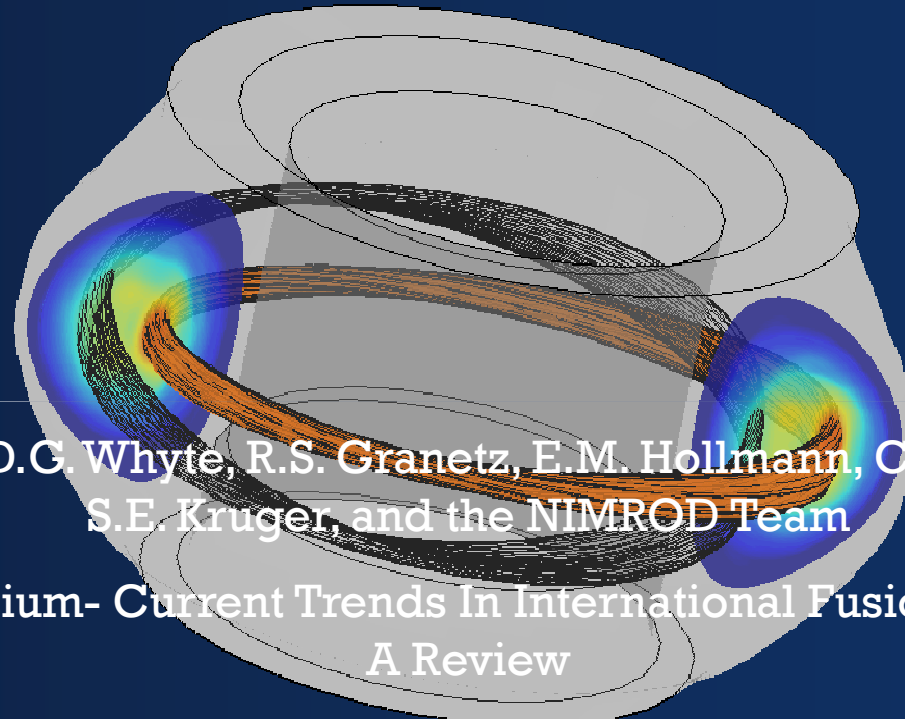


NIMROD EXTENDED MHD SIMULATIONS FOR DISRUPTION MITIGATION STUDIES



V.A. Izzo, D.G. Whyte, R.S. Granetz, E.M. Hollmann, C.R. Sovinec,
S.E. Kruger, and the NIMROD Team

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Key Points - Disruptions

A tokamak **disruption** occurs when a sudden loss of magnetic confinement leads to a rapid transfer of the stored energy in the plasma to the walls and surrounding structure

A disruption can produce **strong electromagnetic forces** on the containing vessel and **large heat fluxes** to the wall, both of which can **damage the device**

On present tokamak experiments, disruptions are a considerable nuisance, but the **larger volume** and **higher stored energy** of ITER create a bigger problem

We need to learn to **avoid disruptions** or **mitigate their damaging effects** in order to avoid potentially serious damage to ITER

Disruption mitigation methods are presently being explored on several tokamaks

Key Points – Disruption Mitigation

Successful disruption mitigation experiments have been performed of several devices, but not all of the physics is well understood

Results from smaller tokamaks can be extrapolated to ITER by two means—analytically or with detailed numerical simulations, but both methods require a good understanding of the relevant physics

Simulations can both aide in understanding the results of present experiments, and, when benchmarked against those experiments, can provide the most accurate predictions for the efficacy of a particular disruption mitigation strategy on ITER

This talk will focus on simulations aimed both at understanding and predicting the effectiveness of mitigating disruptions by massive gas injection

Outline

- Description of NIMROD code
- Examples of tokamak research with NIMROD
- Motivation/Background on disruptions
- Mitigation strategies
- Experimental results → implication for the role of MHD
- NIMROD results, experimental comparison
- Unsolved problems
- Inclusion of atomic physics in NIMROD, results
- Conclusions

The NIMROD code

- NIMROD is a 3D, nonlinear, extended MHD code used for a variety of plasma physics and fusion applications including space physics, innovative confinement concepts, and tokamaks
- Poloidal plane is represented by a mesh of finite elements, with the toroidal direction represented by a finite Fourier series.
- Semi-implicit or implicit time advance
- Initial equilibrium is assumed to be steady state solution– implicitly includes all sources and sinks
- A variety of options for terms in the equations– resistive MHD, hall and two-fluid physics, transport models...
- Can approach realistic tokamak parameters, but not experimental pulse lengths

The NIMROD equations

Momentum

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

Continuity

$$\frac{dn_e}{dt} + n_e \vec{\nabla} \cdot \vec{V} = \nabla \cdot D \nabla n_e$$

Energy

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

Ohm's law

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

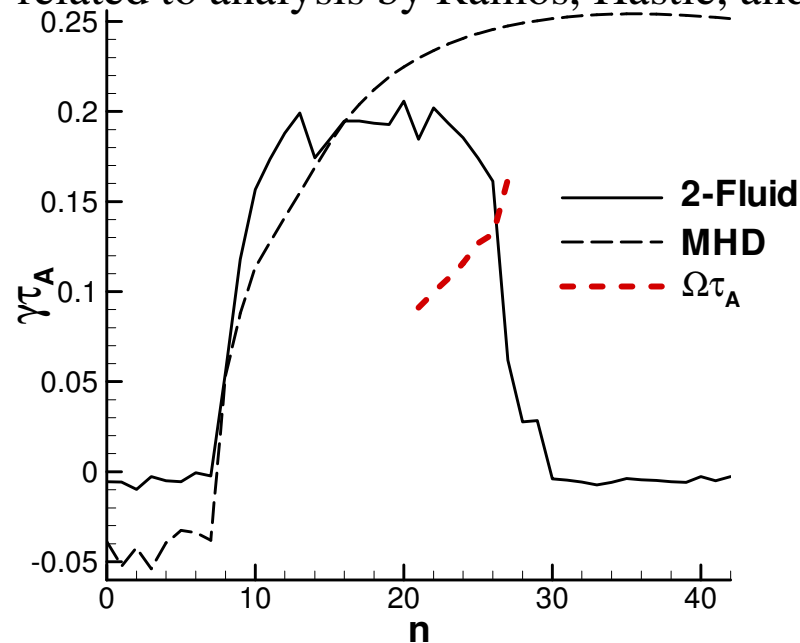
Transport

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

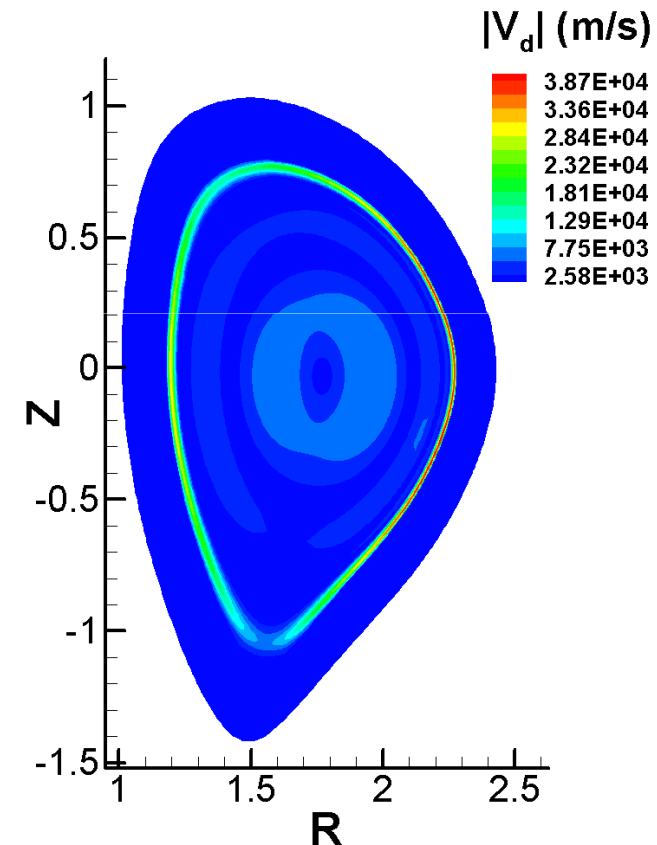
Linear Two-Fluid ELM Results from NIMROD

The NIMROD Team

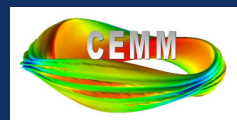
- Two-fluid cutoff of linear ELM spectrum for DIII-D 113317 equilibrium is confirmed.
- The diamagnetic drift profile is narrower than low-n ELM eigenfunctions.
- Computed stability threshold is at ω_{*i} much greater than $2\gamma_{\text{MHD}}$, which appears to be related to analysis by Ramos, Hastie, and Catto.



Comparison of resistive MHD and two-fluid growth-rate spectra. Mode frequency is not a simple Doppler shift.



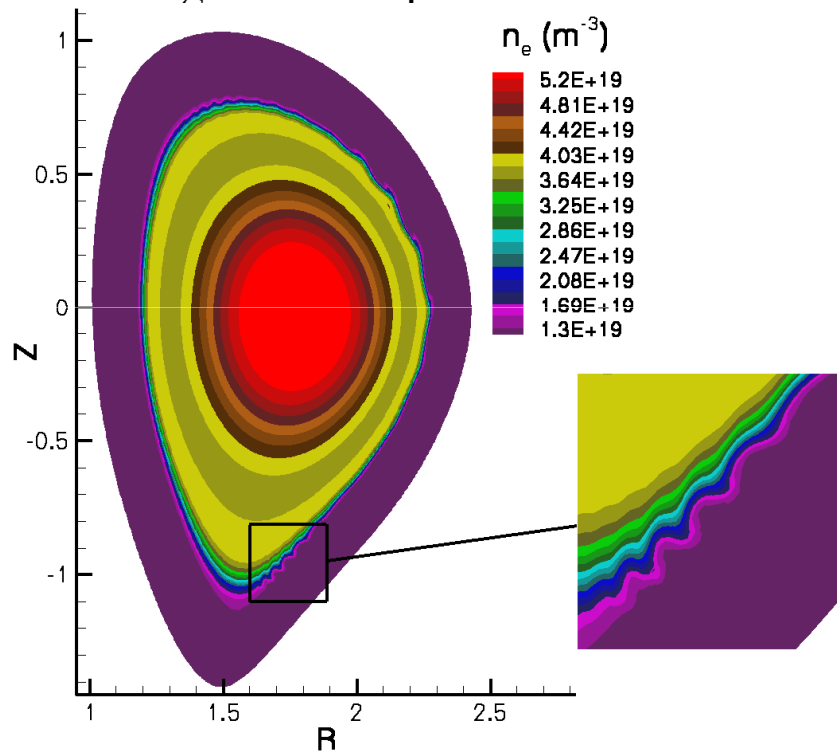
Poloidal component of diamagnetic drift.



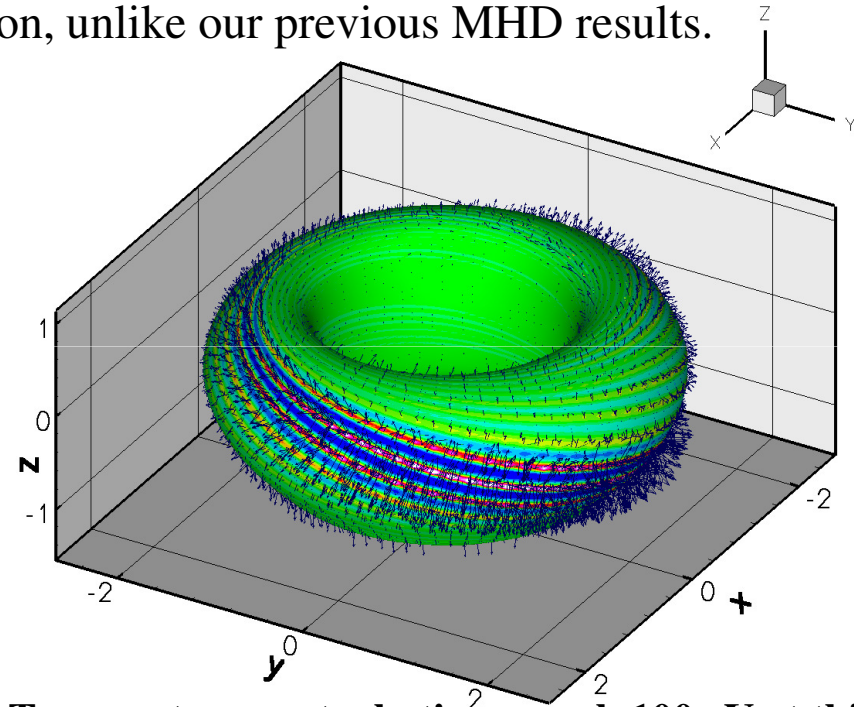
Nonlinear Two-Fluid ELM Computation with NIMROD

The NIMROD Team

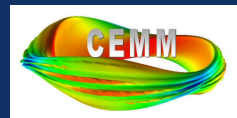
- Project's first large-scale 3D computation with Hall effect and Braginskii gyroviscosity.
- Nonlinear evolution from DIII-D 113317 equilibrium includes toroidal modes $0 \leq n \leq 42$.
- Beating of modes produces helical localization, unlike our previous MHD results.



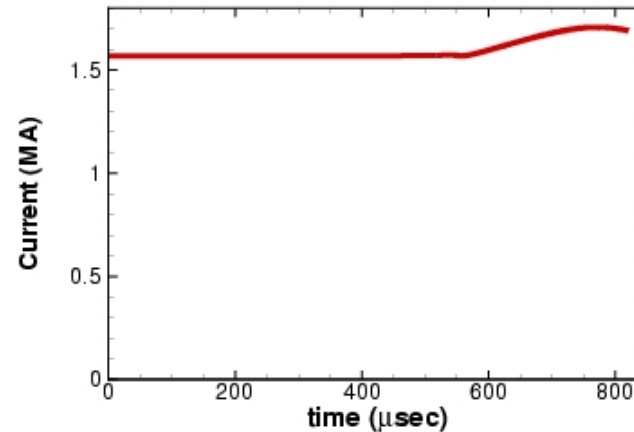
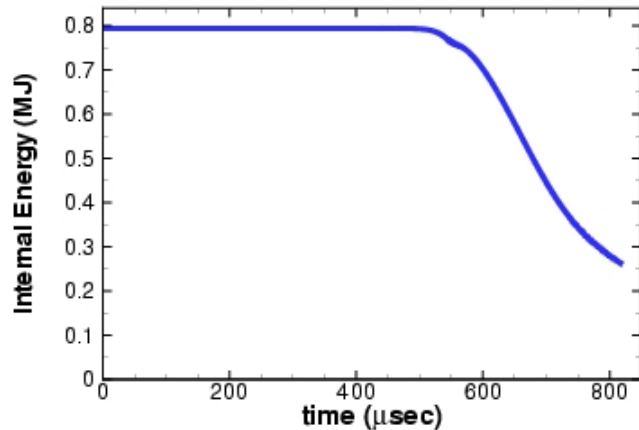
Number density in the $\phi=0$ plane at simulation shows poloidally localized ripples.



Temperature perturbations reach 100 eV at this time ($T_{ped}=400$ eV) and display a nonlinear helical structure. Perturbed plasma flow vectors are superposed.



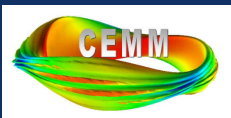
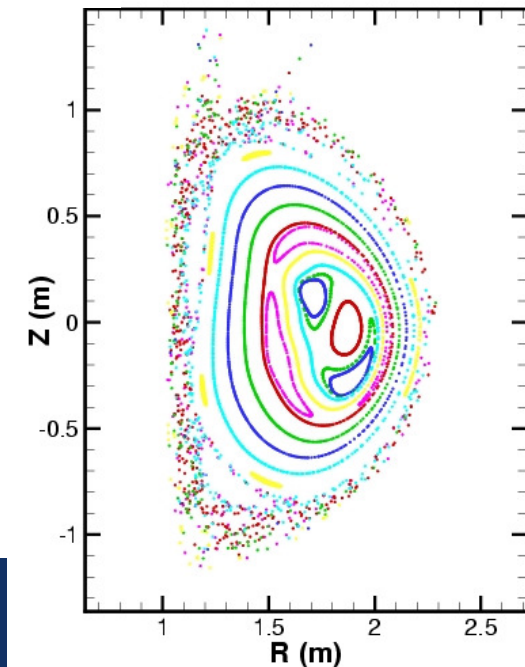
NIMROD Simulation Shows Qualitative Features of Tokamak Plasma Disruptions



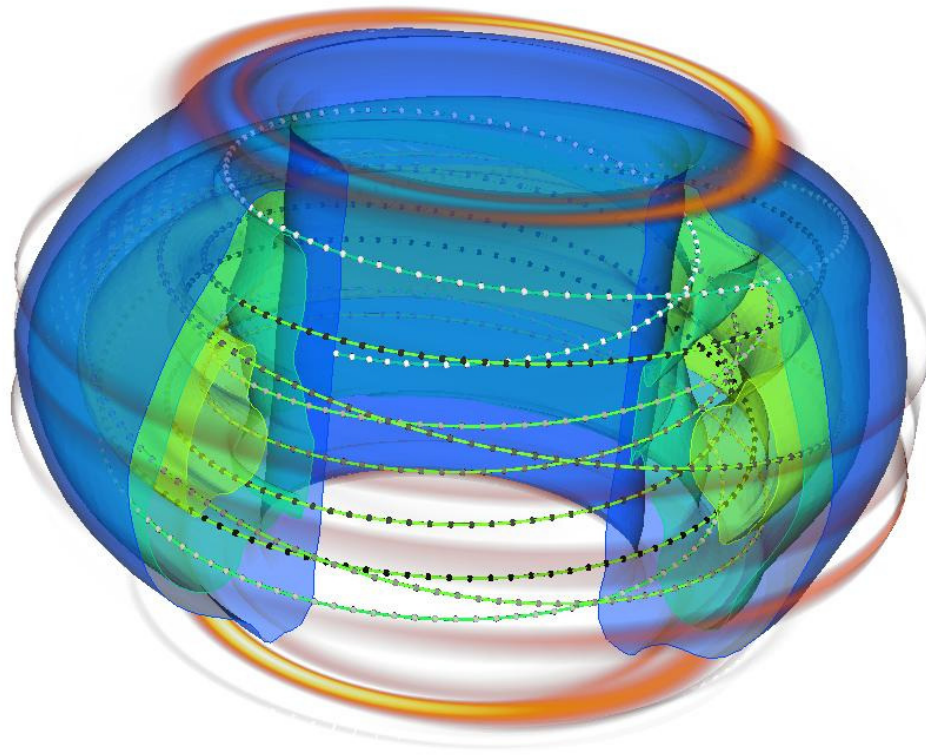
Plasma produces current spike as internal inductance changes

Plasma loses 60% of magnetic energy in ~200 microseconds

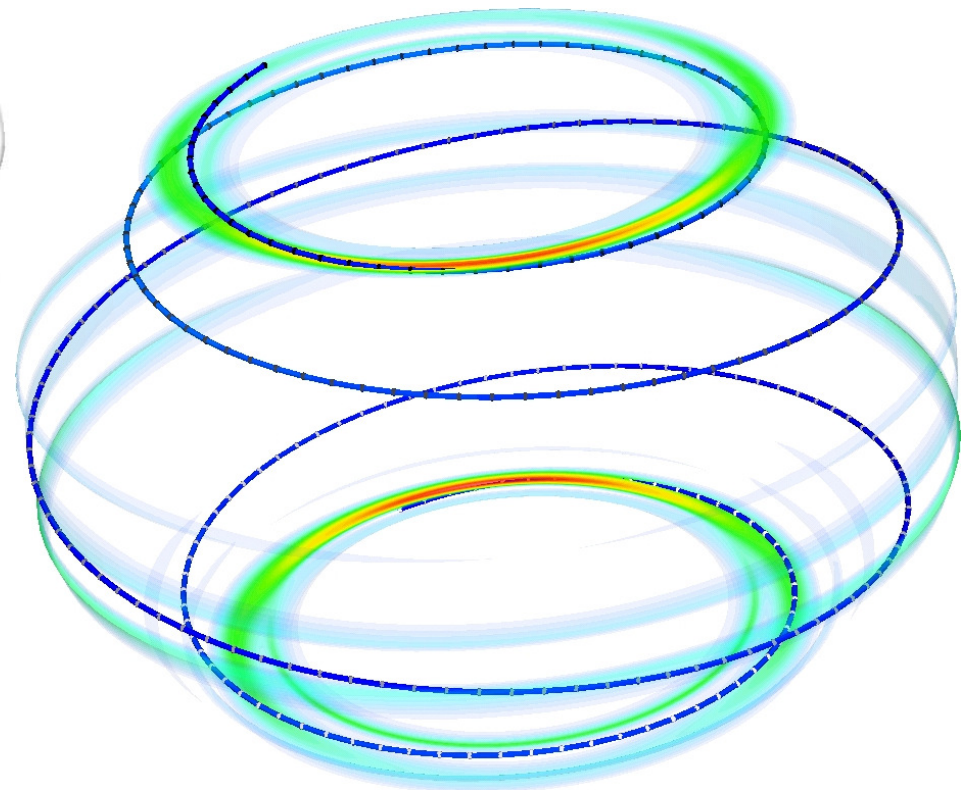
Time scale set by heat transport in complex topological field as the magnetic field becomes stochastic



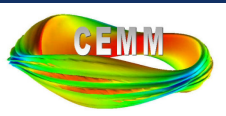
NIMROD Simulation Can Show Heat Flux Localization Due to Magnetic Field Topology



Localization has important
engineering consequences



Mitigation is needed...



Three problems with disruptions

1) Heat loads :

MHD instabilities + plasma vertical motion opens core field lines, large heat loads are conducted to the wall (especially the divertor)

2) Halo currents :

Open field lines conduct current to the wall, current flows poloidally through the divertor (or wall), produces large $j \times B$ forces

3) Runaway electrons :

Rapid thermal quench produces large electric fields leading to production and amplification of high energy runaway electrons (which must be stopped by the wall).

The problems get worse

Heat flux during the thermal quench

$$\sim (W_{\text{th}}/S_{\text{wall}}) \sim R$$

eg. $R_{\text{ITER}}/R_{\text{DIII-D}} \approx 3.6$

Forces due to halo currents during the current quench

$$\sim I_p B_T R$$

eg. $F_{\text{ITER}}/F_{\text{C-Mod}} \approx 50$

Runaway avalanche amplification

$$\gamma t \approx 2.5 I_p (\text{MA})^*$$

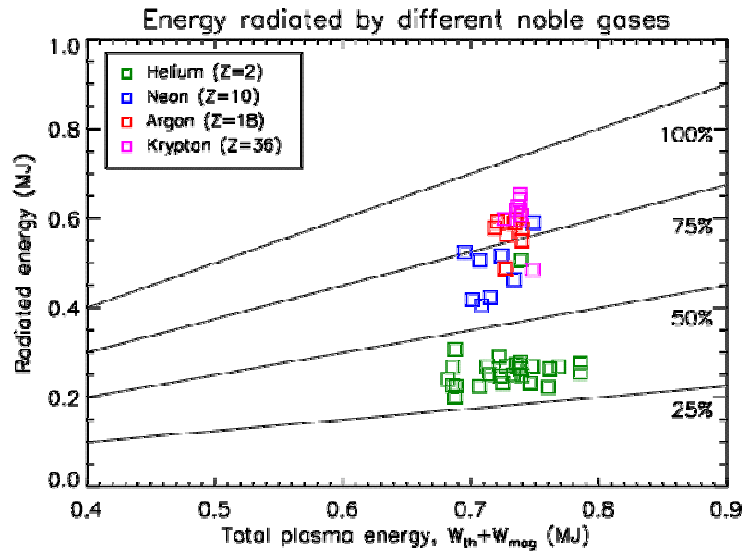
eg. DIII-D: $A = e^{\gamma t} \approx 50$, ITER : $A = e^{\gamma t} \approx e^{40}$

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

What do we do about it?

- Disruptions probably can not be avoided entirely (although disruption avoidance should be attempted)
- Ideal shutdown is isotropic radiation of all plasma stored energy on a controllable time scale → must beat “natural” disruption time scale, but too fast may be a problem
- Critical electric field for runaway avalanche is proportional to density. Fifty fold density increase in ITER would be needed
- Most mitigation strategies involve the injection of large quantities of impurities as a solid, liquid, gas, or plasma
- Massive gas inject (MGI) will be the focus here
- MGI has been attempted on several devices worldwide, including Alcator C-Mod and DIII-D

Results from Alcator C-Mod MGI

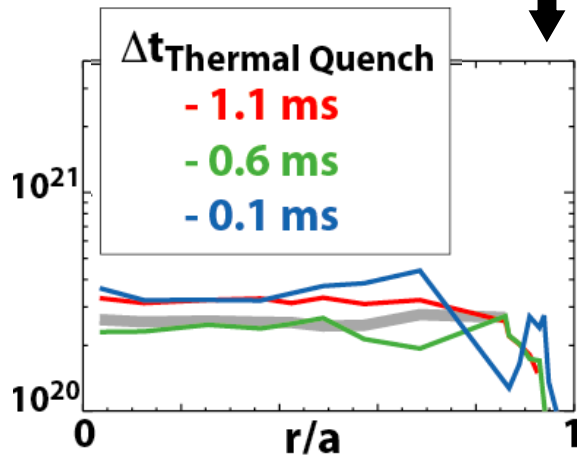


Fraction of total stored energy radiated increases with atomic number of injected impurity

Little or no jet penetration seen for high Z impurities during the thermal quench

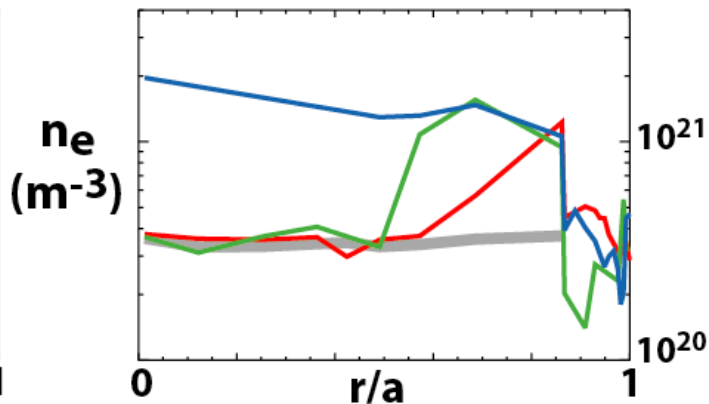
“Weak” penetration

Argon



“Stronger” penetration

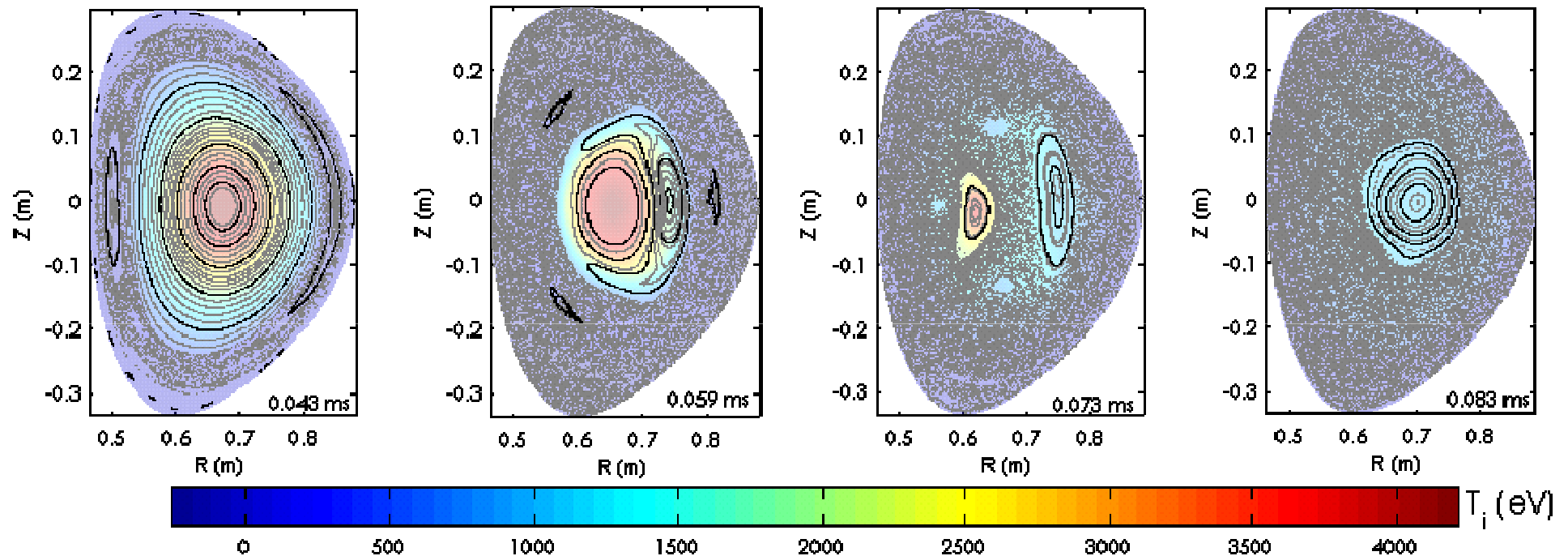
Helium



The Role of MHD

- Neutral jet does not penetrate high pressure plasma like Alcator C-Mod (or certainly ITER)
- Yet, high Z impurity jets show rapid thermal quench and good mitigation for halo currents and heat fluxes
- MHD plays a significant role
- Cooling of edge → MHD instabilities → enhanced transport of heat from core to radiating mantle and/or mixing of impurities in the core

NIMROD simulation of C-Mod mitigated disruption



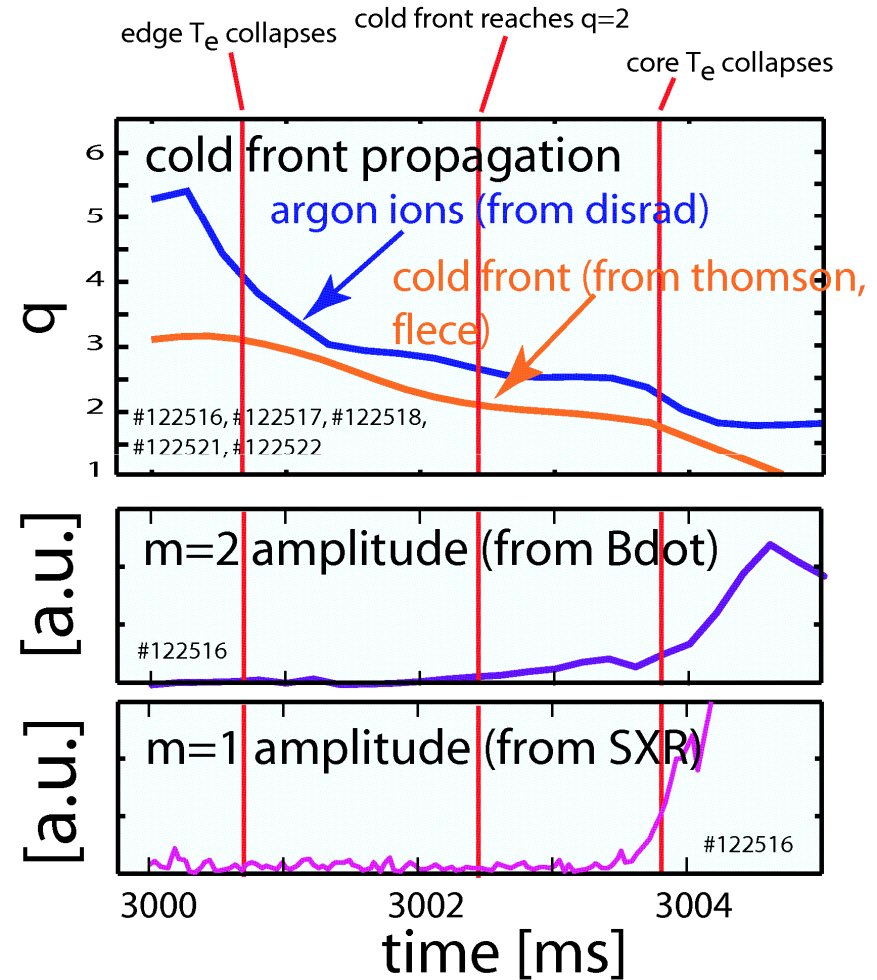
Edge cooling destabilizes 2/1 mode, stochastic region outside $q=1$ forms, 1/1 mode grows and convects heat out of the core

DIII-D experimental evidence shows same MHD sequence

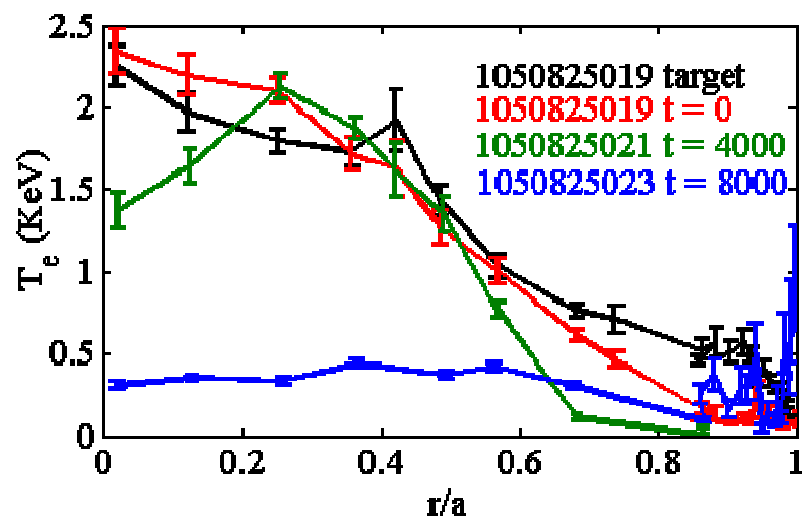
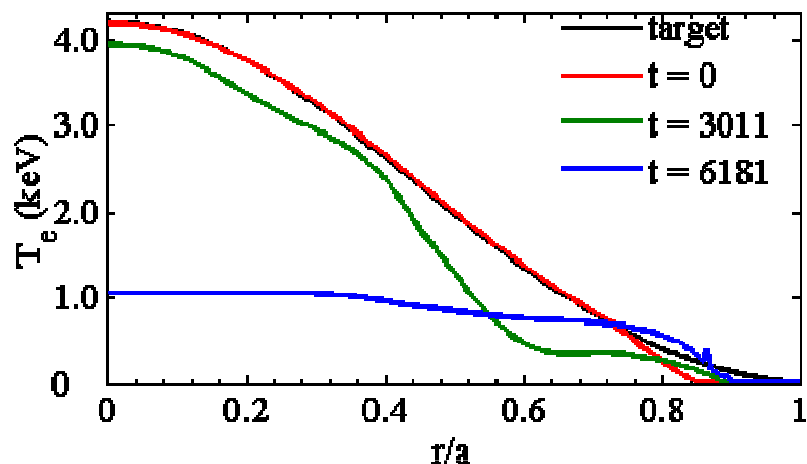
Inward propagation of cold front past rational q surfaces as $2/1$ and $1/1$ modes grow

Mode growth leads cold front

Argon ions lag behind cold front



Thermal quench characteristics are similar to C-Mod experiments



Thermal quench occurs in 3 stages:

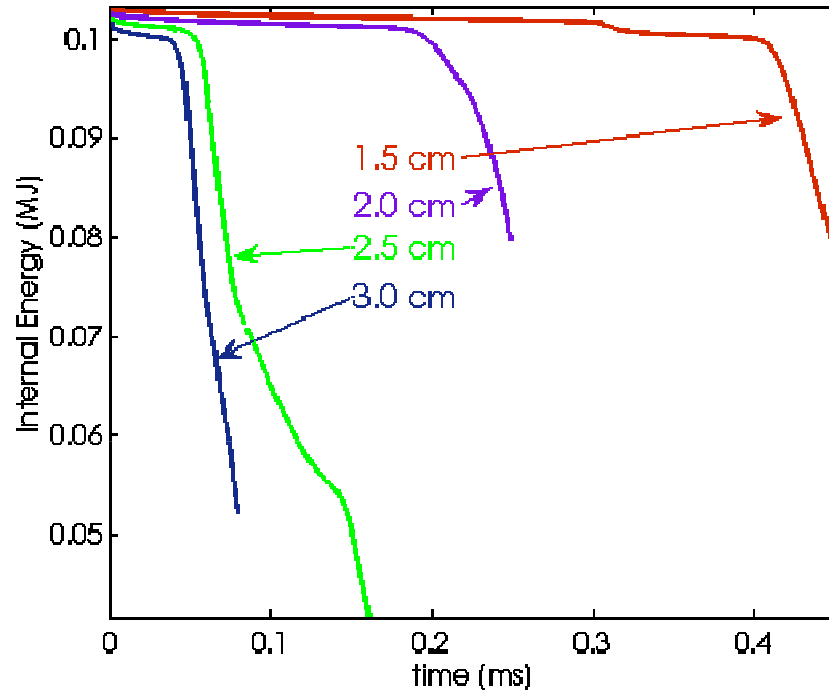
- 1) Outer few cm are cooled directly by impurities
- 2) Stochastic fields outside of $q=1$ lead to cooling of outer $\sim 40\%$
- 3) $1/1$ modes convects heat from core, collapsing central temperature

All times are in units of $(S/2 \cdot 10^7)^{0.6} \tau_A$

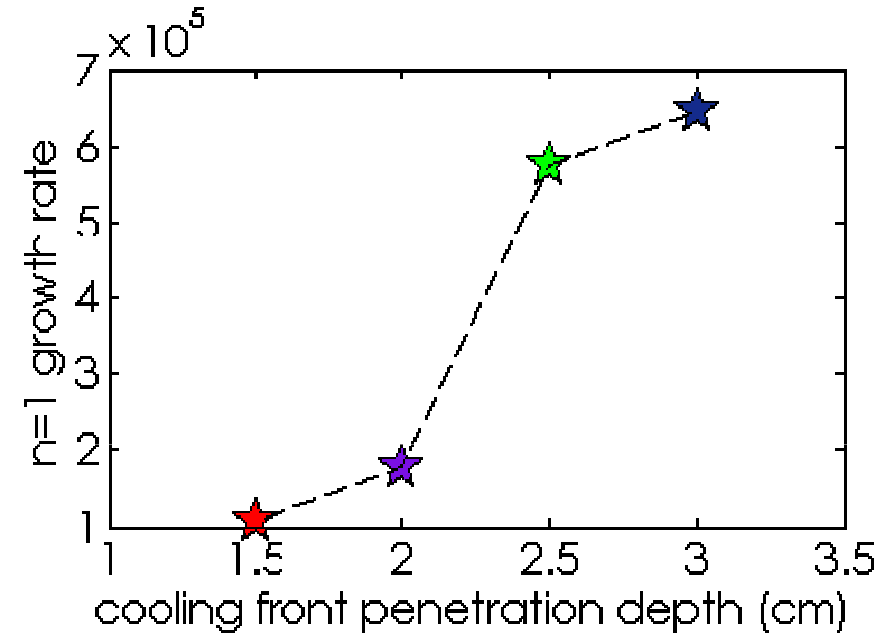
$t=0$ defined by edge temperature collapse

(no direct evidence for MHD modes on C-Mod– disruption time scales are too short)

Quench timing varies with penetration depth



- Delay before thermal quench onset when penetration is very shallow



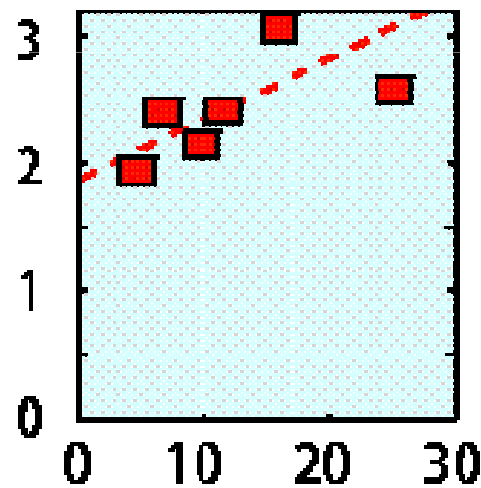
- Modes grow fastest when $q=2$ surface is cooled by the impurities

DIII-D results confirm importance of jet penetration vs. $q=2$ surface location

DIII-D experiments vary $q=2$ location for fixed penetration:

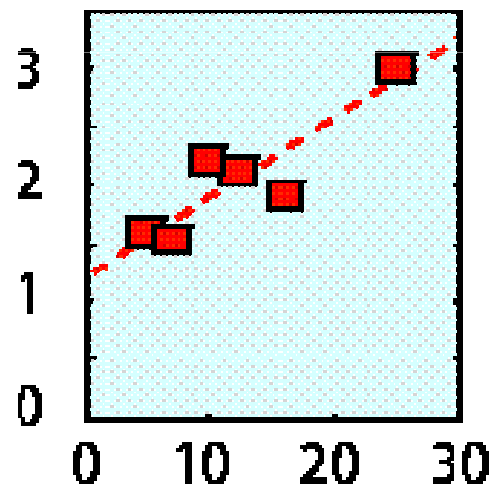
Cold front propagation time

(a) Δt_{CF} [ms]



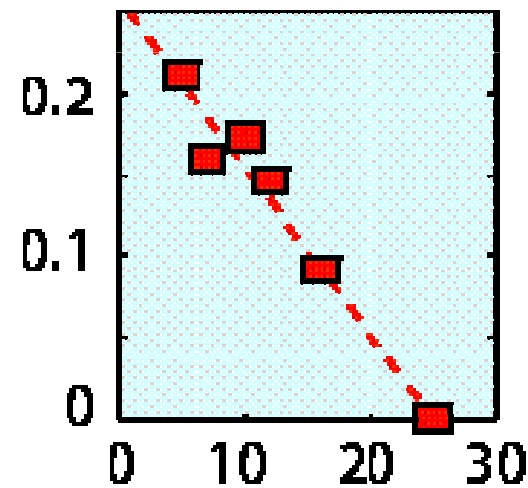
Thermal quench duration

(b) Δt_{TQ} [ms]



Size of current spike

(c) $\Delta I_p / I_p$ [-]



$\Delta r_{q=2}$ [cm]

From E.M. Hollmann

What we've learned about MGI

- MGI is an effective strategy for mitigating halo currents and heat fluxes, despite poor penetration of the jet
- MHD convects significant heat from core to edge and some impurities from edge to core
- Neutral jet penetration and ionized impurity mixing are not fully understood
- Runaway electrons remain a major problem
- Can significant quantities of impurities be mixed into the core of ITER fast enough to stop runaways?
- Will loss of confinement due to MHD turbulence prevent runaway production?
- These can be investigated with more detailed simulations...

Inclusion of atomic physics in NIMROD (KPRAD)

Momentum

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

Energy

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

Ohm's law

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

Continuity

$$\frac{dn_e}{dt} + n_e \vec{\nabla} \cdot \vec{V} = \nabla \cdot D \nabla n_e + \mathbf{S}_{\text{ion/rec}}$$

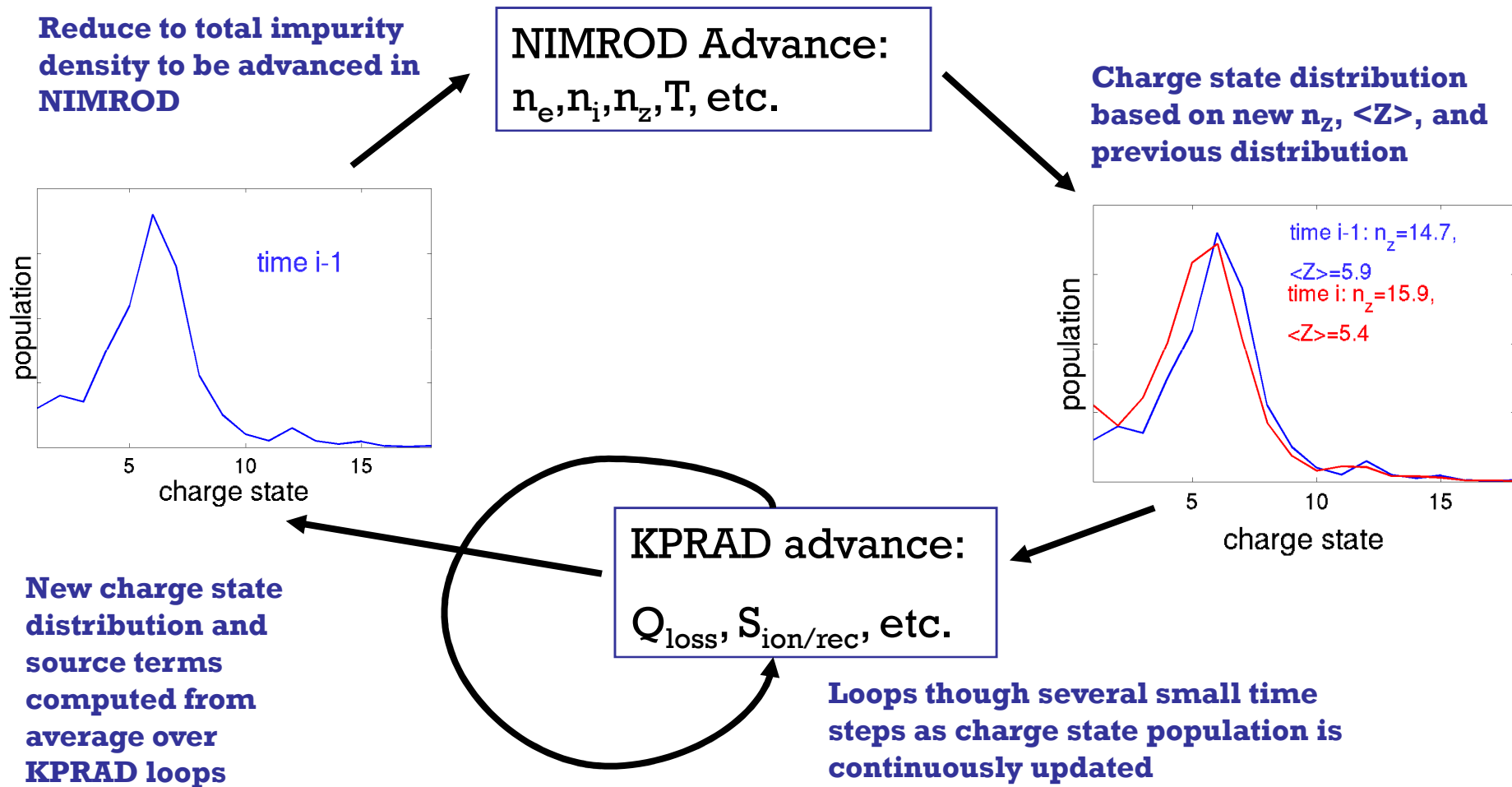
$$\frac{dn_i}{dt} + n_i \vec{\nabla} \cdot \vec{V} = \nabla \cdot \mathbf{D} \nabla n_i + \mathbf{S}_{\text{ion/3-body}}$$

$$\frac{dn_z}{dt} + n_z \vec{\nabla} \cdot \vec{V} = \nabla \cdot \mathbf{D} \nabla n_z$$

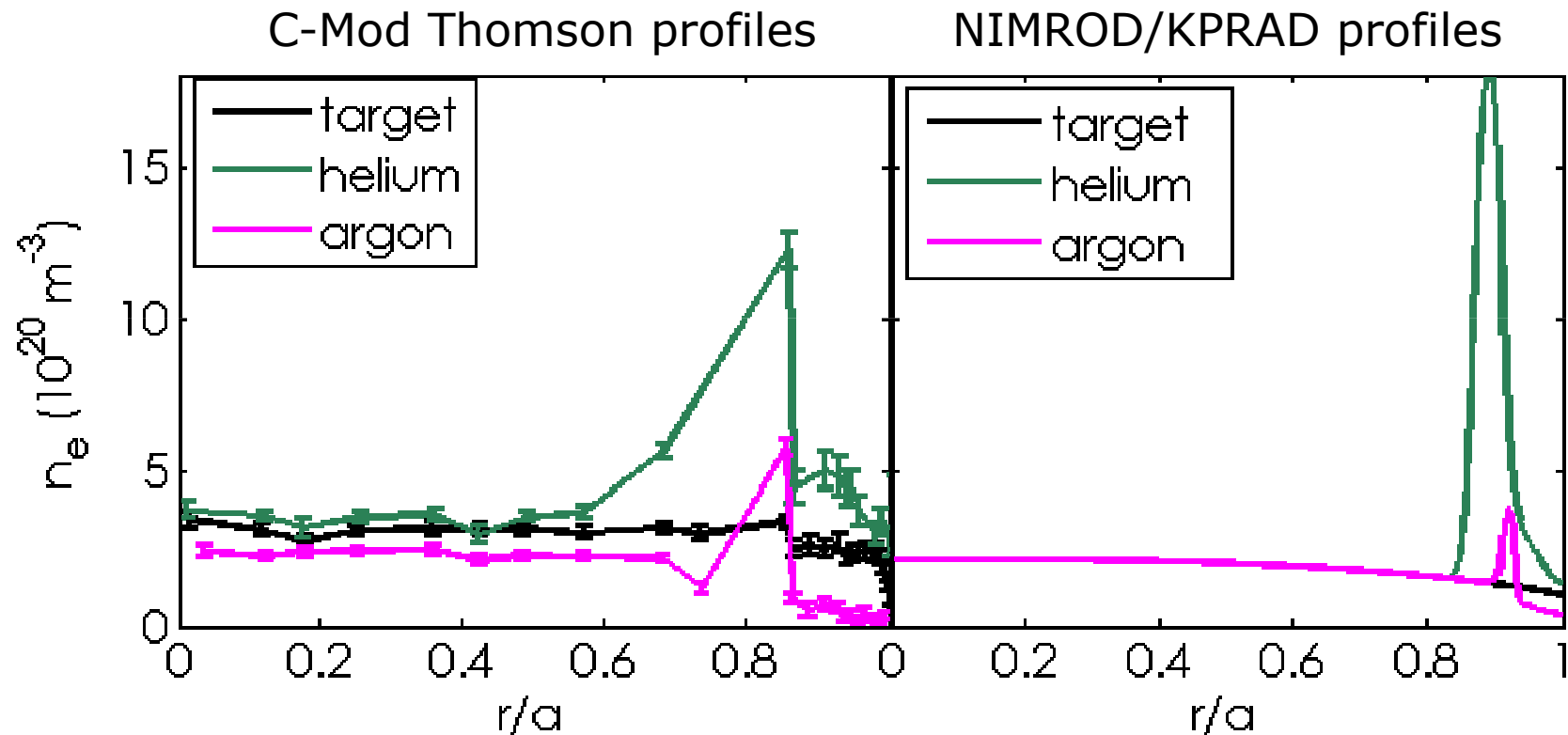
Quasi-neutrality

$$n_e = n_i + \langle \mathbf{Z} \rangle n_z$$

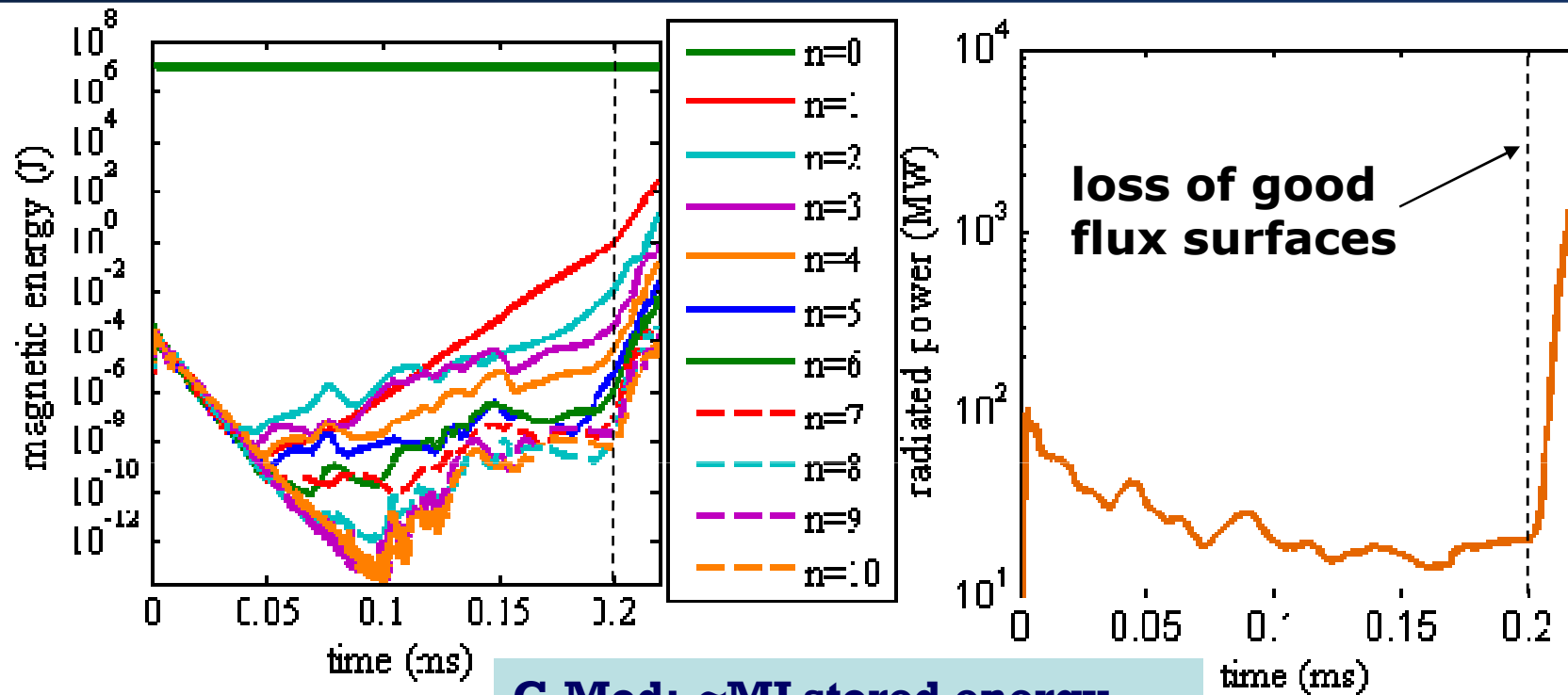
KPRAD called within NIMROD



Differences between low vs. high Z impurities captured by combined NIMROD/KPRAD code



Radiated power reaches necessary levels when flux surfaces are destroyed



C-Mod: ~MJ stored energy
~ms disruption time
⇒ ~GW radiated power

Simulation at low S ($\sim 10^4$)

Conclusions

Massive Gas Injection can effectively mitigate halo currents and heat fluxes, but runaway electrons are still an issue

MHD simulations with NIMROD have aided understanding of an MGI induced thermal quench, and qualitatively agrees with C-Mod and DIII-D results

MHD induced impurity mixing and post thermal quench confinement are not well understood

Predictive NIMROD simulations incorporating accurate atomic physics models can be used to explore both issues and make predictions about runaway electron production, scaling to ITER

Combined NIMROD/KPRAD code will be useful both for MGI simulations as well as alternate mitigation techniques if needed