Runaway Electron Confinement in MHD Disruption Mitigation Simulations

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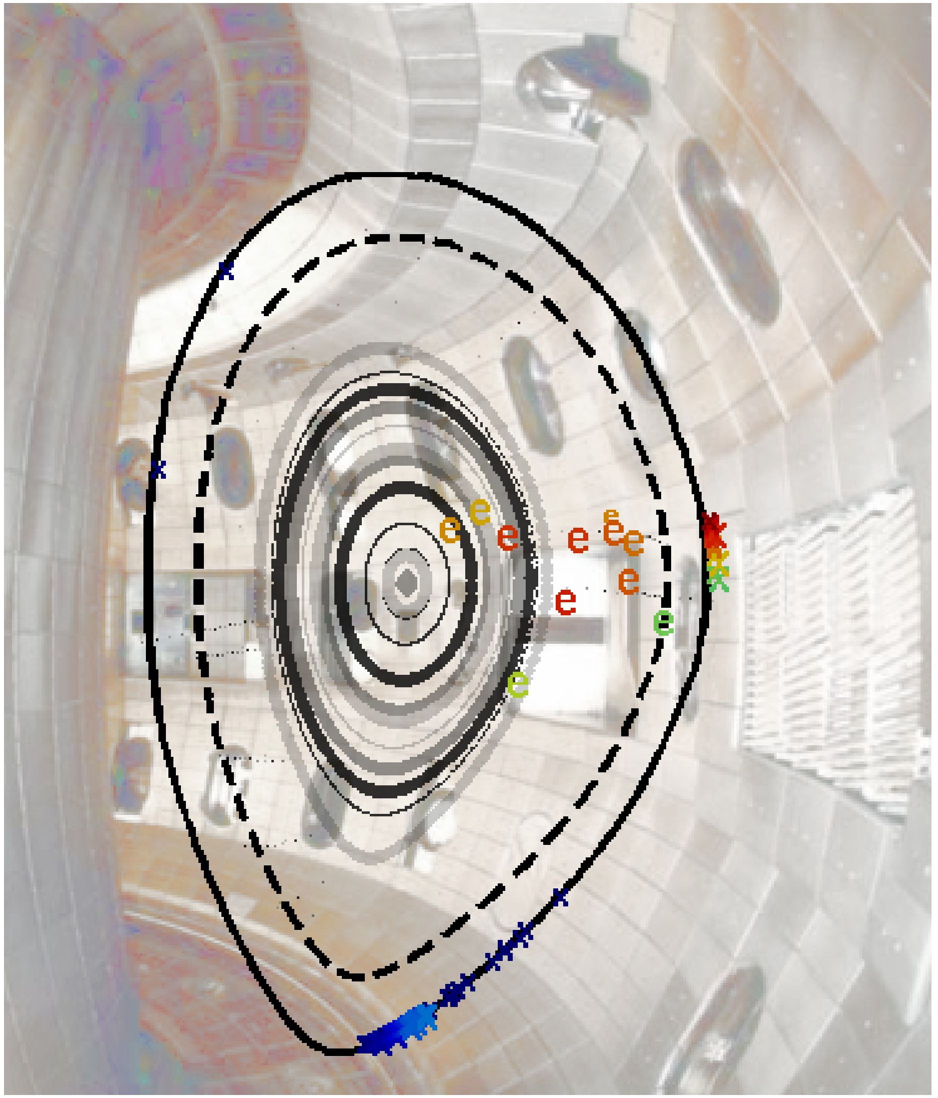
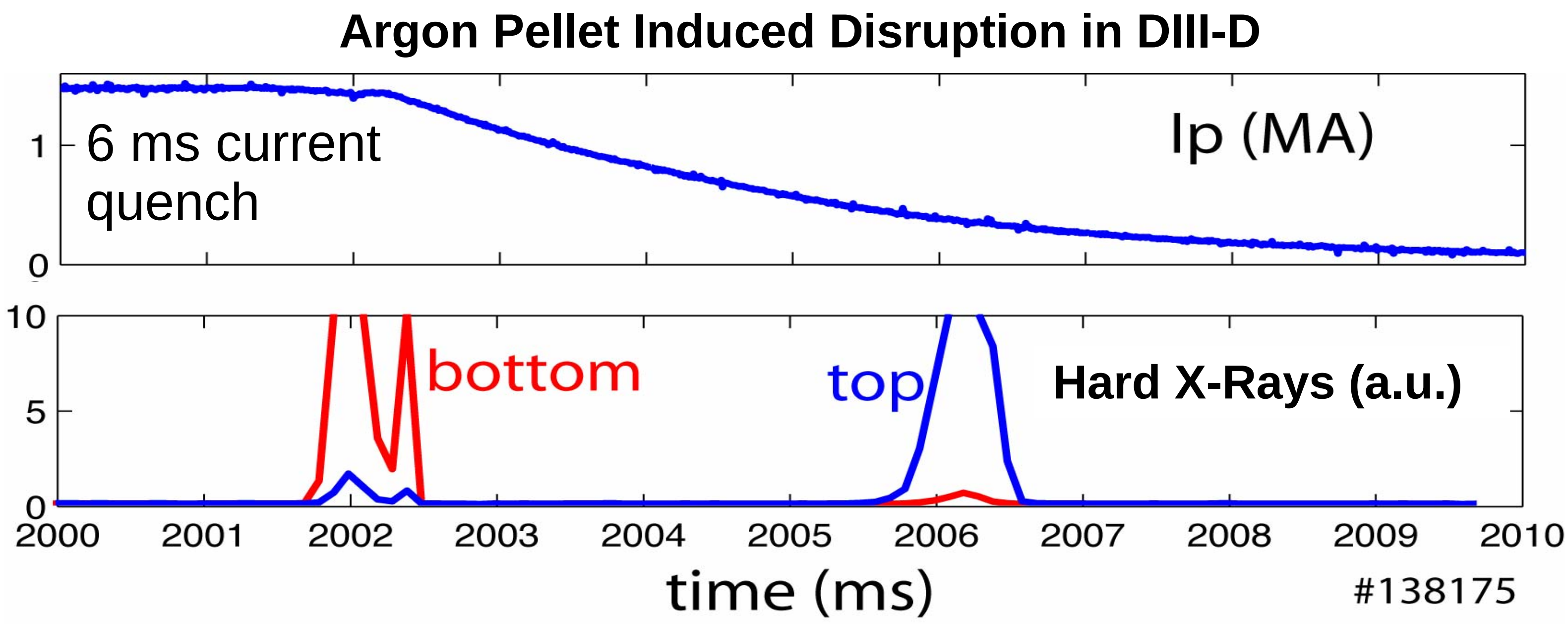


We want to control runaway electron (RE) confinement during DIII-D disruptions



- In experiments, two runaway loss events are observed, well separated in time
- Prompt loss at start of current quench to the divertor
- Late-time loss of REs to main chamber

Question:

Can the application of (n>0) perturbing B-fields degrade runaway electron (RE) confinement during the current quench, and prevent an exponentially growing RE beam?

Answer:

Simulations suggest n=3 fields *improve* RE confinement during <u>current quench</u>

Current quench is modeled with NIMROD

• NIMROD 3D MHD code includes KPRAD modeling for impurity radiation/ionization

• Runaway electron confinement "diagnostic" runs concurrently with NIMROD, integrates single particle orbits for hundreds of fast electron. Four equations (3+1) for space and (parallel) velocity include curvature, grad-B, and ExB drift.

• Applied perturbing fields with n=3 toroidal symmetry produced by DIII-D I-Coils are included in the simulations. Both "even" and "odd" I-Coil spectra are simulated, referring to the relative parity of 2 rows of coils.

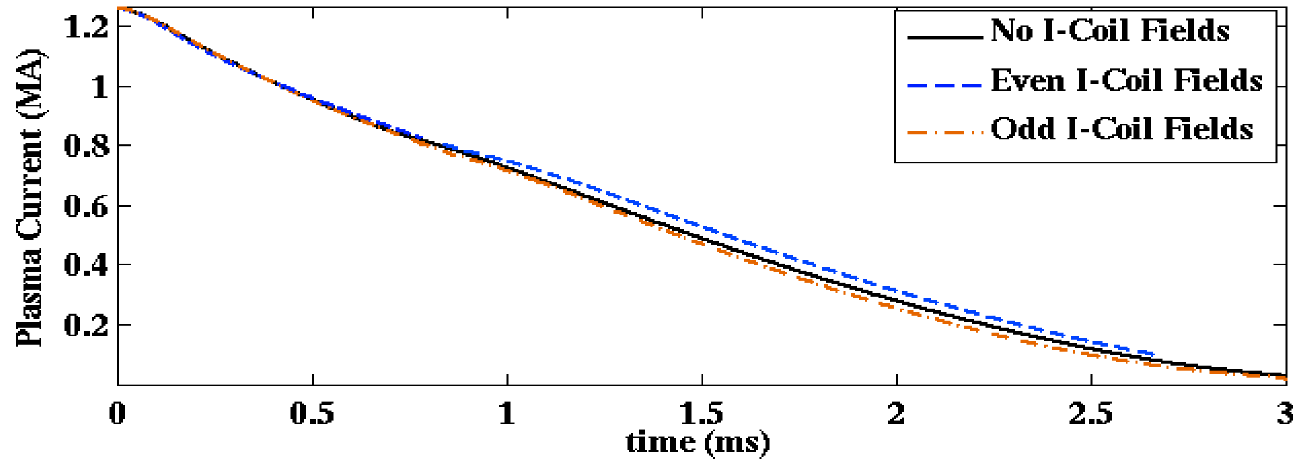
"Ar pellet" simulations show MHD event part way into the current quench

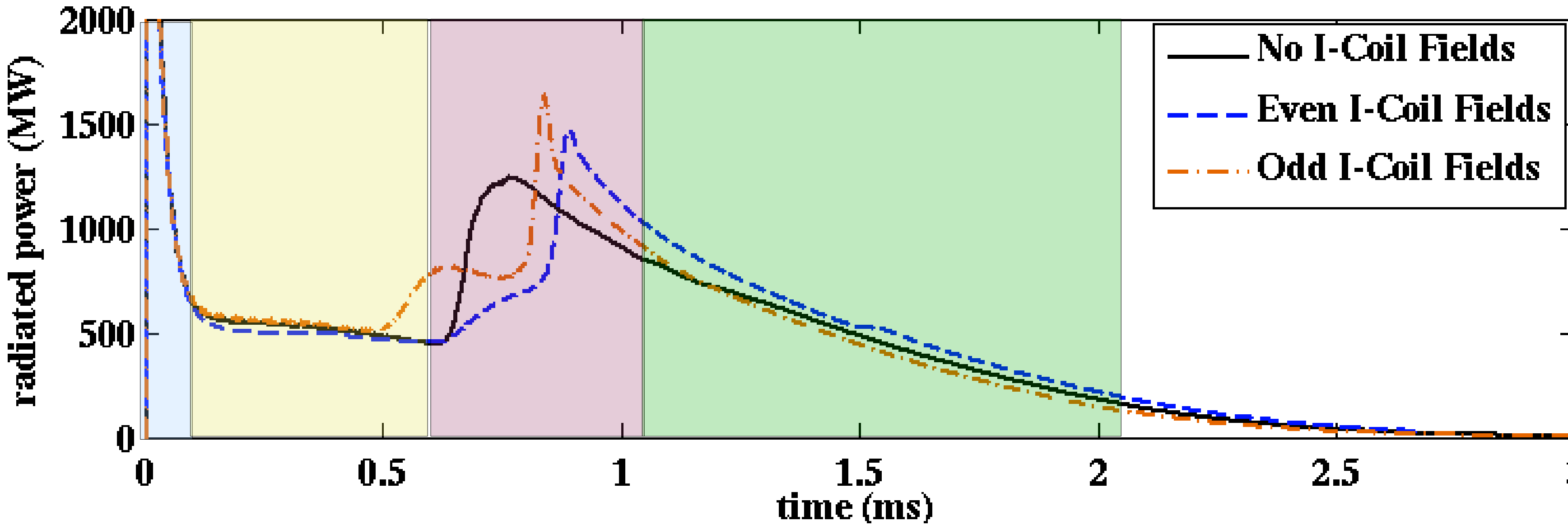
1) Ultra-fast (unphysical) TQ

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

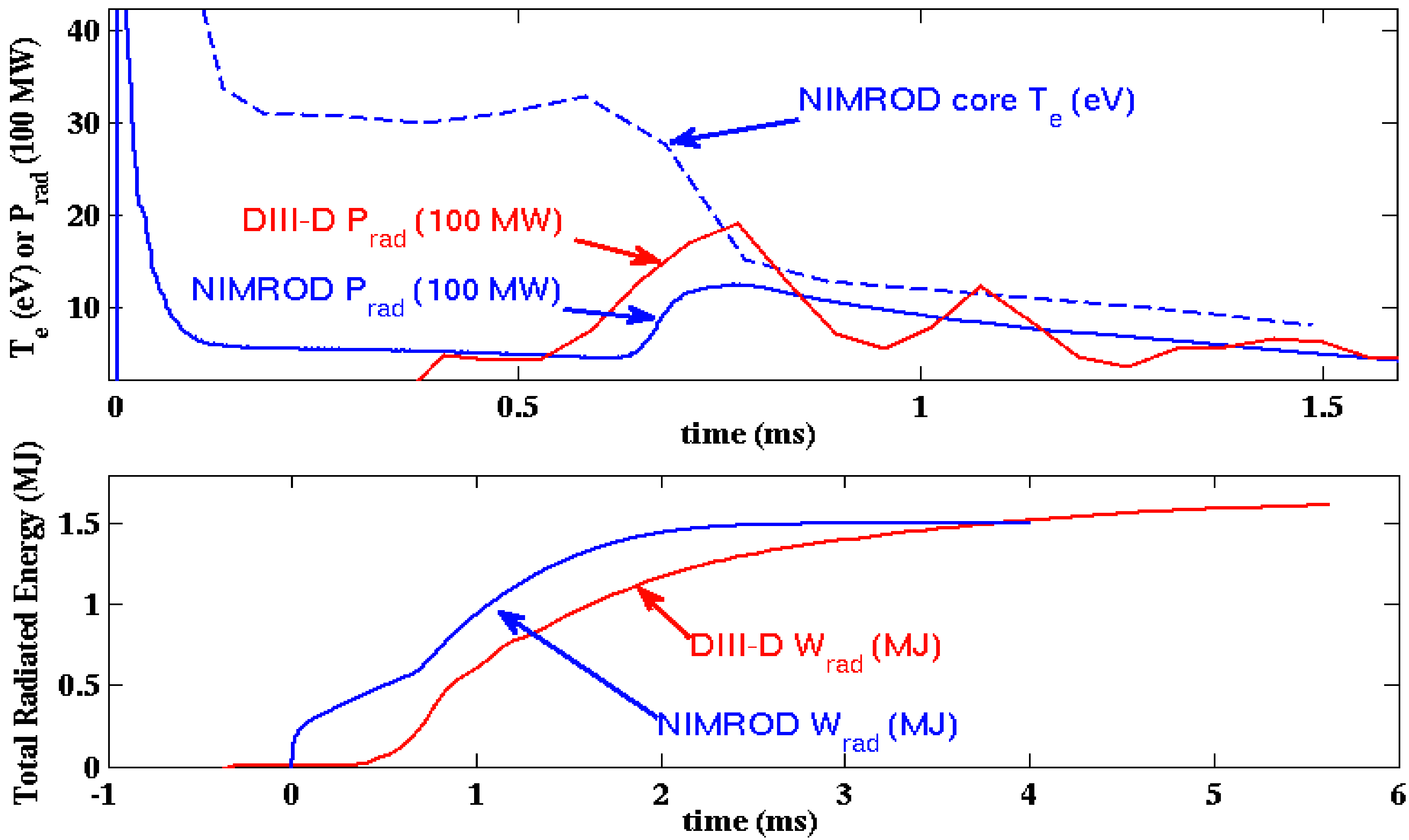
3) MHD phase

4) Late CQ phase

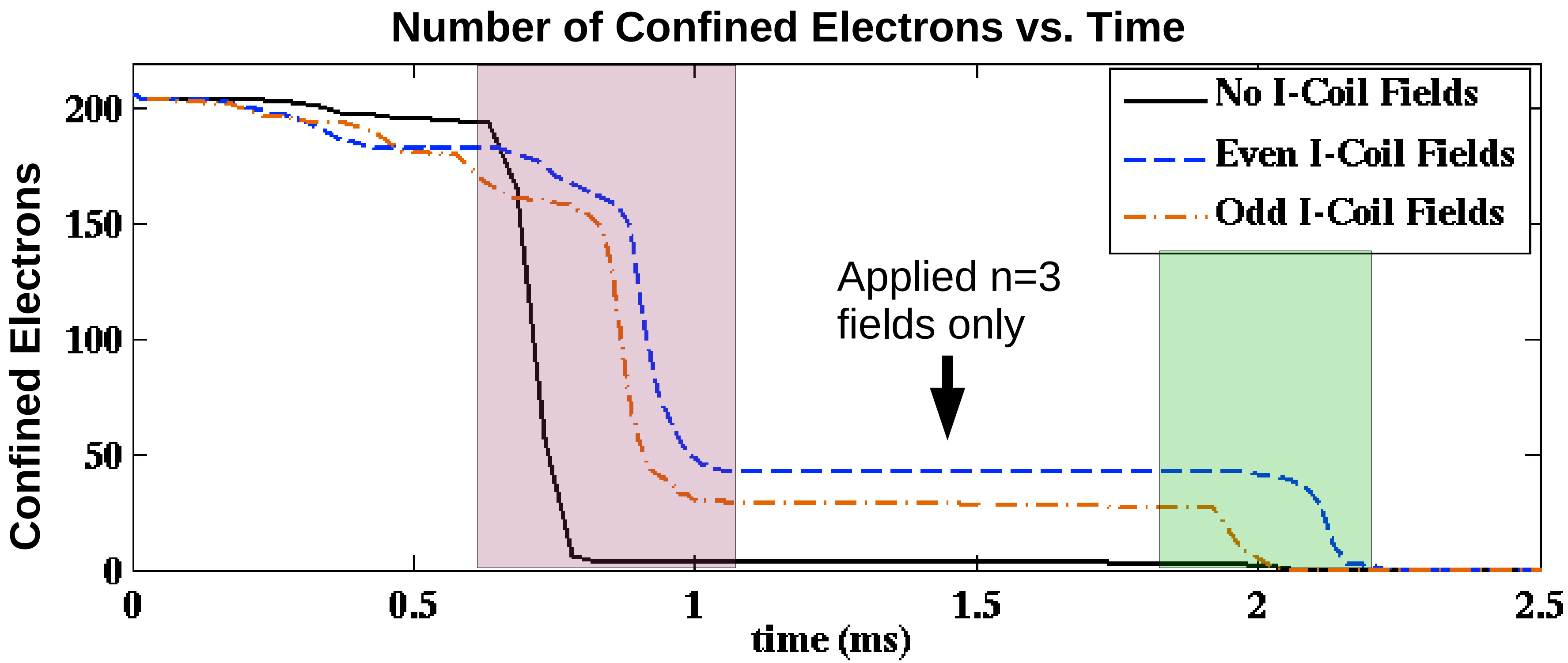




Total radiated energy in simulation agrees well with experiment



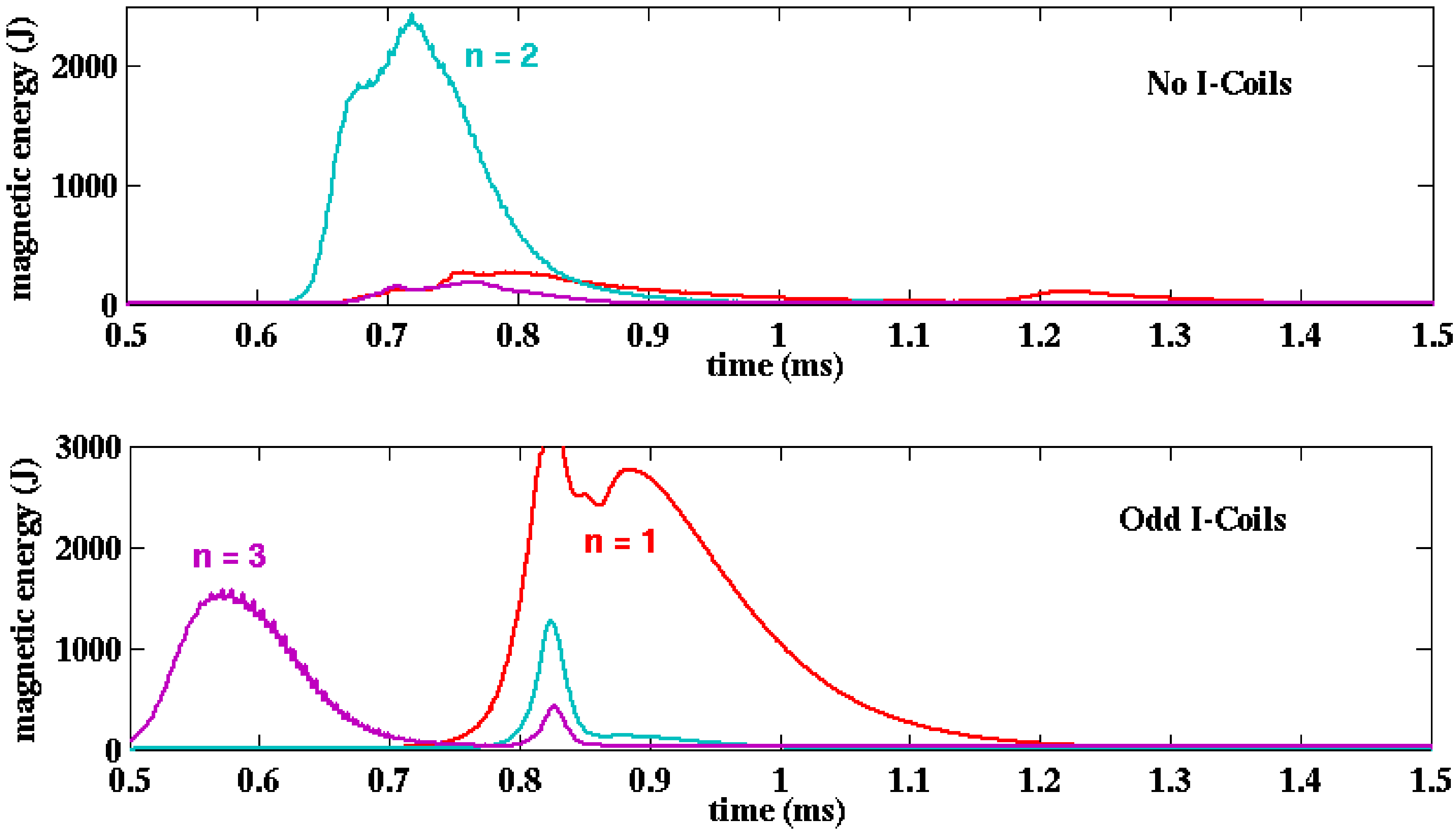
Key Result: NIMROD simulations find that n=3 fields *enhance* RE confinement



• 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



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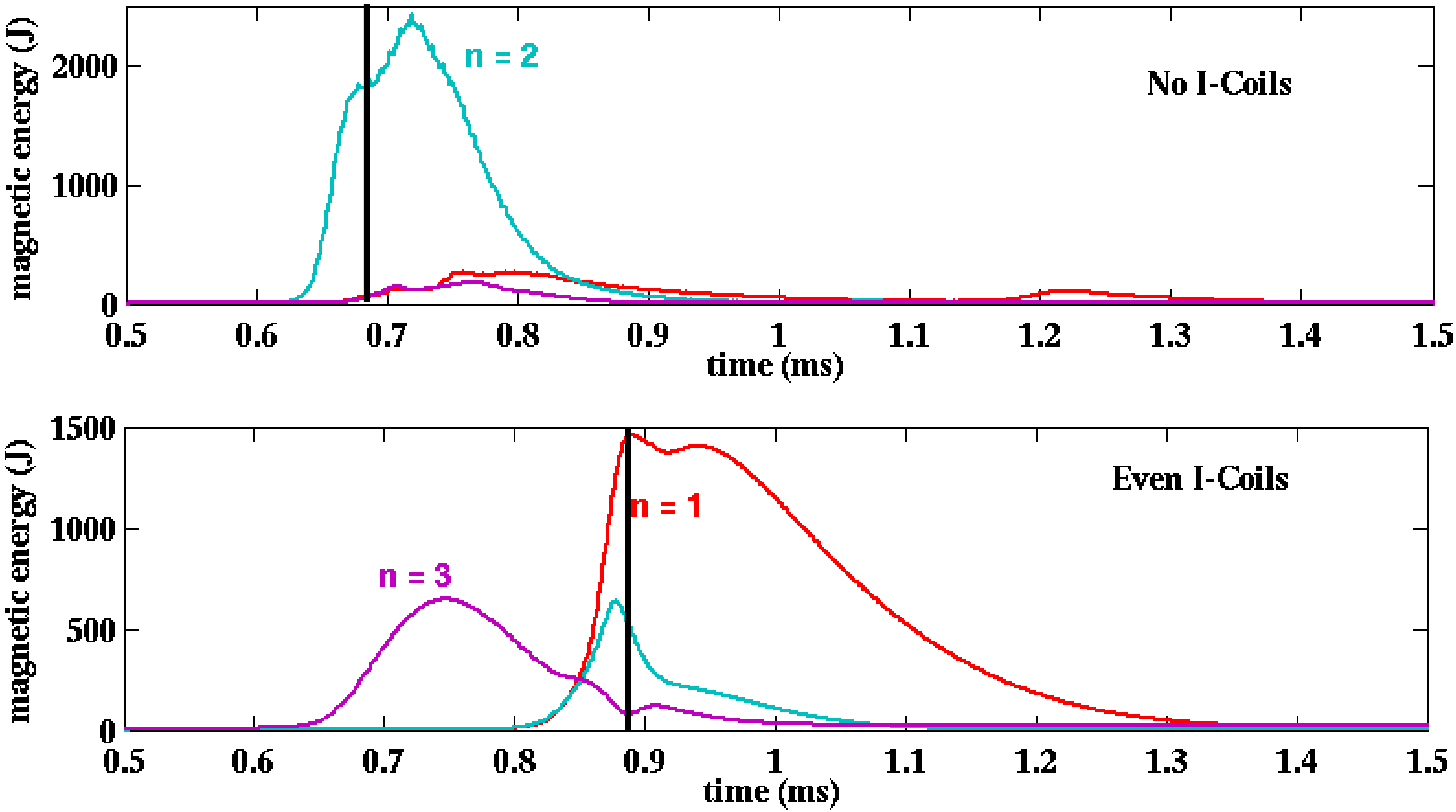

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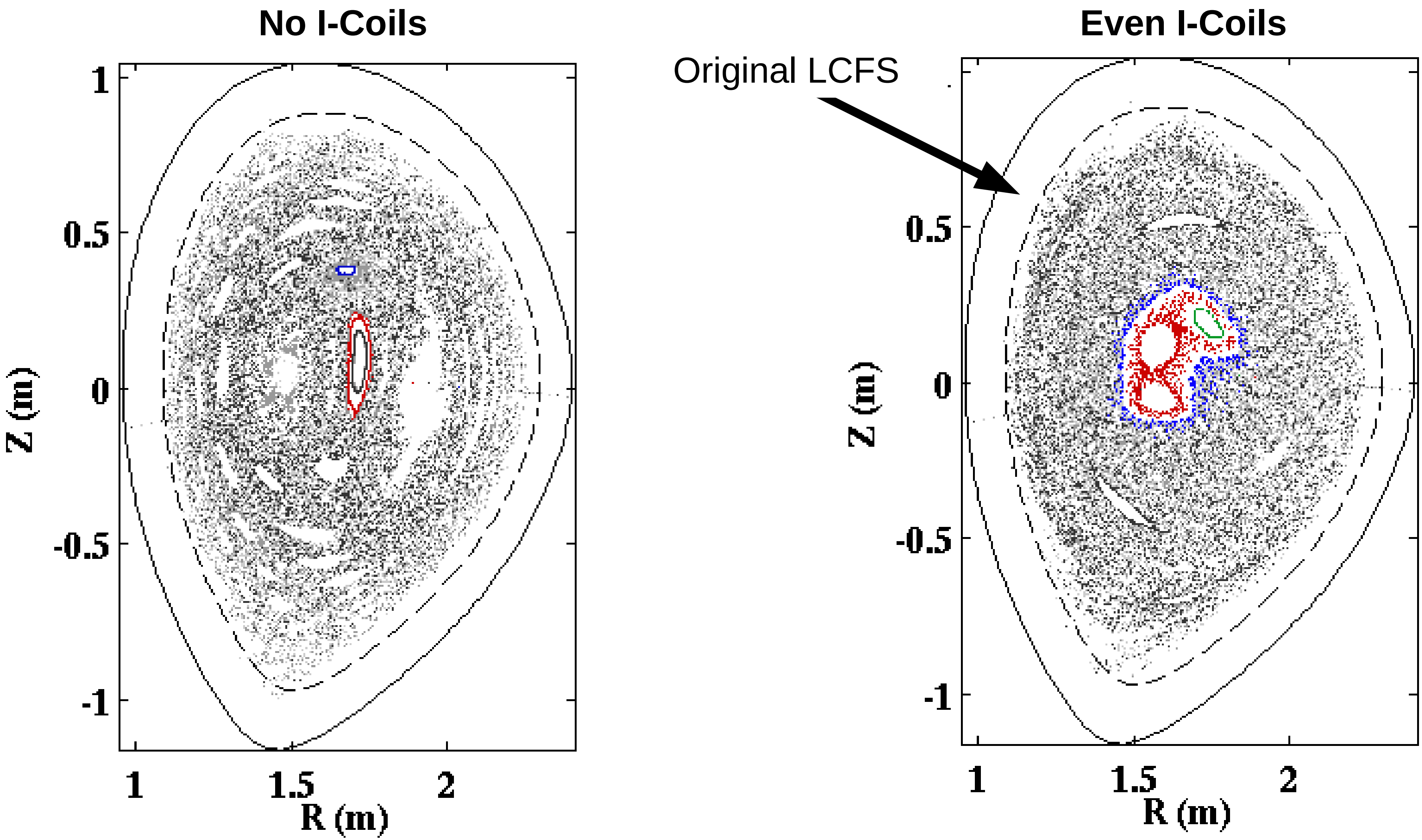
Without I-Coils, core flux surfaces are more thoroughly destroyed by MHD



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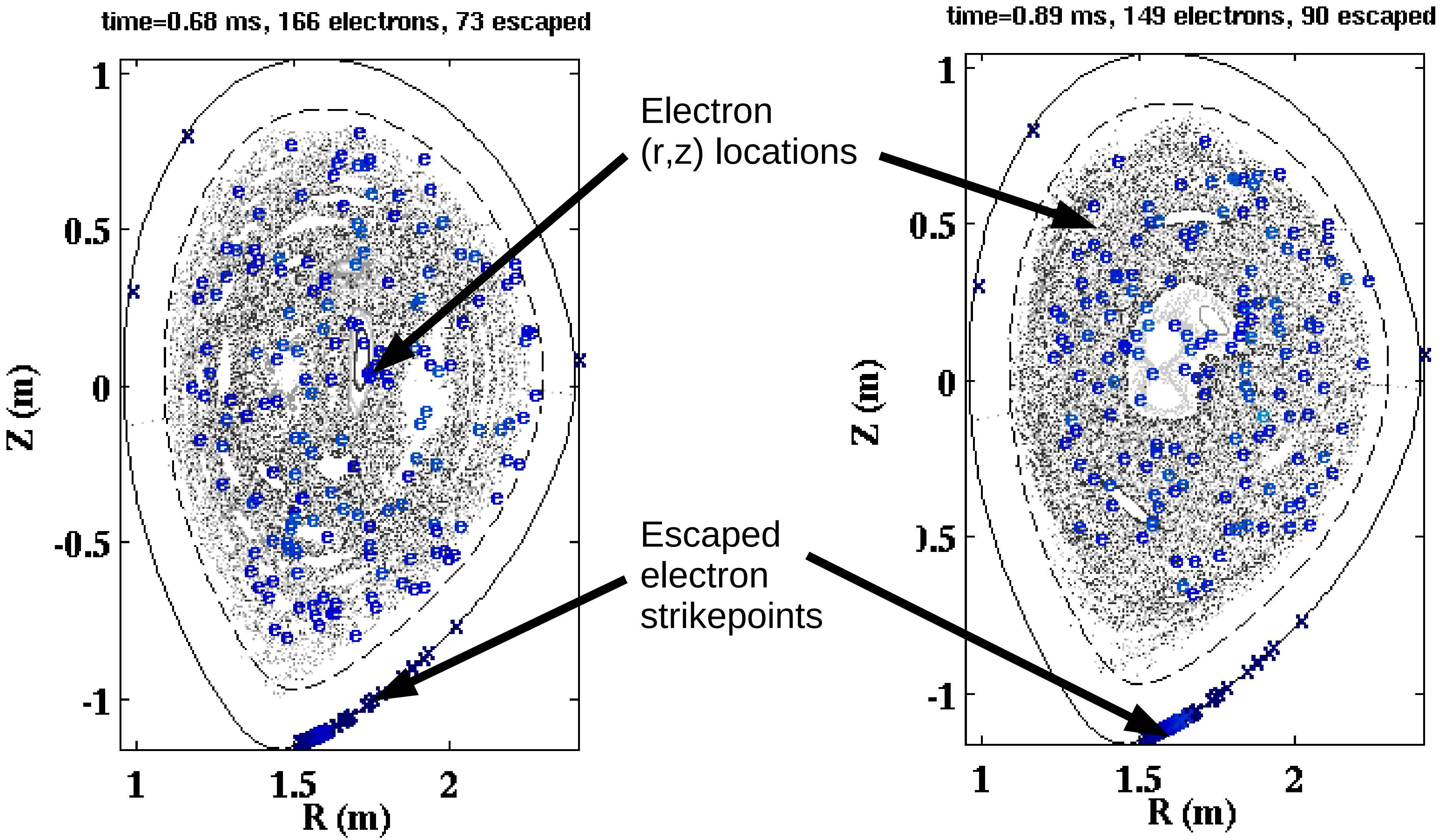
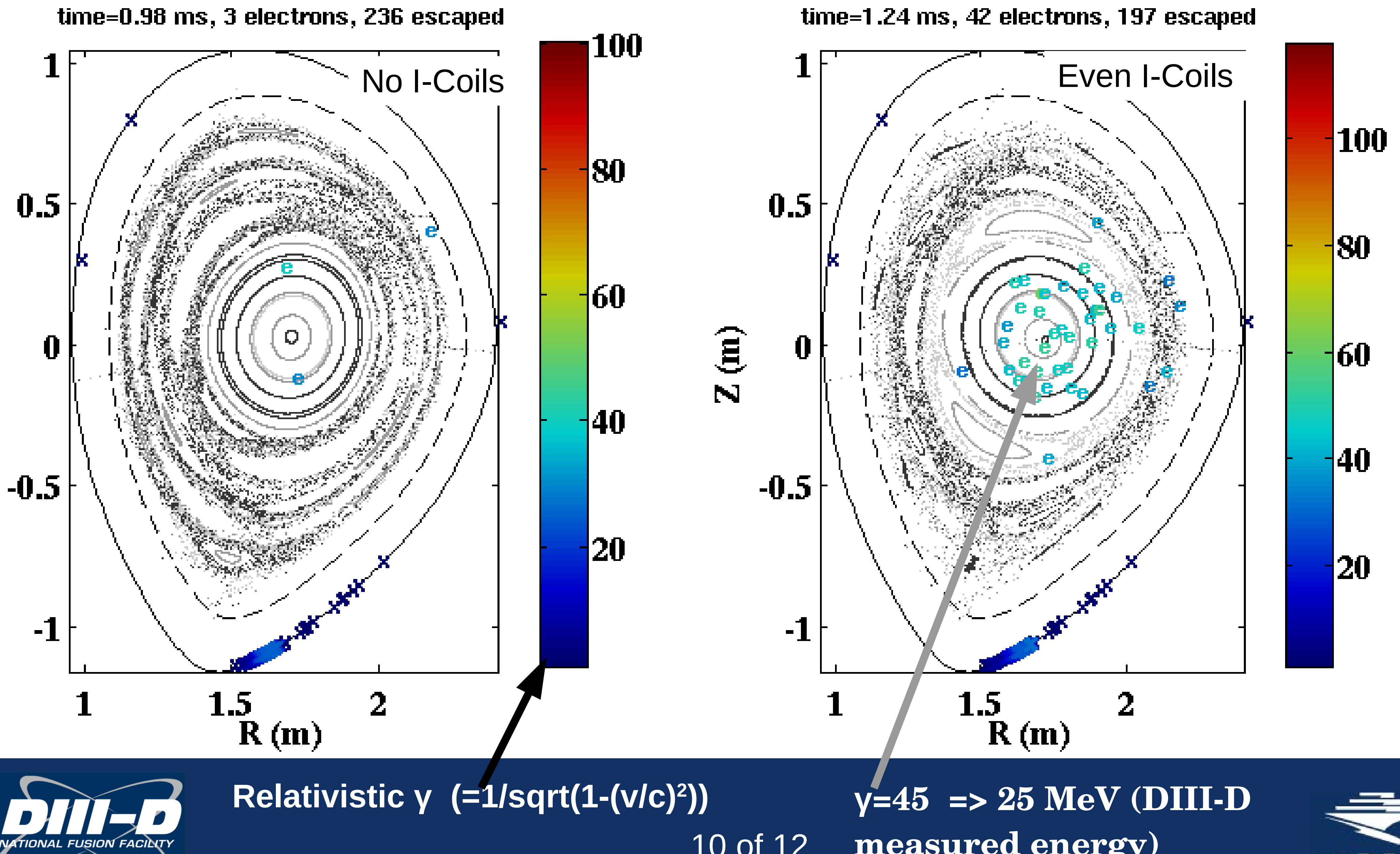
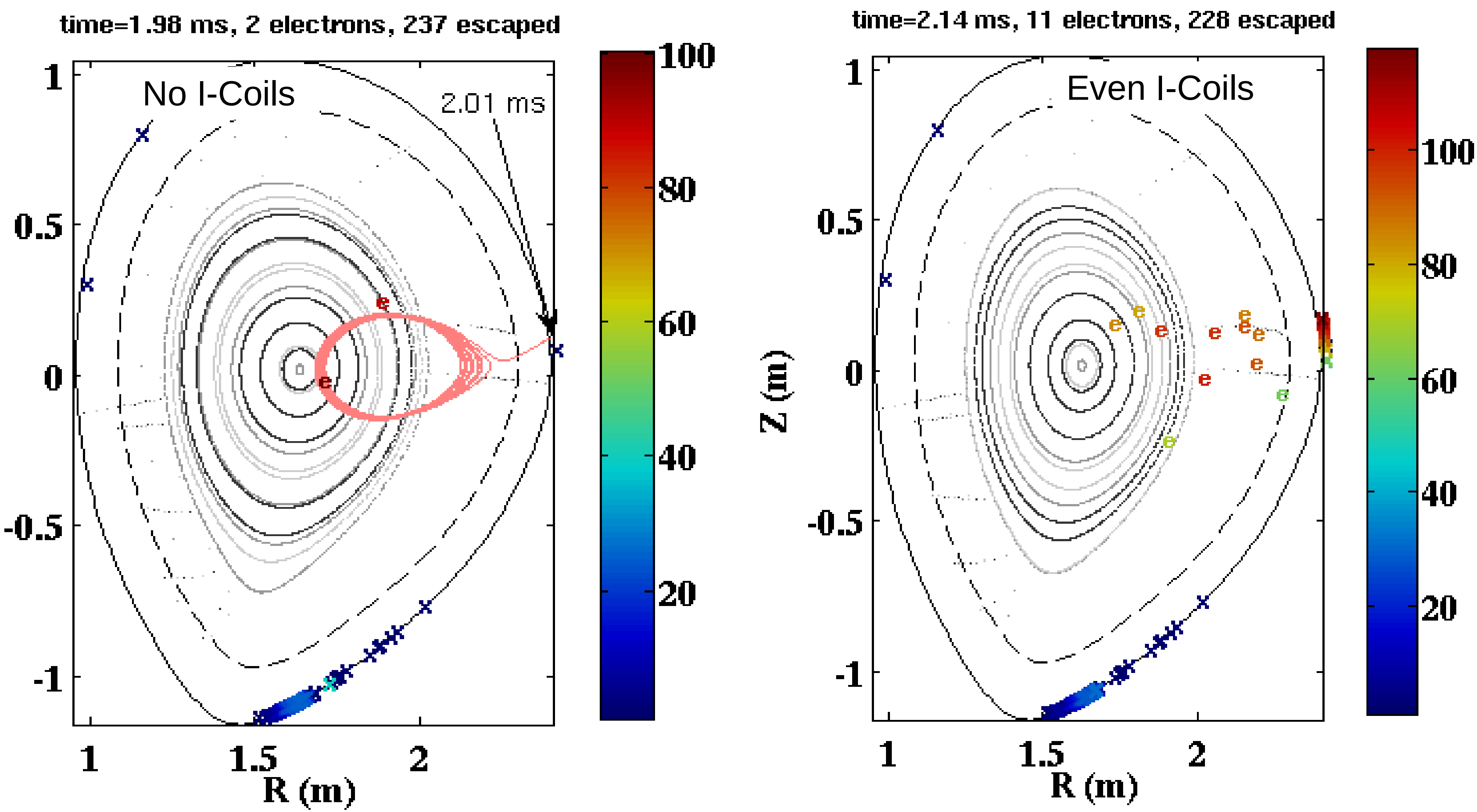


As flux surfaces begin to re-heal, core of well confined REs remains in I-Coil case



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



Summary

- **During the current quench, applied n=3 fields alone do not affect core confinement**

- **Preservation of some confined field lines during MHD crash prevents loss of some fast electrons in the core**

- **In the simulations, n=3 perturbations <u>increased</u> volume of core confinement during crash, thereby <u>enhancing RE confinement</u>**

Extra Slides

Equations

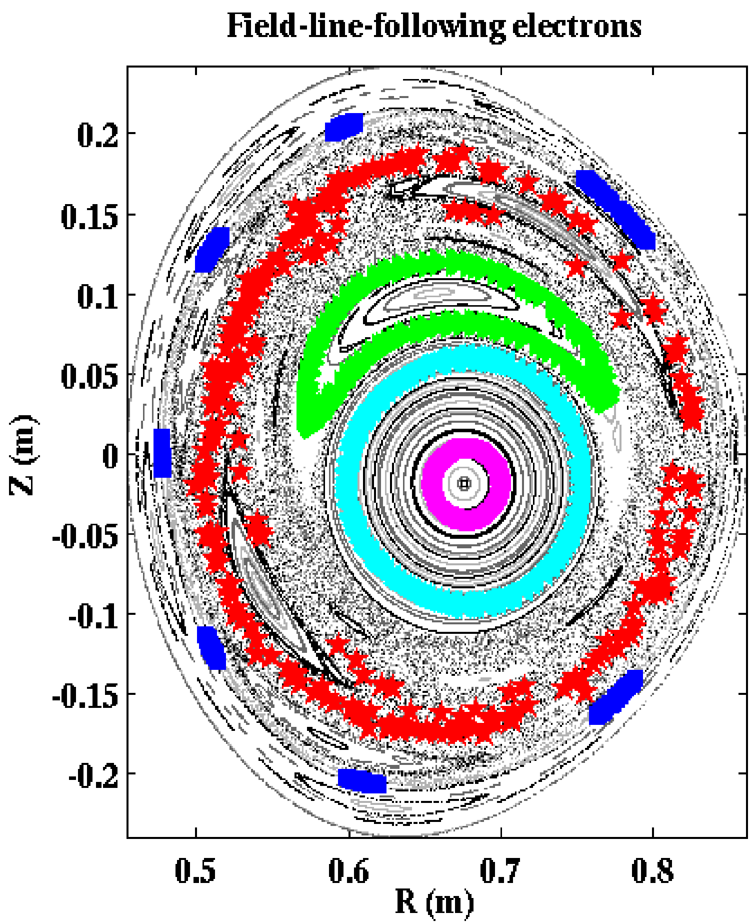
$$dR = \underbrace{\frac{v_{\parallel} B_R}{B} dt}_{\text{basic motion}} + \underbrace{\frac{1}{B^2}\left[V_R\left(B_\phi^2 + B_Z^2\right) - B_R\left(V_\phi B_\phi + V_Z B_Z\right) - \eta\left(J_\phi B_Z - J_Z B_\phi\right)\right] dt}_{\vec{E}\times\vec{B}\text{ drift}}$$

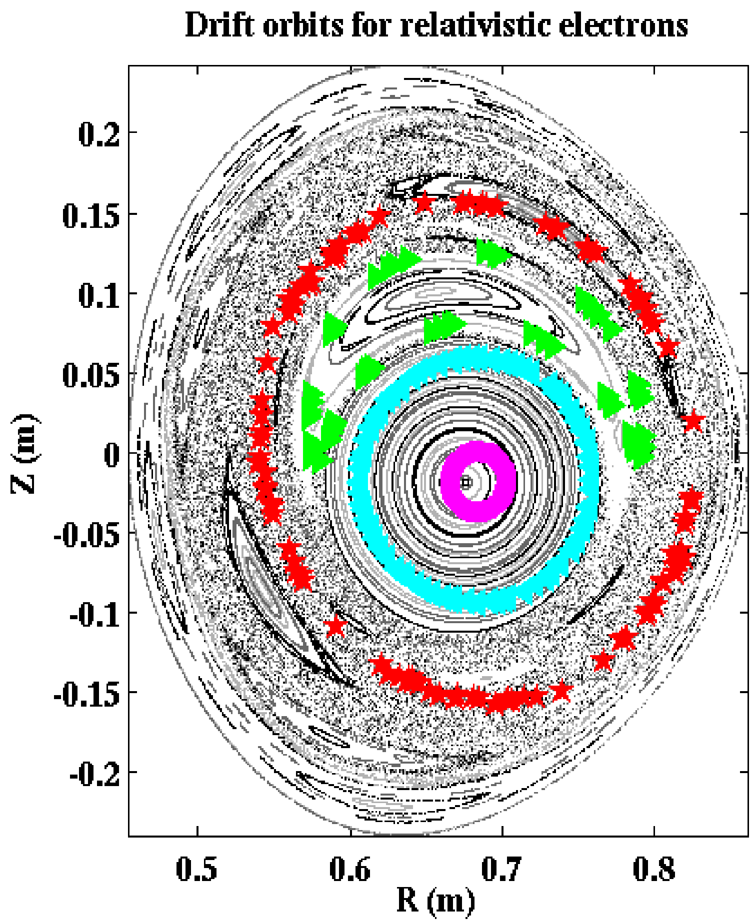
$$dZ = \underbrace{\frac{v_{\parallel} B_Z}{B} dt}_{\text{basic motion}} + \underbrace{\frac{20\,kT_e}{eB}\frac{1}{R} dt}_{\text{grad-B drift}} + \underbrace{\frac{\gamma m v_{\parallel}^2}{eB}\frac{1}{R} dt}_{\text{curvature drift}} + \underbrace{\frac{1}{B^2}\left[V_Z\left(B_R^2 + B_\phi^2\right) -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

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

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

Large drift displacement at high energy can improve confinement



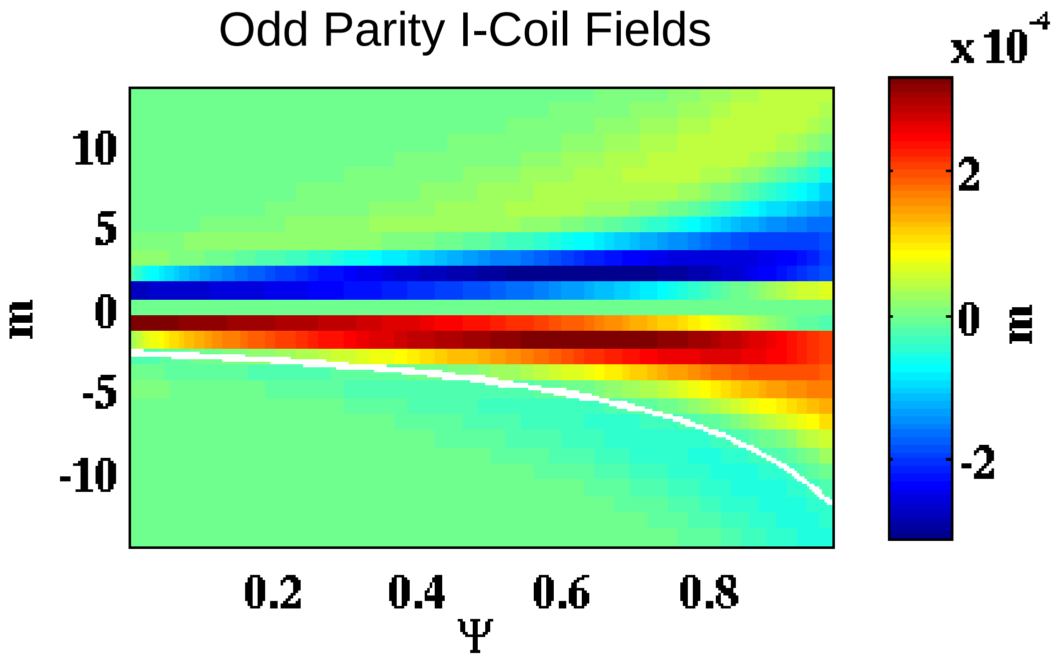


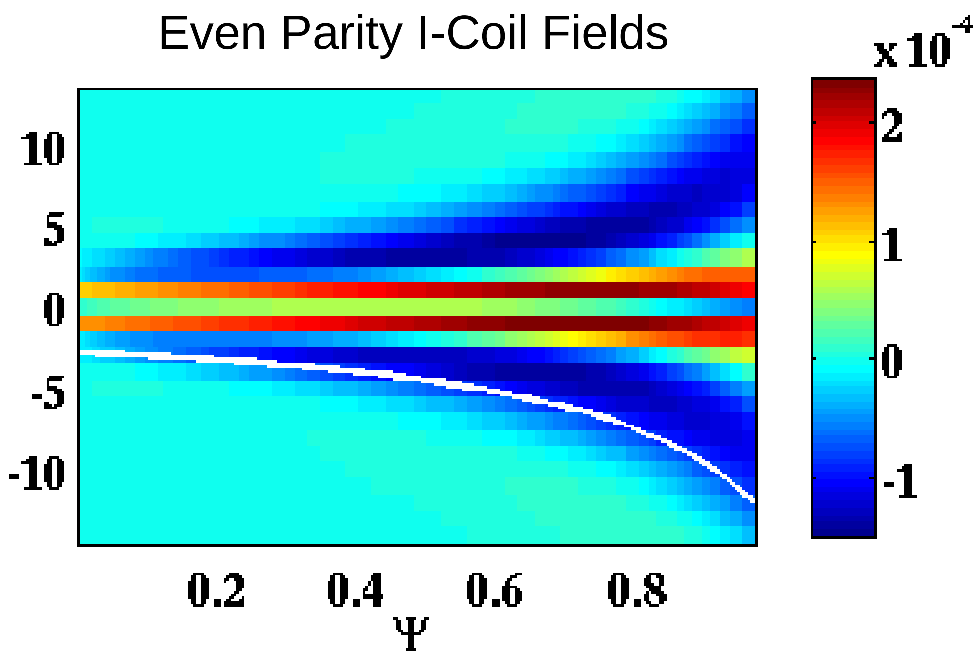
Electrons with γ ($=1/\text{sqrt}[1-(v/c)^2]$) ~20 (10 MeV) have curvature drift displacement of a few cm

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

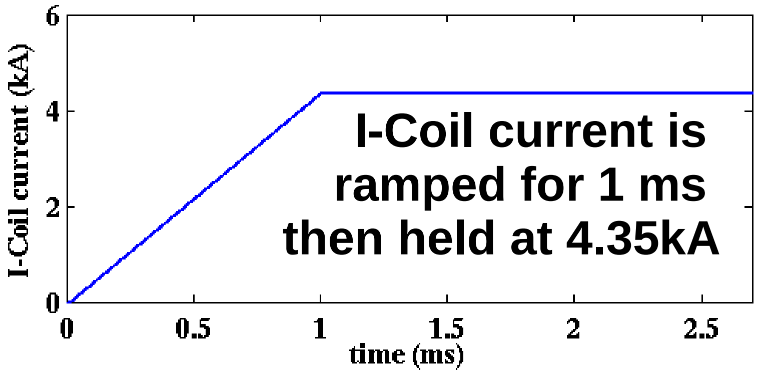
Current quench simulations are run with odd, even, and no I-Coil fields





- 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

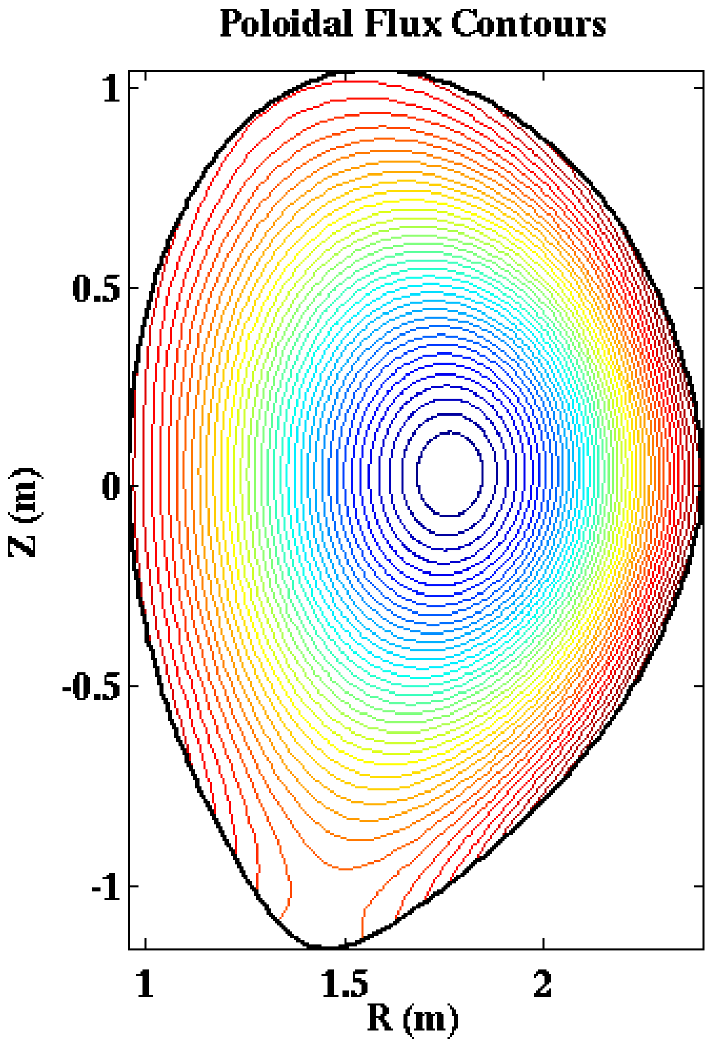
Resistivity is **Spitzer** (cold CQ plasma requires no artificial enhancement):

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



Considerably more density would be required for collisional RE avalanche suppression

Early CQ — Contours of E/E_{crit} — Late CQ