Overview

- Runaway electrons are a major concern for ITER disruptions (in addition to divertor heat load and mechanical forces on the vessel)
- A small seed population of runaway electrons can grow exponentially due to an avalanche amplification process
- A critical electric field (proportional to the plasma density) must be exceeded in order for the runaway avalanche to occur. Rosenbluth calculated this critical field to be:

$$\boxed{E_{crit} = 0.12 n_{e,20}}$$

where $n_{e,20}$ is the (free + bound) electron density in units of $10^{20}/m^3$ and the electric field is in V/m

- A possible runaway electron mitigation strategy is to keep $E_{crit}>E$ by significantly increasing the electron inventory through gas/solid/liquid injection of D_2, noble gas, a mixture or other species

The Bad News for ITER

- The avalanche amplification factor is an exponential function of the plasma current given as:

$$\boxed{A = \exp(\gamma t) \approx \exp(2.5 I_p)}$$

where the growth rate is γ, t is the current quench duration, and I_p is the plasma current in MA

- As an example, a DIII-D plasma with 2 MA of current gives us A~40. For an ITER plasma with 15 MA, this would be A~10^{17}
- DIII-D massive gas injection (MGI) experiments do not show significant penetration of injected impurities into the plasma core, and consistently have $E/E_{crit}>1$

The Good News for ITER

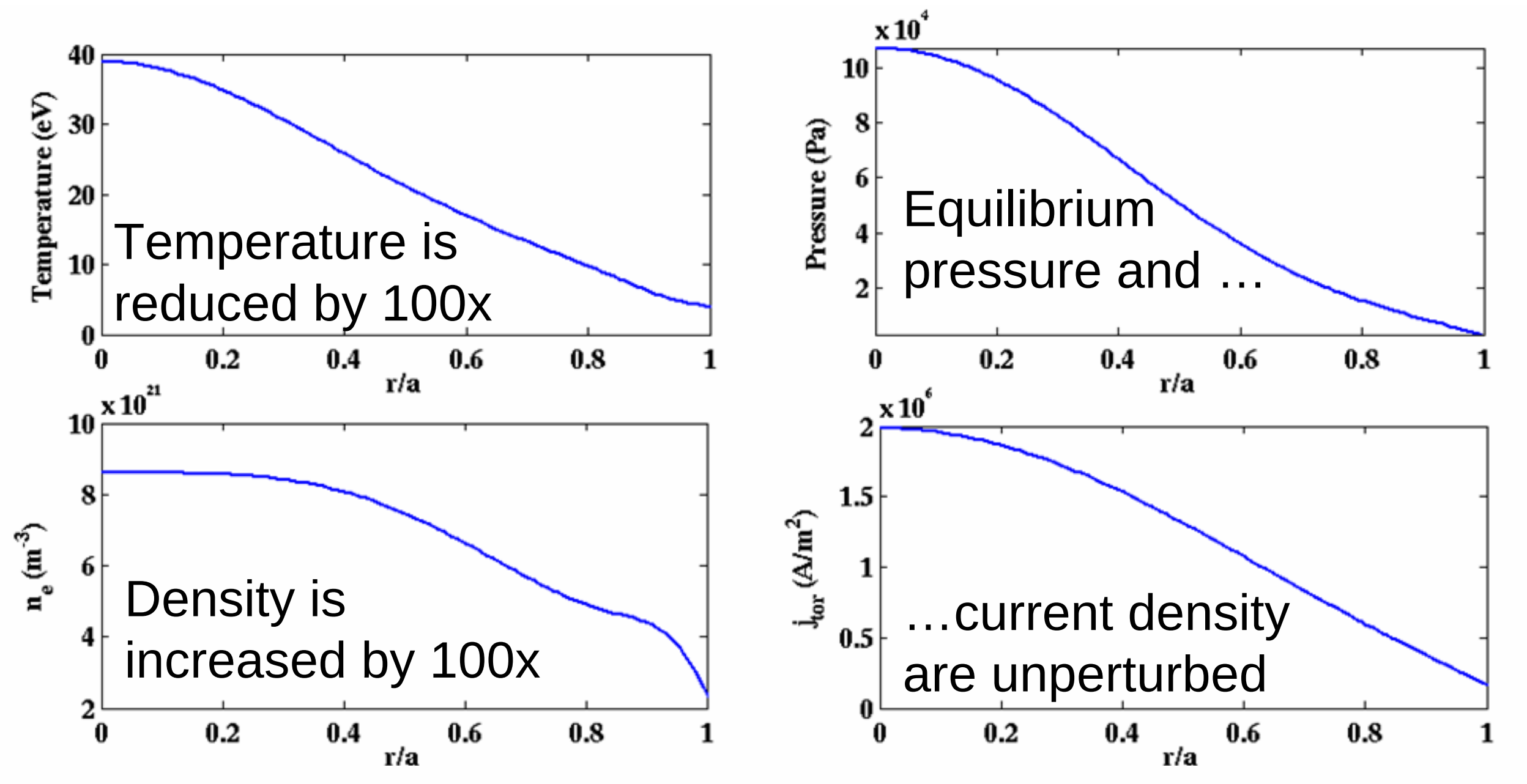
- The Rosenbluth ratio is given as:

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

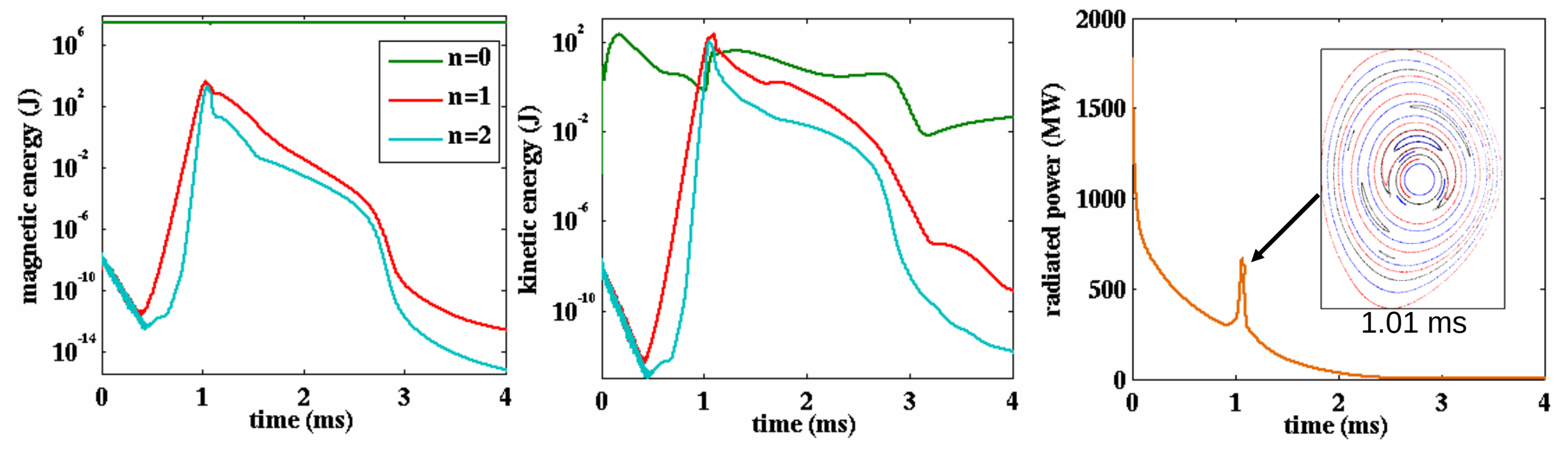
- In normal DIII-D operation, assume T=4keV, n=8x$10^{19}/m^3$, j=2x10^6A/m^2. Then we have **E/E_{crit}=0.09**
- Imagine cooling DIII-D purely by dilution, neglecting all radiation and atomic physics. Then T~n^{-1}. In this case, E/E_{crit} ~ $n^{1/2}$
- At 100 times densification of DIII-D, E/E_{crit} is already marginal
- 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
- For ITER nominal parameters of T=8.9keV, n=$10^{20}/m^3$, j=1.4x10^6A/m^2, this gives us **E/E_{crit}=0.01**
- Thus, ITER is well below marginal for a densification of 100 or even 500
- ITER stands a much better chance than DIII-D of maintaining $E/E_{crit}<1$ during a mitigated disruption

DIII-D Simulation

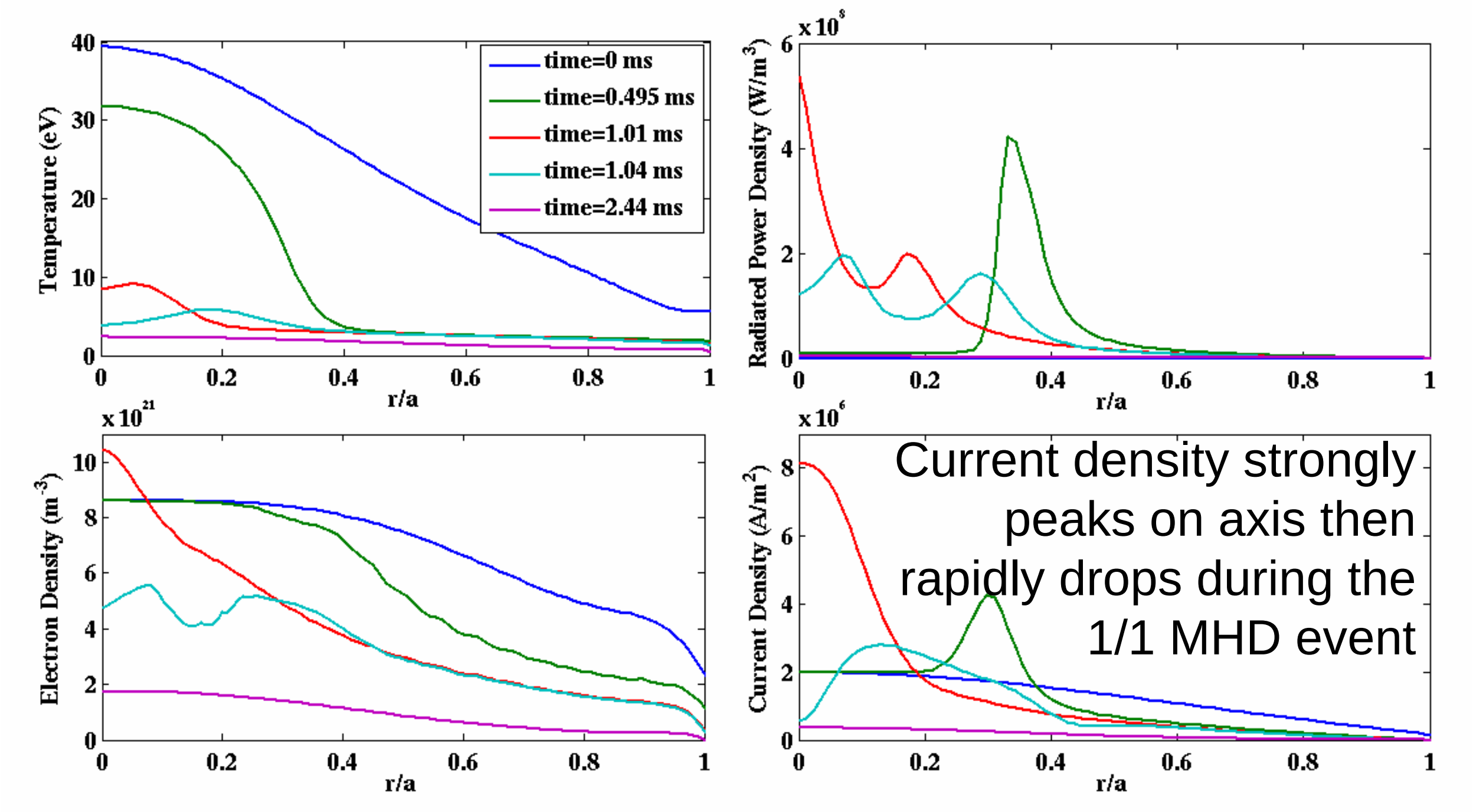
- A DIIII-D EFIT equilibrium from discharge 128226 is used
- A uniform D_2 dilution cooling by a factor of 100 is assumed for the initial condition



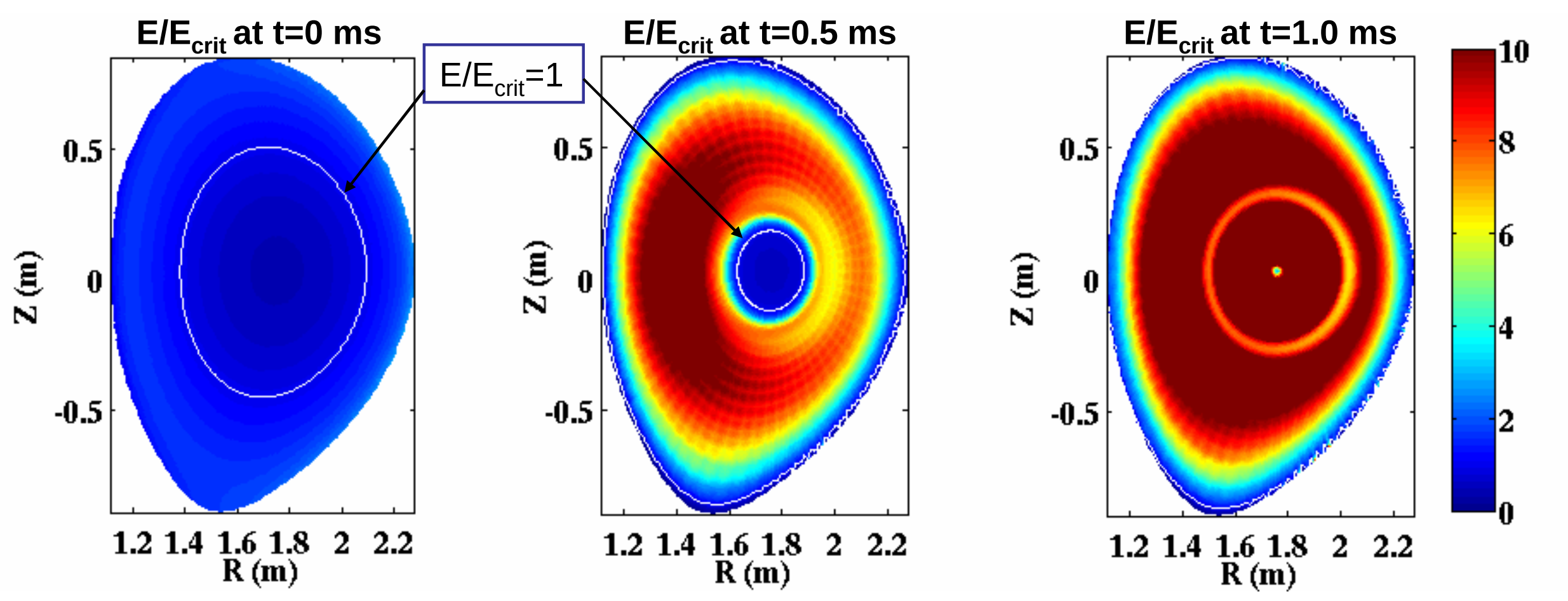
- A uniform carbon density of 1% of the pre-dilution core electron density (8.6x$10^{17}/m^3$) is assumed. The in-situ carbon is the dominant radiator following the 100x dilution
- At this initial T_e (~40eV), the physical value of Spitzer resistivity can be used for the simulation without numerical difficulty



- Simulations have 1 ms thermal quench, ending with n=1 MHD event, and 3-5 ms current quench depending on value of $\chi_\perp$ (in multiple simulations this ranged from ~50-150)
- Cooling front initially propagates inward due to the carbon radiation peak around 10eV



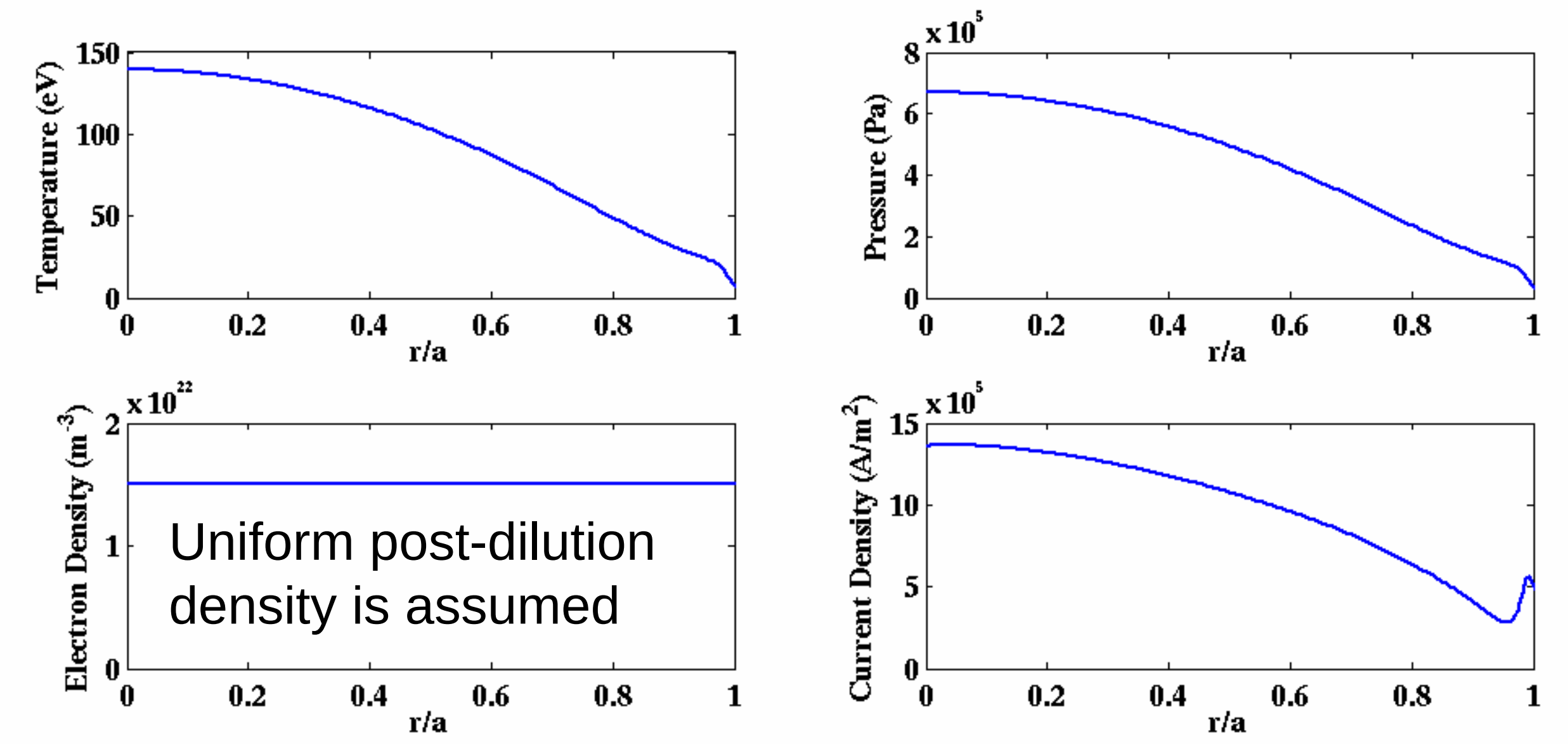
- Convection drives particles from the center toward the edge, where they recombine due to very low T_e. Particle loss is enhanced during the 1/1 event



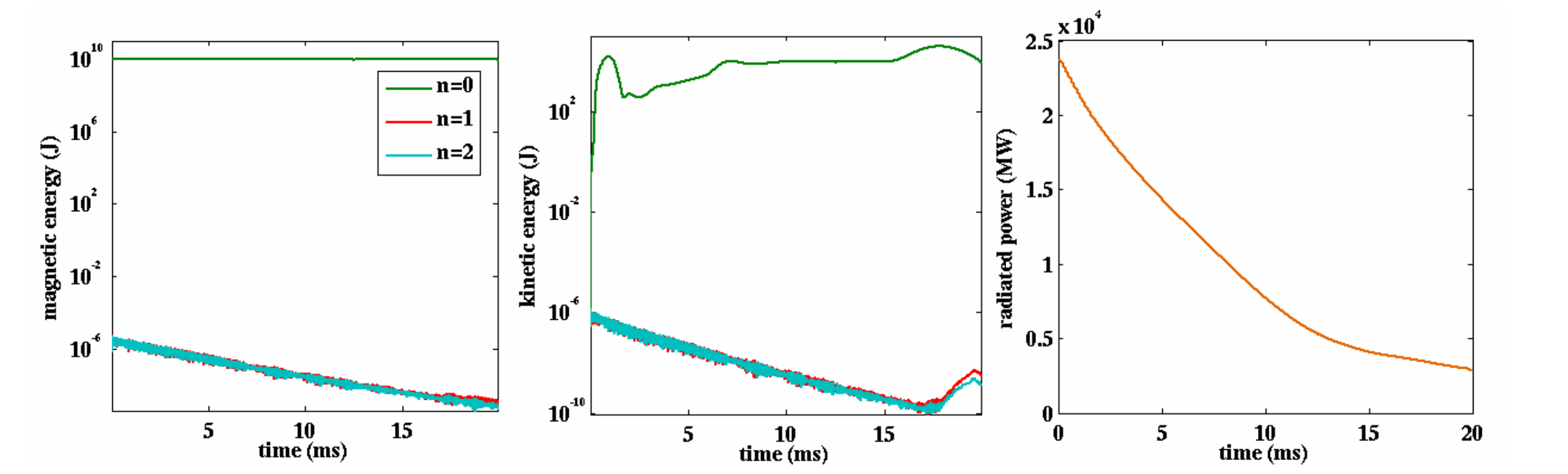
- At the start of the simulation, 100x dilution cooling produces $E>E_{crit}$ in roughly the outer half of the plasma, and marginal in the core
- As the carbon radiation cooling wave propagates inward during the thermal quench, the region of $E<E_{crit}$ shrinks, and E/E_{crit} reaches 10 or higher in large regions of the plasma
- After the thermal quench, the Rosenbluth criterion for collisional suppression of runaways is satisfied almost nowhere

ITER Simulation

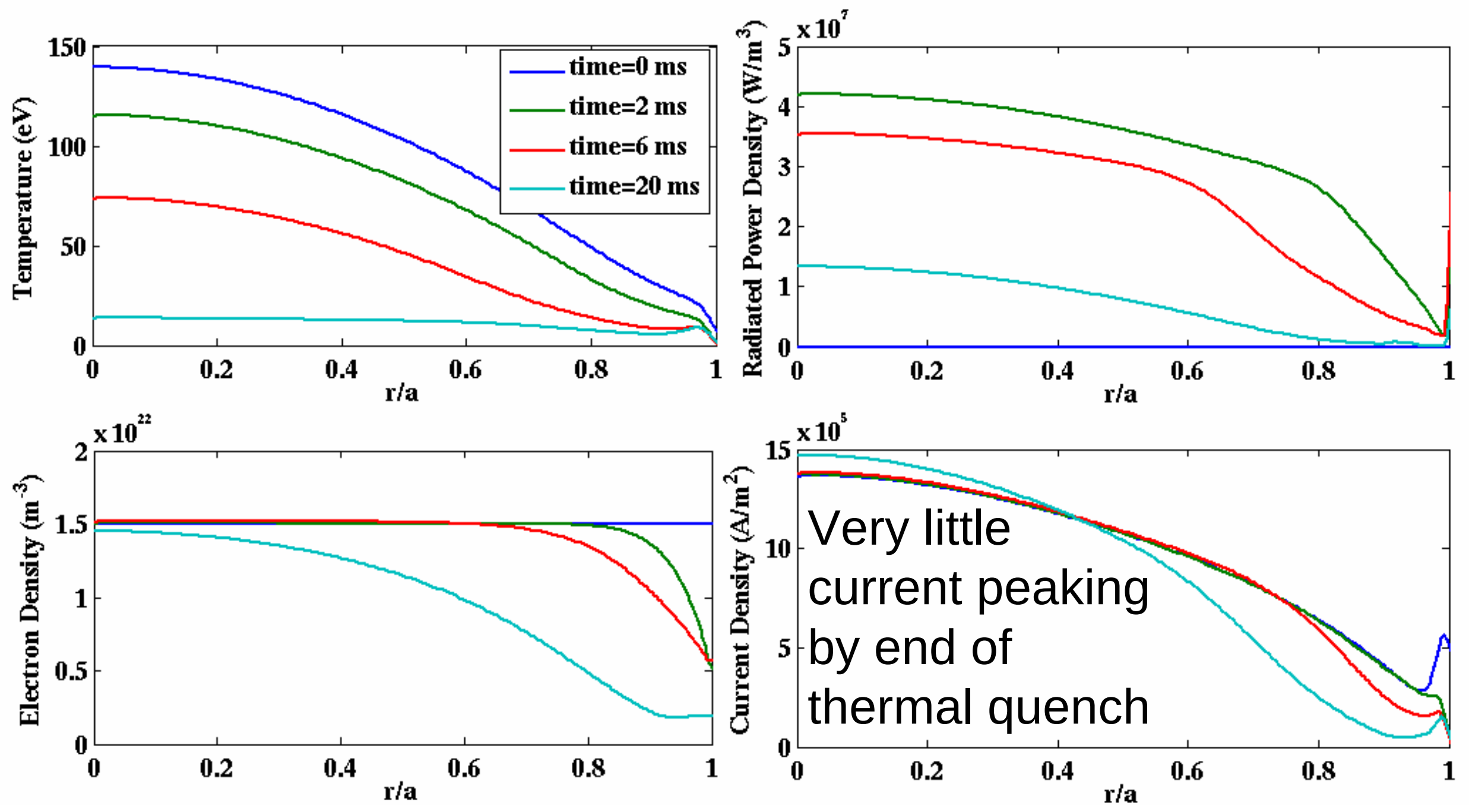
- An ITER equilibrium generated by L. Lao is used
- D_2 dilution cooling by a factor of 150 is assumed for the initial condition, where the post dilution density is assumed to be a uniform value of 1.5x$10^{22}/m^3$



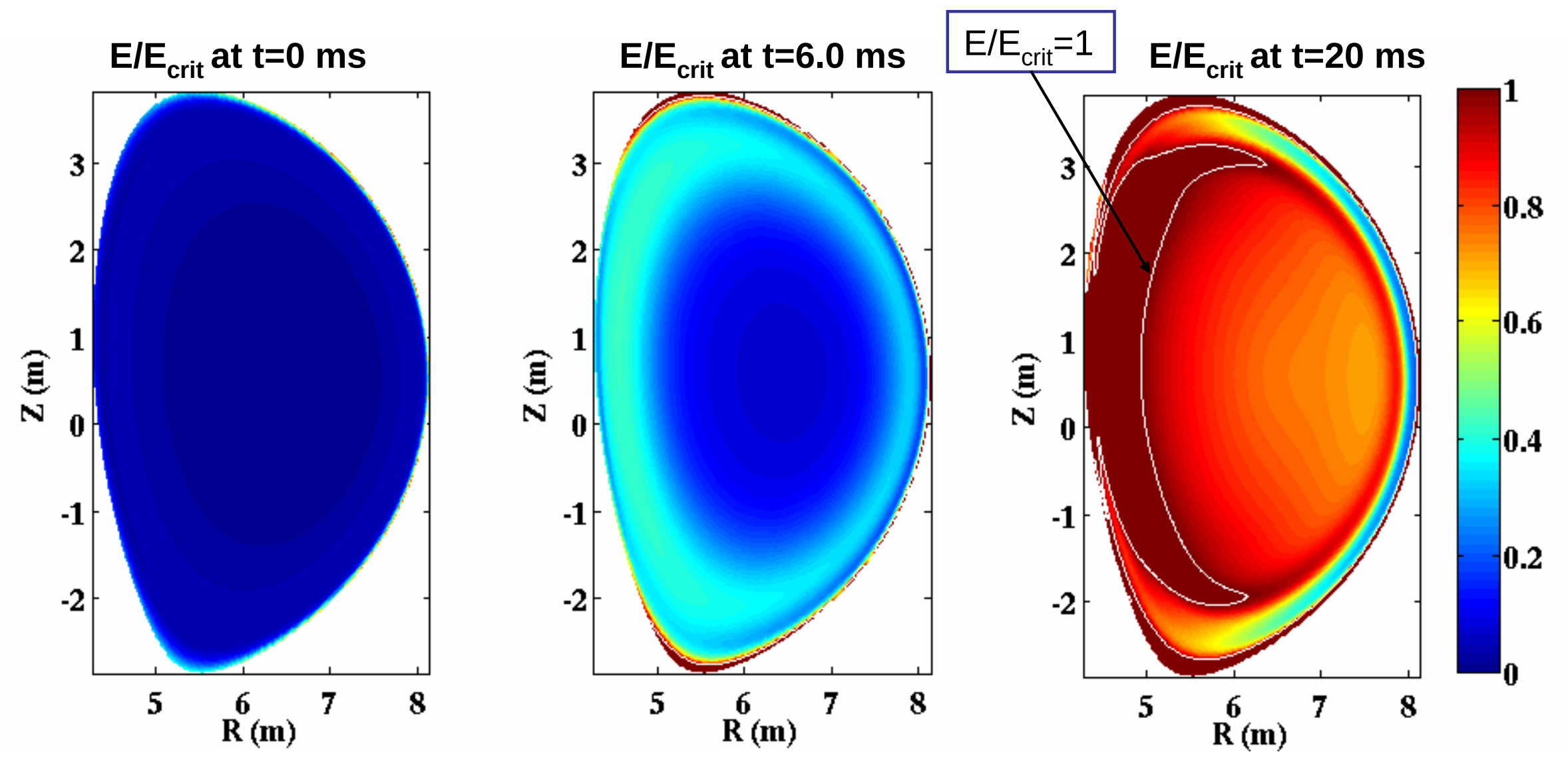
- A uniform beryllium density of 1% of the pre-dilution electron density ($10^{18}/m^3$) is assumed. The beryllium radiation is comparable to the bremsstrahlung in some regions, but does not dominate the overall radiated power
- Again, simulation is run at actual Spitzer resistivity



- No appreciable MHD in the first 20 ms. Thermal quench is ~15 ms, while current quench looks to be ~100 ms
- Cooling is much more uniform due to large bremsstrahlung contribution relative to Be radiation



- Particle loss is observed just as in DIII-D, although core loss is not hastened in this case by a 1/1 MHD event
- More uniform cooling leads to less current peaking by the end of the thermal quench



- E/E_{crit} is very low at the start of the simulation and remains below unity for most of the thermal quench
- E/E_{crit} reaches ~1 on the inboard side during the current quench, primarily due to the particle loss
- If particle loss is less or non-existent experimentally, then ITER can maintain $E<E_{crit}$ throughout the current quench

Summary

- Runaway electrons in ITER may be much more problematic than DIII-D due to the avalanche mechanism and its exponential dependence on plasma current
- But, runaway electrons could be less problematic for ITER than DIII-D due to the inherently lower E/E_{crit} operating space
- DIII-D and ITER simulations of disruption mitigation by massive D_2 dilution cooling have been carried out with the NIMROD code
- These simulations are done irrespective of the actual mechanism for producing the large core density increase– MGI has not demonstrated significant core penetration of impurities; conceivably a pellet train or liquid jet could achieve the desired penetration

Conclusions

- **Maintaining $E/E_{crit}<1$ across the entire plasma during a mitigated DIII-D disruption is nearly impossible due to the temperature and density in normal operation**
- **Dilution cooling by 150x D_2 densification in ITER could maintain $E/E_{crit}<1$ throughout the current quench, avoiding runaway avalanche amplification**
- **The ability to massively increase the core electron density in DIII-D is a sufficient demonstration for ITER**
- **Particle loss in the NIMROD simulations due to convective flows, and strongly associated with the m=1/n=1 MHD event, threaten to reduce n_e below the threshold value during the current quench**

Future Work

- Particle loss is the biggest issue: reasonableness of this result must be investigated in some fashion– experimentally, or by altering numerical model or parameters to understand when it occurs or can be eliminated in the simulations
- Only examining E/E_{crit} is not the full runaway picture. Detailed numerical models to look at generation, acceleration and confinement of runaways will be developed
- Some comparisons with 1D FCQ code of Parks and Wu have been made, more detailed attempts to understand the similarities and differences in the results can be made
- Simulations of all types of disruption mitigation based on more realistic impurity deposition models

Reprint Requests