# Runaway Electron Confinement in MHD Disruption Mitigation Simulations

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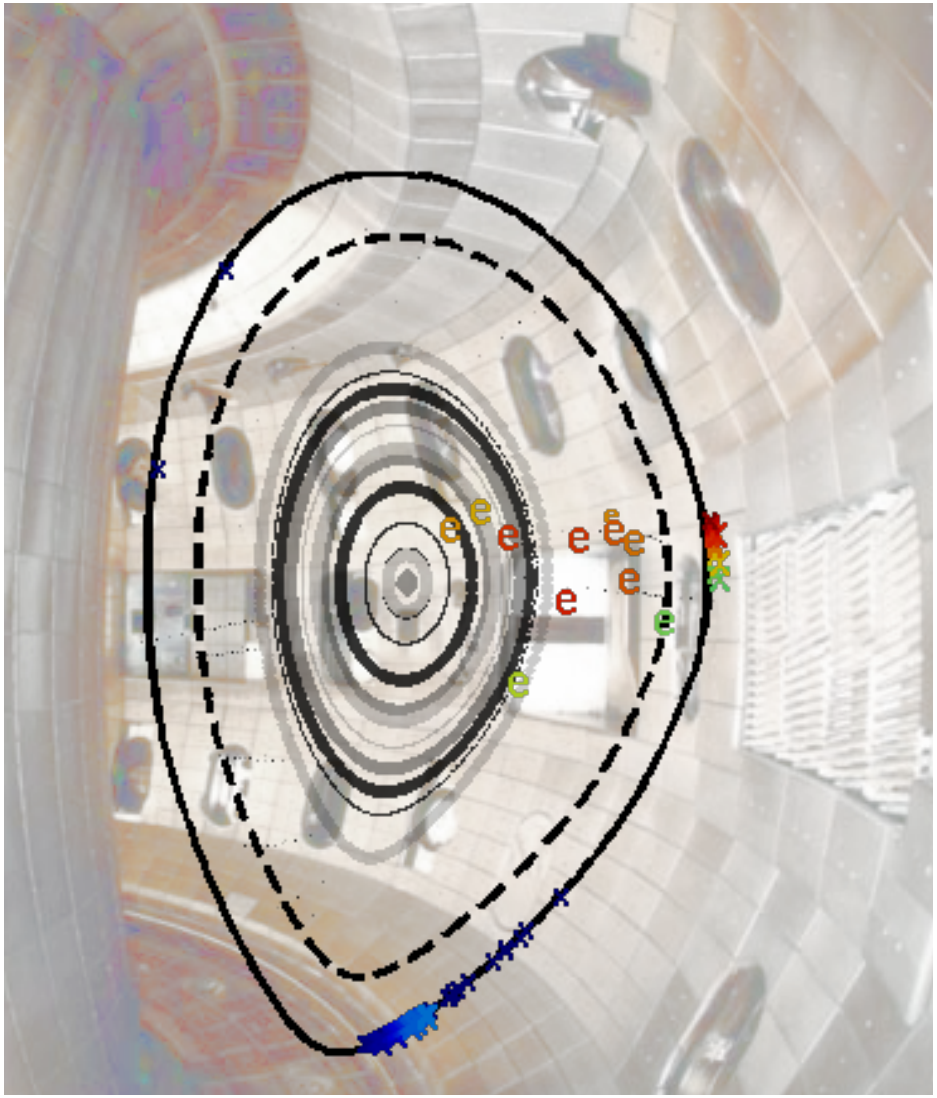


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# Motivation

- Suppression of runaway electron (RE) avalanche during an ITER current quench will require that one of two conditions are met:

  1) Sufficient electron density to achieve $E/E_{crit}<1$ (where $E_{crit}\approx 0.12 n_{e,20}$) **Or**

  2) Short enough RE confinement time such that secondary REs are not produced in great enough numbers to sustain an avalanche

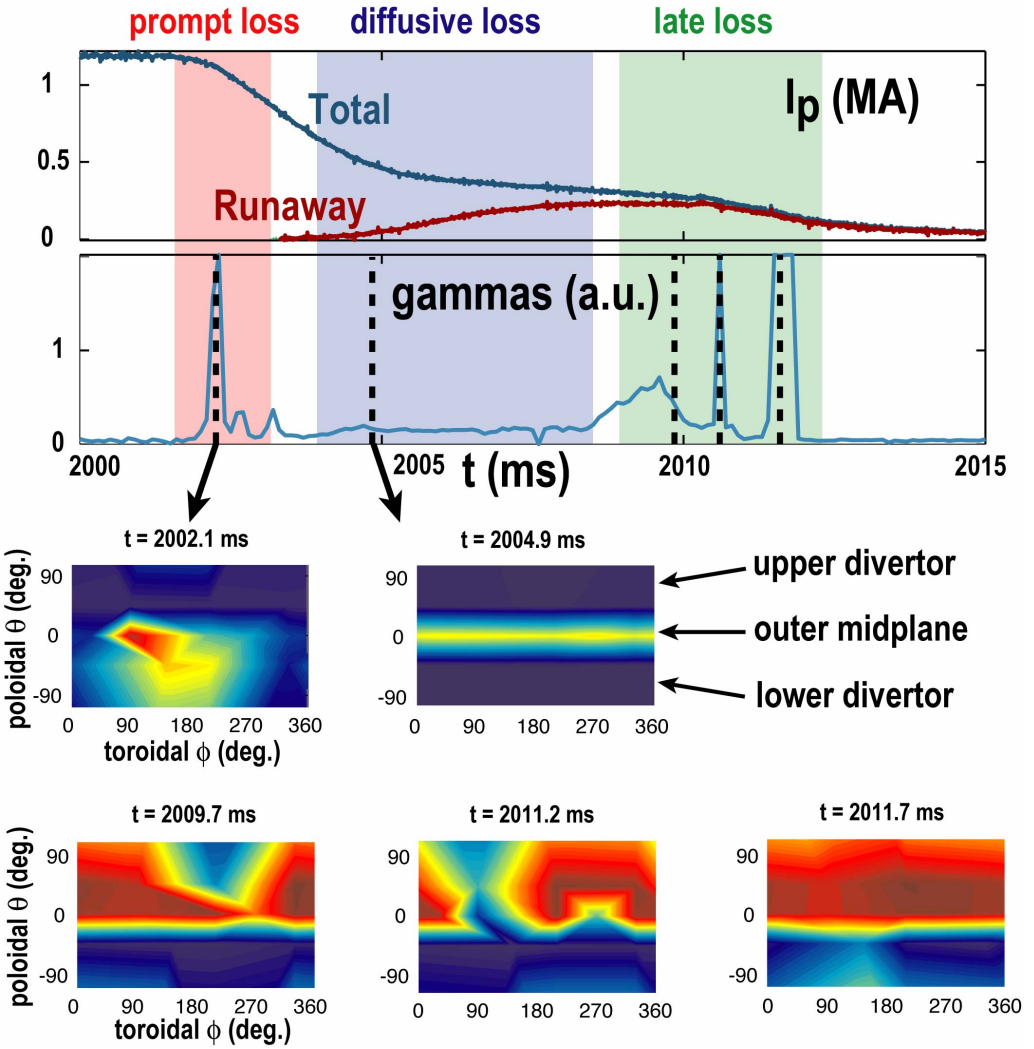
- Condition 2) might be met by "natural" disruption-induced MHD turbulence, or by the application of external perturbing fields

- DIII-D has performed disruption/RE experiments with injected Ar ice pellets both with and without applied I-Coil fields

- NIMROD simulations with atomic physics from KPRAD and single-particle orbit RE modeling examine both criteria under this scenario

# DIII-D shows prompt loss of runaways to divertor, later losses to main chamber

- **Runaways give gamma flashes ($\varepsilon$ > 0.5 MeV) upon hitting wall.**
- **Strong prompt loss flash of REs lost into lower divertor at start of CQ.**
- **Weaker loss of REs into main chamber wall during CQ.**
- **Strong late loss flashes when RE beam drifts into wall at end of CQ.**



# Electron Single Particle Orbits in NIMROD

**The fast electron orbit model is a diagnostic tool that runs concurrently with NIMROD to study runaway electron *confinement***

- A small set (presently hundreds) of electrons is initialized at random locations with specified energies, and the RE orbits are integrated as the magnetic and electric fields evolve in NIMROD
- The governing equations include curvature and grad-B drift, acceleration by the electric field, and slowing due to collisions, bremmstrahlung and synchrotron radiation
- The electrons are purely trace—they do not impact the NIMROD fields

**The model does not include runaway *generation***

- Seed and avalanche terms are not included, the population of REs is fixed based in the (random) initial conditions

**Model can tell us about:** runaway confinement time, strike points of escaping electrons. **The model cannot predict:** total runaway current, energy distribution of REs

# Equations

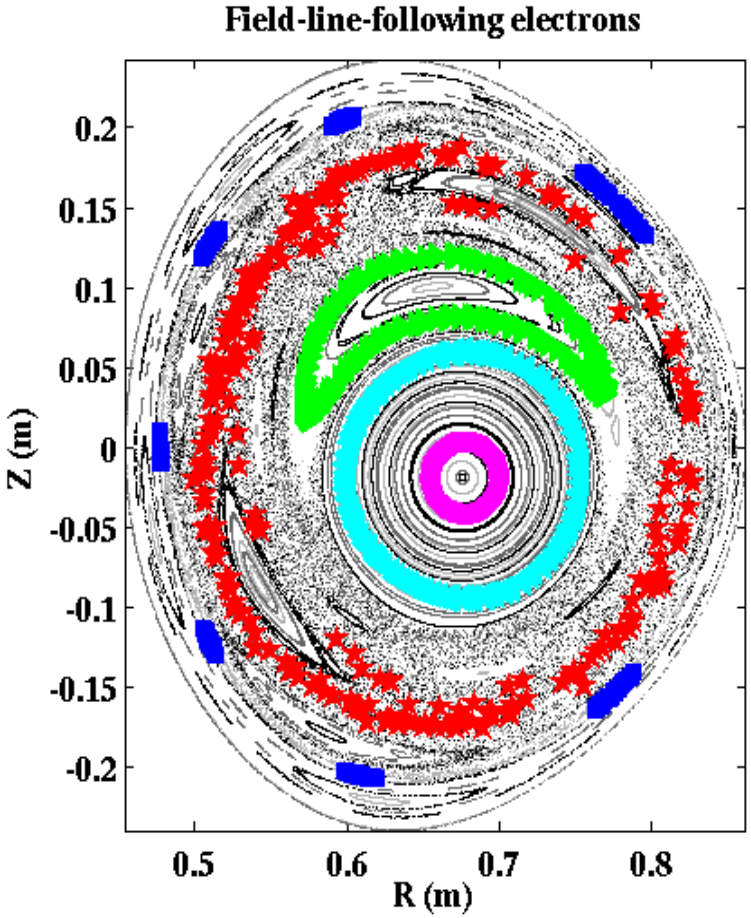
$$dR = \underbrace{\frac{v_\parallel B_R}{B} dt}_{\text{basic motion}} + \underbrace{\frac{1}{B^2}\left[V_R\left(B_\phi^2 + B_Z^2\right) - B_R\left(V_\phi B_\phi + V_Z B_Z\right) - \eta\left(J_\phi B_Z - J_Z B_\phi\right)\right] dt}_{\vec{E}\times\vec{B}\text{ drift}}$$

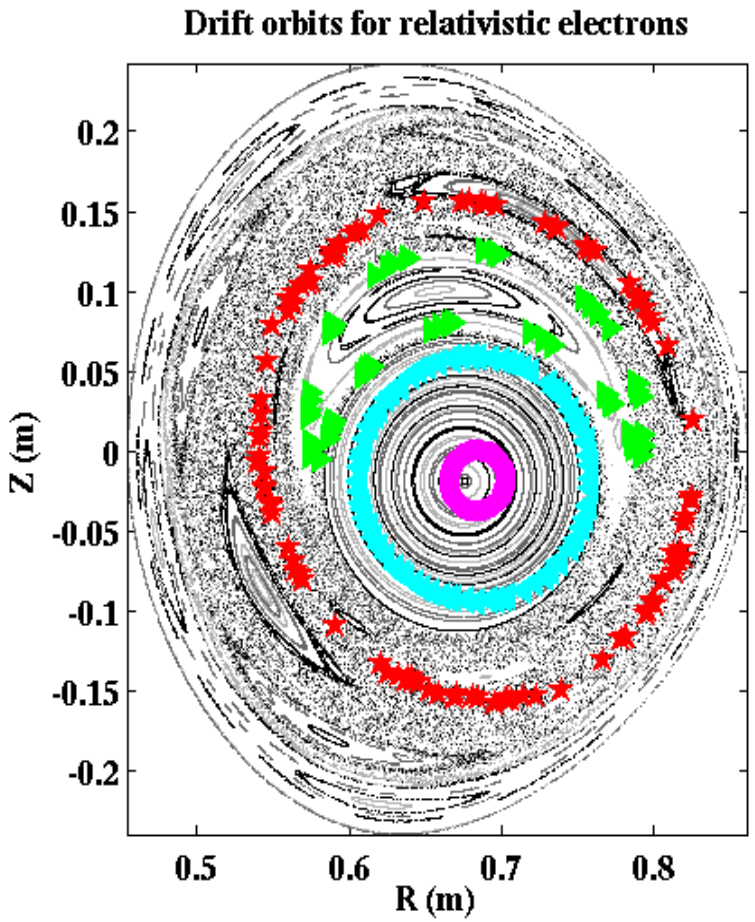
$$dZ = \underbrace{\frac{v_\parallel B_Z}{B} dt}_{\text{basic motion}} + \underbrace{\frac{20\,kT_e}{eB}\frac{1}{R} dt}_{\text{grad-B drift}} + \underbrace{\frac{\gamma m v_\parallel^2}{eB}\frac{1}{R} dt}_{\text{curvature drift}} + \underbrace{\frac{1}{B^2}\left[V_Z\left(B_R^2 + B_\phi^2\right) - B_Z\left(V_R B_R + V_\phi B_\phi\right) - \eta\left(J_R B_\phi - J_\phi B_R\right)\right] dt}_{\vec{E}\times\vec{B}\text{ drift}}$$

$$d\phi = \underbrace{\frac{v_\parallel B_\phi}{RB} dt}_{\text{basic motion}} - \underbrace{\frac{1}{RB^2}\left[V_\phi\left(B_R^2 + B_Z^2\right) - B_\phi\left(V_R B_R + V_Z B_Z\right) + \eta\left(J_Z B_R - J_R B_Z\right)\right] dt}_{\vec{E}\times\vec{B}\text{ drift}}$$

$$dv_\parallel = -\underbrace{\frac{e\eta J_\parallel}{m_e\gamma^3} dt}_{\text{electric field}} + \underbrace{\frac{e^4 \ln\Lambda}{4\pi\epsilon_0^2 m_e^2} n_e\left(Z_{\text{eff}} + 1 + \gamma\right)\frac{1}{v_\parallel^2}\frac{1}{\gamma^4} dt}_{\text{collisional slowing}} - \underbrace{\frac{e^2}{6\pi\epsilon_0 m_e c^3} v_\parallel^3 \gamma\left(\frac{1}{R_0^2} + \frac{19.4\,e^2 B^2 v_{te}^2}{m_e^2 v_\parallel^4}\right) dt}_{\text{synchrotron}} + \underbrace{n_e \frac{e^4\left(Z_{\text{eff}} + 1\right)}{548\,\pi^2\epsilon_0^2 m_e^2 c^2}\frac{1}{\gamma^2}\left(\ln\left(2\gamma\right) - \frac{1}{3}\right) dt}_{\text{bremsstrahlung}}$$

# Large drift displacement at high energy can improve confinement




Electrons with $\gamma$ ($=1/\sqrt{1-(v/c)^2}$) ~20 (10 MeV) have curvature drift displacement of a few cm

With drift displacement ~ perturbation width, RE can appear well confined

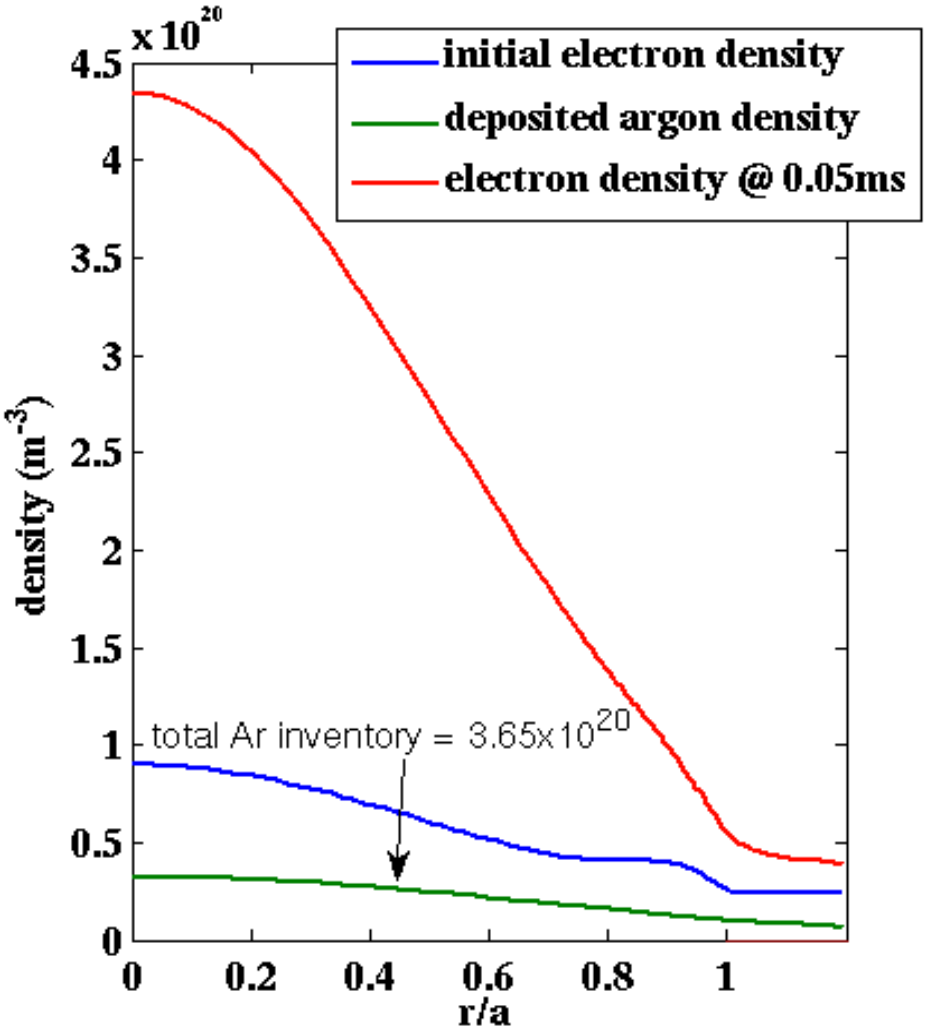
**Curvature drift can improve confinement on stochastic fields, but also reduce confinement on field lines that approach the boundary**

# In DIII-D simulations, impurity delivery is instantaneous and uniform

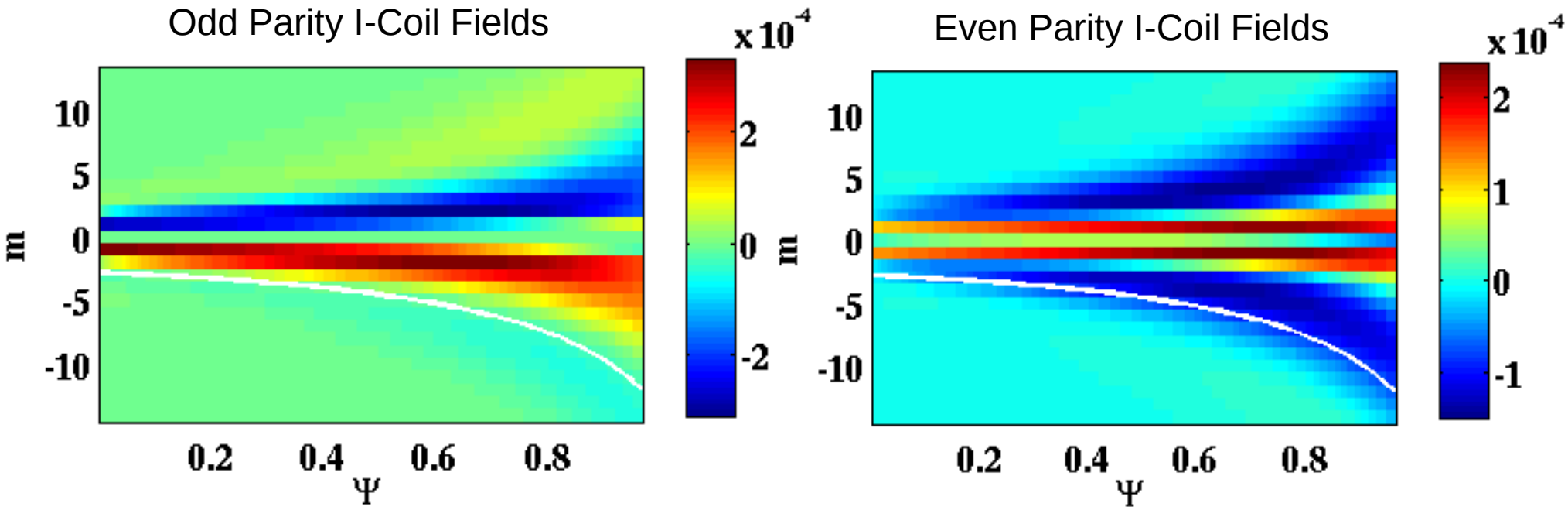
**Simulation is initiated with large neutral density of Ar everywhere in the plasma**

- "Instantaneous delivery" creates extremely fast (unphysical) thermal quench and very high radiated power for a very short time
- Following a real DIII-D TQ, impurities are well mixed and plasma is cooled everywhere
- Following simulated (super fast) TQ, impurities are well mixed and plasma is cooled everywhere

**Cold, Low S CQ simulation commences on physical time scales**

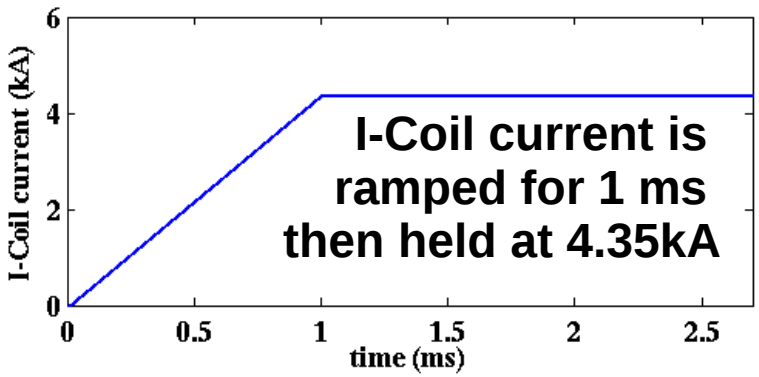


# Current quench simulations are run with odd, even, and no I-Coil fields




- Applied fields are n=3 vacuum fields for both even and odd parity I-Coil currents

- Even parity has strong resonant components, odd parity is mostly non-resonant



# Simulations are free-boundary, but domain does not extend to the DIII-D wall

Boundary extends beyond LCFS, but must be kept inside I-Coil location

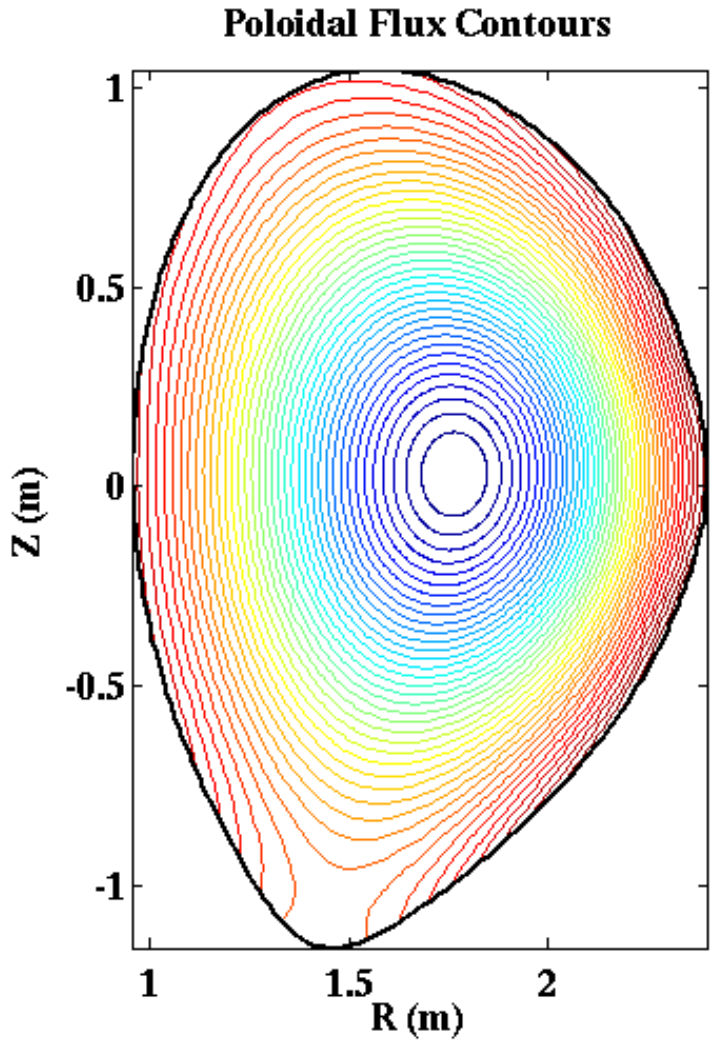
Resistivity is **Spitzer** (cold CQ plasma requires no artificial enhancement):

$\eta = 13.7 \mu_o Z_{eff} (10/T_e)^{3/2}$ Ohm-m

Heat transport is approximately Braginskii:

$\chi_\perp = 0.2(40/T_i)^{1/2}(1/B^2)$ m/s

$\chi_{||} = 2x10^6(T_e/40)^{5/2}$ m/s



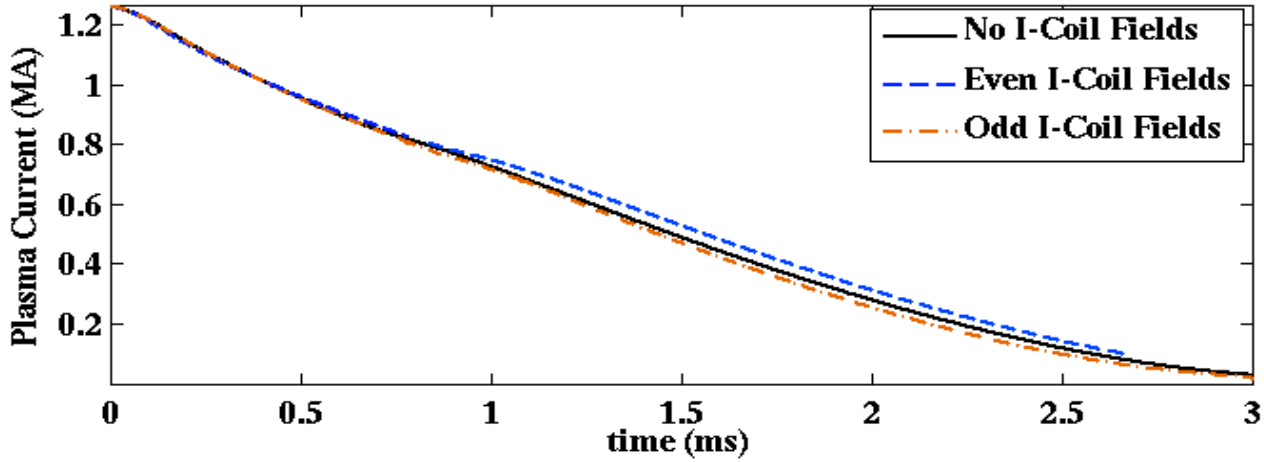
# “Ar pellet” simulations show MHD event part way into the current quench

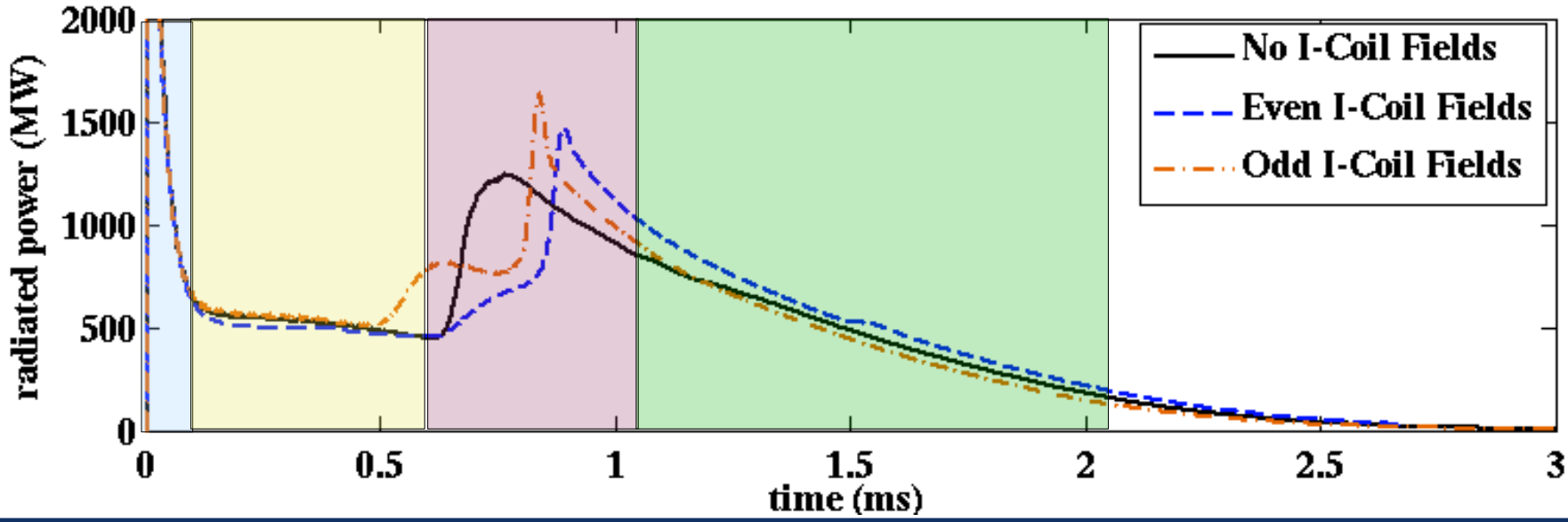
1) Ultra-fast (unphysical) TQ

2) Early CQ ($P_{rad}$=$P_{ohmic}$)

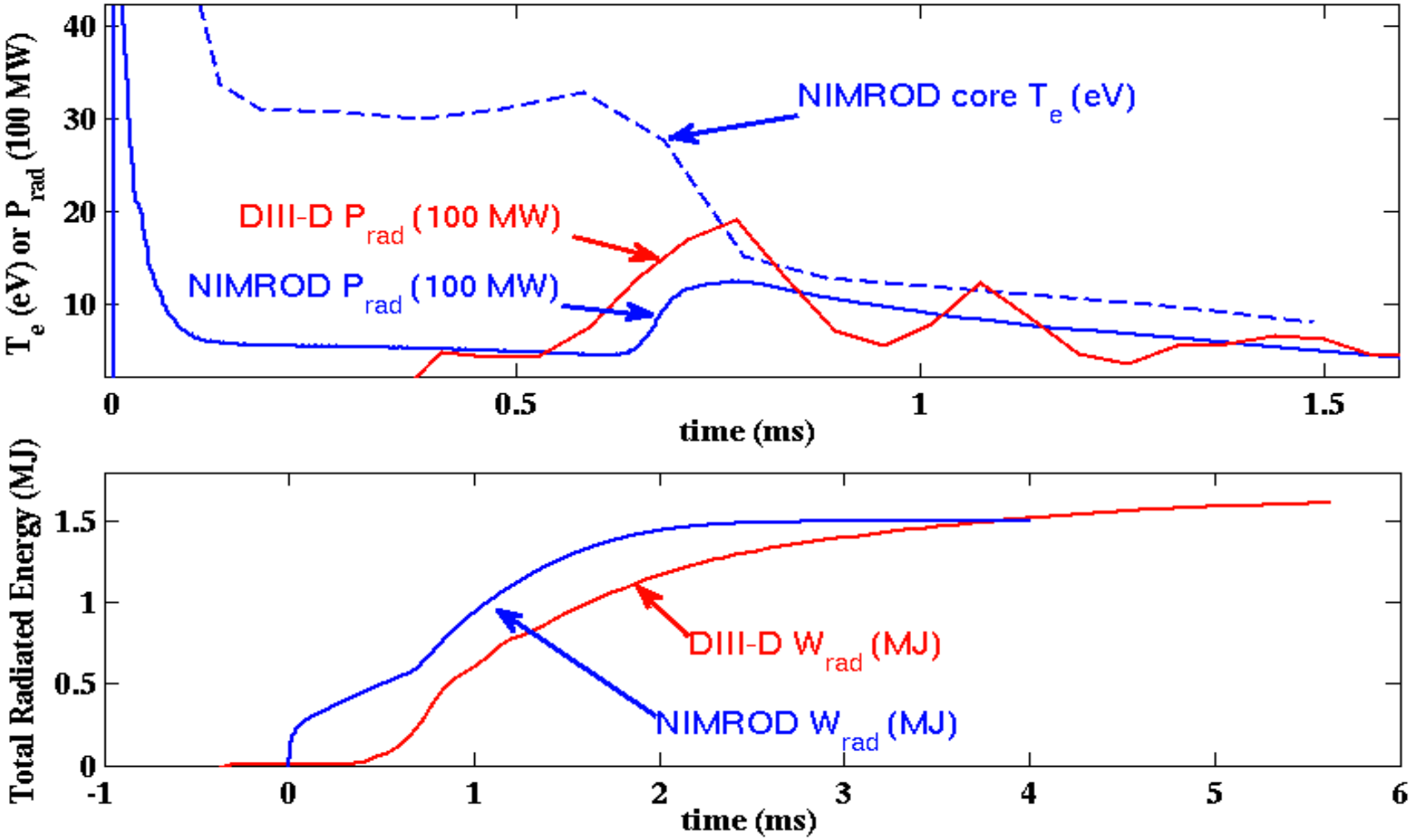
3) MHD phase

4) Late CQ phase

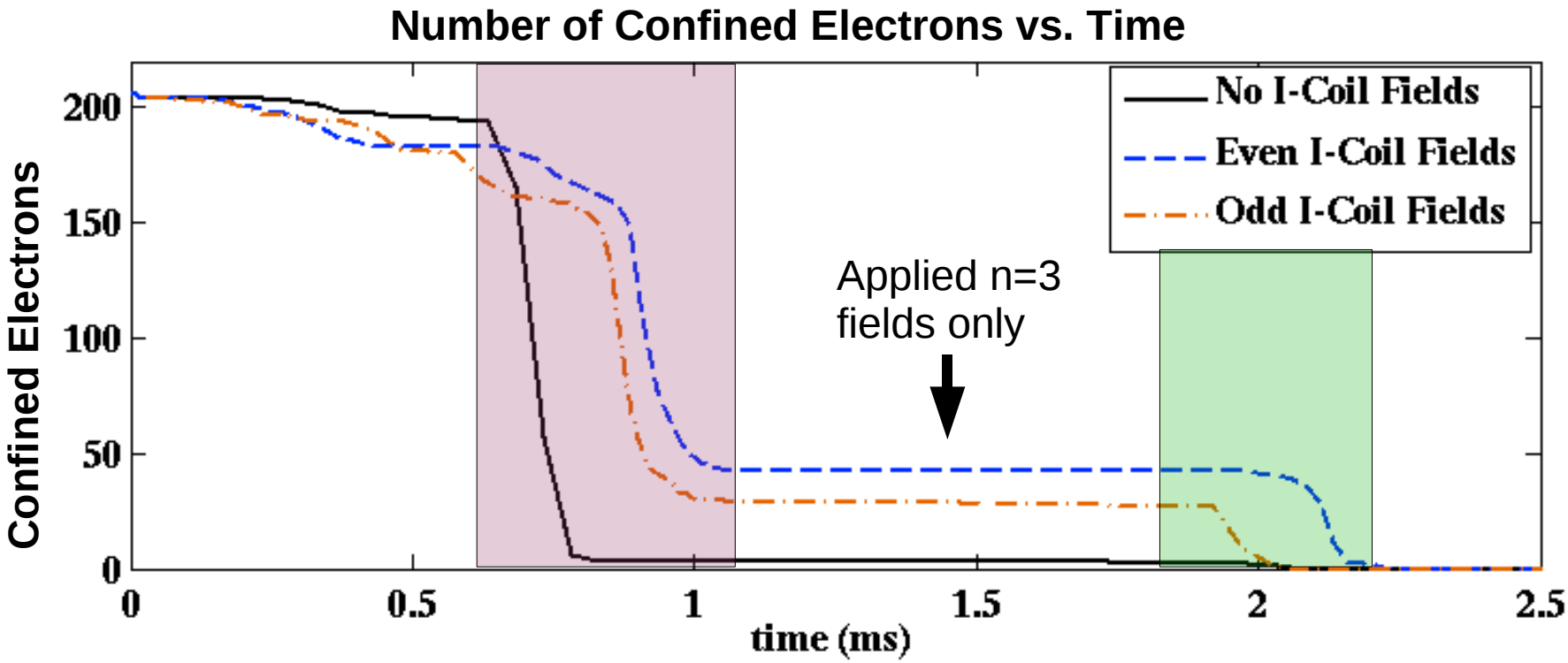


# Total radiated energy in simulation agrees well with experiment



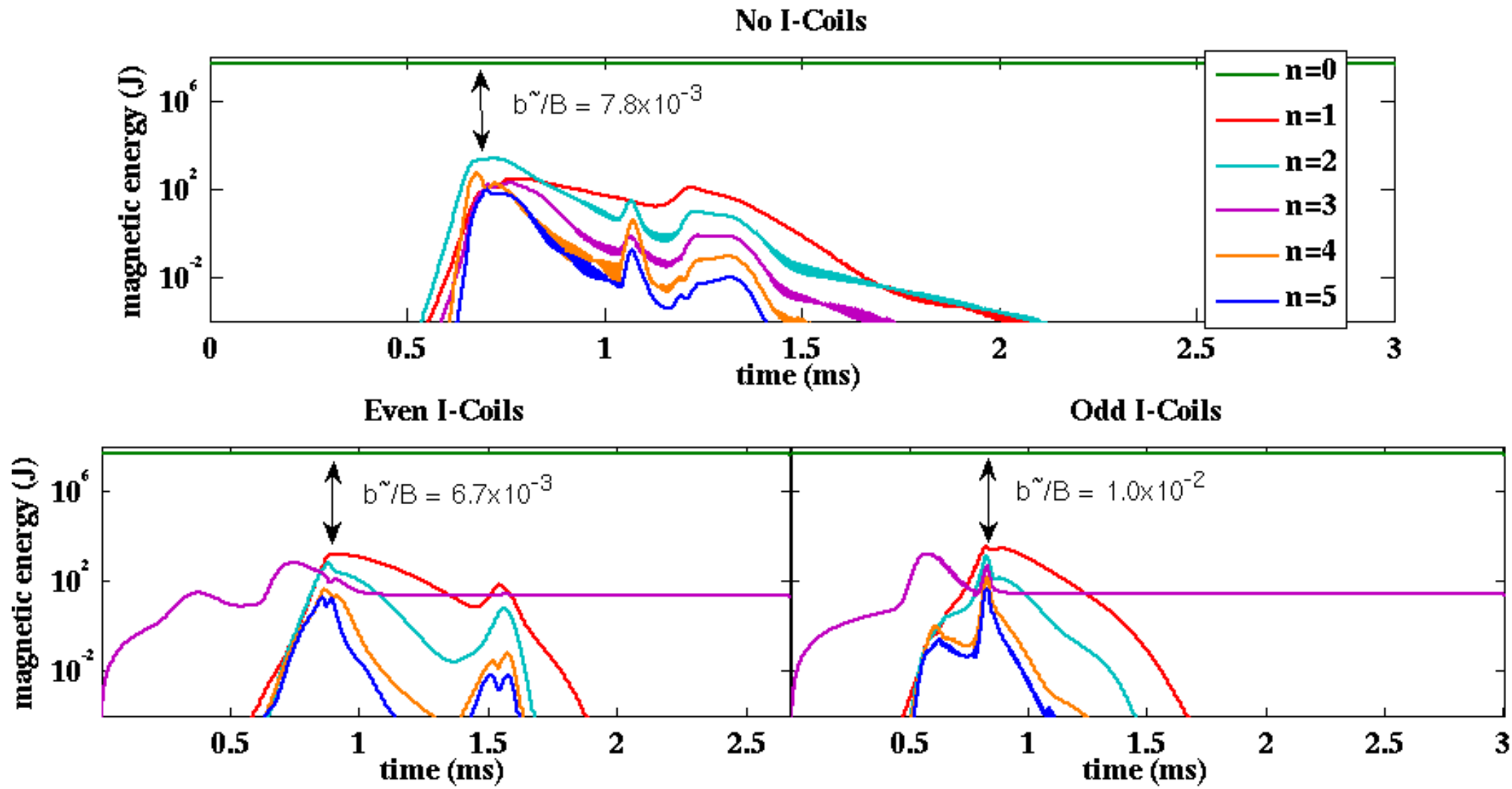
# **Key Result:** NIMROD simulations find that n=3 fields *enhance* RE confinement




• In each case, 239 fast electrons were launched from identical starting points at t=0. Prompt loss to divertor occurs during MHD phase. Late loss is to main chamber.

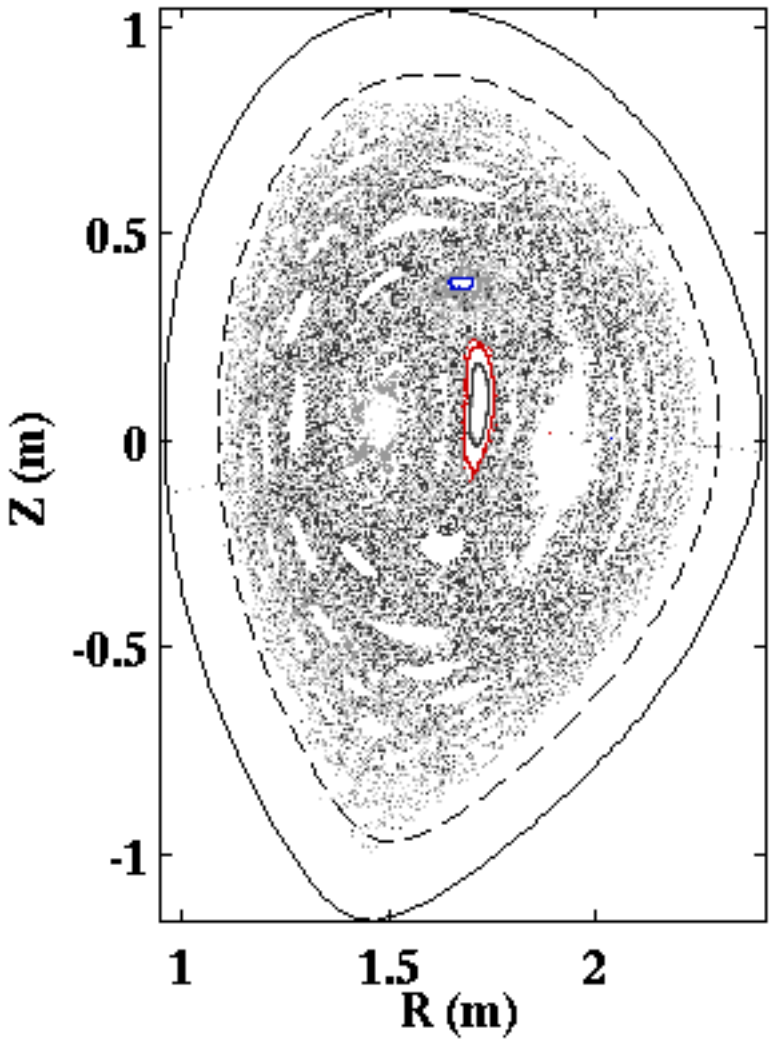
**Confinement is better with even or odd I-Coil fields.**

# I-Coil fields alter details of the MHD crash, amplitudes are quite similar

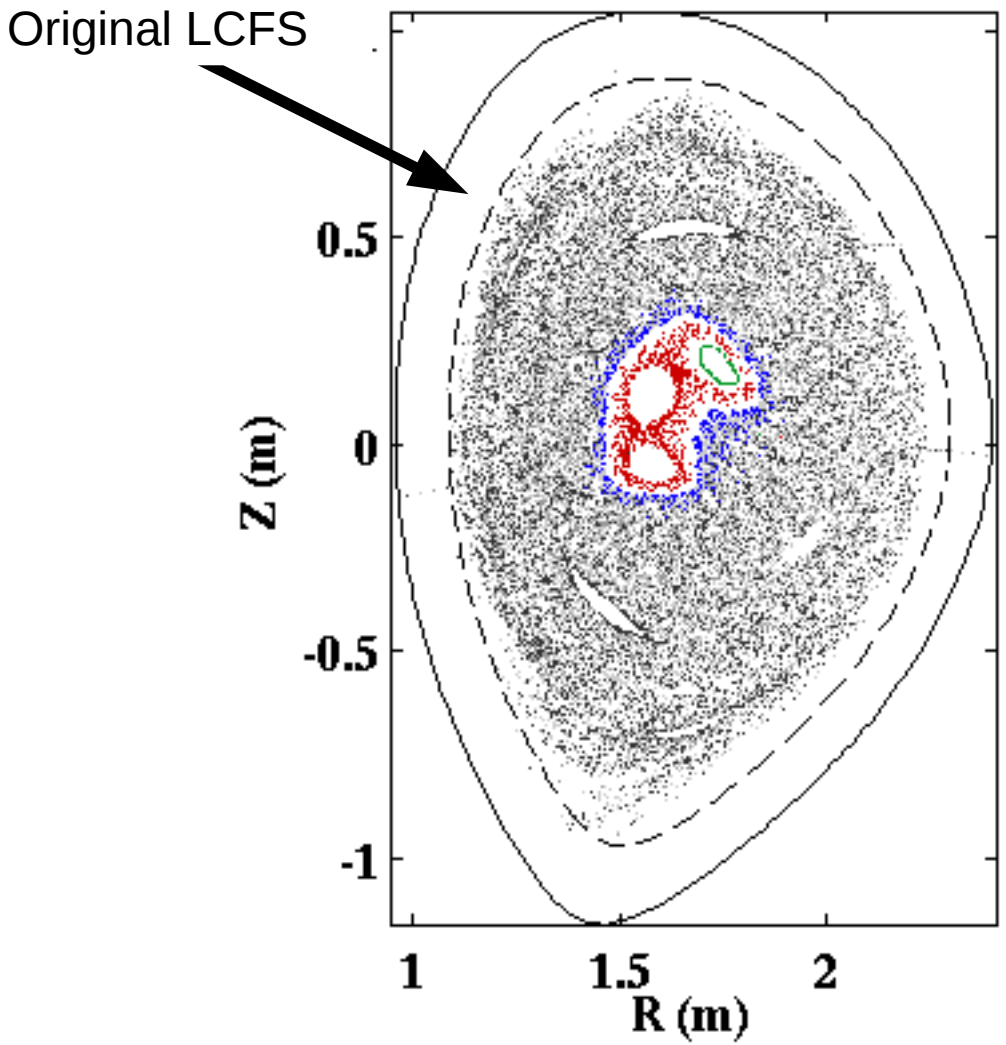


# Without I-Coils, core flux surfaces are more thoroughly destroyed by MHD

**No I-Coils**




**Even I-Coils**



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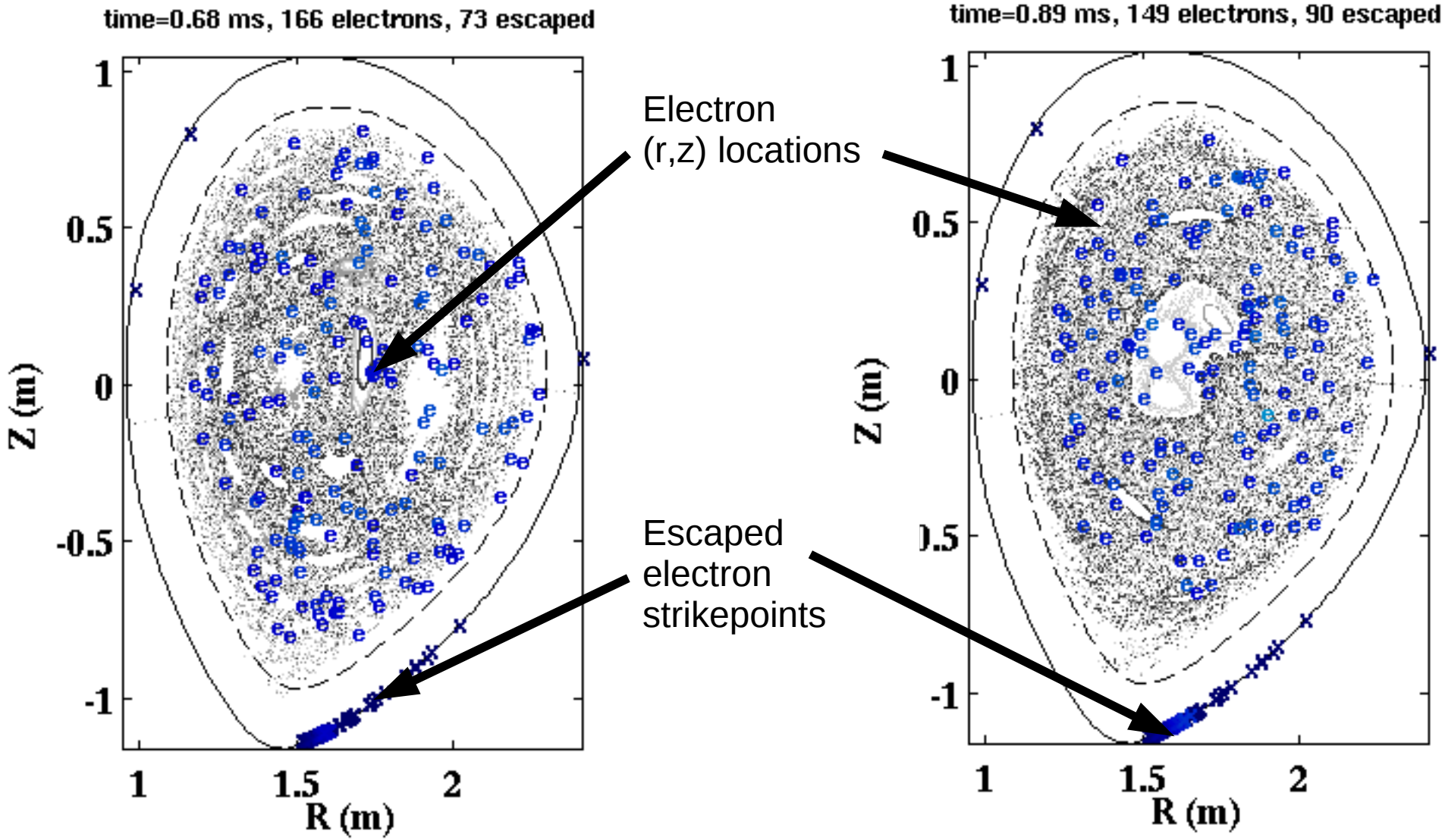
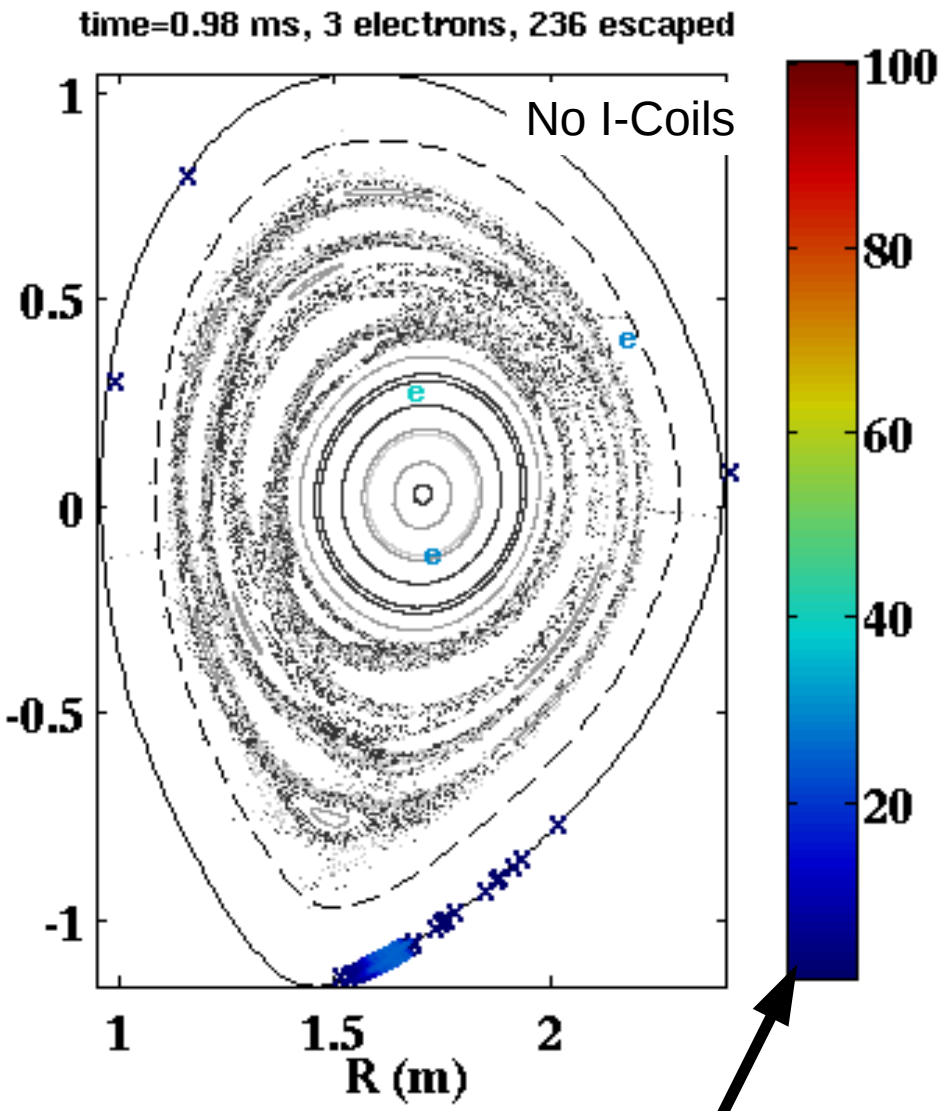
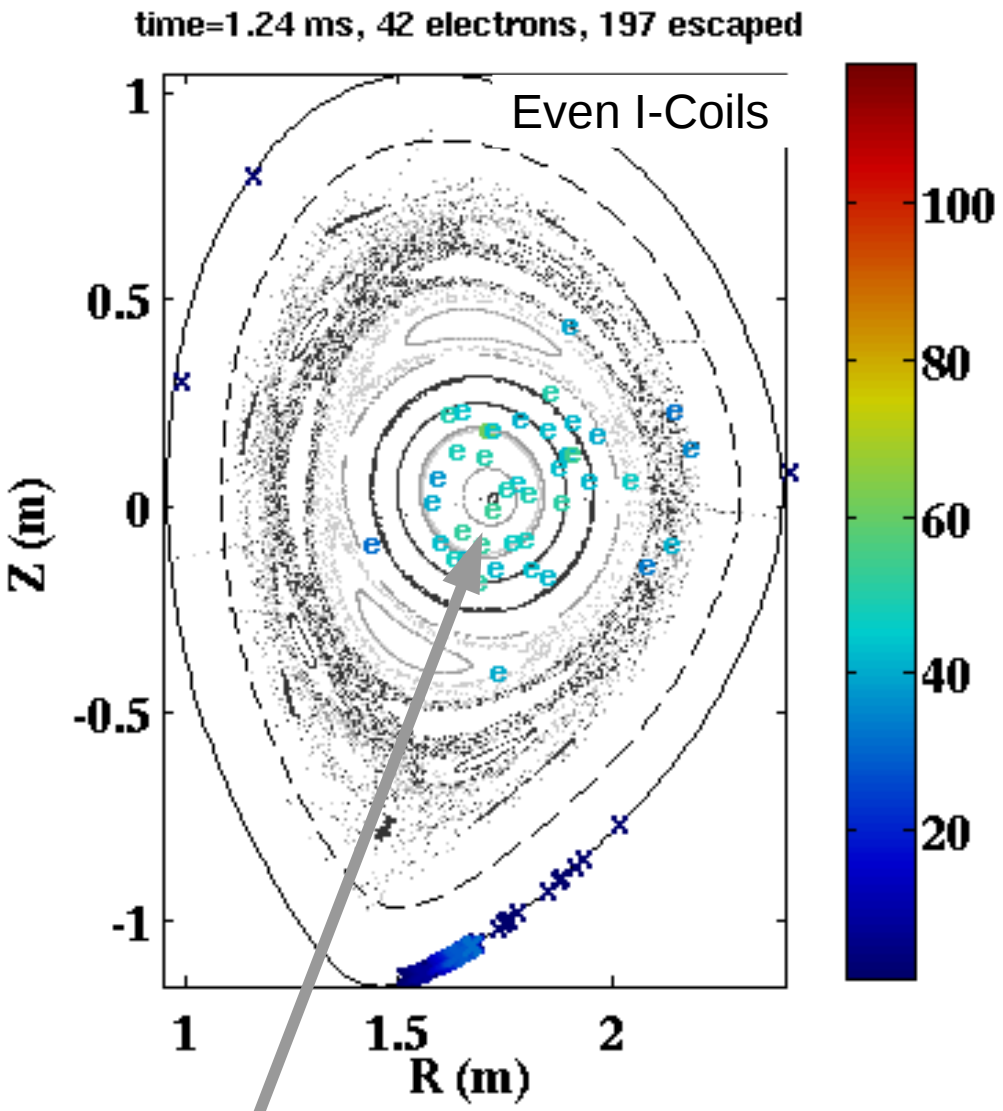


# As flux surfaces begin to re-heal, core of well confined REs remains in I-Coil case




Relativistic γ (=1/sqrt(1-(v/c)²))

γ=45 => 25 MeV (DIII-D measured energy)

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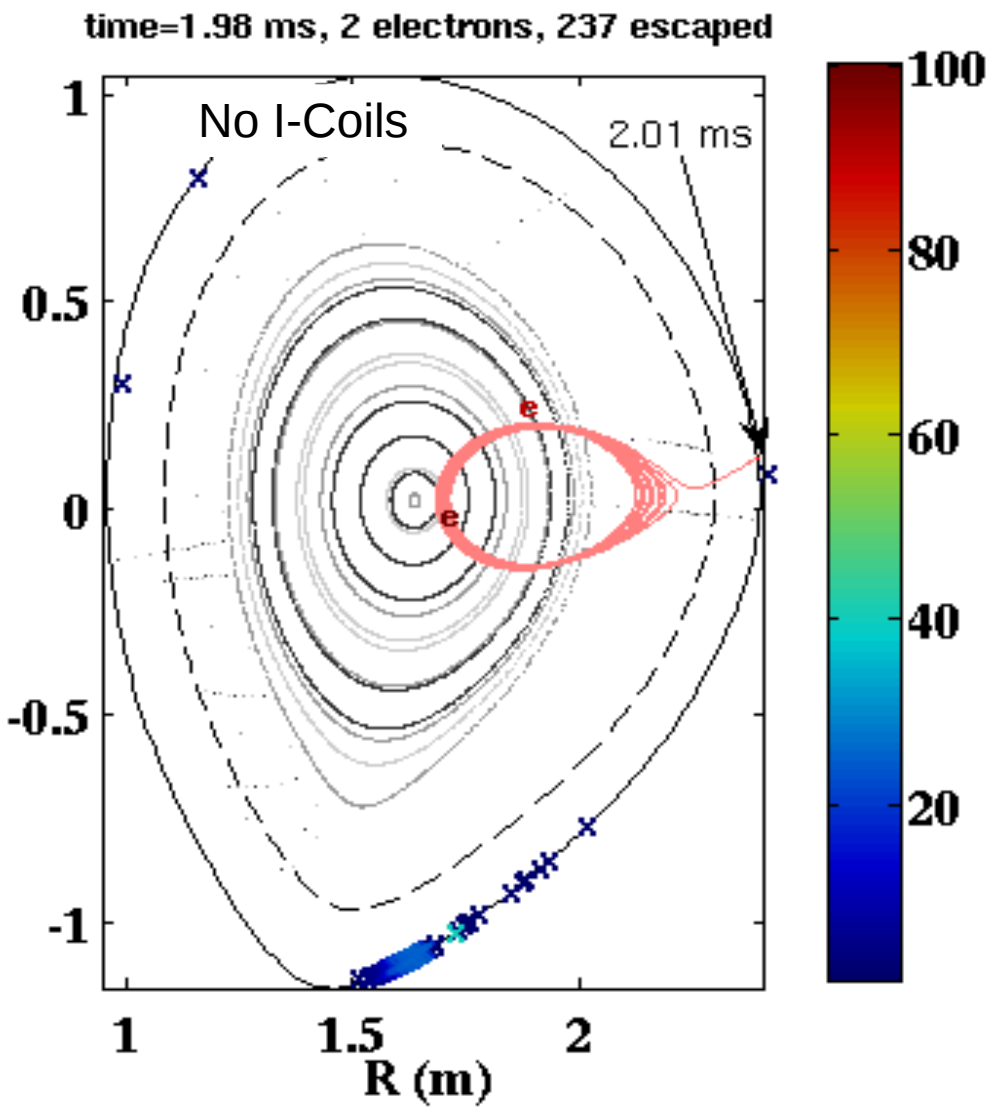
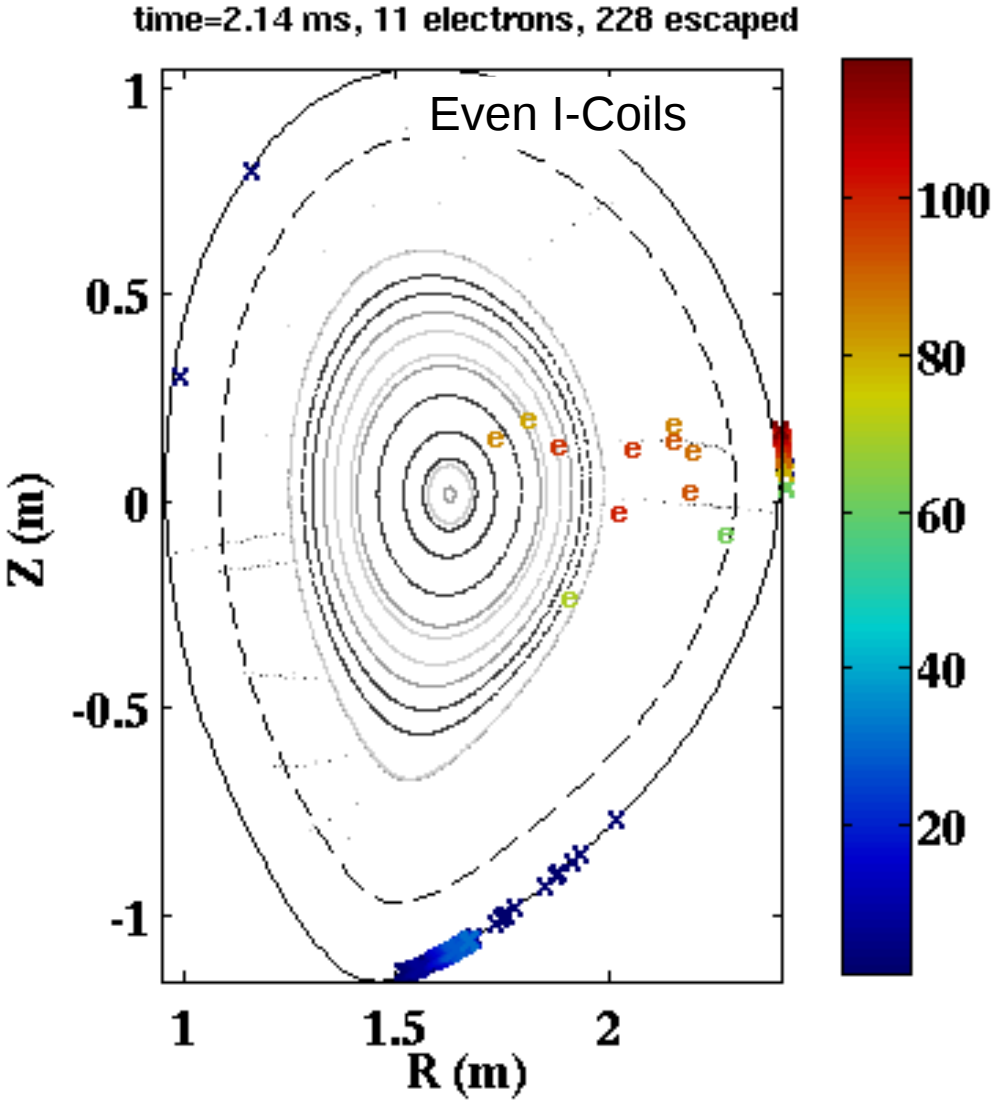
# Late in time, high energy REs become deconfined due to large drift displacement

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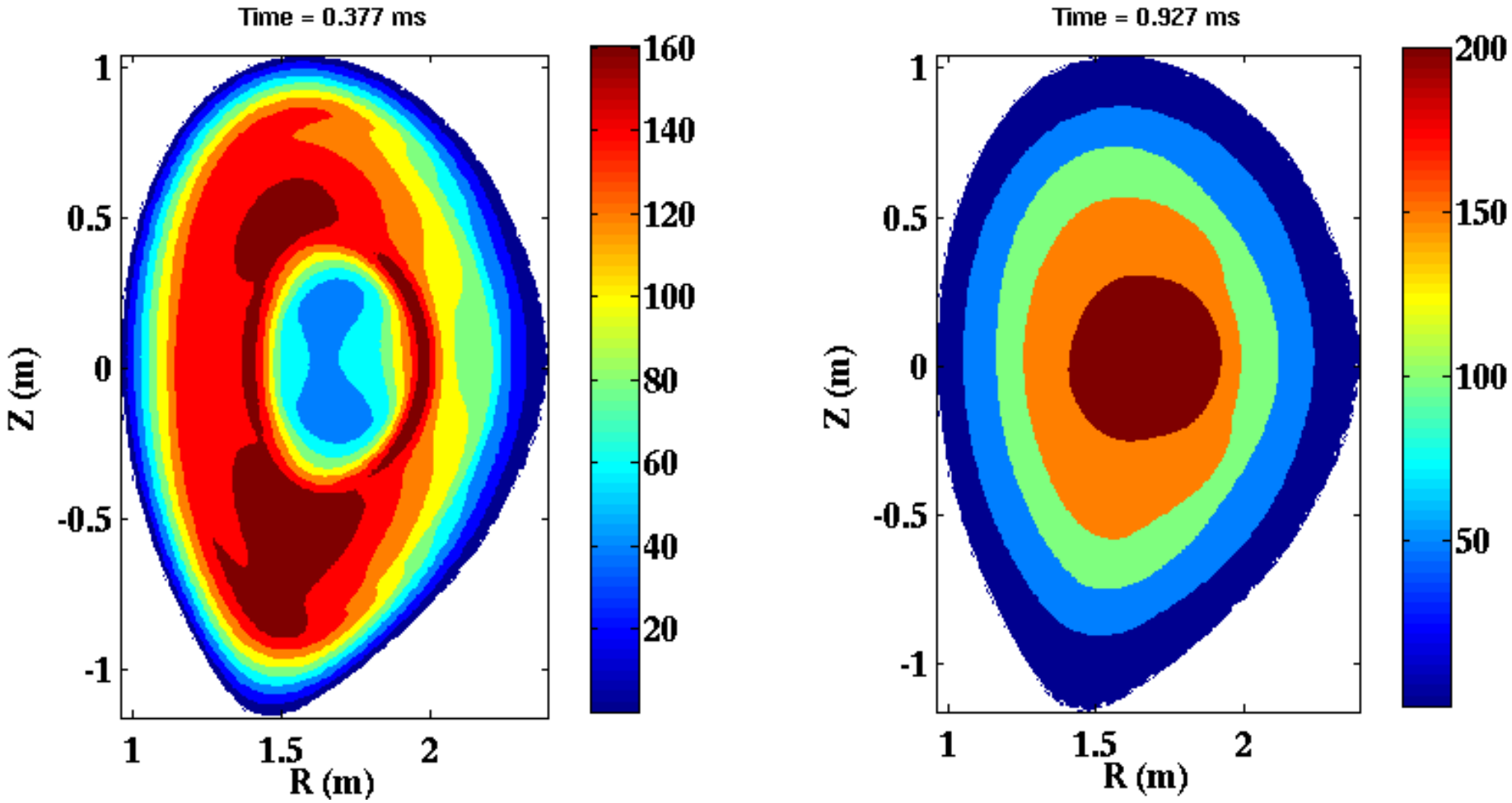
# Considerably more density would be required for collisional RE avalanche suppression

Early CQ

Contours of $E/E_{crit}$

Late CQ



# Conclusions

1) The direct impact of RMP fields from the DIII-D I-Coils on RE confinement during the current quench is negligible, but …

2) The details of the MHD crash are altered by the presence of perturbing n=3 fields

3) The amplitude of the fluctuating fields alone is not a good measure of RE confinement

4) In the case where n=2 was the dominant mode (no I-Coils) the destruction of the flux surfaces was maximum

5) I-Coil fields with n=3 symmetry enhance RE confinement during current quench in NIMROD. Maybe n=2 perturbations?

6) Findings may not contradict DIII-D results, which show loss of seed population before current quench

# Possible Model Improvements

1) Avalanching: probably the easiest next step using simple expression to generate secondary electrons as the simulations progresses:

$$\frac{dn_{sr}}{dt} = \frac{n_r\, eEc}{2\mathrm{m}_0 c^2 (\ln \Lambda)(2+Z_{eff})/3}$$

Could produce the correct exponential distribution with high energy REs gradually lost, while bulk remains confined.

2) Seed terms are harder: Dreicer appears not to be a plausible mechanism for primaries on DIII-D. Might be hot-tail, but still unclear. Would need to get cooling rate correct for hot-tail.

3) Modeling the runaway beam in NIMROD: Probably needed to understand upward drift, but seems difficult. No plans on this.