Mitigation of runaway electrons with a passive 3D coil

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Runaway electron mitigation coils (REMC), passively driven by CQ loop-voltage, are planned for both SPARC and DIII-D

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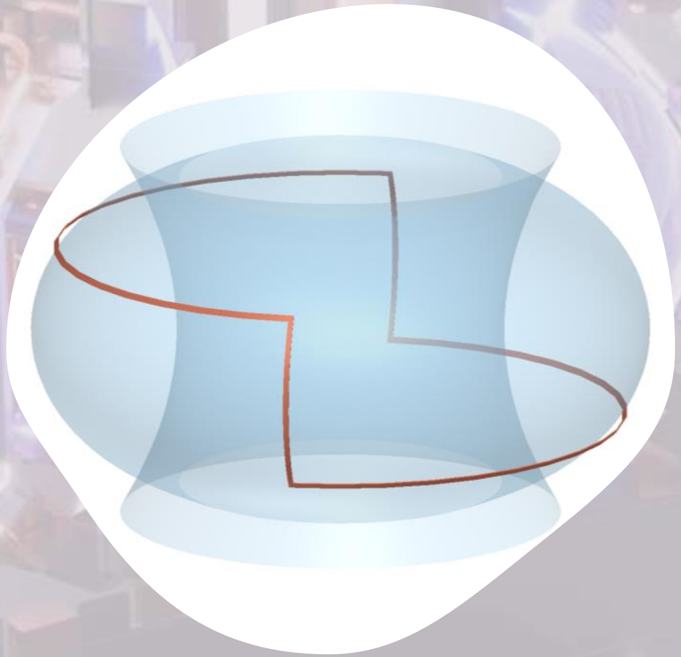

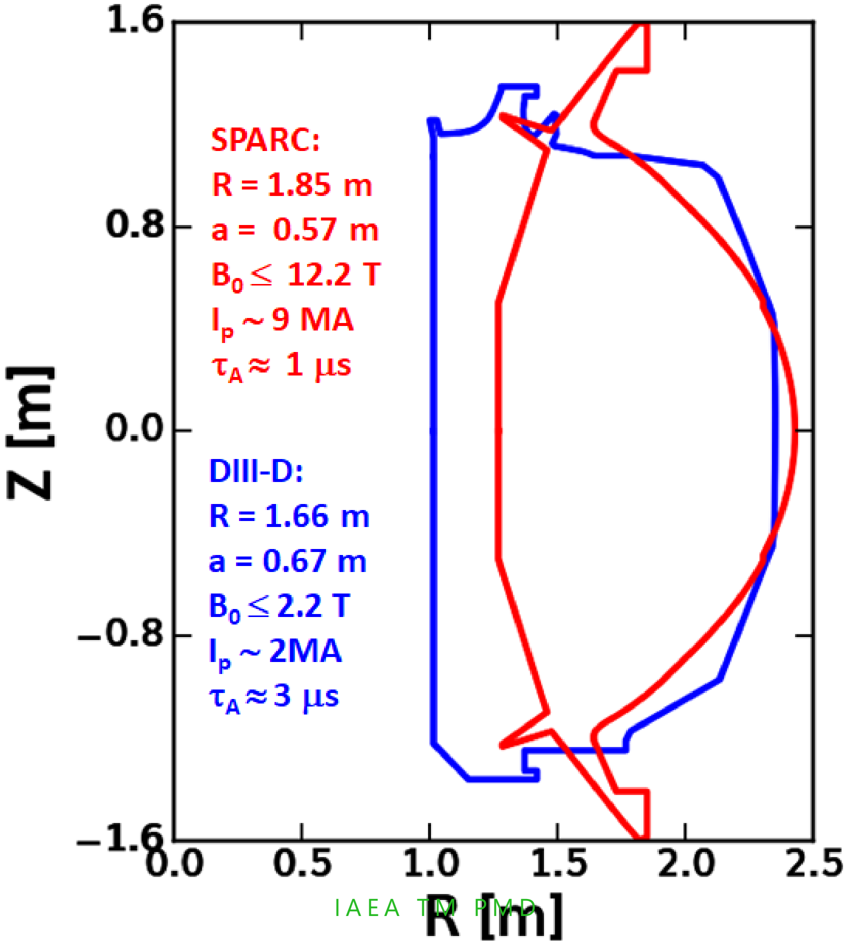

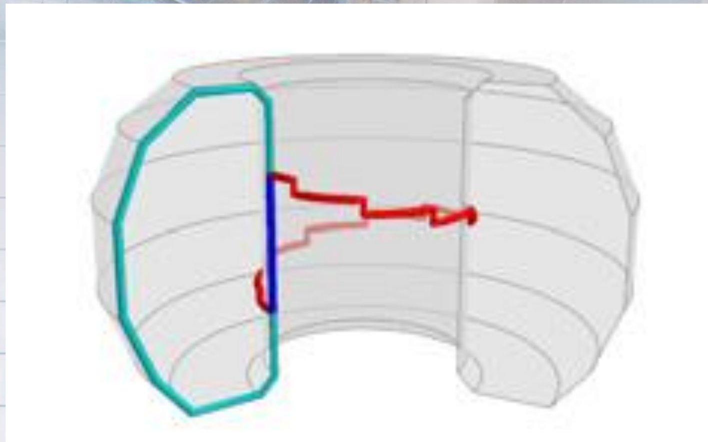

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SPARC and DIII-D occupy very different regimes of RE avalanche growth

+ SPARC avalanche gain factor is ~6 billion: even a tiny fraction of retained seed REs (1mA) can avalanche to near full conversion

    → **Seed insensitive regime**

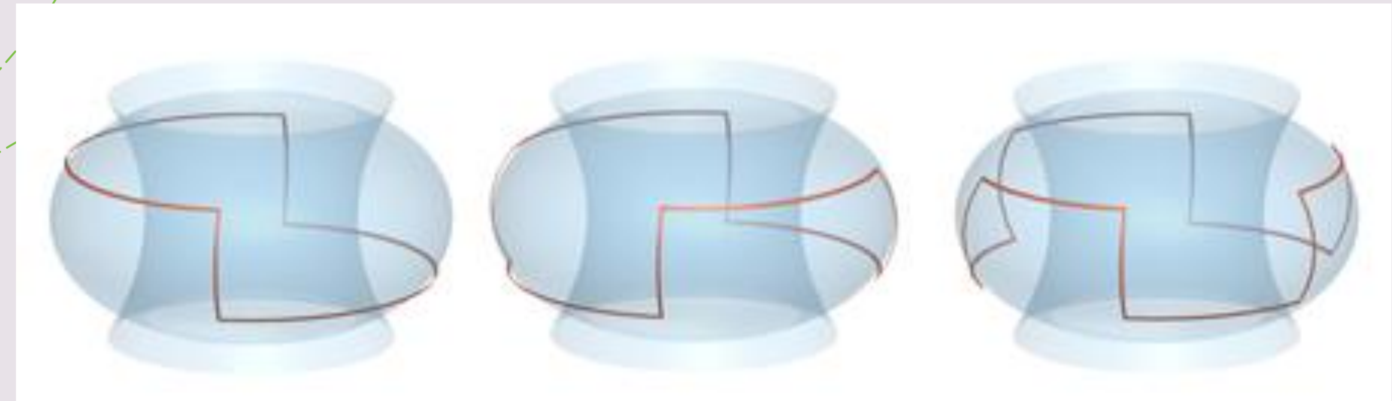
+ DIII-D avalanche gain is 50-150: reduction of the seed from, say 10kA to 1kA, would significantly reduce final RE current

    → **Seed sensitive regime**

Coils do not need to achieve the same level of performance to meet their respective goals

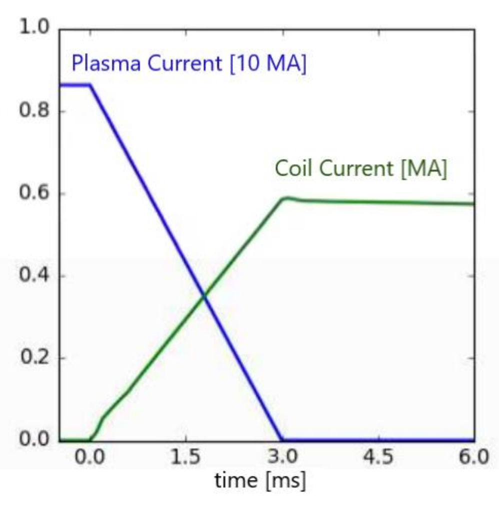
PART 1: SPARC REMC modeling

NIMROD 3D MHD modeling was performed for coils with n=1,2,3 symmetry



3D fields imposed at the NIMROD simulation boundary are taken from a COMSOL calculation

COMSOL also finds the maximum coil current obtained during a prescribed CQ, and a near-linear relationship to plasma current



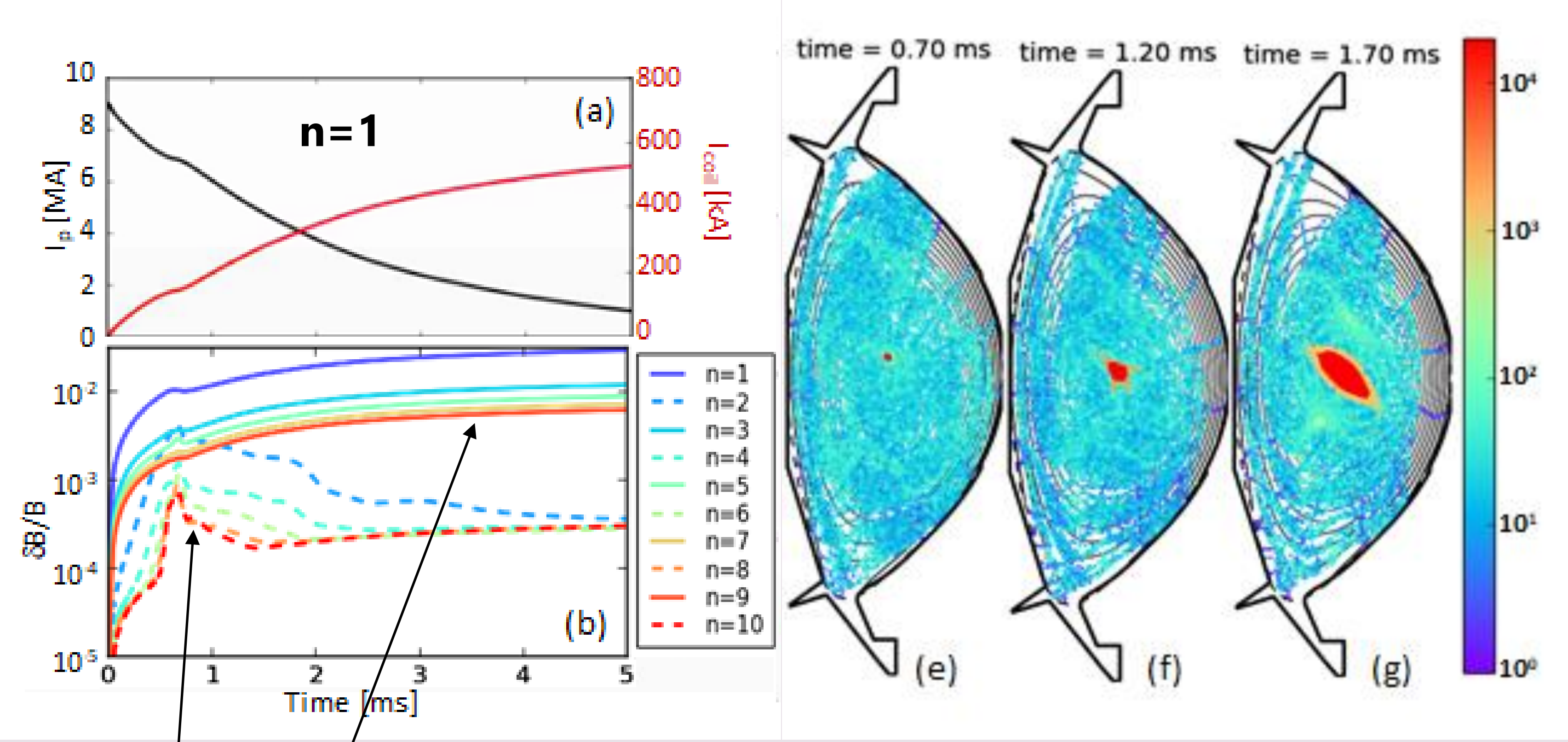
Used in NIMROD:

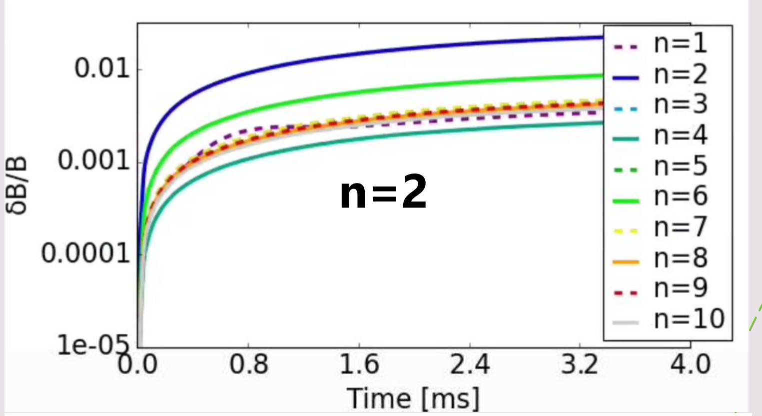
$$I_{\mathrm{REMC}} = I_{\max}\left(1 - \frac{I_p}{I_{p,t=0}}\right)$$

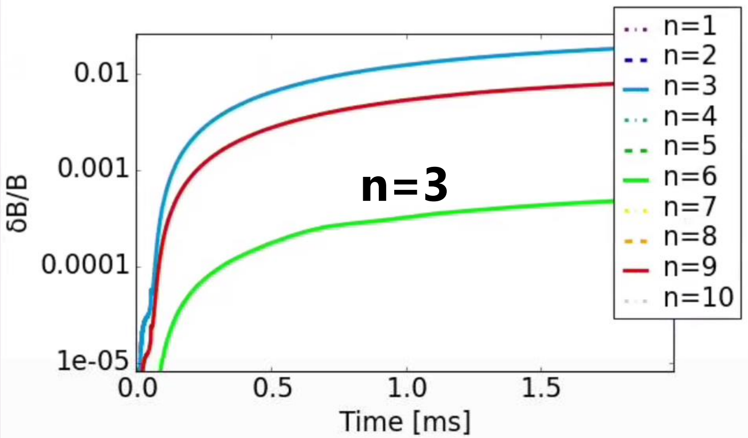
Nonlinear response to coil fields seen mainly with n=1 coil

+ CQ begins immediately after artificially rapid TQ

+ n=2, n=3 coils do not produce any significant nonlinear response







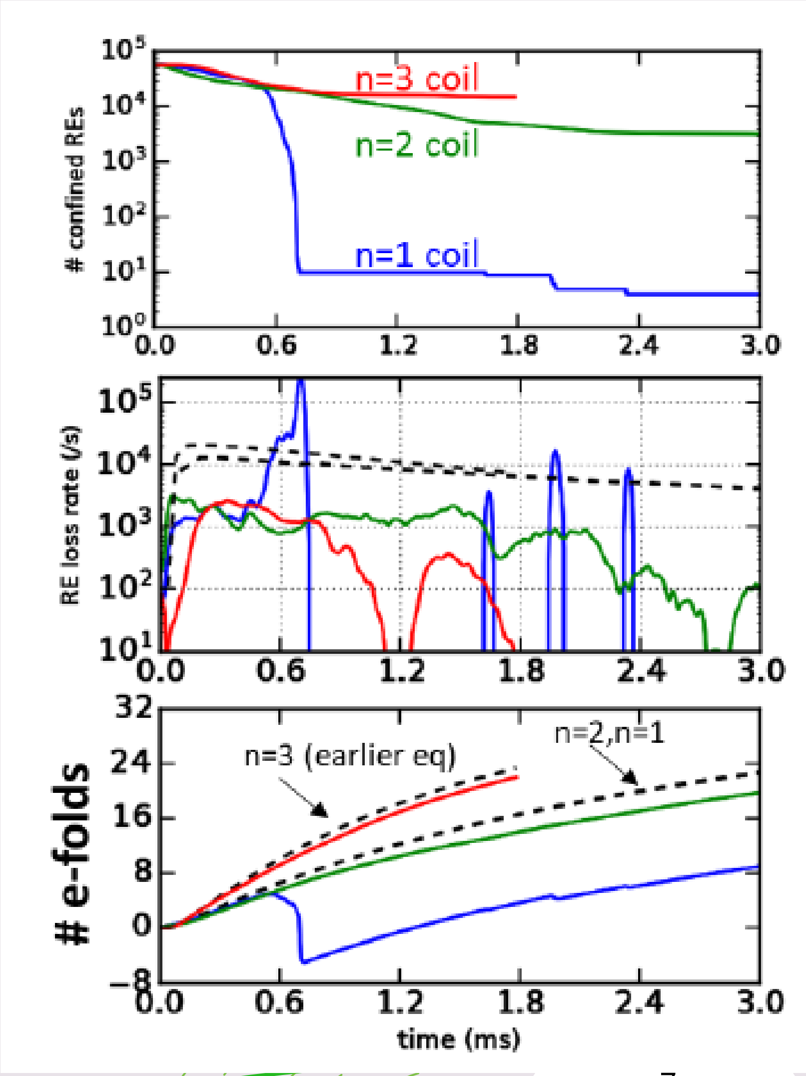
+ Odd modes (solid) driven by the coil, even modes (dashed) nonlinearly grow and saturate @ 0.7 ms

NIMROD calculates RE drift-orbits: n=2 & 3 coils can be ruled out

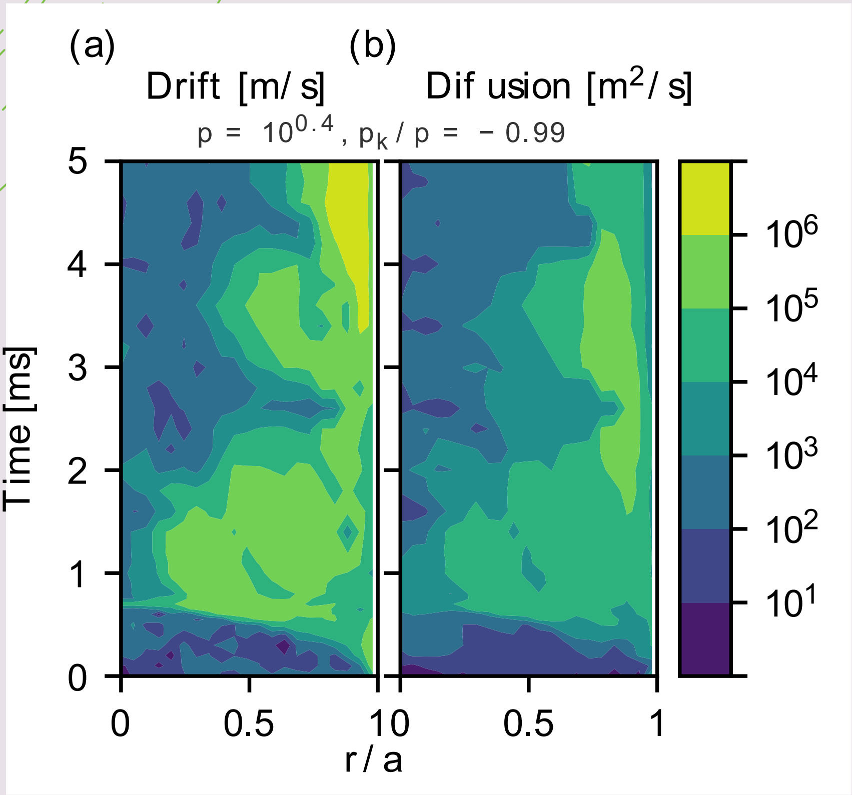
- At t=0, ~50,000 RE test-particles are launched, most are lost as flux surfaces break up
- Loss rate is compared to the approximate avalanche growth rate

$$\gamma_{RA} \approx \frac{eE}{2mc\ln\Lambda} \approx \frac{e\dot{\psi}_{pol}}{4\pi Rmc\ln\Lambda}$$

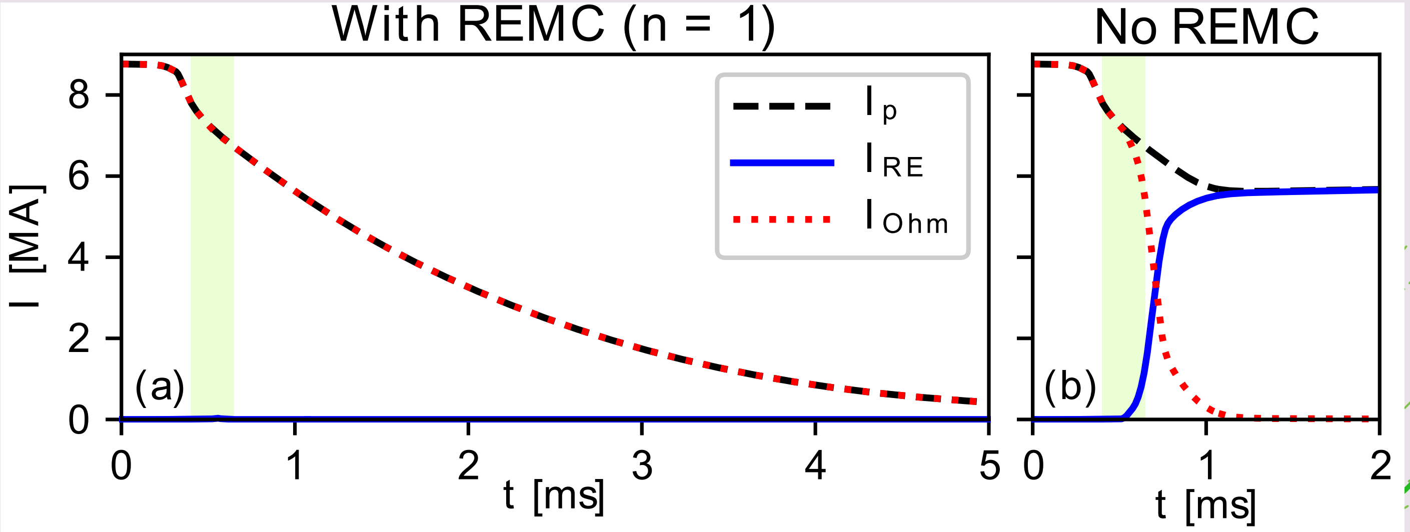
- Only n=1 coil has a loss rate that ever exceeds the growth rate



Additional modeling with ASCOT5+DREAM shows full suppression with the n=1 coil*



- NIMROD fields are used to calculate transport coefficients vs time, space, energy, pitch with ASCOT5
- Coefficients are used in DREAM calculation of RE evolution → mapped based on value of plasmas current



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NIMROD simulations explore additional scenarios/approximations in the modeling*

+ REMC current clamped at 250kA (max is 590kA)
+ Higher final temperature (slower CQ)
+ Inclusion of realistic thermal quench
+ Effects of close ideal wall (no-coil simulations)

→ In some cases, ASCOT5+DREAM modeling is repeated, *with more conservative assumptions about transport in closed flux regions*

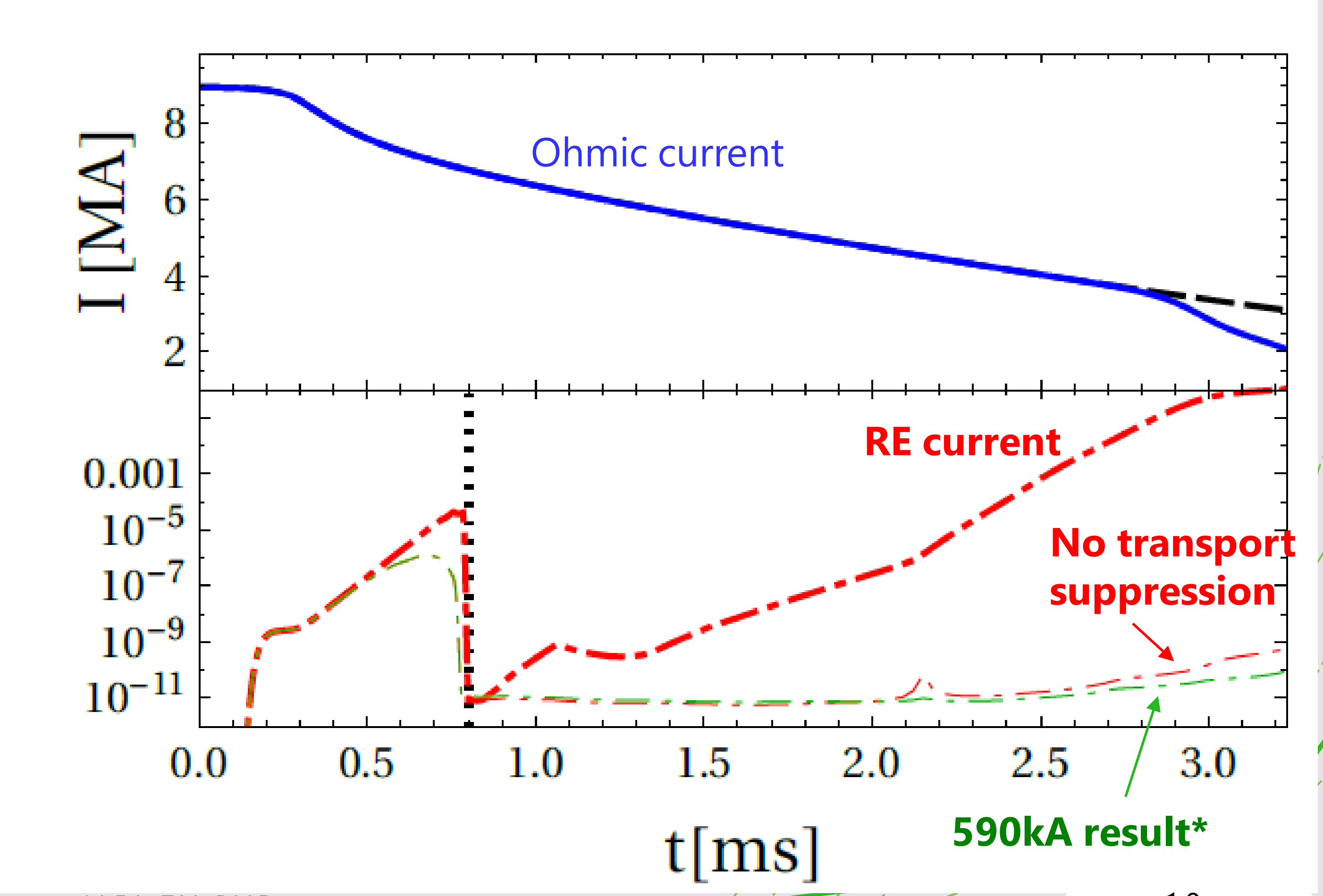
* Izzo, et al, "Runaway electron deconfinement in SPARC and DIII-D by a passive 3D coil", NF, under review

Current clamped simulation (250kA) has ~1MA RE current *when transport is suppressed*

+ ASCOT5+DREAM calculation is done in twice:

1) same methodology as 590kA simulation (full suppression still achieved)

2) Low levels of transport are suppressed, especially in closed flux regions (~1 MA RE current)



* Result from Tinguely, et al.

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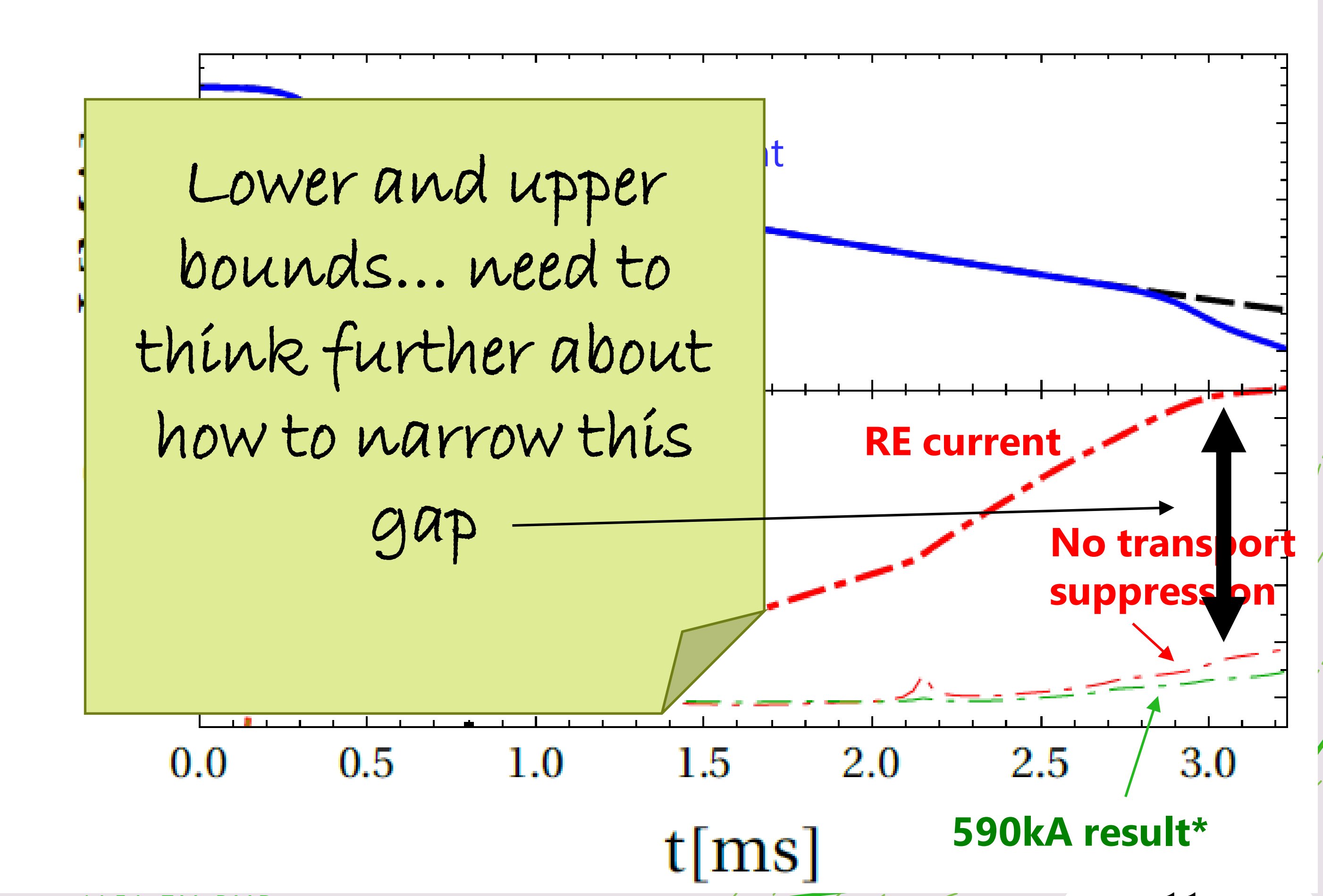
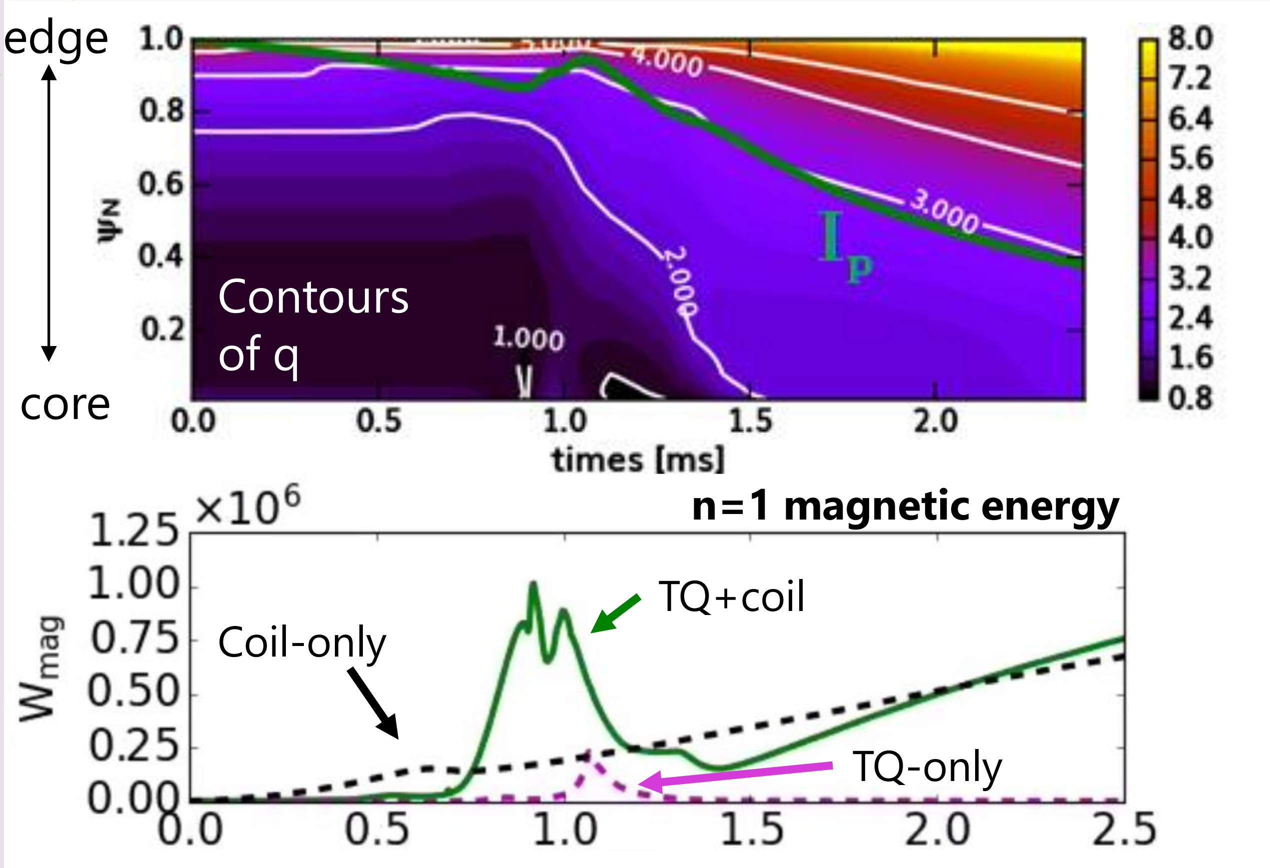
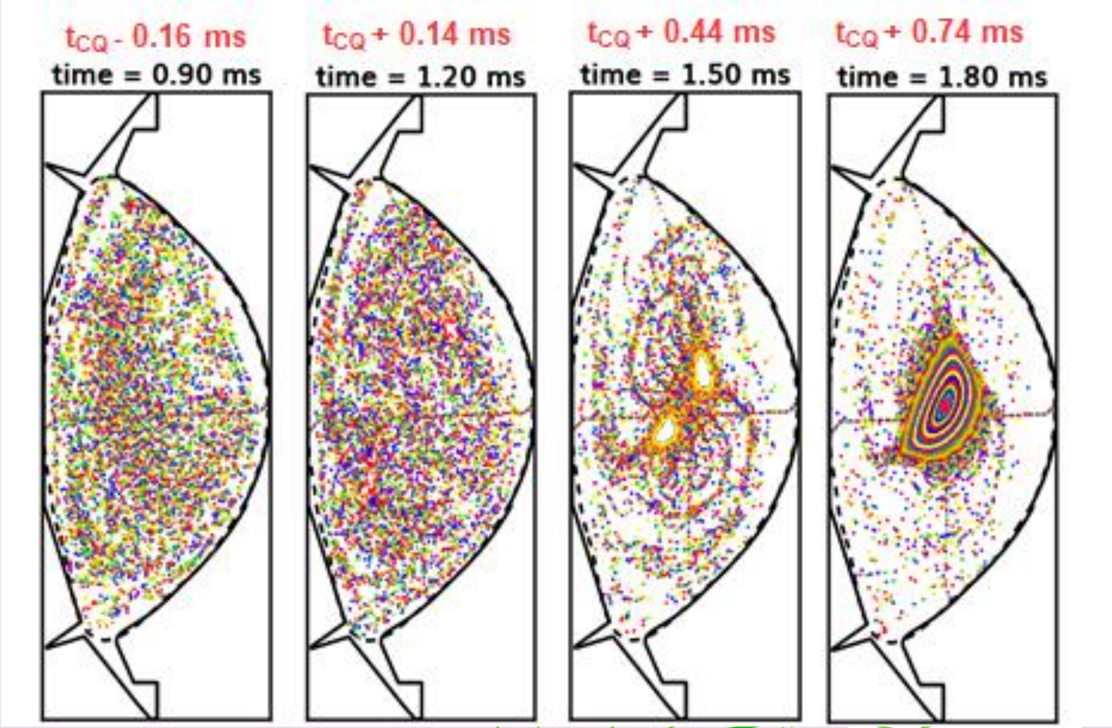


* Result from Tinguely, et al.

Realistic TQ results in higher δB/B ⇒ faster RE loss rate 🙂, earlier re-healing ☹

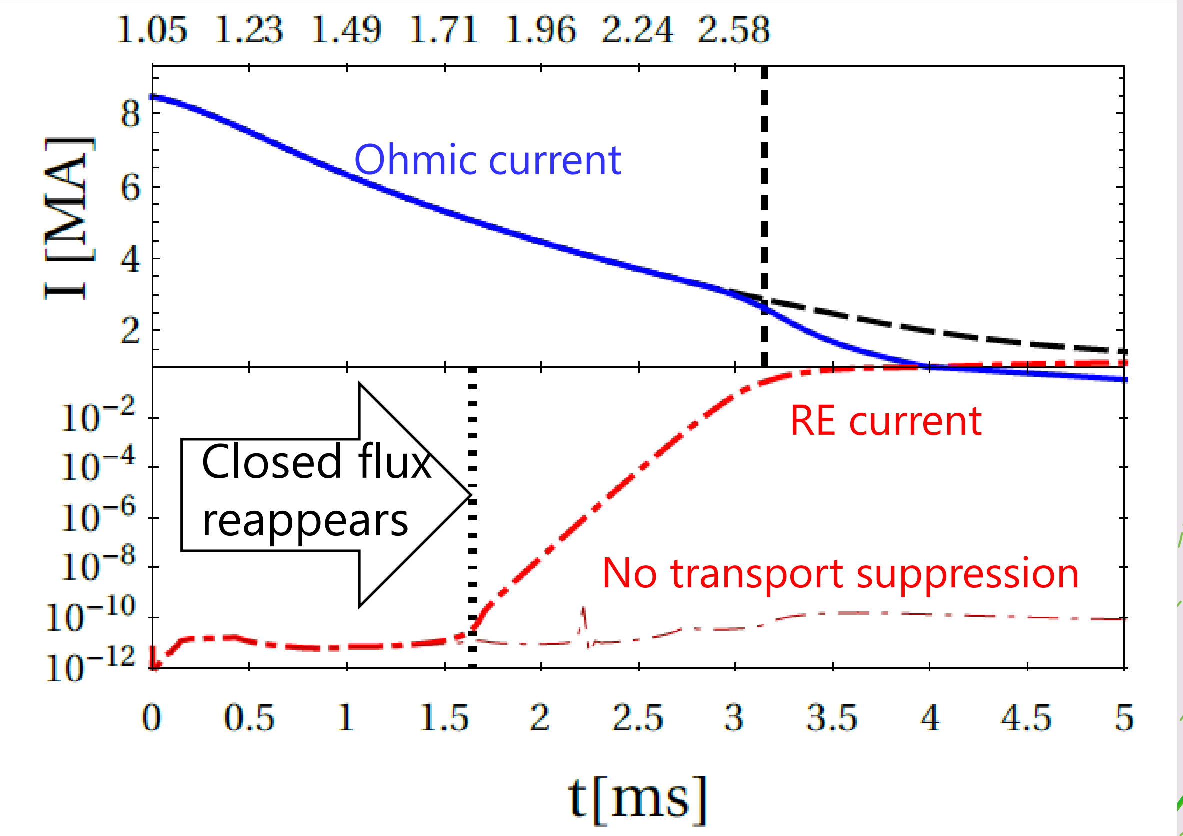
- Large MHD modes lead to rearrangement of current profile
- Once $q_0 > 2$, core begins to rapidly re-heal





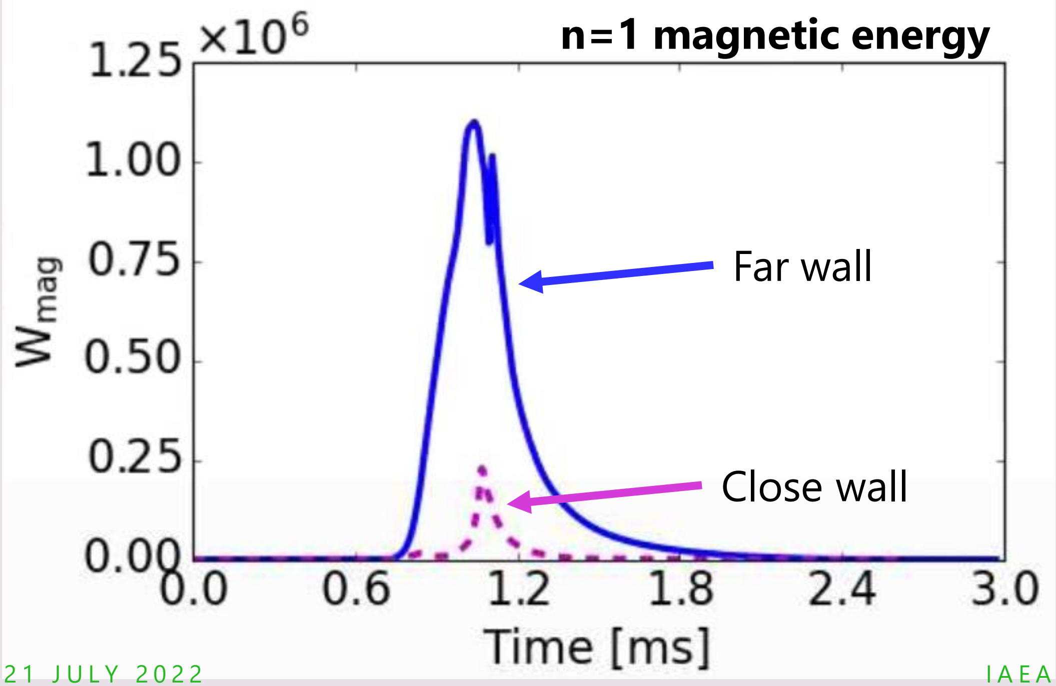
ASCOT5+DREAM modeling shows RE growth under more conservative assumptions

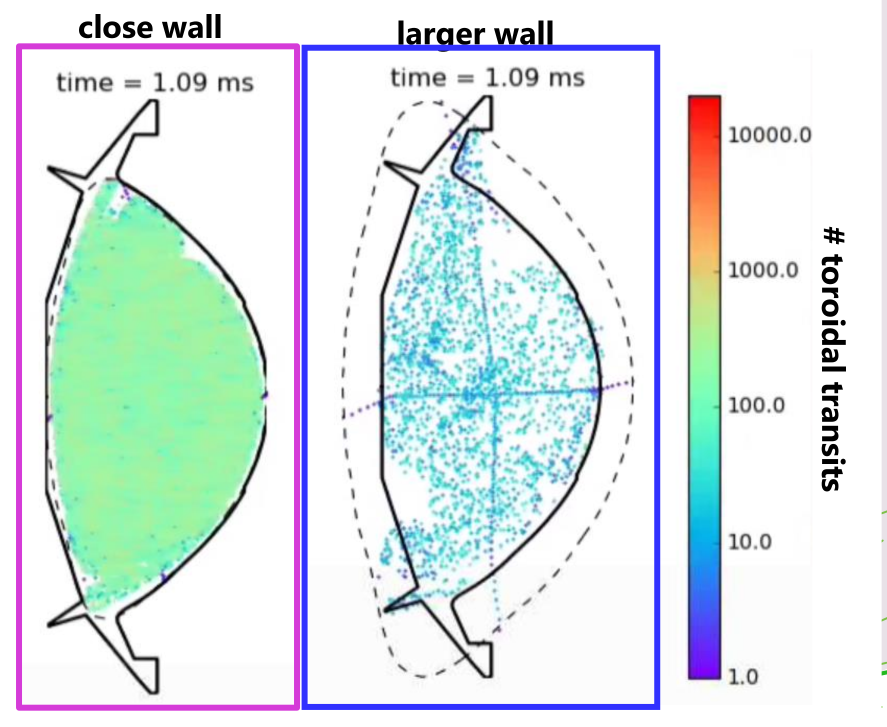
- Using the same methodology as the coil-only case, negligible RE current is predicted
- When low levels of transport are suppressed (zero transport in closed flux regions) 1.15 MA of RE current is predicted



Close ideal wall in the simulations is found to suppress mode growth, limit RE losses

- In TQ-only simulations, modes saturate at higher amplitude with farther wall
- Result is order-of-magnitude shorter field lines and faster RE losses





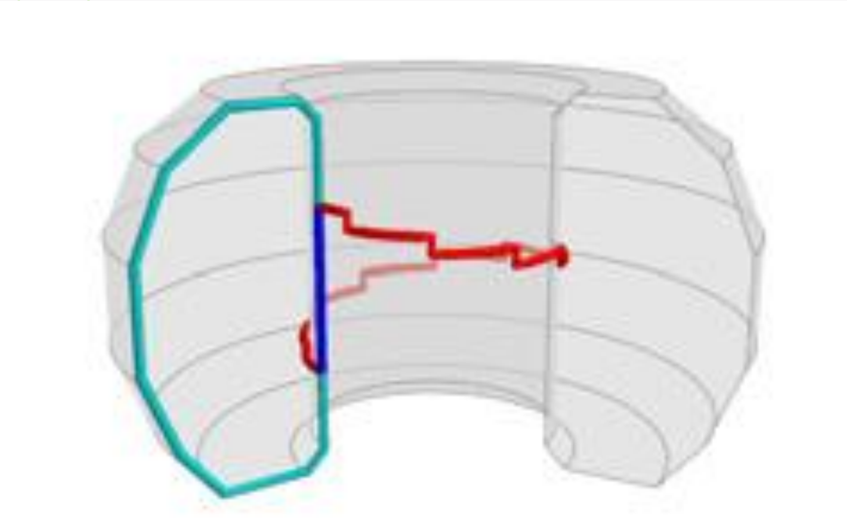
Summary of SPARC modeling

+ Combination of COMSOL+NIMROD+ASCOT5+DREAM modeling with REMC predicts RE currents ranging from ~0 to ~1MA depending on transport assumptions in closed flux regions (reduced from 5MA w/ no REMC)
+ Inclusion of a realistic TQ produces faster RE losses but also earlier flux surface re-healing (evolution of q-profile is important)
+ Close ideal wall is a conservative approximation re: RE-losses

→ Fastest CQ (3 ms) is also found to be most RE-prone case

PART 2: DIII-D REMC modeling

DIII-D REMC winds along inboard wall; linear response was modeled with MARS



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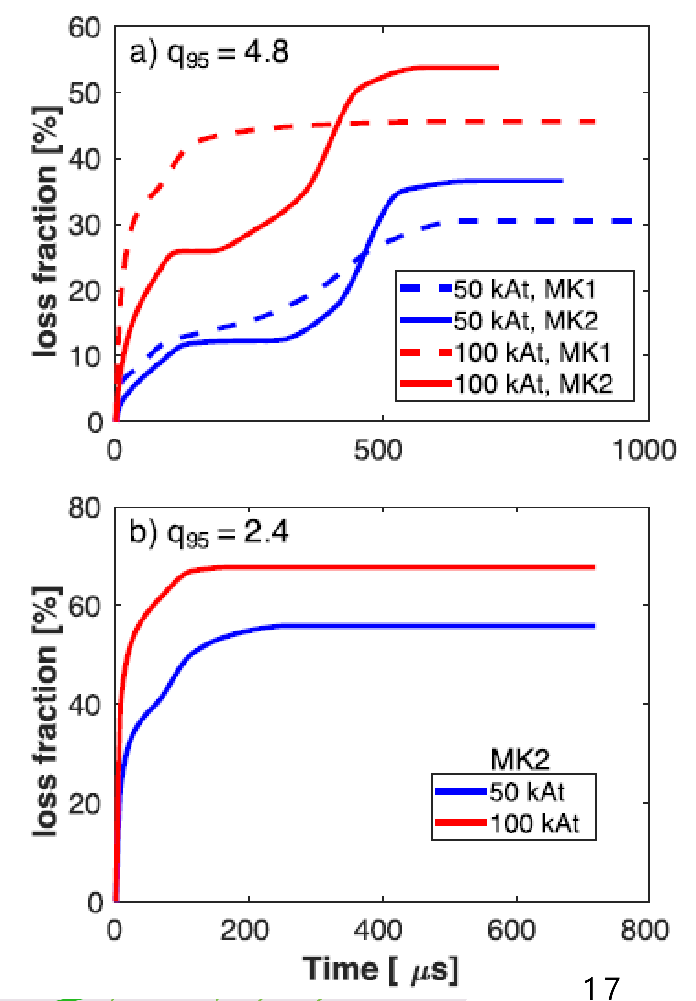
Losses of RE test particles at mid-CQ, for an IWL equilibrium were calculated.

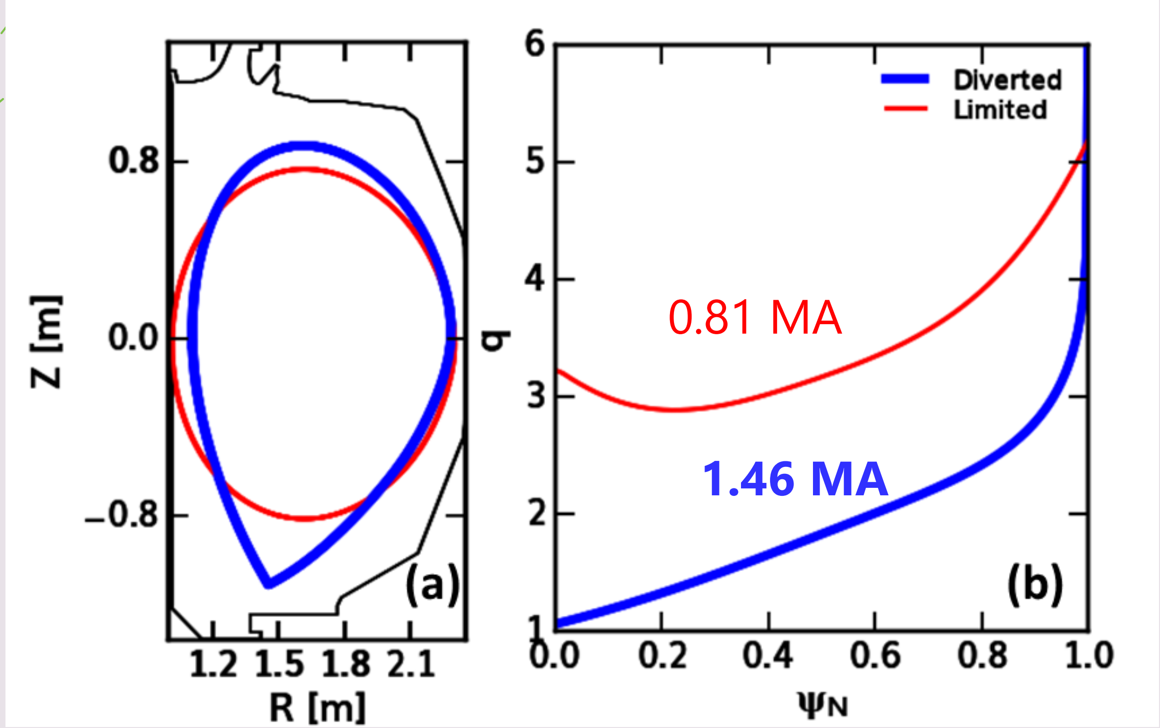
Depending on q-profile and maximum REMC current, loss fractions of ~40-70% of test particles were found.

Details also in Weisberg poster

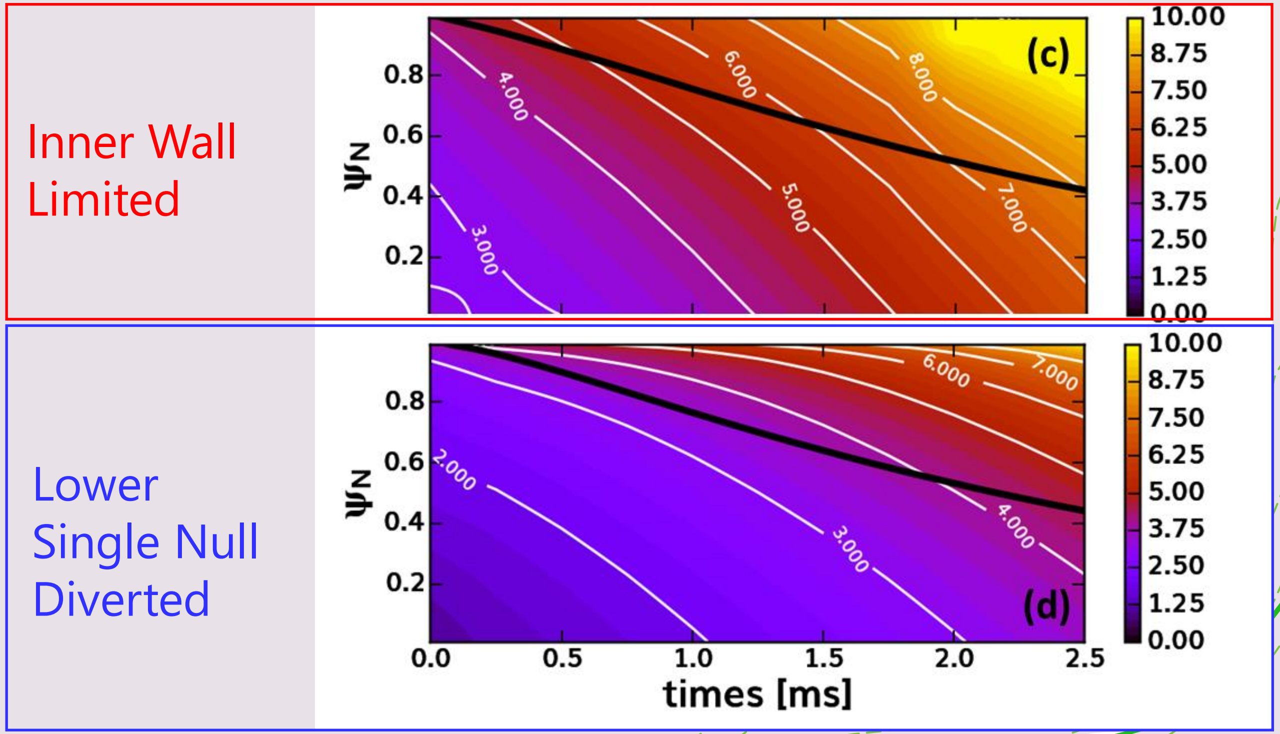


NIMROD modeling of limited and diverted equilibria was performed

+ Seeks to make connection with SPARC modeling, and the DIII-D linear modeling



q on axis starts higher and increases faster in the IWL case



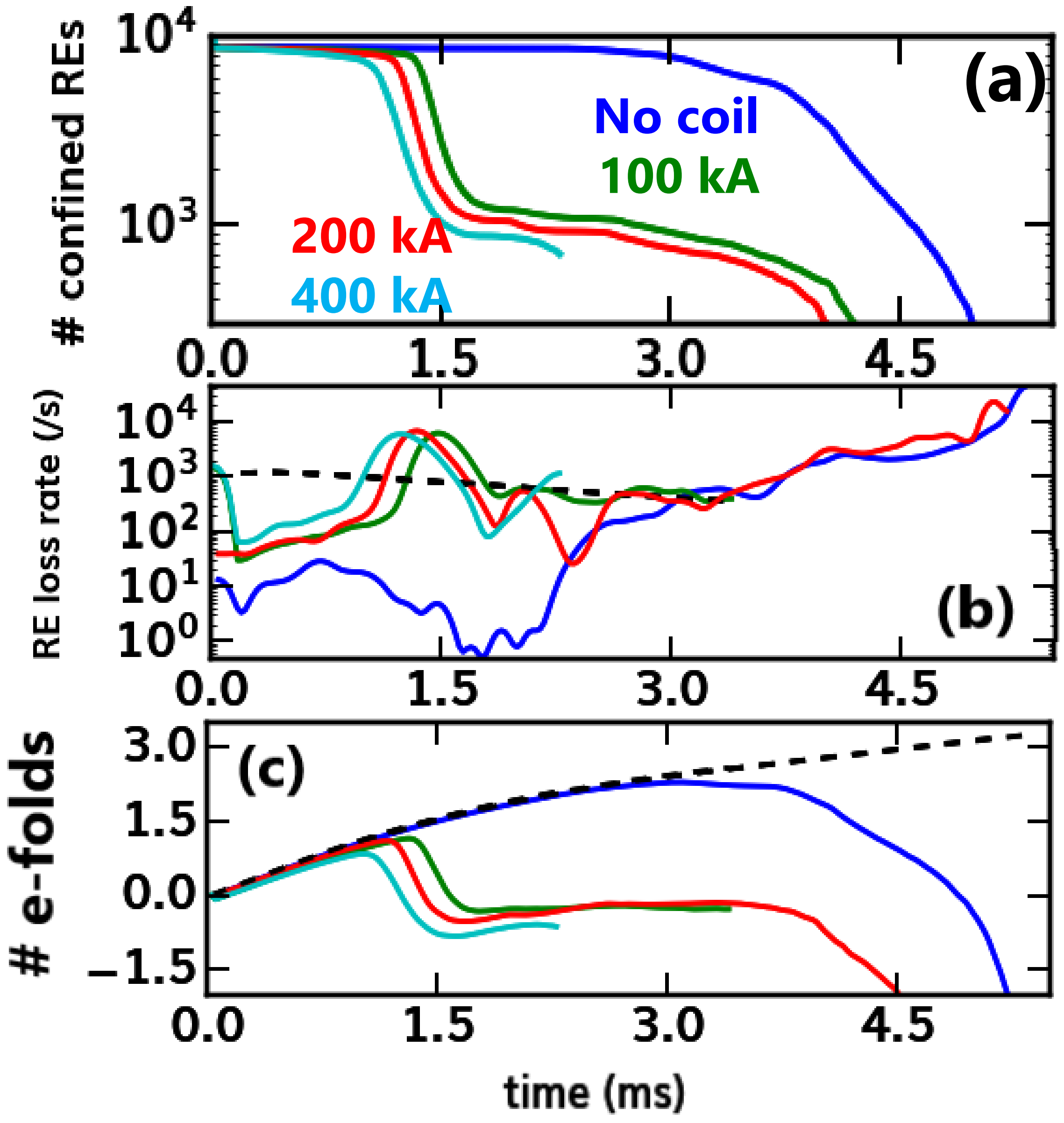
IWL simulations are surprisingly insensitive to the maximum REMC current

- Maximum currents of 100kA and 200kA are chosen to match mid-CQ currents of 50&100kA from linear response modeling

- Nonlinear modeling shows higher loss fractions (~90%) but this does not significantly increase as coil current is doubled

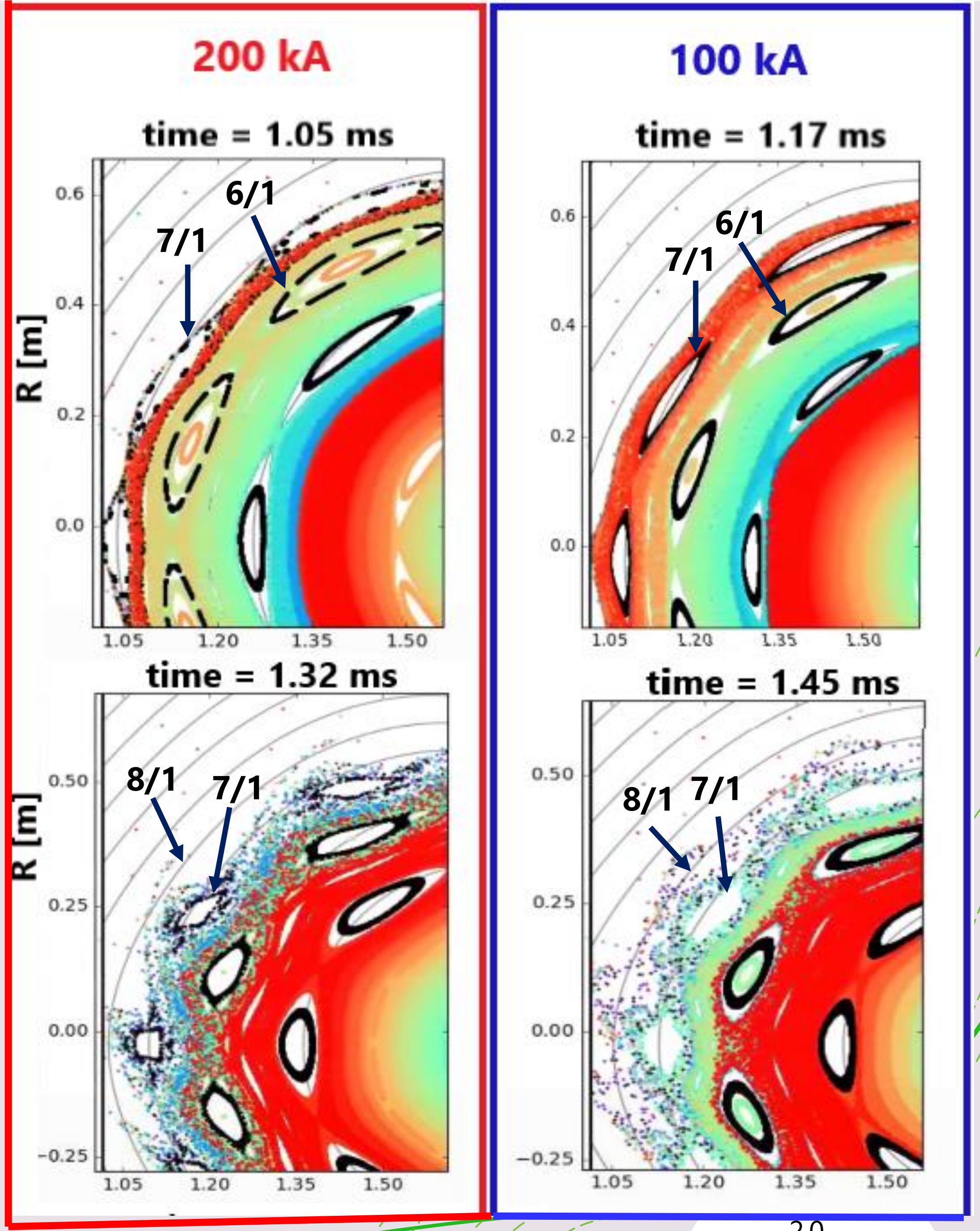
- Similar/related to step-wise behavior of VIOW calculations

- In each case a loss rate that exceeds the avalanche growth rate is observed



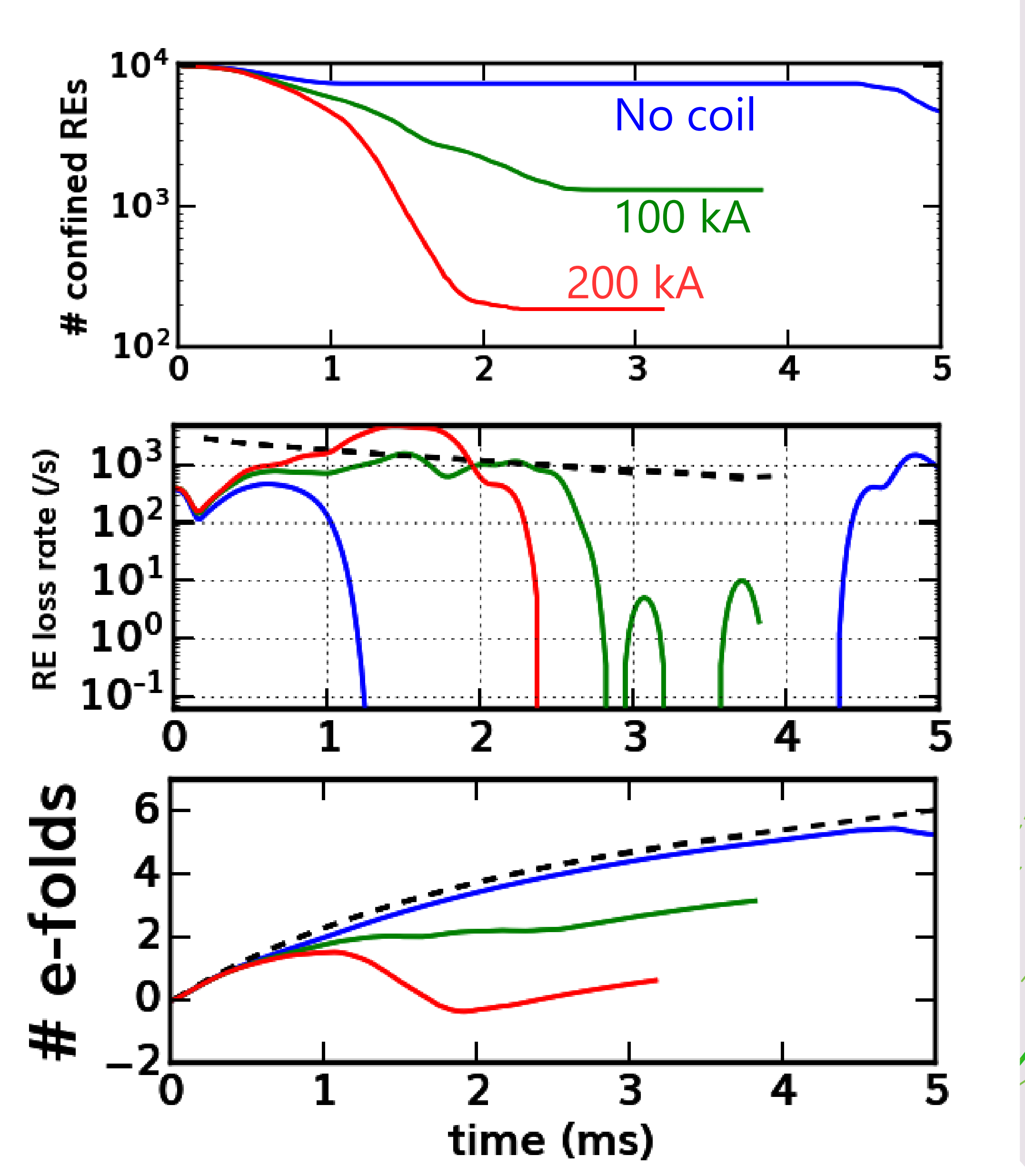
Regardless of REMC current, island overlap first occurs when q_a>8

- As expected, isolated islands with 200kA coil are larger than with 100kA coil…
- But islands remain isolated until edge-q exceeds 8, at which point island width is already large enough to produce overlap in either case
- After initial island overlap, stochastic region is seen to propagate inward toward the core



LSN diverted case shows increase in loss fraction with REMC current

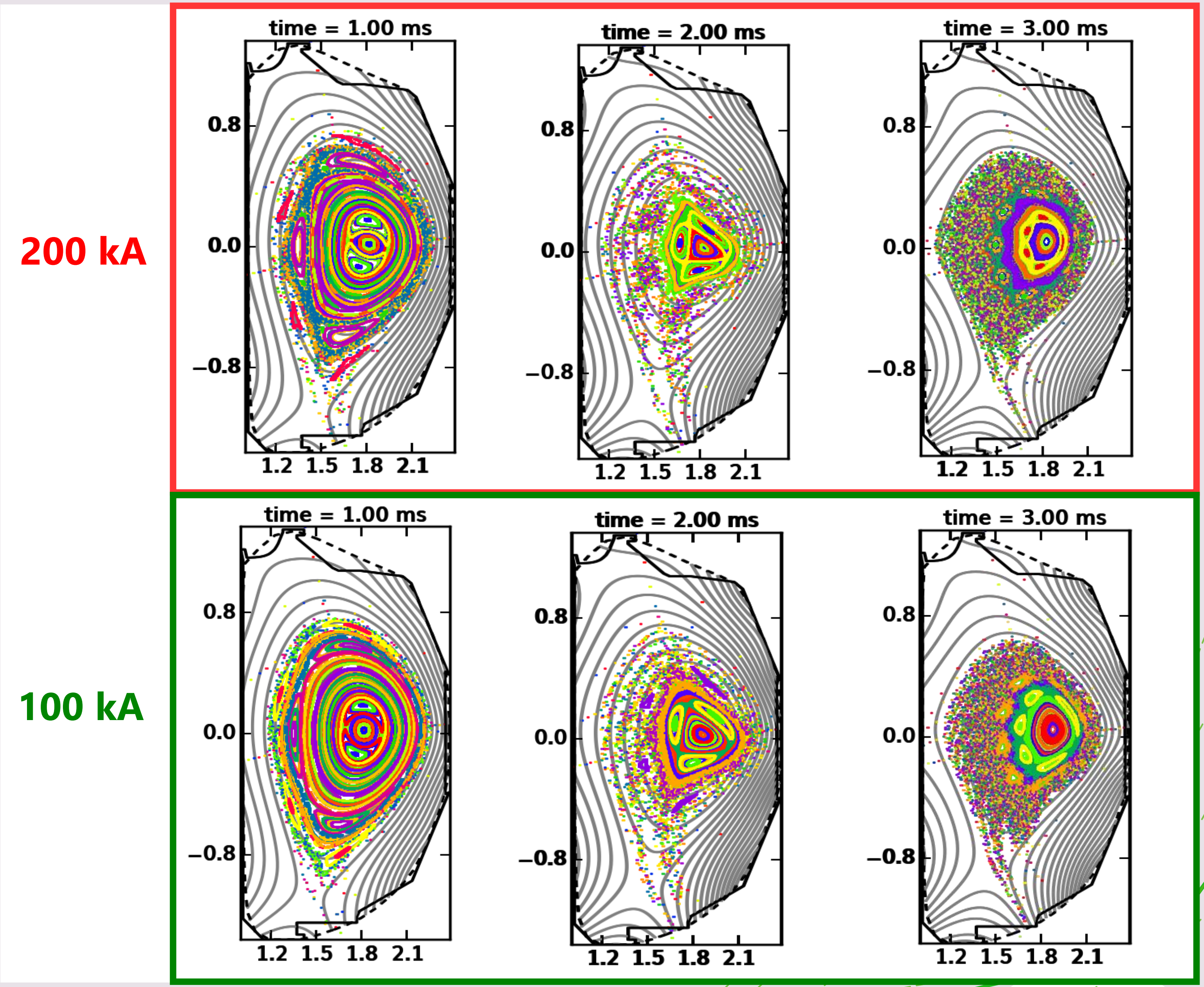
- At 100kA coil current, simulation loses 90% of test-particles. Loss rate barely exceeds avalanche gain.
- At 200kA max current, 98% losses are achieved, several times higher loss rate
- Either loss fraction would be expected to produce a measurable difference in the final RE current in DIII-D



Some good flux surfaces are retained in the core, even at 200kA

Size and I_{REMC}/I_p are comparable to SPARC case, so why does the coil seem to be less effective?

- Coils have a different design: Inboard/outboard (based on where they fit). DIII-D coil is optimized for IWL scenario typical of the CQ-phase
- SPARC has a shorter Alfvén time→ faster MHD mode growth
- Differences in equilibrium details: this DIII-D case is good at retaining test-particles



Modeling predicts successful operation of REMC in both devices

+ Even with several very conservative assumptions*, SPARC calculations never predict more than ~1-2MA of RE current, compared to 5MA with no coil
    + *(close ideal wall, fastest possible CQ, fully suppressed transport in closed flux regions, neglect of RE current in NIMROD model)
+ DIII-D calculations predict more RE losses than linear response modeling, more that sufficient to reduce/eliminate RE current in the seed-sensitive regime

On-going and future REMC modeling work focused on resistive wall

+ Approximation of a close ideal wall has several important impacts on results:
  1) Stabilizes MHD modes
  2) Shortens the CQ time (lower inductance)
  3) Effects the evolution of the plasma shape, q-profile (important for late time behavior of the coil)

→Present efforts to employ a Green's Function based resistive wall model which is not well exercised in NIMROD, only recently upgraded to include n=0