# Dilution Cooling for Disruption Mitigation on DIII-D and ITER

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# Motivation 1: The bad news for ITER

- ✓ Exponential avalanching of a seed population of runaway electrons occurs above the Rosenbluth critical electric field ($E_{crit}=0.12n_{e,20}$), which can be achieved during tokamak disruptions
- ✓ The amplification factor ($A=e^{\gamma t}$) depends on the growth rate and the current quench duration, who's product is given by $\gamma t \approx 2.5 I_p(MA)$. Therefore, A~40 in DIII-D, but $A \sim 10^{17}$ in ITER
- ✓ Disruption mitigation experiments on DIII-D using massive gas jets have poor particle penetration and have E much greater than $E_{crit}$

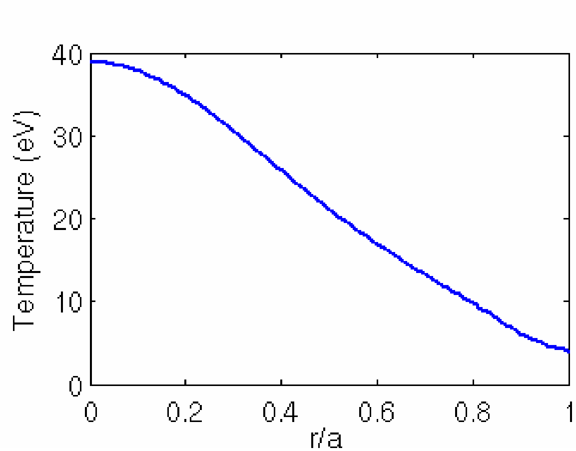
# Motivation 2: The good news for ITER

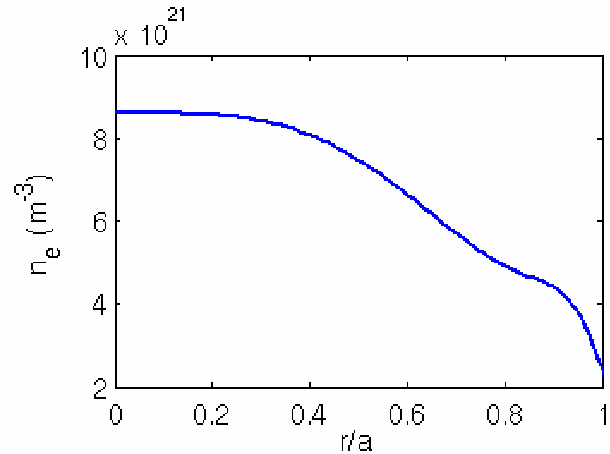
- For DIII-D @ 4keV, $8x10^{19}/m^3$, $2x10^6 A/m^2$: $E/E_{crit}=\eta(T,n)j/0.12n_{e,20} = 0.09$
- Imagine cooling DIII-D or ITER purely by dilution with $D_2$ gas (in some sense, the best case scenario for $E/E_{crit}$), then for a dilution ratio $R_d$, $E/E_{crit}$ scales like $R_d^{1/2}$
- DIII-D is already marginal at $R_d$~100, will get worse before it gets better (thermal quench precedes current quench)
- Consider ITER @ 8.9keV, $10^{20}/m^3$, $1.4x10^6 A/m^2$: $E/E_{crit}=0.01$
- ITER is well below marginal @ $R_d$=100 or even $R_d$=500.

ITER is an inherently lower $E/E_{crit}$ device than DIII-D

# DIII-D shutdown with 100x $D_2$ dilution

Equilibrium pressure and current profiles are used, but density is multiplied by a factor of 100, and temperature reduced by a factor of 100




NIMROD can easily simulate these conditions with true Spitzer resistivity (no enhancement, no rescaling)

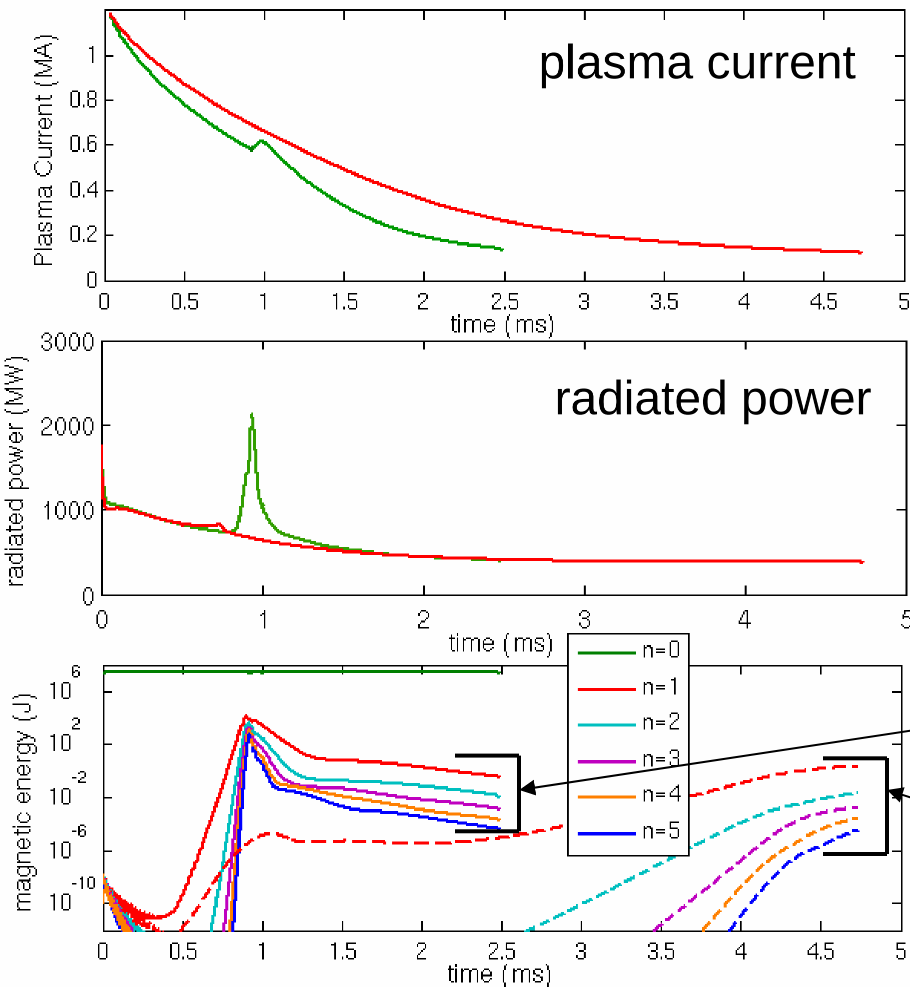
→In-situ carbon density of $8.6 \times 10^{17}/m^3$ is assumed (1% pre-dilution density)

Pfirsch-Schlüter heat conductivity is used for highly collisional plasma

$$\chi_\perp = \frac{136}{B^2}\left(\frac{40}{T}\right)^{1/2}$$

Braginskii $\chi_\perp$ is a factor of 4-5 smaller. But, at these temperatures $\chi_{||}$ is small enough compared to either that it is not important even with stochastic fields

# MHD assisted vs. MHD-free thermal quench depends on resistivity




Two simulations:

$\eta = \eta_{spitzer}$ and $\eta = 2.3\eta_{spitzer}$

Slightly higher resistivity produces qualitatively different behavior

More resistive case has much larger amplitude MHD, radiated power spike at 1 ms, small current spike

n=1-5 energy for higher resistivity

n=1-5 energy for Spitzer resistivity

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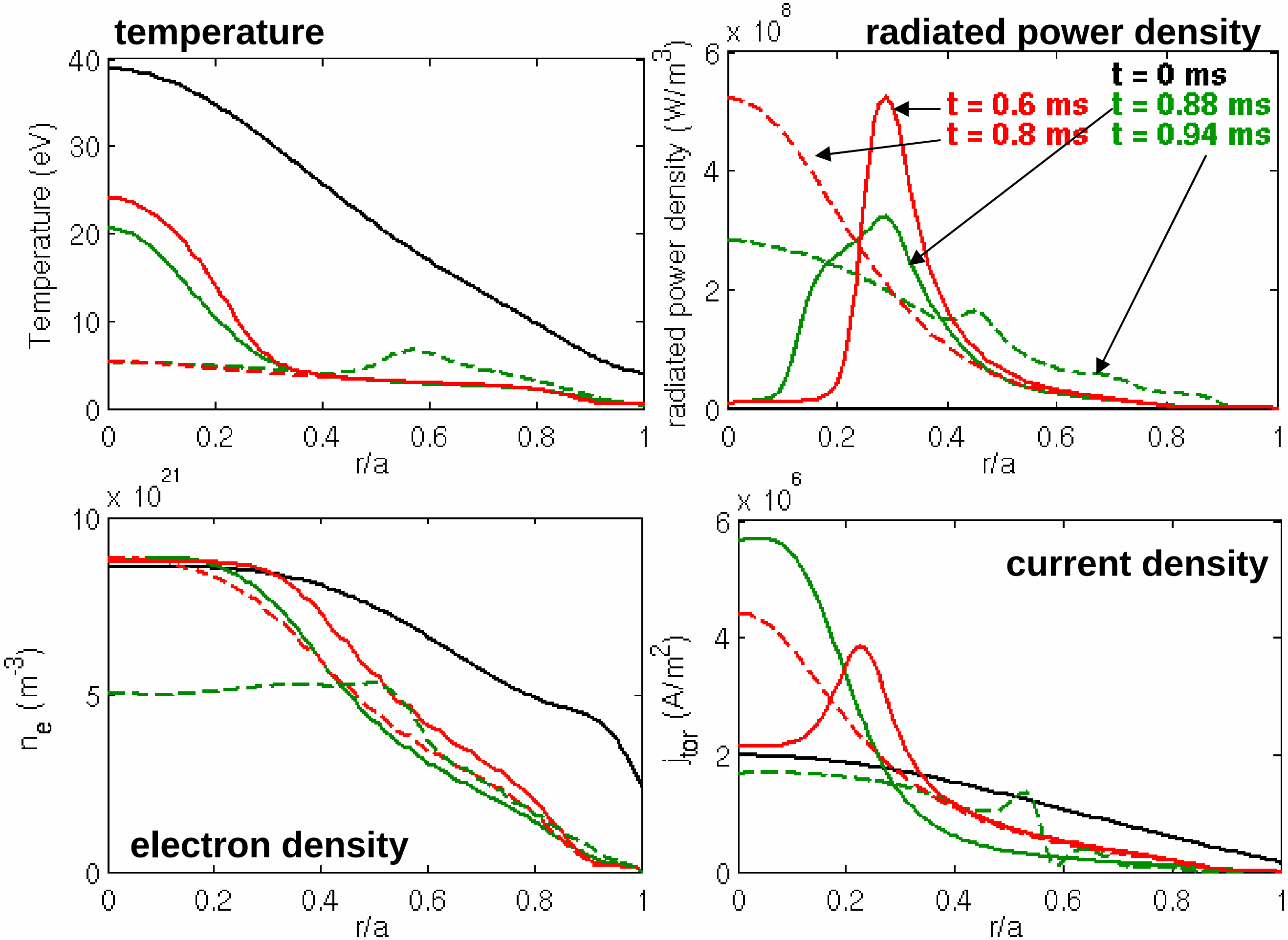
# More current density peaking at higher resistivity triggers MHD




$\eta = \eta_{spitzer}$ $\eta = 2.3\eta_{spitzer}$

Cooling wave propagates inward due to C radiation peak at 10eV

More resistive case cools more slowly, has higher current density peak

MHD event drops central $T_e$, $j_\phi$, and $n_e$ rapidly

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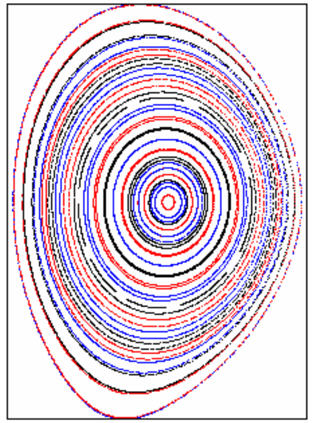
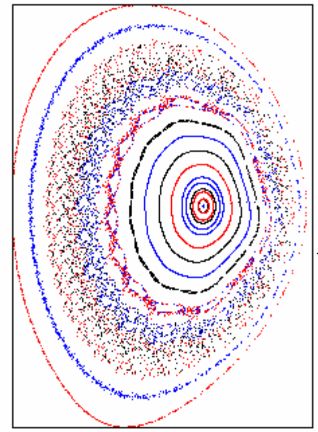
# With Spitzer resistivity, flux surfaces remain intact until late current quench

end of thermal quench

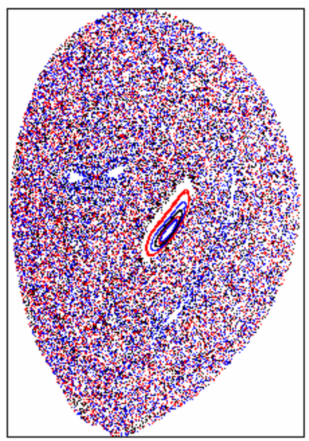


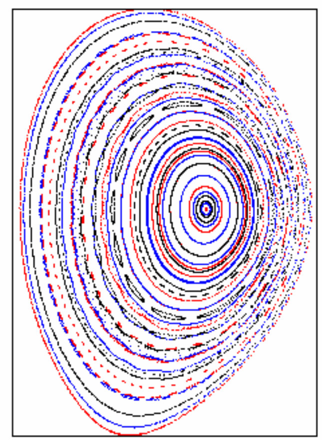


end of current quench

$\eta = \eta_{spitzer}$

$\eta = 2.3\eta_{spitzer}$

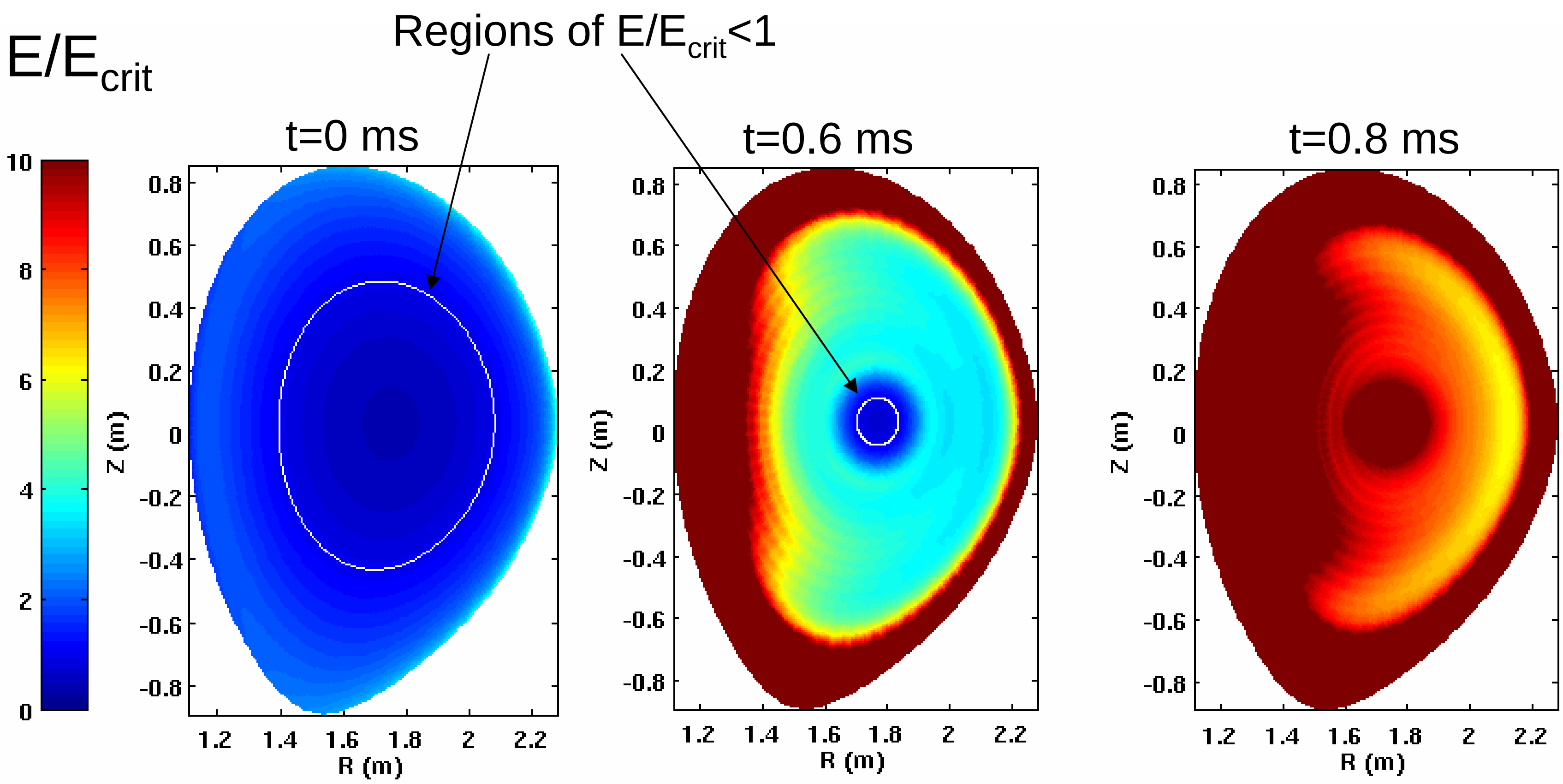




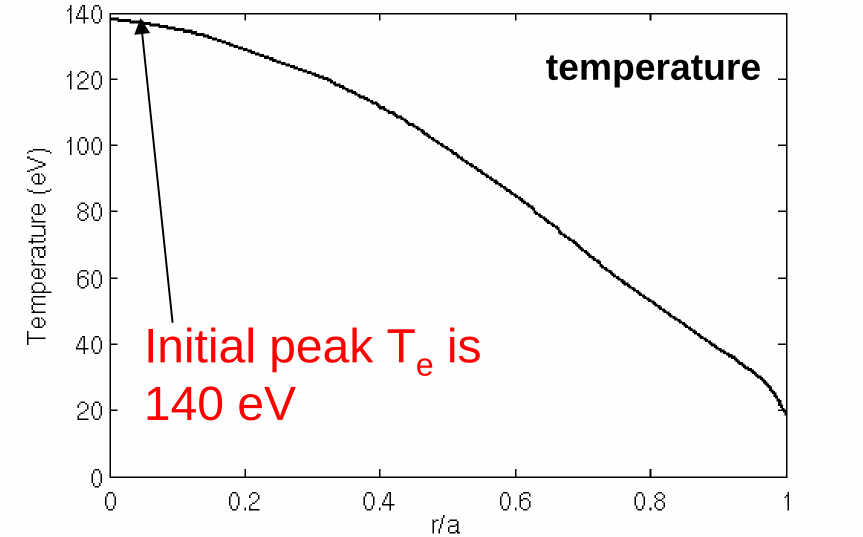
end of thermal quench

end of current quench

# Rosenbluth ratio is well above unity after thermal quench



# ITER shutdown with 150x D2 dilution

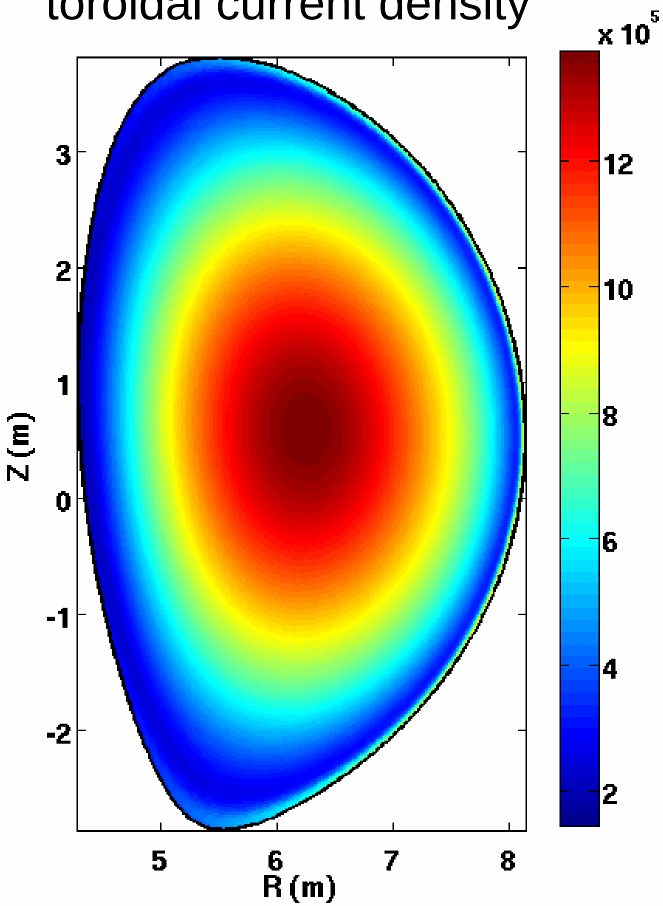



Initial condition has constant density of $1.5 \times 10^{22}$ $m^{-3}$

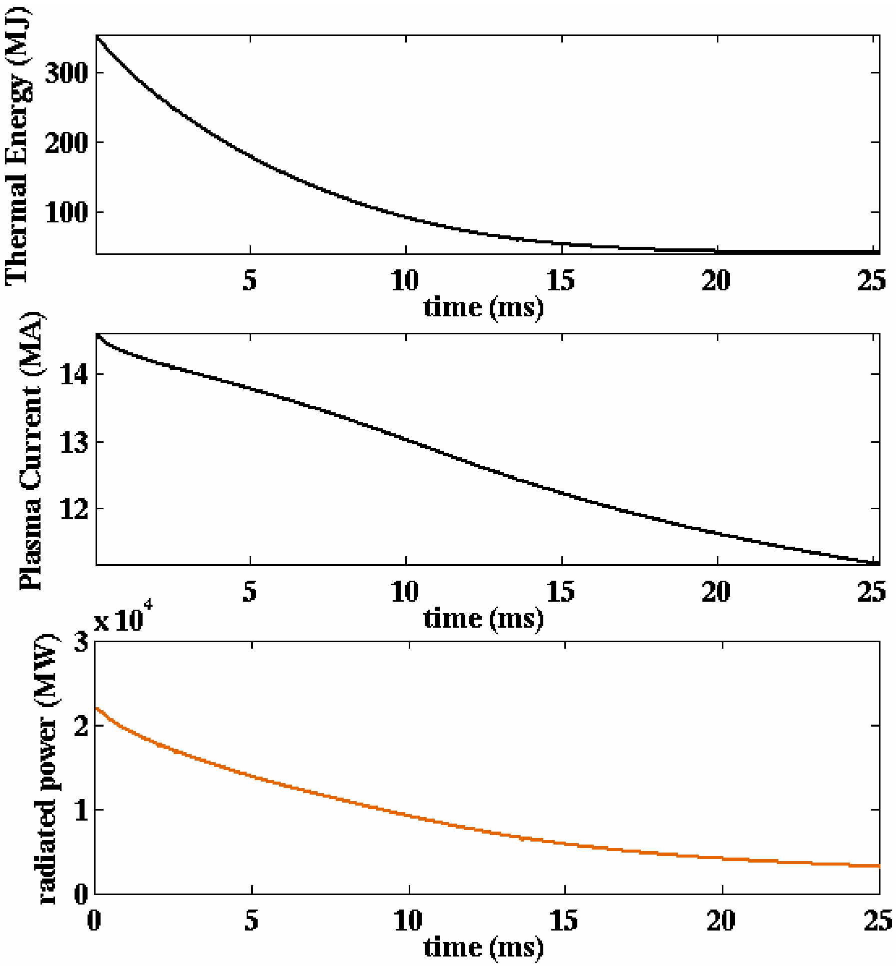
Pfirsch-Schlüter $$\chi_\perp = \frac{156}{B^2}\left(\frac{140}{T}\right)^{1/2}$$

This simulation includes no impurities; radiation is purely bremsstrahlung

toroidal current density



# Thermal quench phase is MHD-free

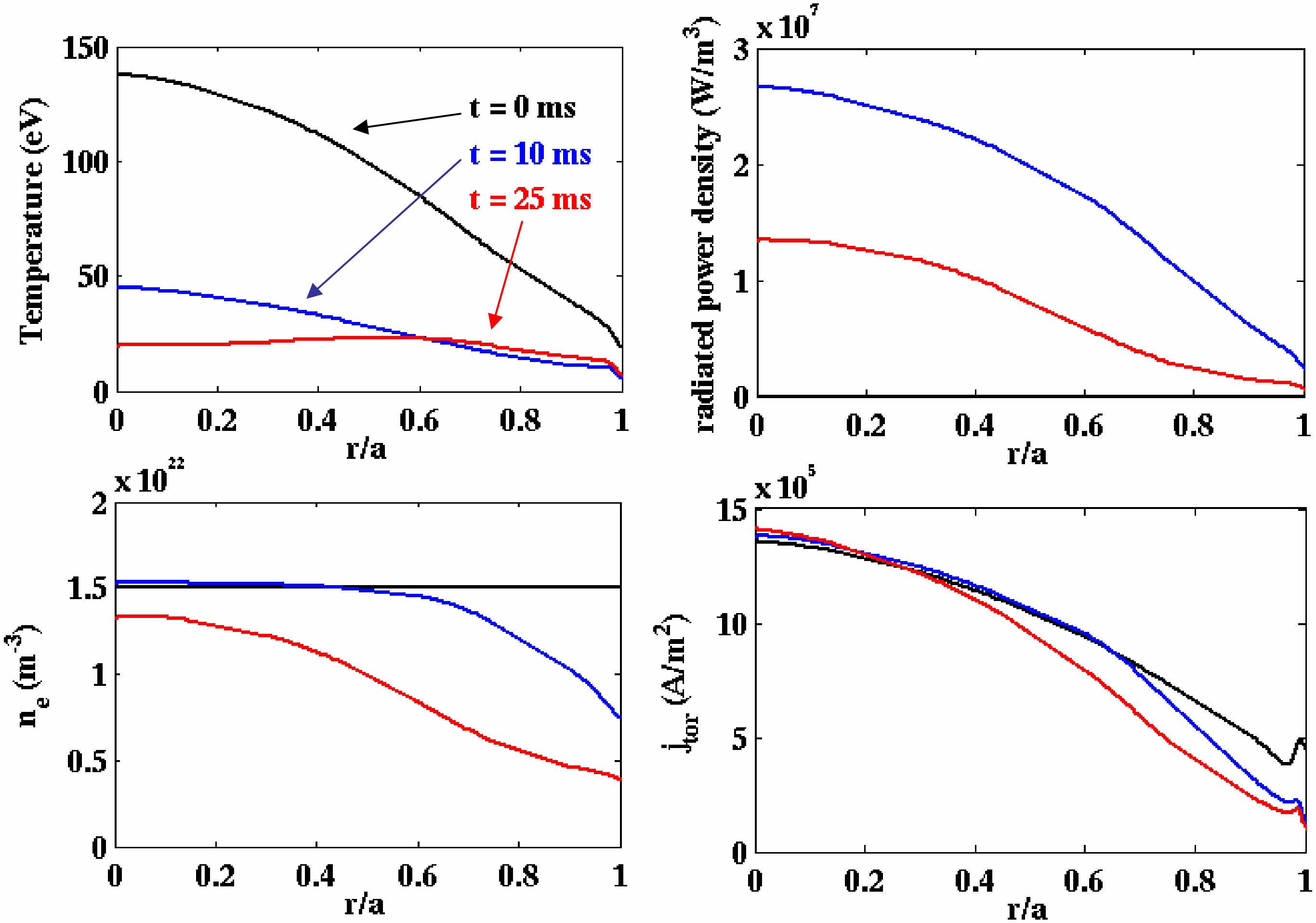



Bremsstrahlung radiation quenches thermal energy on ~10 ms time scale

Beginning of current quench proceeds on ~100 ms time scale

Initial 20 GW of radiated power slowly falls to <5 GW by end of thermal quench

# Broad radiated power cools plasma more uniformly

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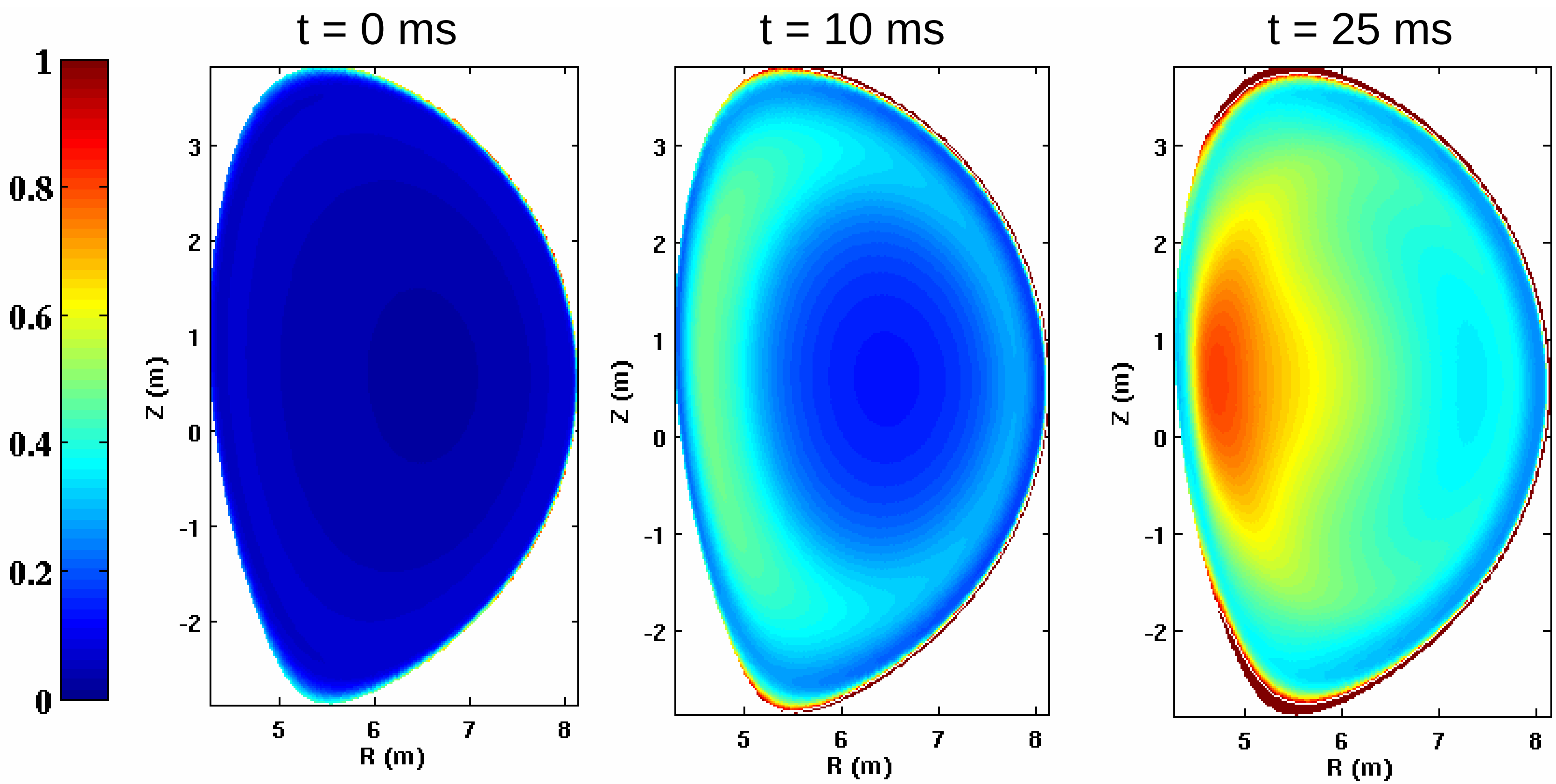
# Rosenbluth ratio less than one (so far)




Following the thermal quench, only increase in $E/E_{crit}$ is due to particle loss

# Conclusions

1) It is nearly impossible to beat the Rosenbluth criterion in a DIII-D disruption
2) It may be possible to achieve $E<E_{crit}$ in a mitigated ITER disruption by ~150 fold densification with $D_2$*
3) NIMROD simulations have significant particle loss, which is concerning, but not necessarily realistic

* Also found in Parks, Wu, 1D simulations, APS 2007