Progress on NIMROD disruption mitigation modeling

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Presented at CEMM Meeting

11-16-08

DIII-D NATIONAL FUSION FACILITY

UCSD

Recent efforts focus on many aspects of the runaway electron problem

Three topics:

- D_2 Dilution cooling as an "optimal" runaway suppression mechanism (vast majority)
- Effects of plasma elongation on MHD and runaway confinement (very brief)
- Direct calculations of suprathermal electron acceleration and confinement (also brief)

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Overview of the runaway electron problem

- The crux of the problem:
  - Disruptions → large E fields → high energy runaway electrons
  - Avalanche amplification of runaways:

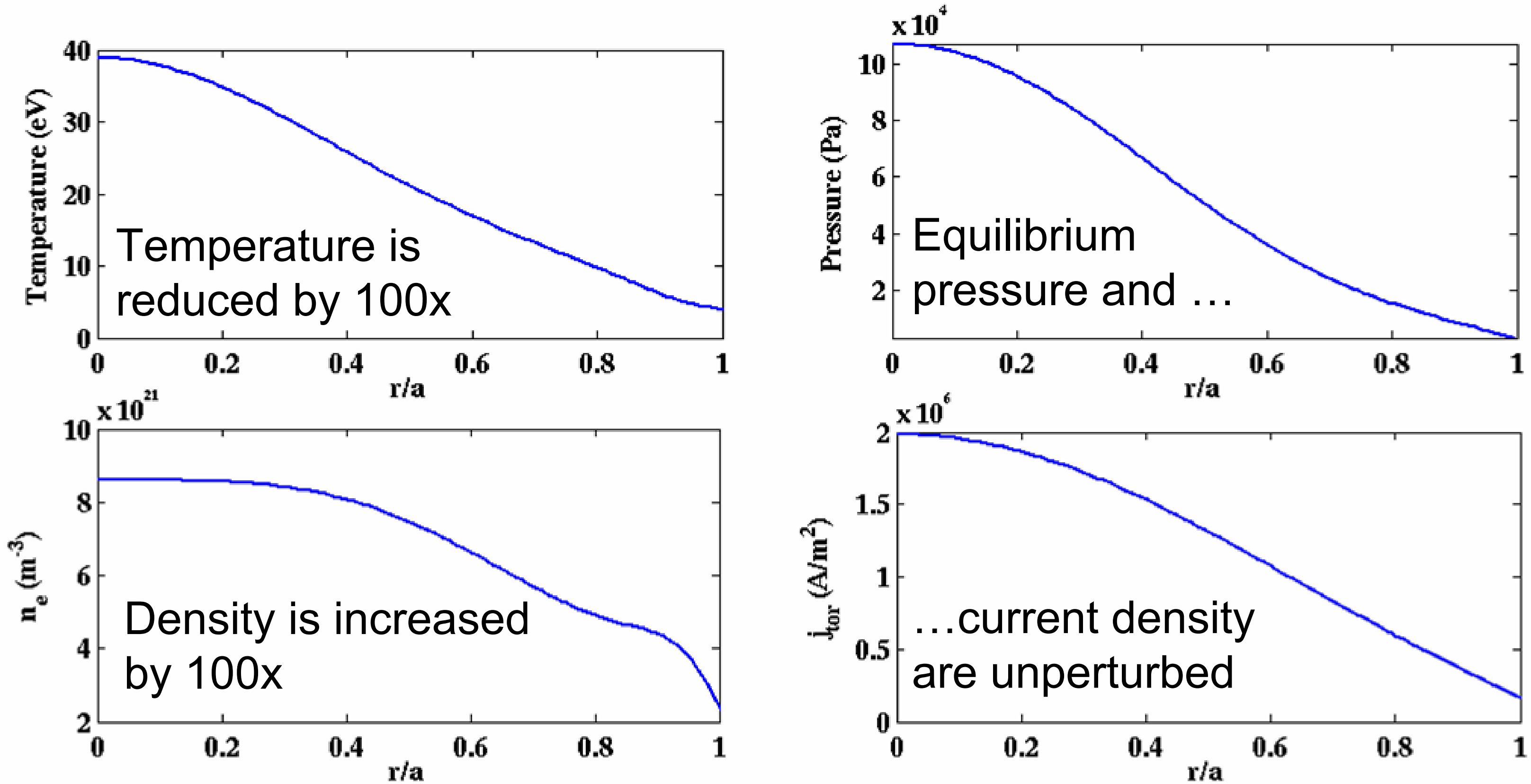
    $$A = \exp(\gamma t) \approx \exp(2.5 I_p)$$ (Huge in ITER)
- Solutions?
  - Collisional suppression $E_{crit} = 0.12 n_{e,20}$
  - Confinement time shorter than acceleration time

D_2 dilution should be optimal for collisional suppression

$$E / E_{crit} = \eta(n, T) j / 0.12 n_{e,20} \propto T^{-3/2} n^{-1}$$

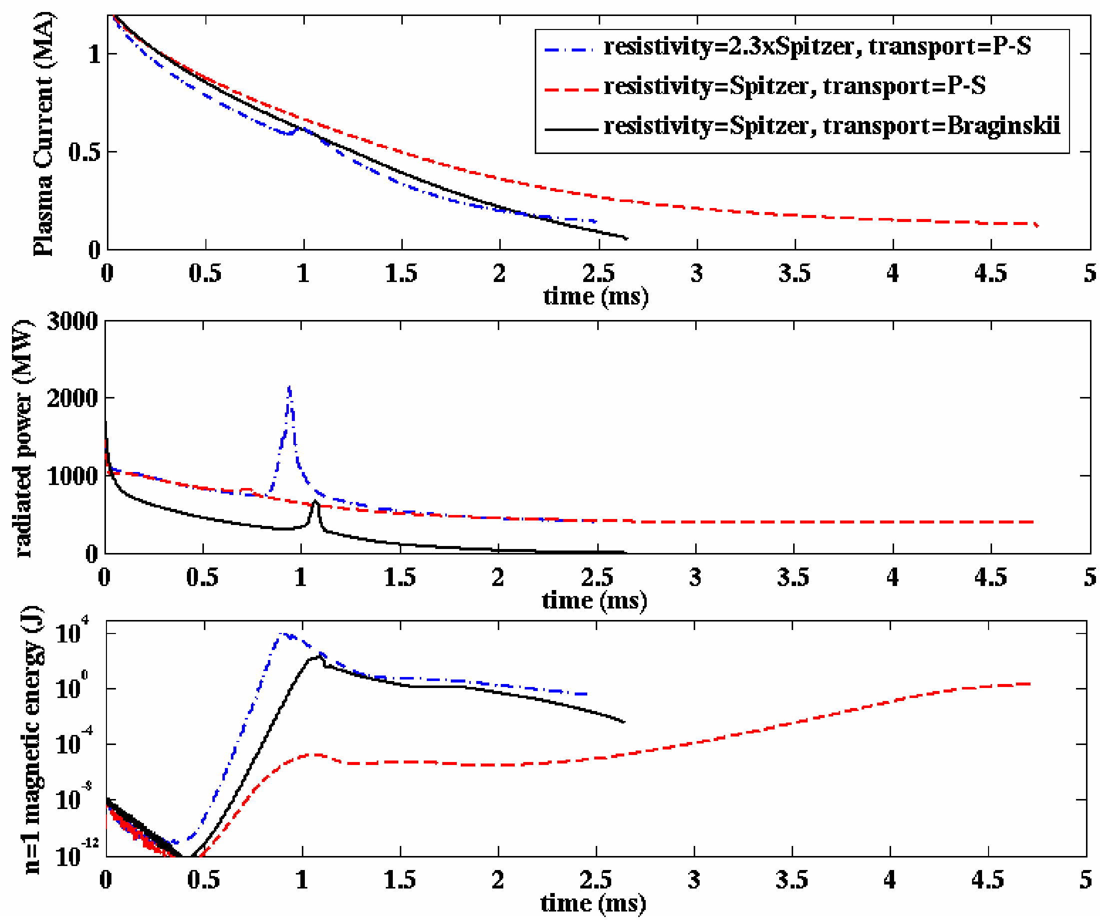
- The least cooling for the largest density increase minimizes E/E_{crit}
- Imagine cooling purely by D_2 dilution, neglecting all radiation and atomic physics. Then $T \sim n^{-1}$. In this case, $E/E_{crit} \sim n^{1/2}$
- When the temperature drops more strongly due to radiative cooling, then E/E_{crit} rises more sharply with density. Since the thermal quench precedes the current quench, E/E_{crit} always gets worse before it gets better
- In normal DIII-D operation, assume T=4keV, $n=8\times10^{19}/m^3$, $j=2\times10^6 A/m^2$. Then we have **E/E_{crit}=0.09**
- For ITER nominal parameters of T=8.9keV, $n=10^{20}$/m3, $j=1.4\times10^6 A/m^2$, this gives us **E/E_{crit}=0.01**

DIII-D Simulation assumes 100x density increase, in-situ carbon



A uniform carbon density of 1% of the pre-dilution core electron density ($8.6\times10^{17}/m^3$) is assumed. At this initial T_e (~40eV), the physical value of Spitzer resistivity can be used for the simulation without numerical difficulty

Both resistivity and thermal conduction impact occurrence/amplitude of MHD



Two perpendicular heat transport models are considered:

Pfirsch-Schluter-

$$\chi_\perp (m^2/s) = \frac{1.411\times 10^{-21} n \ln \Lambda_i}{B^2 T^{1/2}} (1+1.6q^2)$$

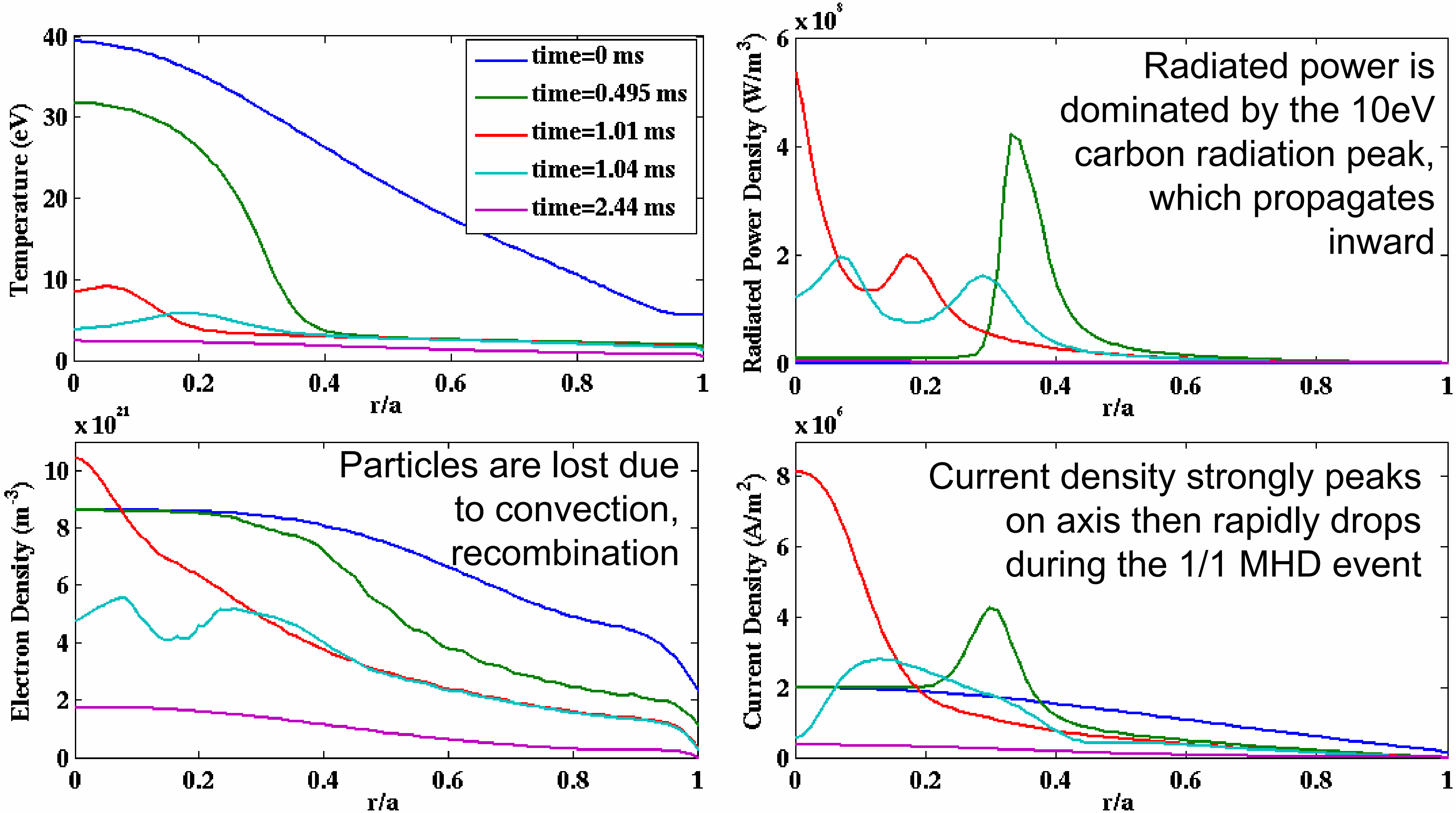
Braginskii-

$$\chi_\perp (m^2/s) = \frac{2kT}{m_i \omega_{ci}^2 \tau_i} \approx \frac{2.4\text{x}10^{-20} n}{B^2 T^{1/2}}$$

Difference is ~3-4x

Two values of resistivity, Spitzer and a factor of 2.3 higher

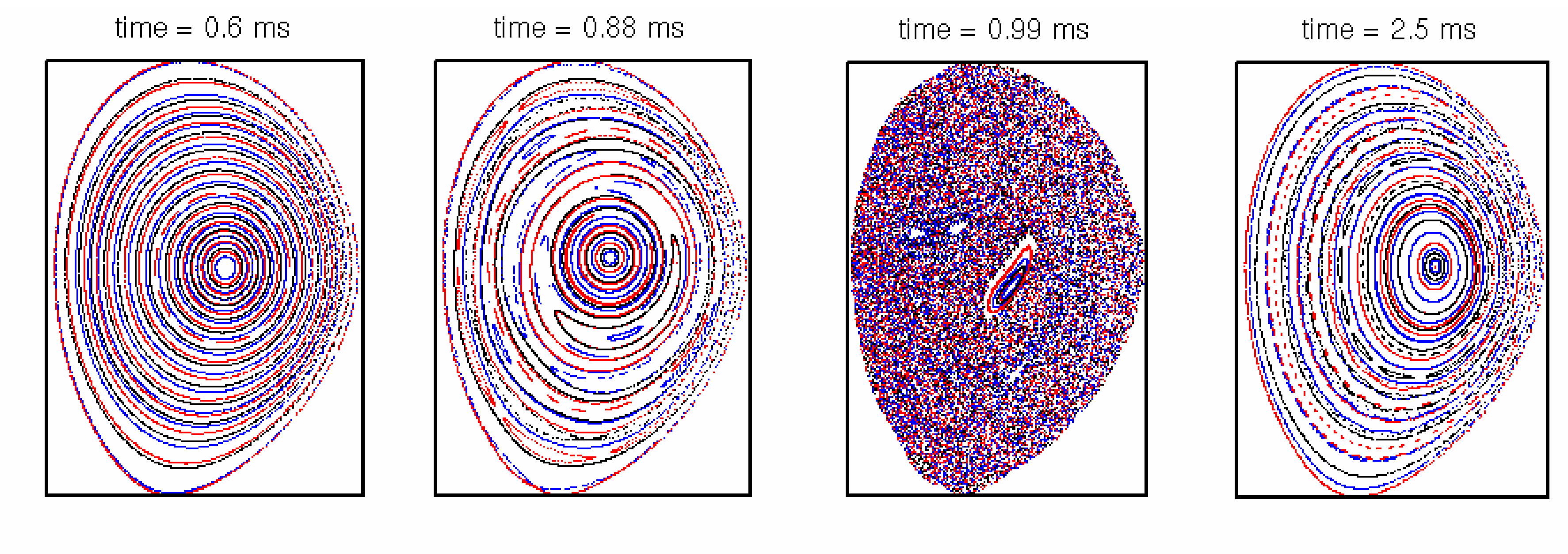
Significant current peaking can occur



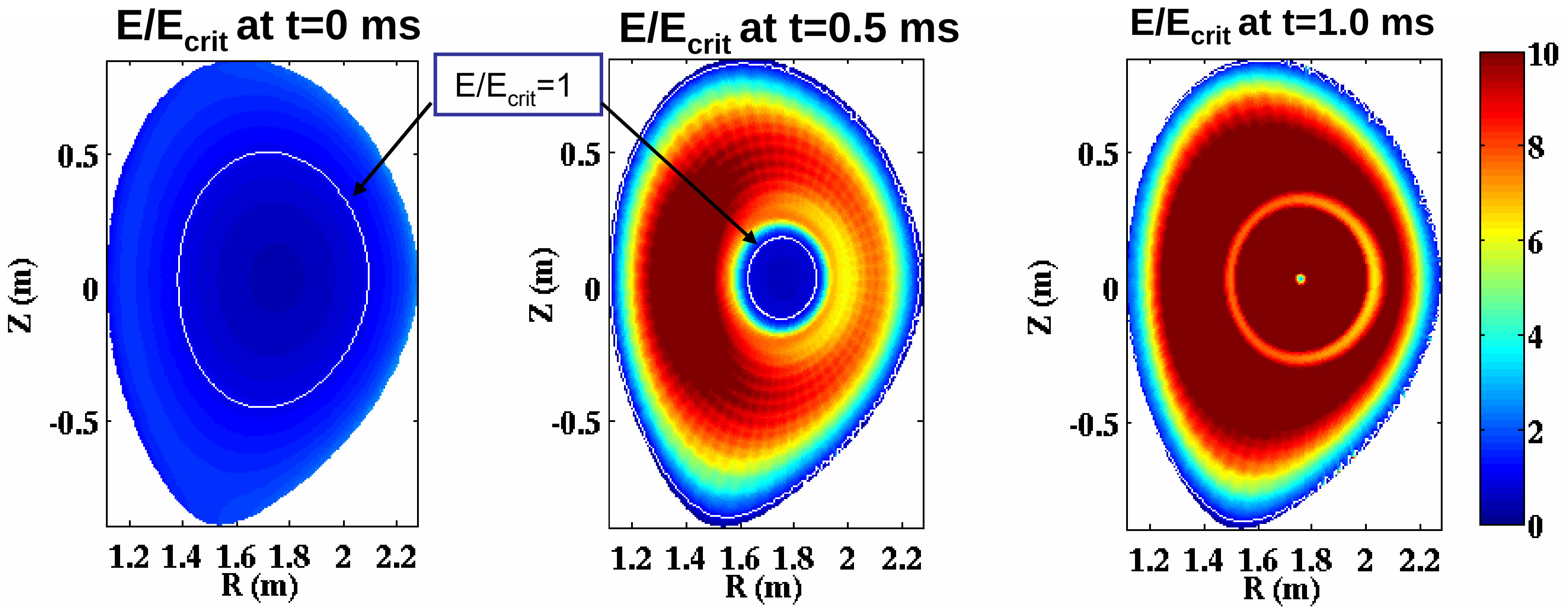
Spitzer resistivity, Braginskii transport

Flux surfaces tend to re-heal in the current quench

The case with the most significant MHD (P-S transport, 2.3 times Spitzer resistivity) sees nearly all flux surfaces destroyed after 1/1 crash, but the flux surfaces mostly reform by the end of the current quench

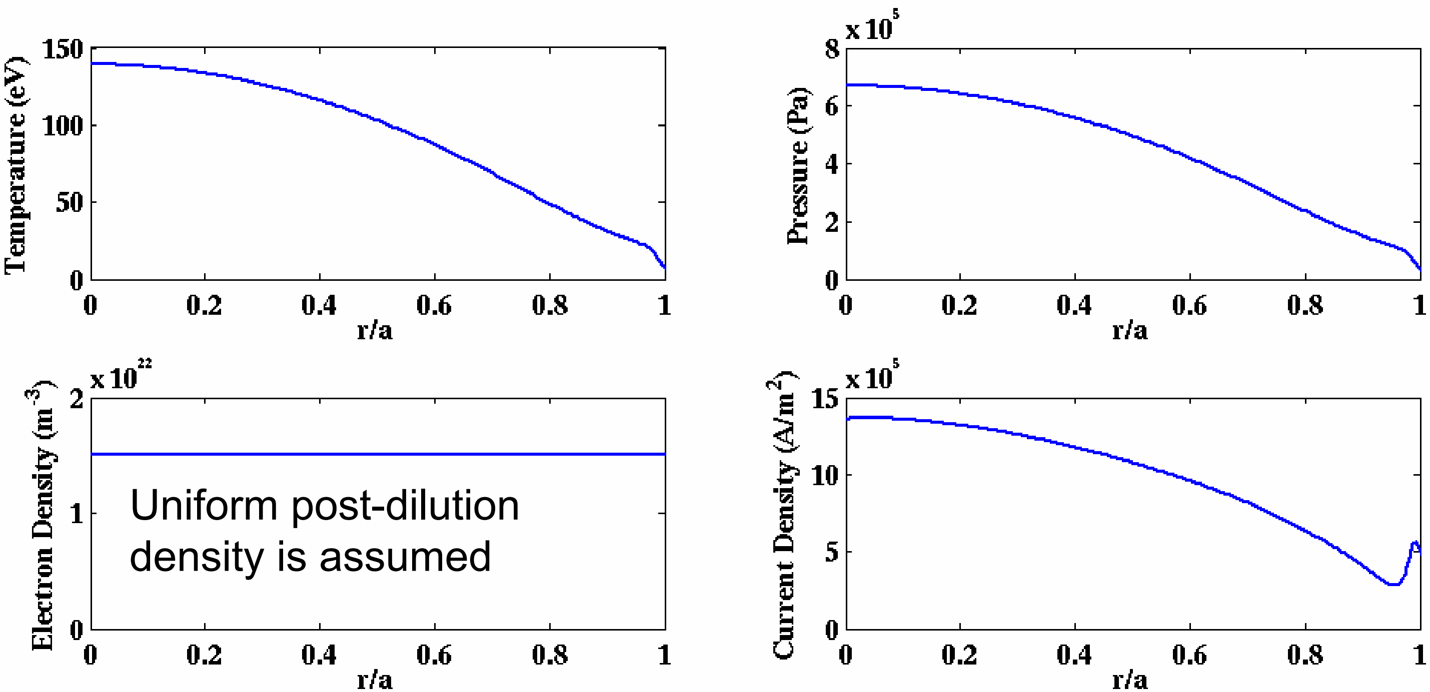


Rosenbluth ratio in DIII-D is bad news



ITER simulation has 150x density multiplication

- An ITER equilibrium generated by L. Lao is used
- D_2 dilution cooling by a factor of 150 is assumed for the initial condition, where the post dilution density is assumed to be a uniform value of $1.5x10^{22}/m^3$



- A uniform beryllium density of 1% of the pre-dilution electron density ($10^{18}/m^3$) is assumed. The beryliium radiation is comparable to the bremsstrahlung in some regions, but does not dominate the overall radiated power

- Simulation is run at actual Spitzer resistivity, P-S transport

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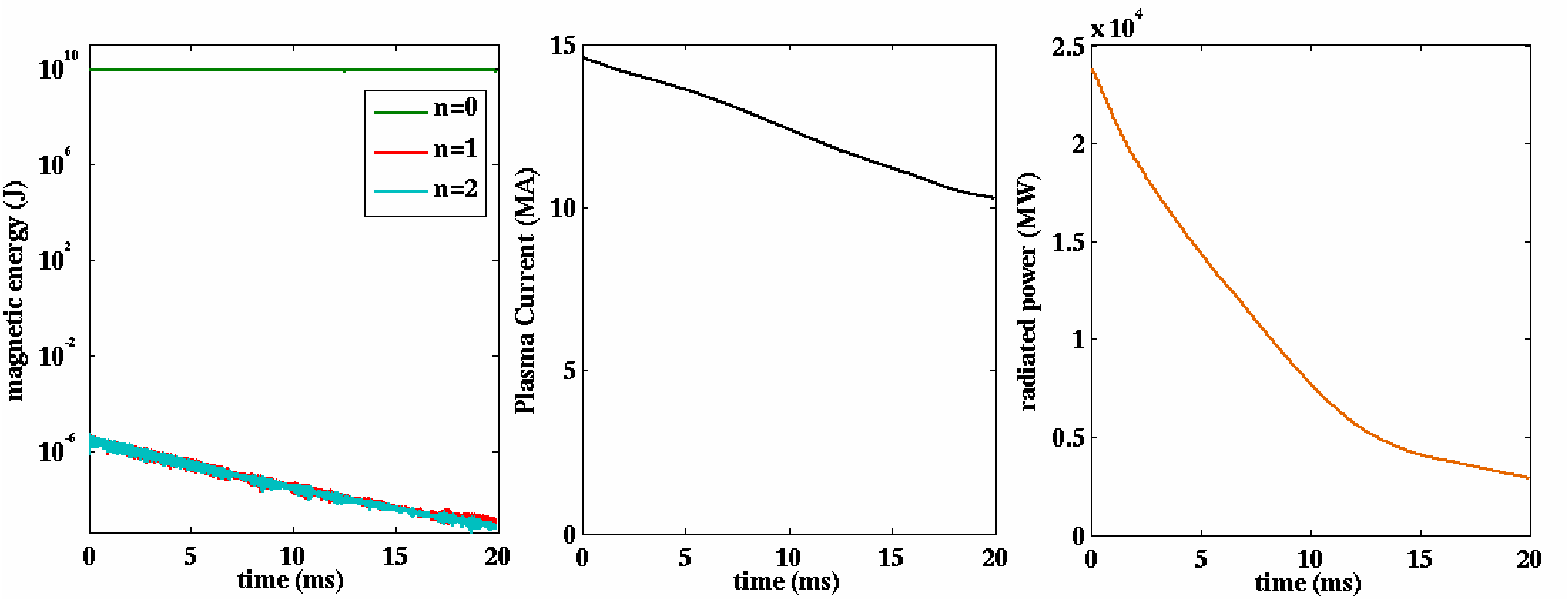
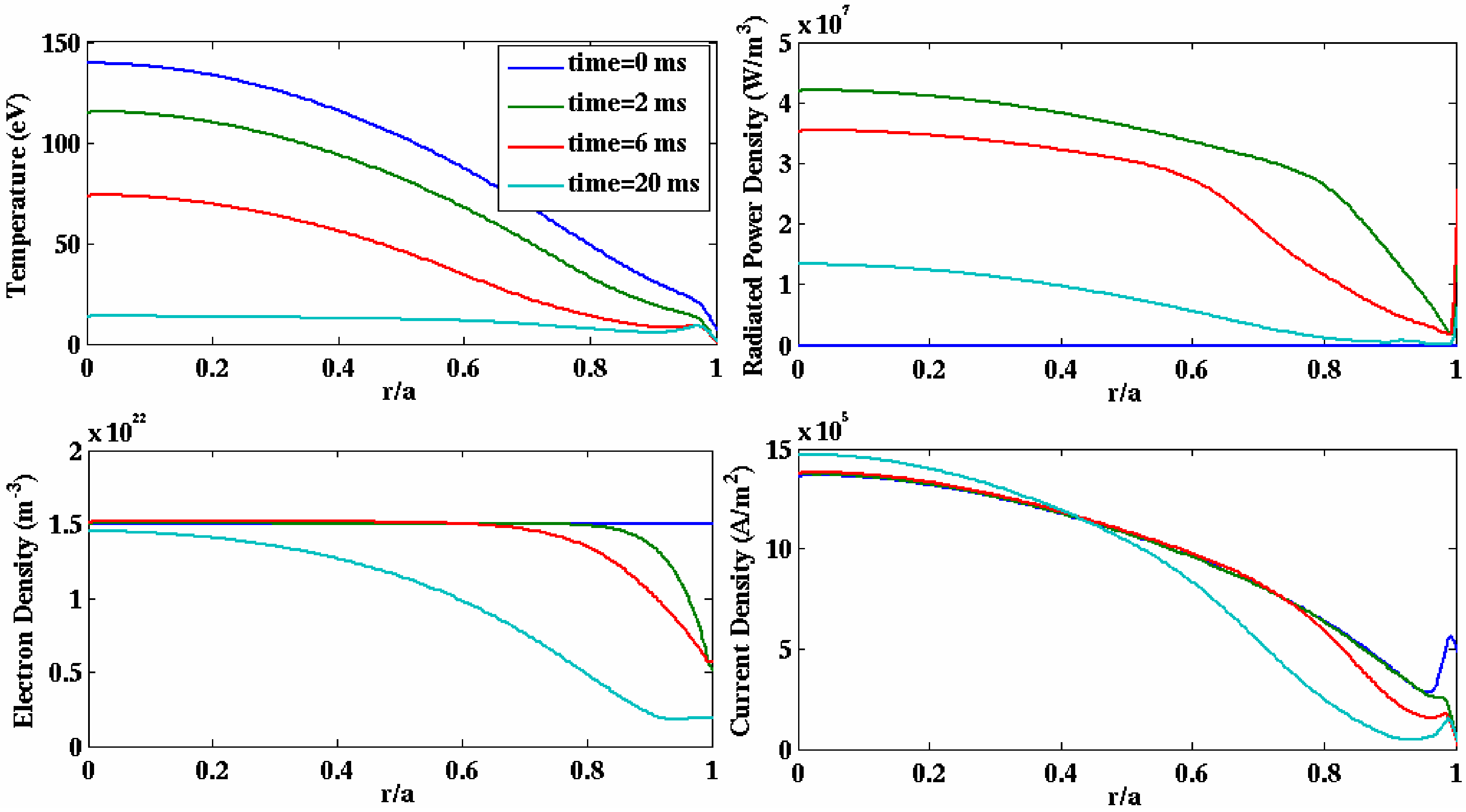
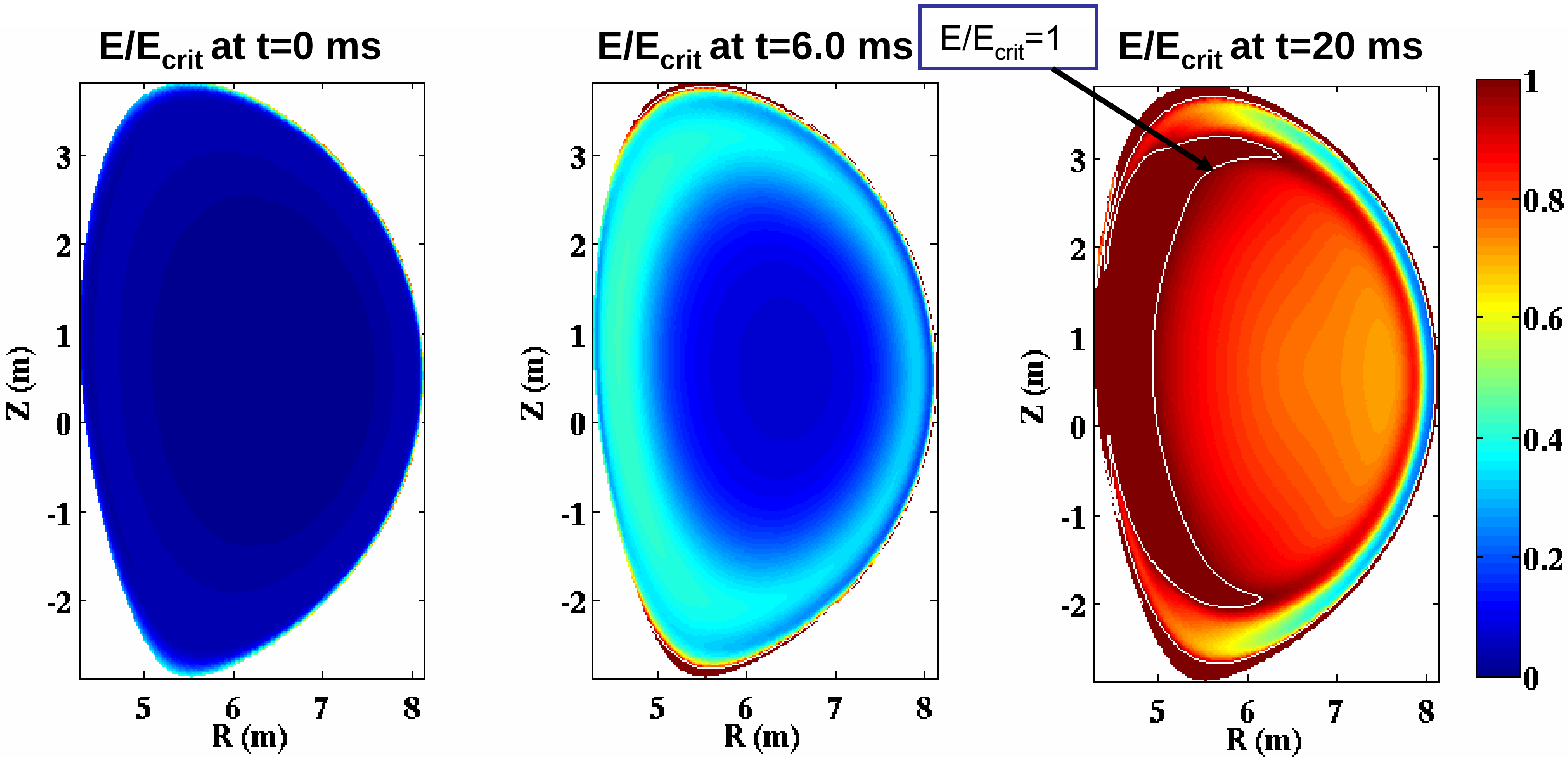
Thermal quench is MHD-free



More uniform cooling, little current peaking



Rosenbluth ratio is much better in ITER



Dilution cooling conclusions

- You can't really beat the Rosenbluth criteria in DIII-D, but demonstration of massive particle injection in the core maybe sufficient for ITER
- ITER shows less propensity for MHD in this mitigation scenario. Also, flux surfaces heal during the current quench in DIII-D
- Particle loss in the NIMROD simulations is the biggest issue for ITER– but I have no idea if this is real

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Does elongation effect runaway electron confinement during disruptions?

Some tokamaks tend to observe RE's during some current quenches:

FTU, Tore-Supra, TEXTOR all run circular, limited plasmas

JET ran only limited plasmas for a number of years before the installation of its first divertor. Disruption runaways were much more prevalent back then, compared to now.

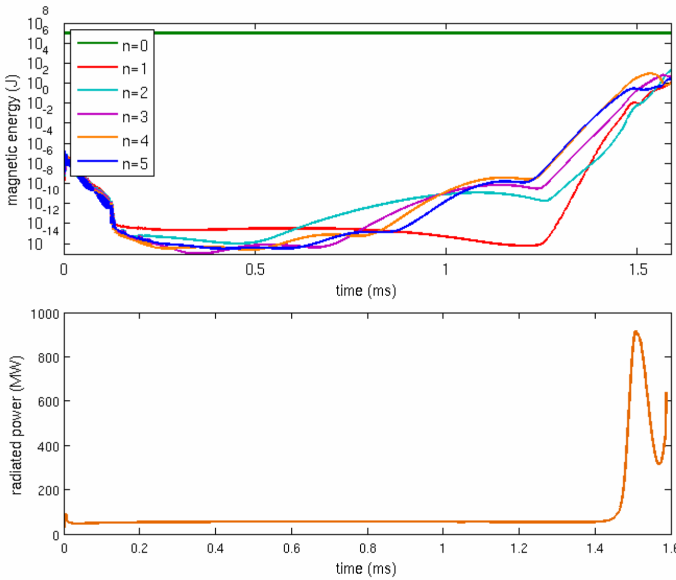
JT-60U is diverted, with low elongation

Some tokamaks don't see RE's during the current quench (except perhaps during killer pellet experiments):

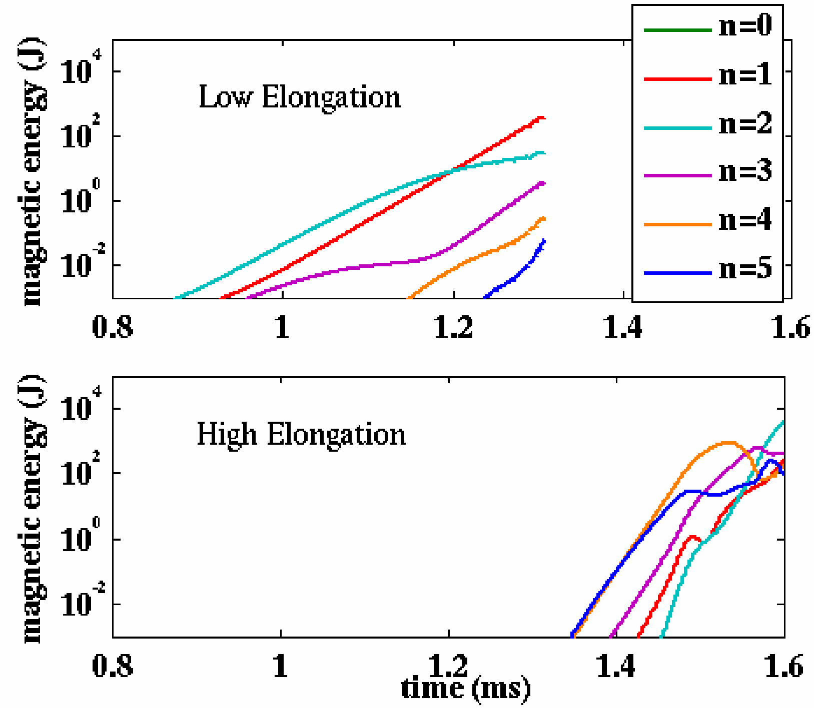
DIII-D, ASDEX-U, and C-Mod run diverted, elongated plasmas (vertically unstable)

This suggests that elongation and/or vertical stability might have something to do with generation of runaways during a disruption.

C-Mod low elongation simulation in progress



Previous high elongation C-Mod simulation with Ne gas jet. Higher n modes grow first, fast growth of n=1 tends to trigger thermal quench



Low elongation simulation with other wise similar plasma parameters and Ne jet parameters in progress– no conclusions yet

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Postprocessing to determine runaway confinement time in NIMROD results

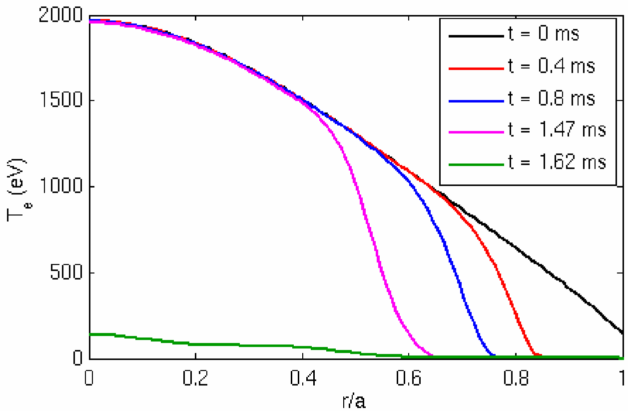
Experimental Motivation:

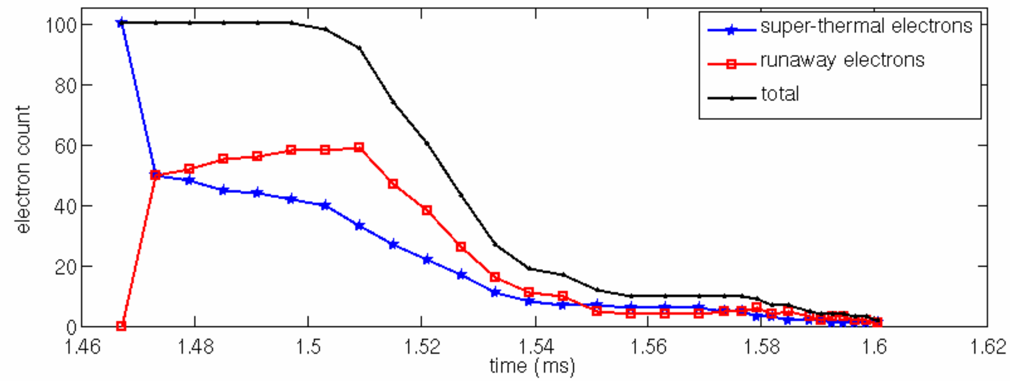
- C-Mod experiment seeds plasma with suprathermal electrons to study runaway conversion and confinement during the disruption.

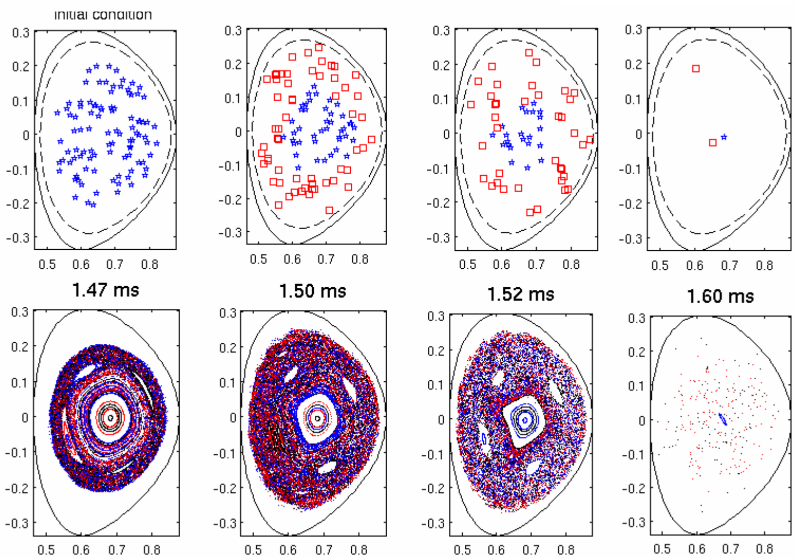
Procedure:

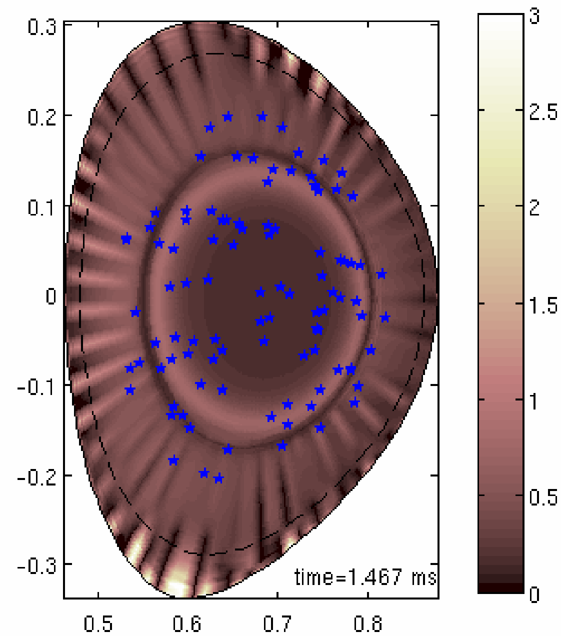
- Assume (initially) that suprathermal/runaway electrons follow the field lines perfectly
- Initialize suprathermal electrons with given positions and velocities
- Run nimfl to track electron trajectories, but advance electron velocity and time using F=eE-mvμee

Rapid loss of electrons during the thermal quench









Summary

- D_2 Dilution cooling as an “optimal” runaway suppression mechanism
  - → Mostly wrapped up, some interesting results, probably a short paper
- Effects of plasma elongation on MHD and runaway confinement
  - → Very preliminary, eventual experimental comparison w/ C-Mod
- Direct calculations of suprathermal electron acceleration and confinement
  - → Some results, but more physics to include, possible inclusion in nimrod during run time