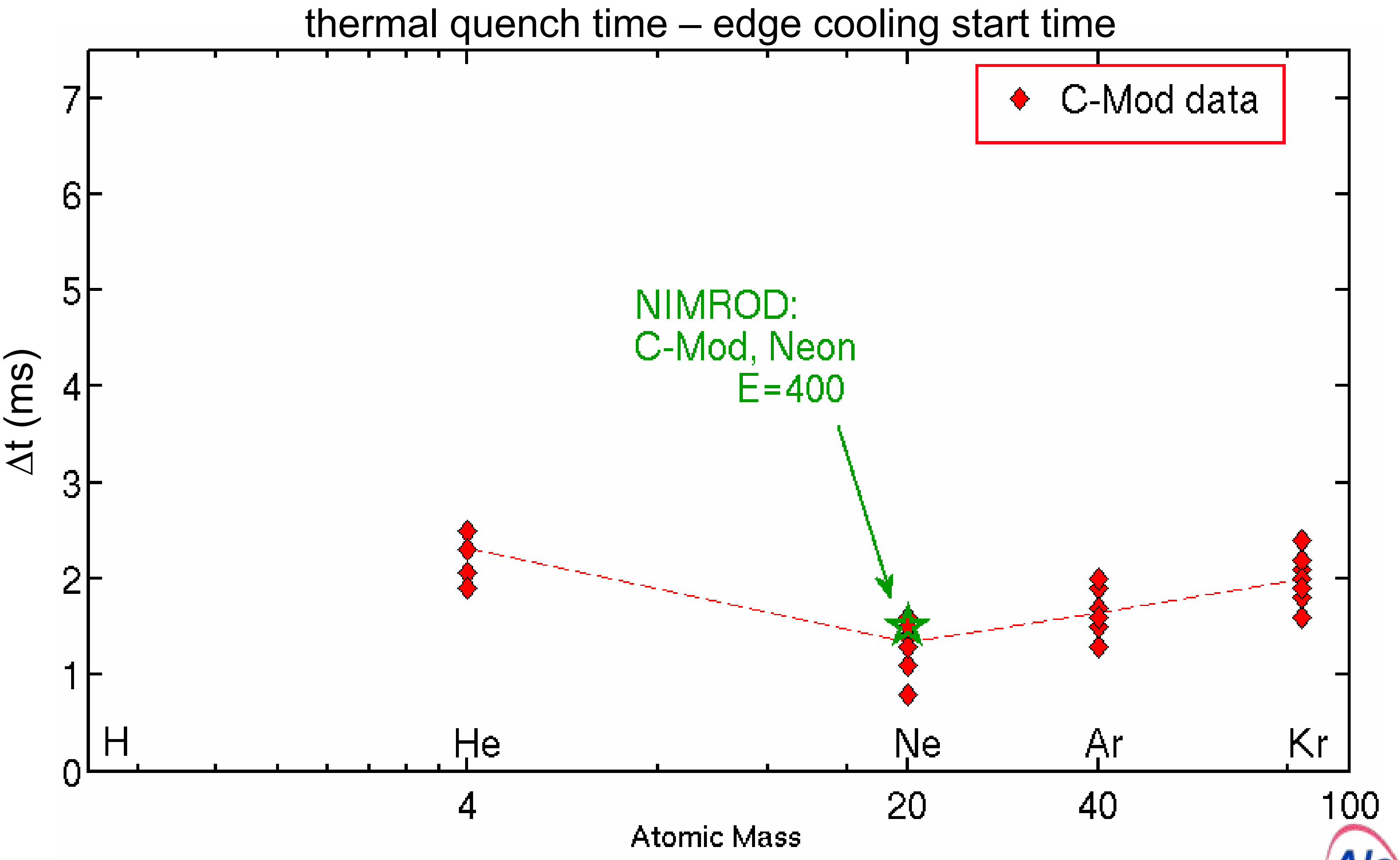
$n/n_{crit} \approx 0.12$ / E(V/m)*

Regions of runaway electron avalanching

→New runaway electron diagnostic on DIII-D will allow comparison

* ITER Physics Basis, Chapter 3, (pg. 2346)

Thermal Quench Onset Time Agrees With Data for C-mod Neon Simulations



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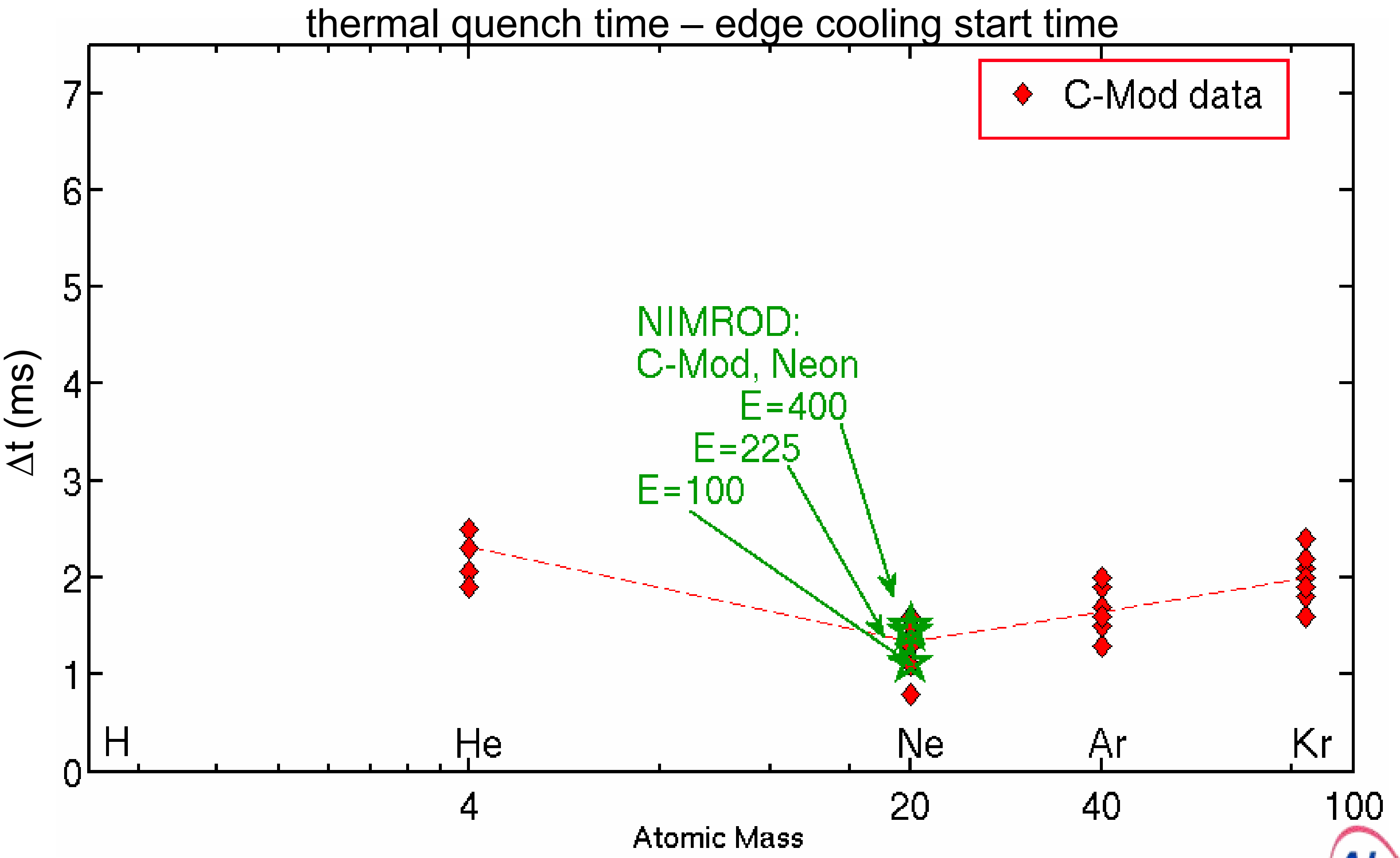
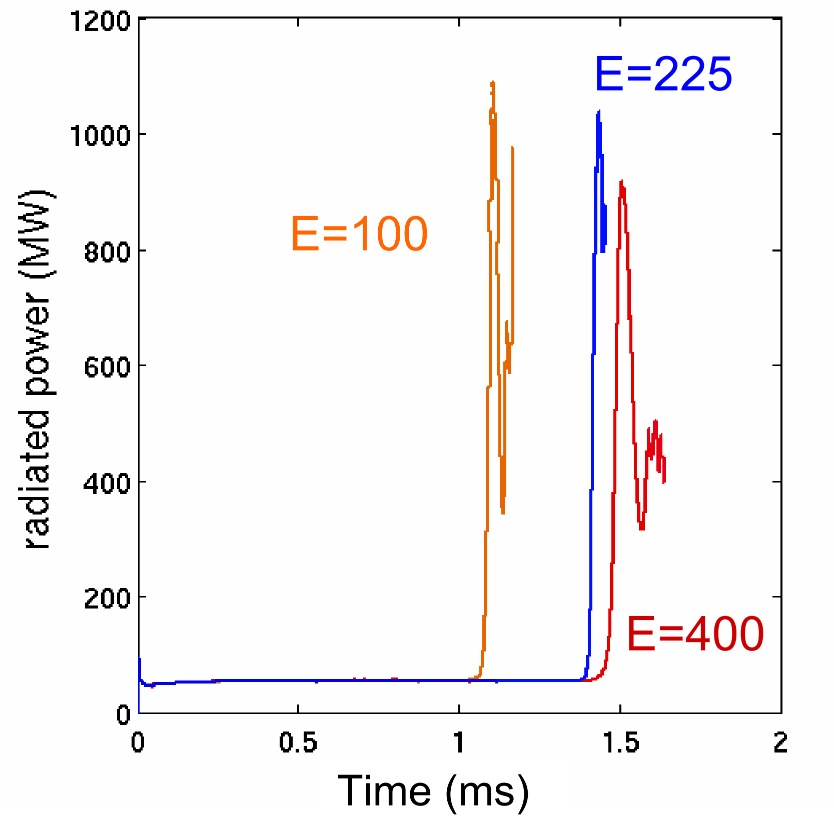
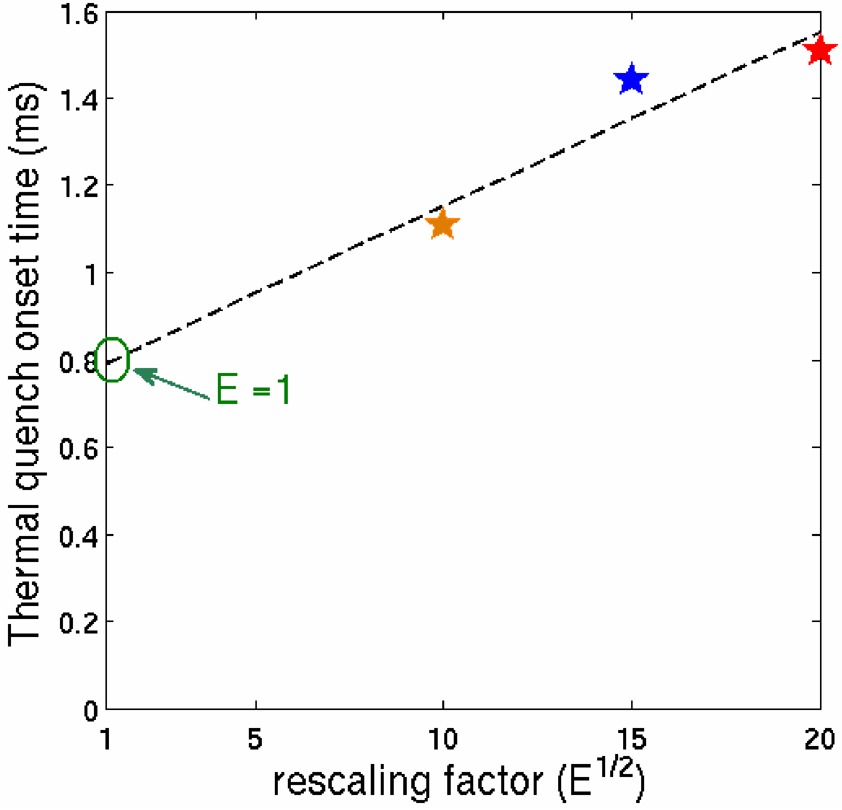


More Cases Required for Convergence of Onset Time With Rescaling Factor

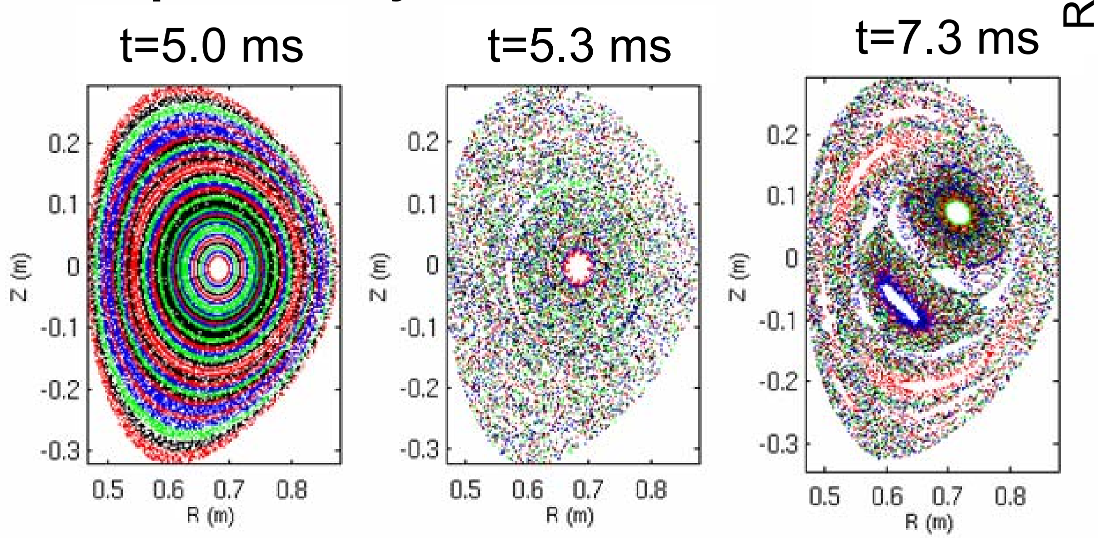




$S \sim 1/E$

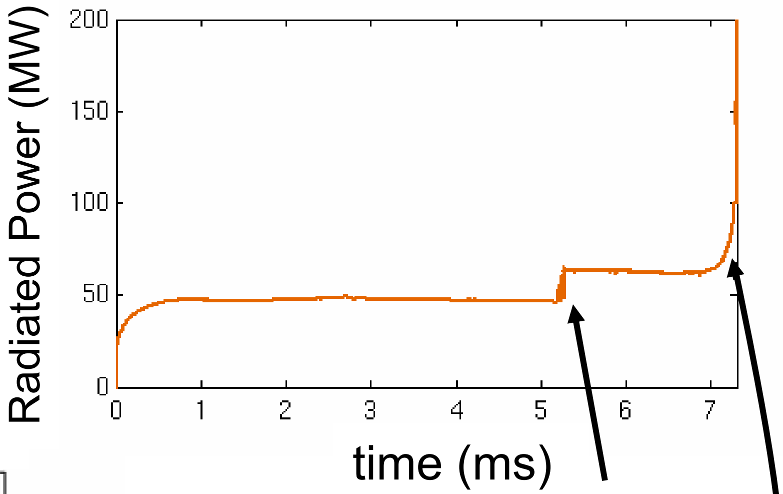
Pure Helium Jet Simulation Produces Very Long Thermal Quench Onset Time

- **Onset time >7 ms, compare with experimental time of 2-2.5 ms**
- **Simulation does not include intrinsic (or sputtered) boron radiation**
- **Thermal quench also differs qualitatively**



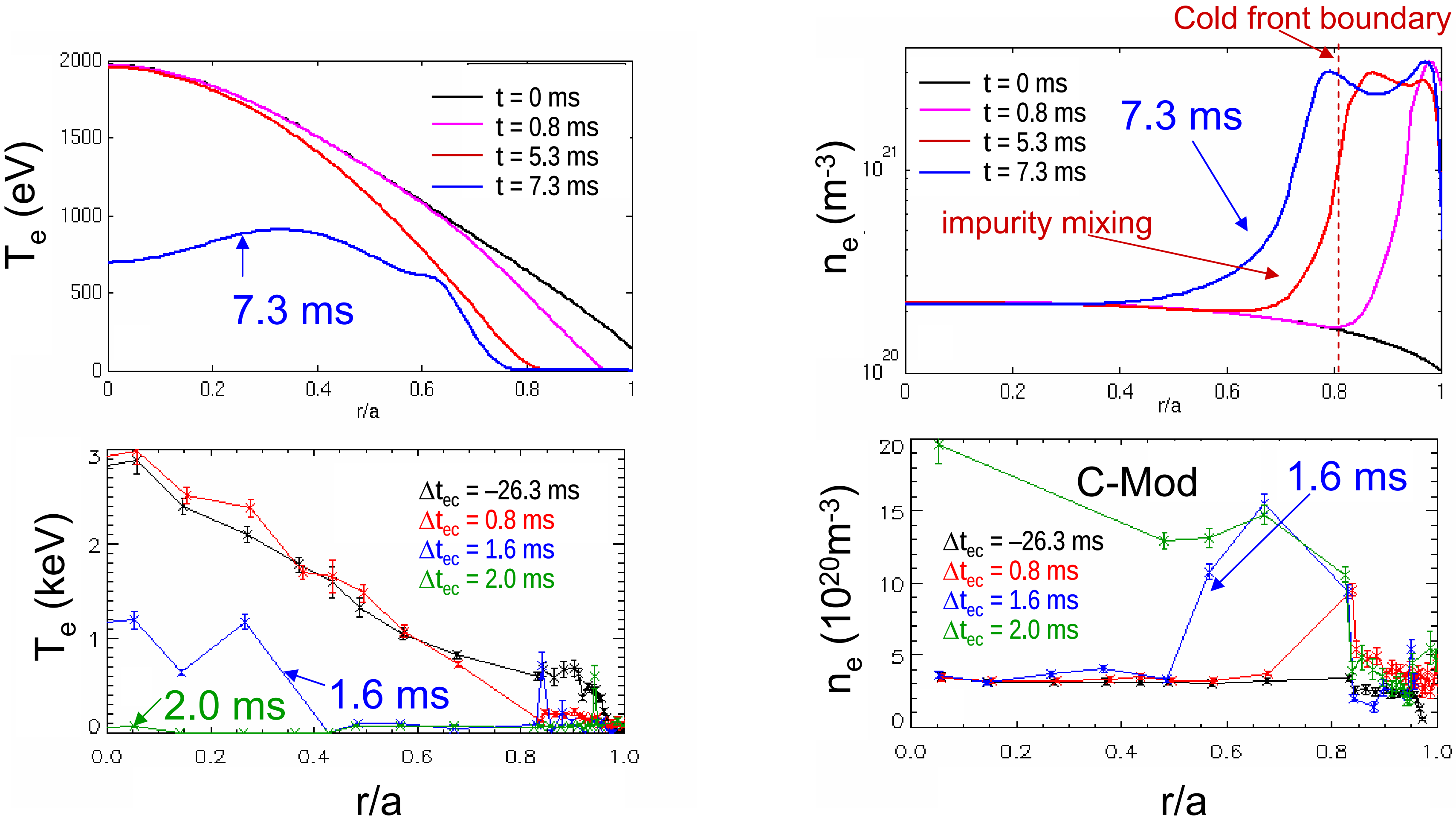
Simulation with E=400

($S_{C\text{-}Mod}=2\times10^7$, $S_{sim}=5\times10^4$)



- **At 5.3 ms, stochastization of flux surfaces results in merely incremental increase in total radiated power**
- **Larger radiated power spike associated with 1/1 convection of heat from core to edge**

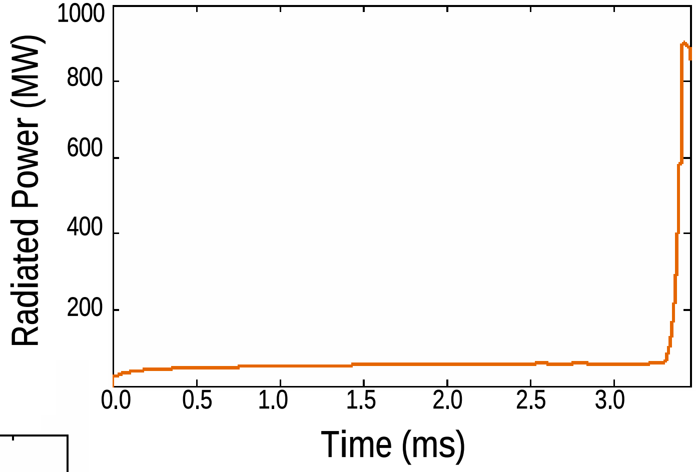
Slow Cold Front Penetration Without Background Impurity Radiation

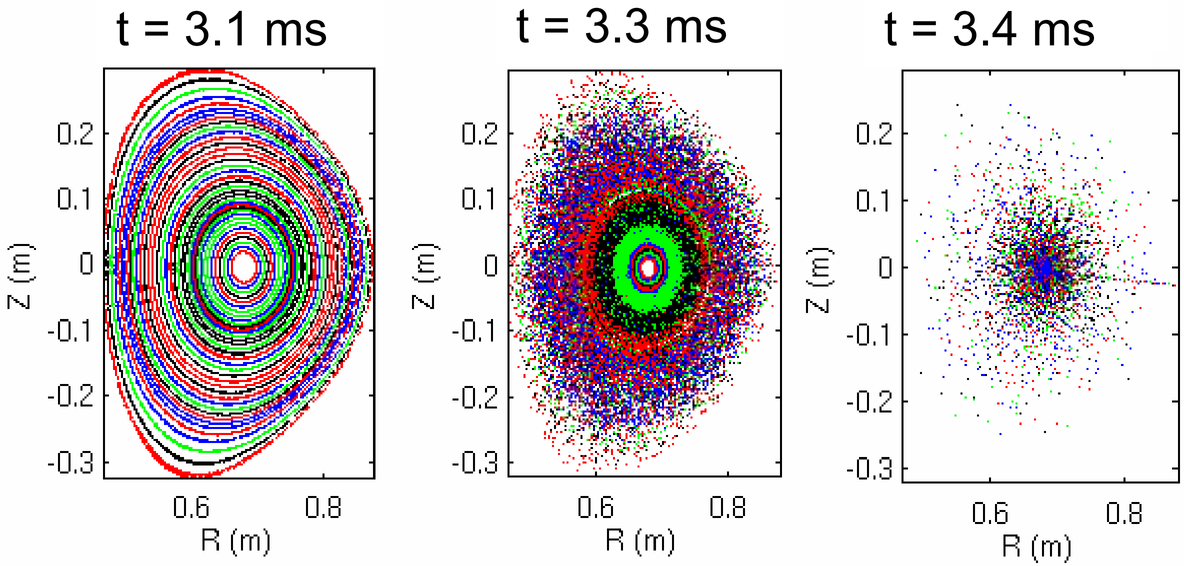


Alcator C-Mod

Background Impurity Radiation Can Be Significant for Helium Jet Experiments

- **Identical helium simulation but with assumed constant boron density of $4\times10^{18}/m^3$**
- **Coronal boron cooling rates are assumed**
- **Thermal quench start time is shortened to 3.4 ms**

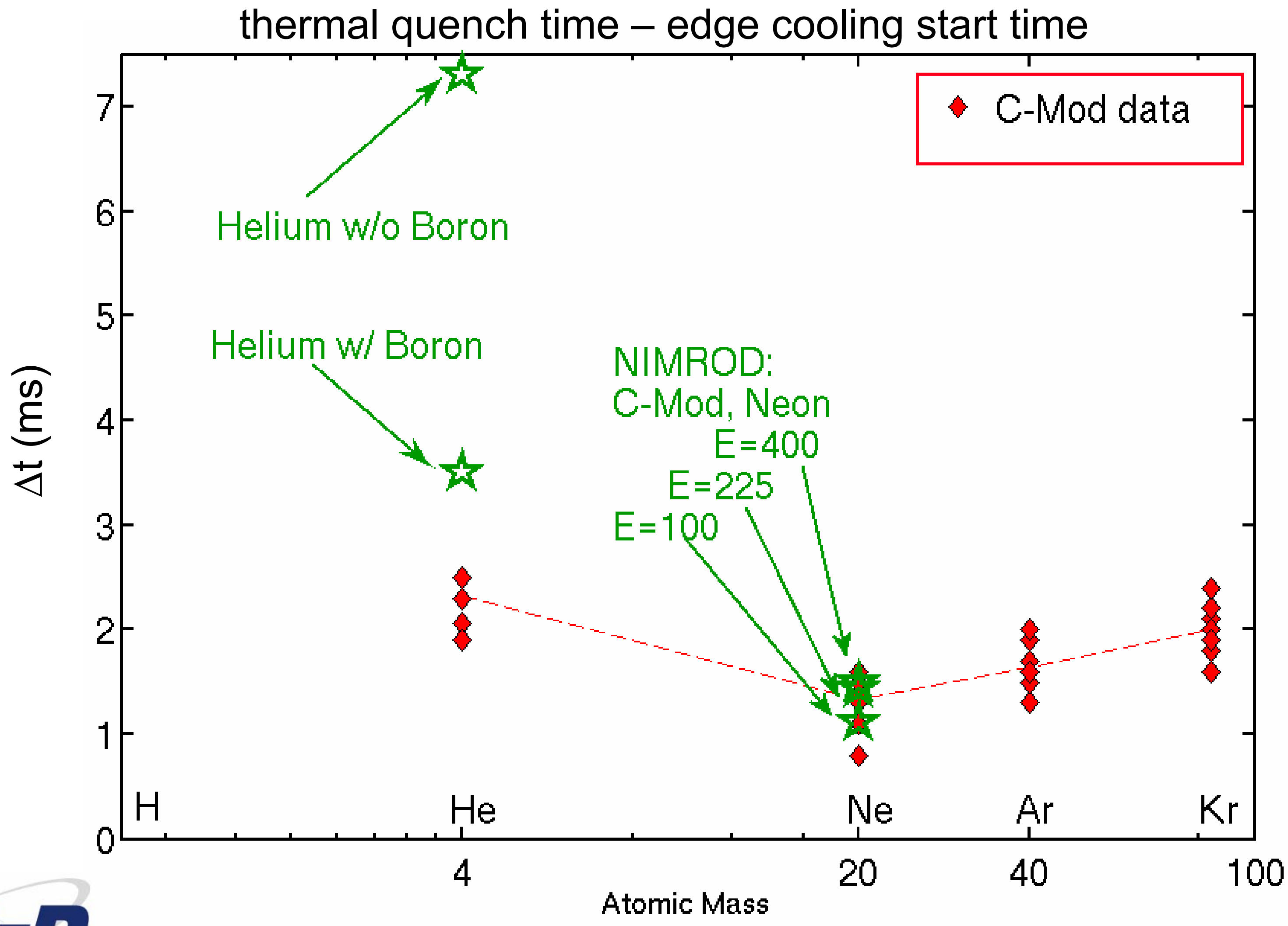




- **Unlike pure helium, stochastization of flux surfaces occurs sooner, produces very large radiated power spike**

Alcator C-Mod

Helium Simulations Will Require Accurate Boron Profile for Quantitative Comparison



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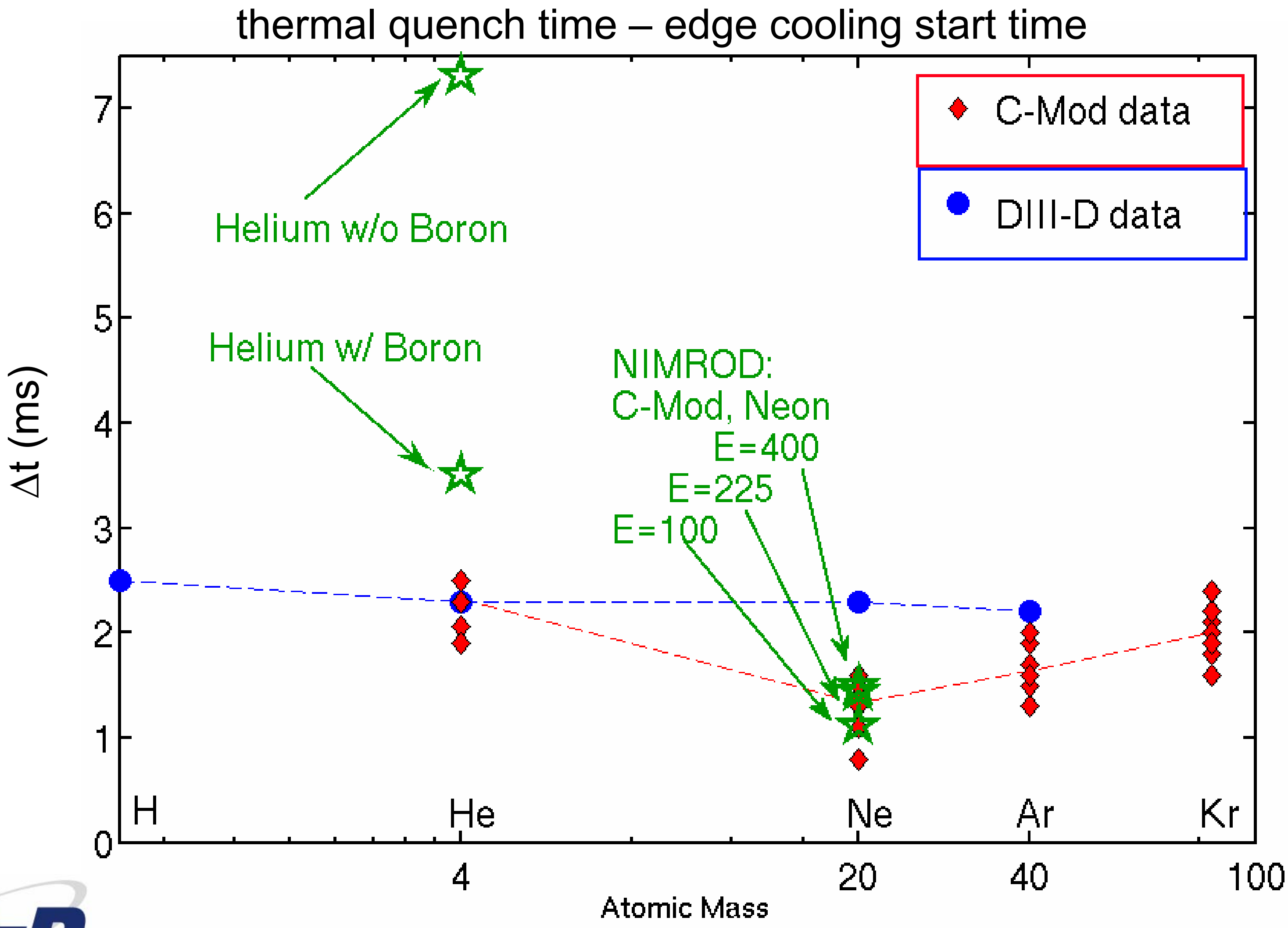
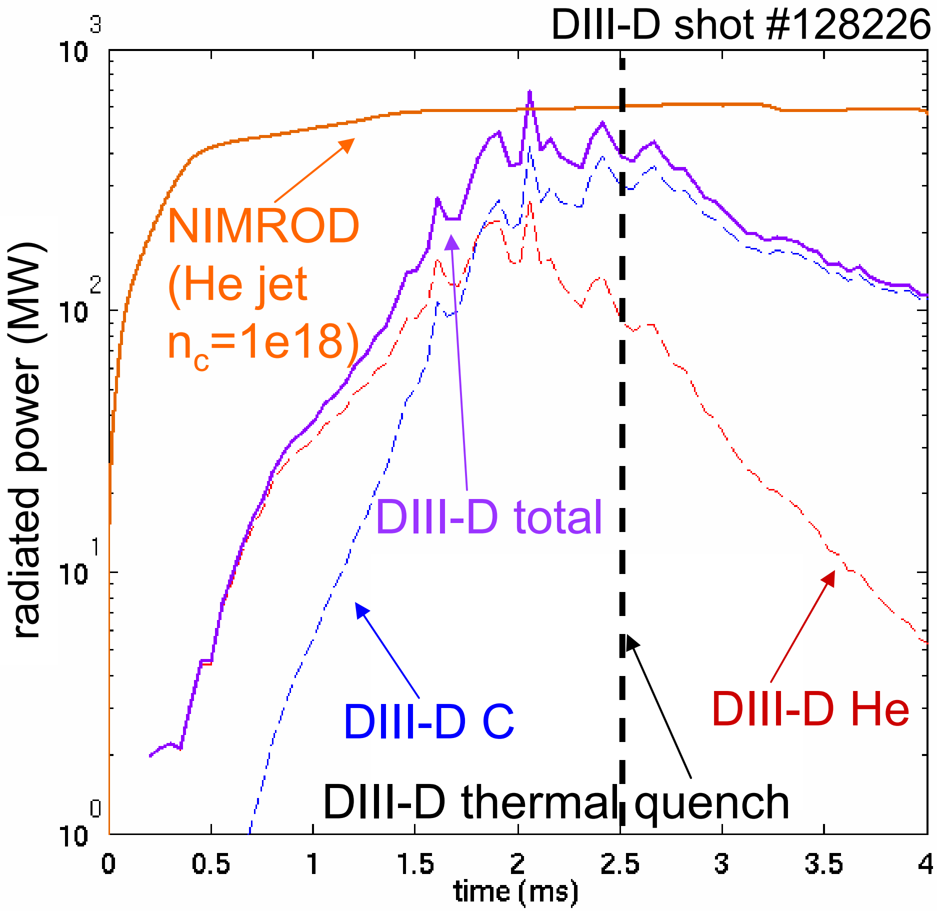


DIII-D Fast Radiated Power Measurement Allows Direct Comparison With NIMROD



- **DIII-D helium jet radiated power measurements show slow rise, not constant low level then large spike**
- **Helium radiation dominates early on, carbon radiation dominates later in time**
- **NIMROD simulation has fast rise time for total P_{rad} – may be due to toroidally, poloidally uniform gas injection**
- **Peak amplitude is comparable**

Simulation with E=900

($S_{DIII\text{-}D}=9\times10^7$, $S_{sim}=1\times10^5$)

Summary

- **Research on MGI for Disruption mitigation is ongoing on both Alcator C-Mod and DIII-D, but densification of the core for runaway prevention remains the biggest concern**
- **Atomic physics package has been incorporated into NIMROD to simulate disruption mitigation techniques**
- **Simulations reproduce the qualitative behavior of MGI experiments: jet cools edge, destabilizes MHD modes, rapid core thermal quench**
- **Simulated and experimental density profile results must be reconciled**
- **Thermal quench onset time at E = 100-400 approximately matches C-Mod experimental time for neon gas jet**
- **Simulations with helium gas jets will require accurate background impurity profiles for better comparison with experiment**

ITER Predictability is the Ultimate Goal

- **Improvements to the Model**
  - better understanding of neutral fueling, localization of gas jet
  - Free boundary simulations (allows transport across separatrix)
  - More accurate background impurity profiles/modeling
  - Higher S, further exploration/validation of rescaling

- **Further benchmarking against DIII-D, including high Z gases**

- **Runaway electron analysis including seed terms, avalanching and confinement**
  - DIII-D runaway diagnostic will allow comparison with code
  - C-Mod plans to study runaway confinement by intentionally creating seed population with LHCD
- **Other mitigation techniques: designer pellets, liquid jets, etc.**

- **ITER simulations of promising, well benchmarked techniques**