Modeling of runaway electron deconfinement by a passive coil during a DIII-D current quench

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PPPL TSWD

19 July 2023

Outline

- Motivation: disruption resilient tokamak for fusion energy
- REMC as an element of a DRT
- Preliminary modeling of REMCs for DIII-D and SPARC
- Model improvements for the DIII-D REMC: Resistive wall, ThinCurr, extended boundary
- Summary

Tokamaks are for fusion and have disruptions

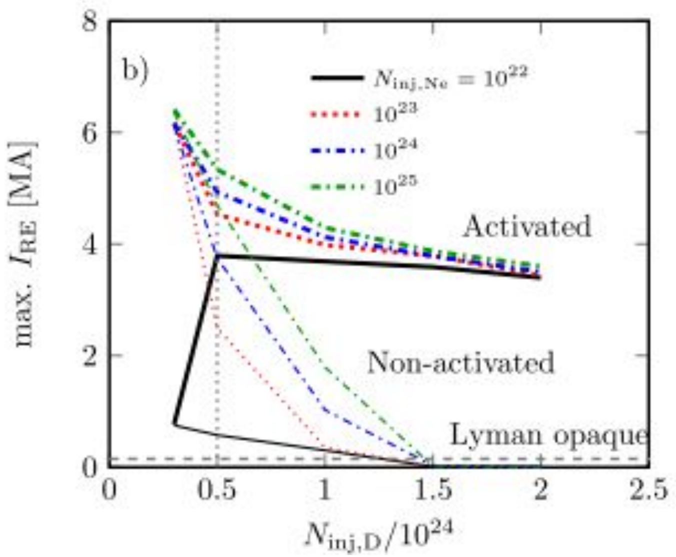
- ~~Power plants can't have disruptions~~
- ~~Disruption mitigation is for big experiments~~
- A tokamak power plant needs to be able to withstand a disruption
- Disruption mitigation needs to work on power plants

See: N.W. Eidietis, "Prospects for Disruption Handling in a Tokamak-Based Fusion Reactor", *FST* **77** (2021) 738

A tokamak power plant needs RE losses during the CQ that beat the avalanche growth rate

- Some RE mitigation strategies are stopgap measures designed to ensure success only in the non-nuclear phase of ITER (e.g. prevent the hot-tail seed through 2-stage cooling, or de-confine the hot-tail seed)

- A power plant will have ineliminable seed sources and a large enough avalanche gain to convert small sources to large RE plateau current



O. Vallhagen, *et al*, "Effect of two-stage shattered pellet injection on tokamak disruptions", (2022) Nucl. Fusion **62** 112004

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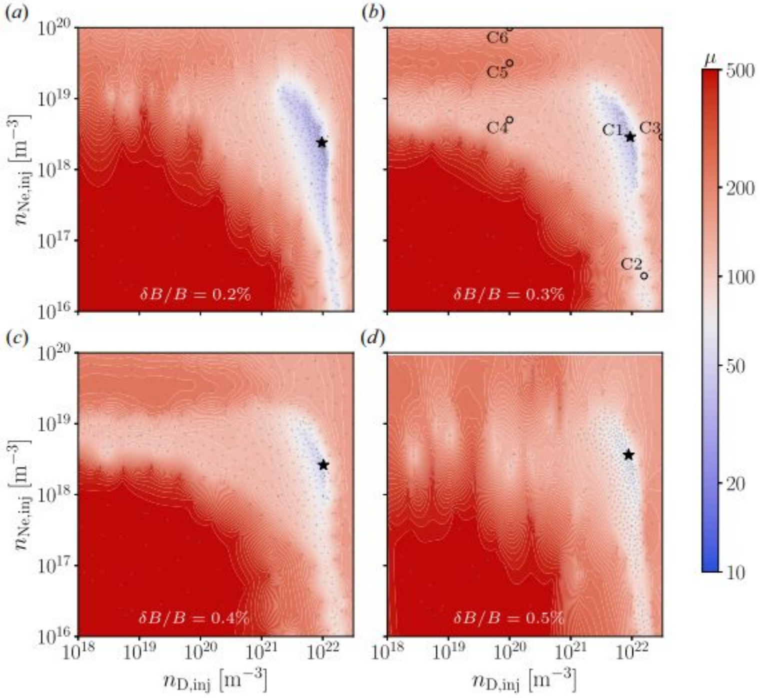
(The back-up plan needs a back-up plan too)

- If we would like to imagine a tokamak power plant with no disruptions but need disruption mitigation in case there is one then …

- Shouldn't we also say that we would like to imagine disruption mitigation with no RE plateau, but need a benign termination plan in case there is one…

- Yes! Not my topic, but benign termination is an important back-up to the back-up plan, rather than a competing plan

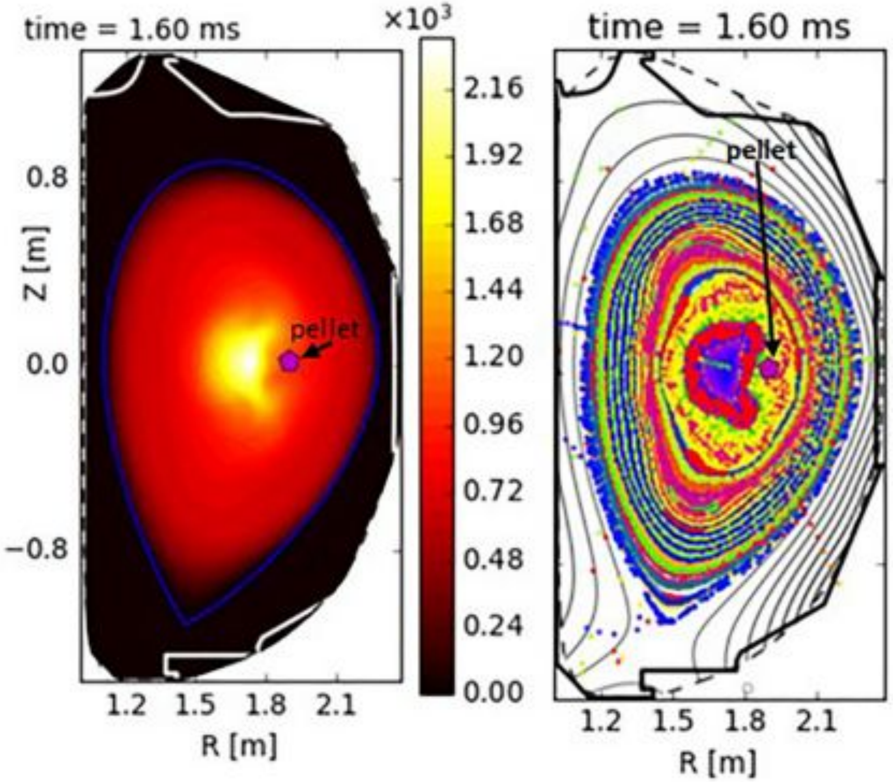
Silver lining: abandoning the seed elimination strategy reduces constraints for TQ mitigation



I. Pusztai, *et al*, "Bayesian optimization of massive material injection for disruption mitigation in tokamaks", J. Plasma Phys (2023) 905890204

- Tilts in favor of TQ mitigation strategies that maintain edge flux surfaces, like shell pellets
- **(See poster by G. Bodner at this workshop)**
- See also, V. Izzo, "Simulation of shell pellet injection strategies for ITER-scale tokamaks," accepted to *Plasma Phys. Control. Fusion (2023)*

Izzo, V.A., *Phys. Plasmas* **28** (2021) 082502



A DRT not a DMS

- A disruption mitigation system (DMS) has the connotation of something that is tacked on after all the other aspects of design and engineering have been worked out
  - Design for performance, figure out how bad disruptions will be, create DMS to solve
- A DRT (disruption resilient tokamak) would have a designed constrained from the outset by disruption tolerance and achievable mitigation levels
  - I do not mean that all aspects need to be passive—active massive material injection will inevitably play a role

See: N.W. Eidietis, "Prospects for Disruption Handling in a Tokamak-Based Fusion Reactor", *FST* **77** (2021) 738

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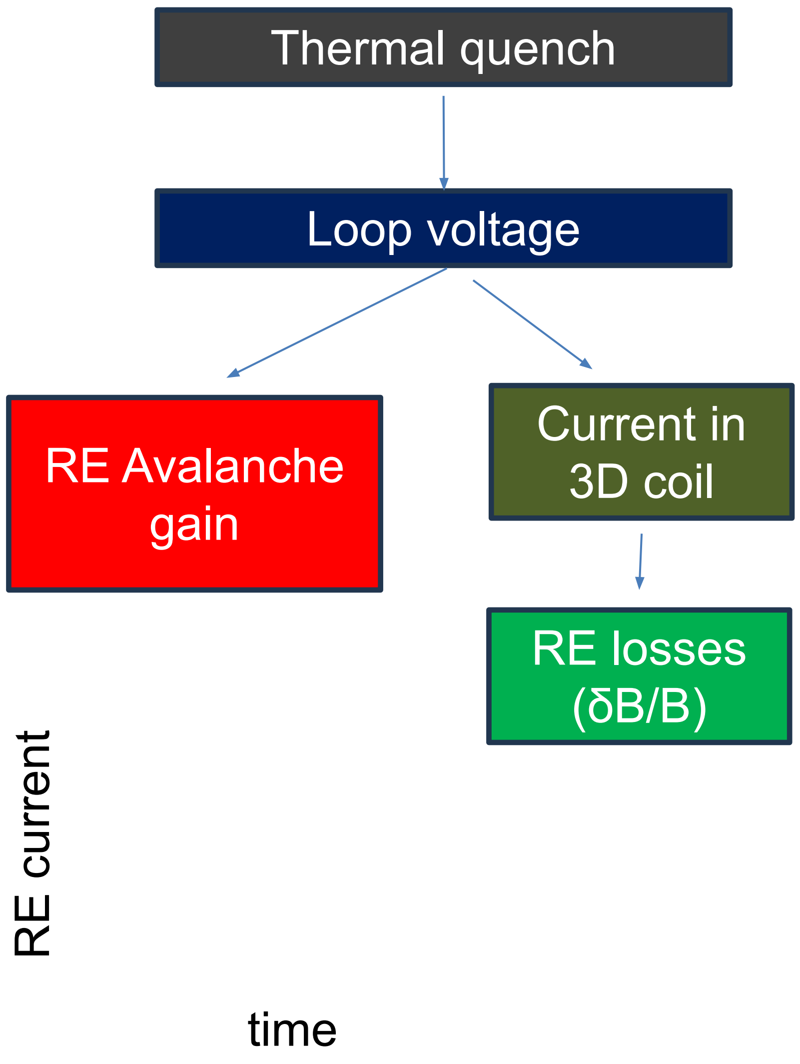
The runaway electron mitigation coil concept

- The REMC is a 3D coil intended to produce sufficient magnetic perturbations during the current quench (CQ) to continuously deconfine REs faster than the RE avalanche mechanism can produce them*
- The REMC concept makes use of the fact that the current quench phase of a disruption has a large loop voltage (that's the problem actually), and uses it to drive current in the coil without the need for power supplies
- The strategy is therefore passive and ideally works to prevent RE avalanche growth regardless of whether the disruption is predicted



* Allen H Boozer 2011 *Plasma Phys. Control. Fusion* **53** 084002

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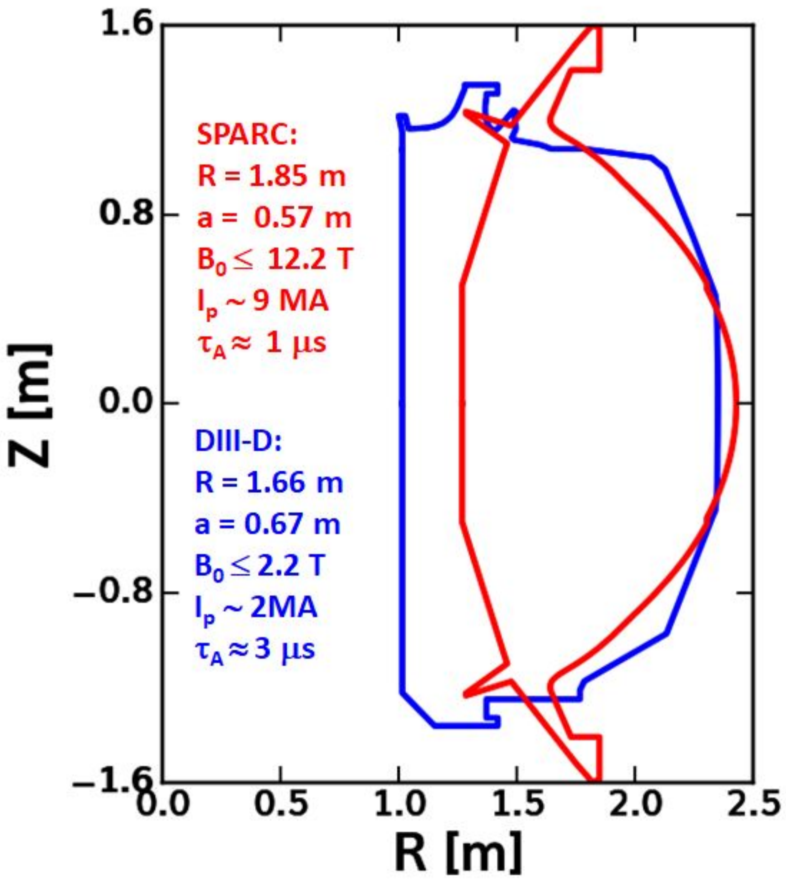
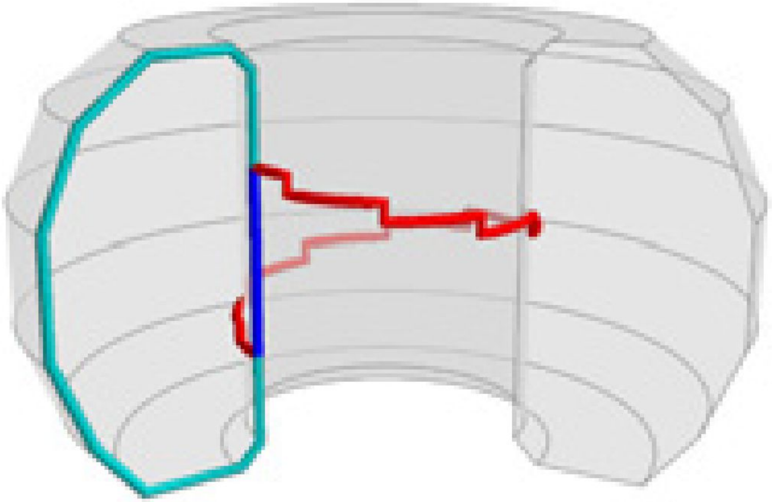
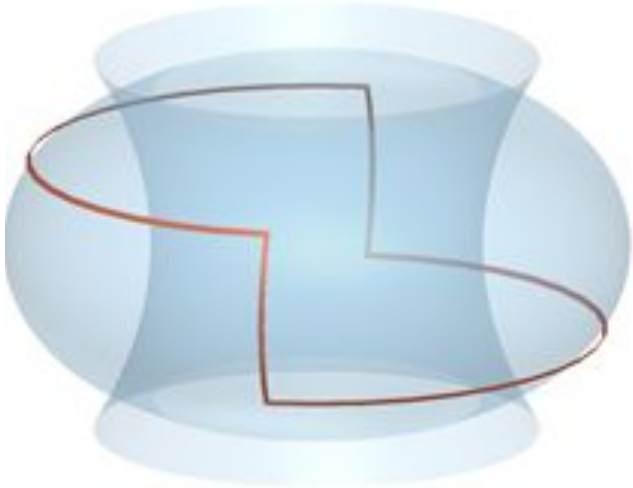
REMCs have been designed for both DIII-D and SPARC





D.B. Weisberg , C. Paz-Soldan , Y.Q. Liu, A. Welander and C. Dunn, Nucl. Fusion **61** (2021) 106033



R. Sweeney, et. al, J. Plasma Phys. (2020), vol. 86, 865860507

Time frame for coils to be operational is 2025-2026

DIII-D and SPARC 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

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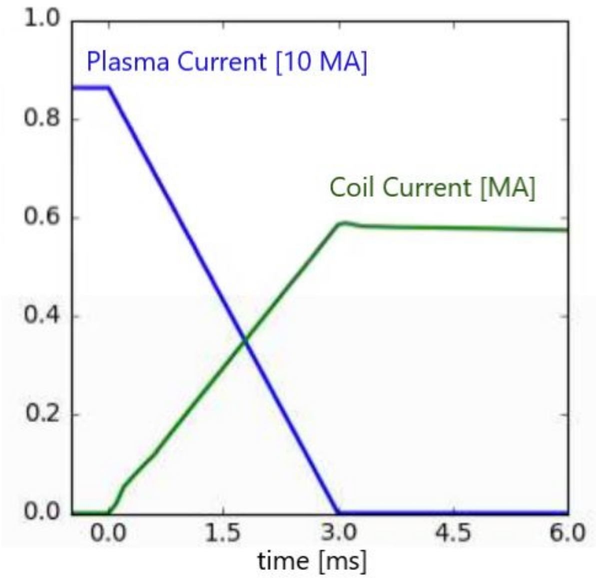
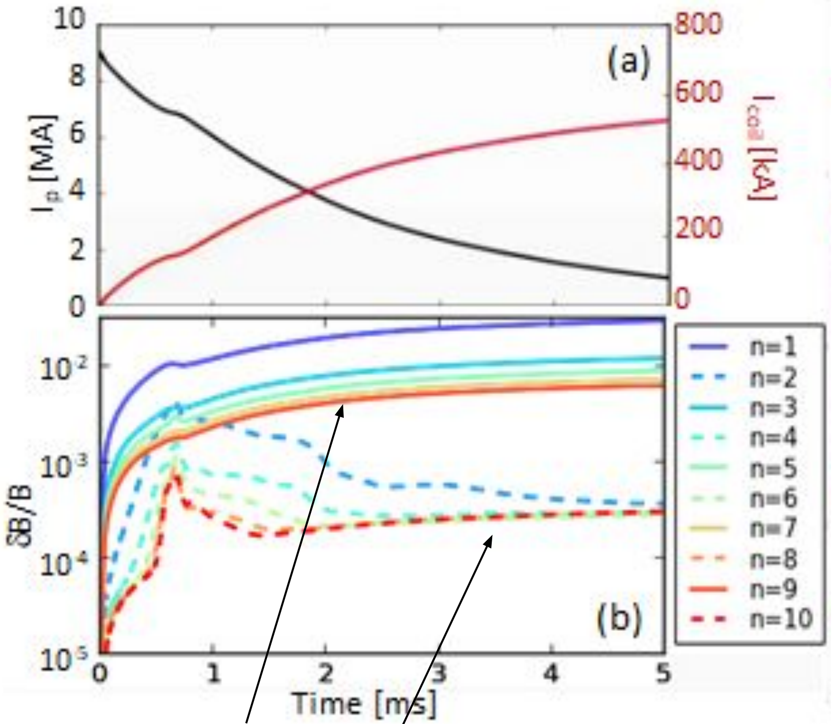
Nonlinear modeling of SPARC REMC with COMSOL+NIMROD+ASCOT+DREAM

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

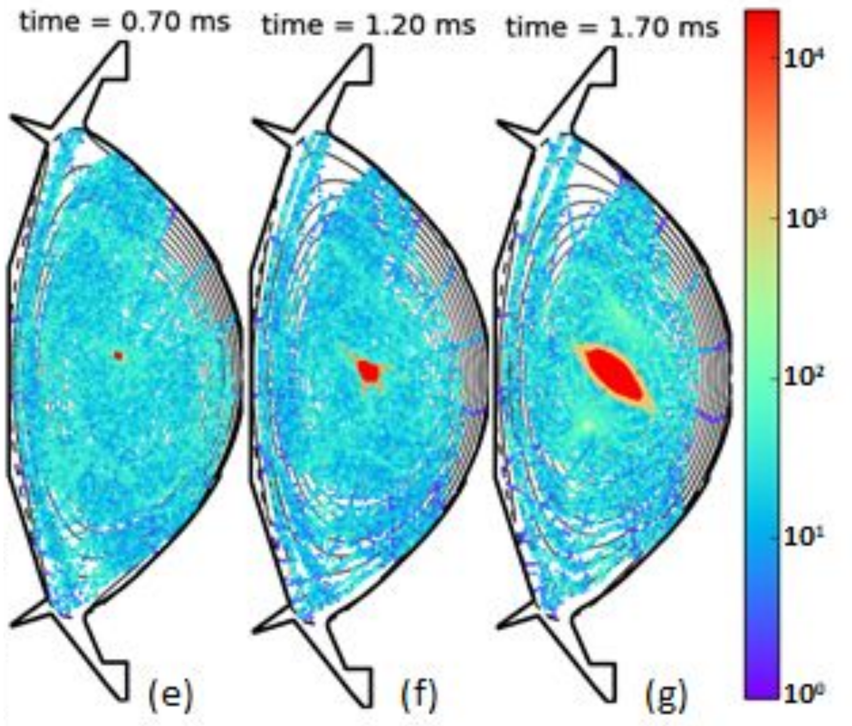


$$I_{\mathrm{REMC}} = I_{\max}\left(1 - \frac{I_p}{I_{p,t=0}}\right)$$



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

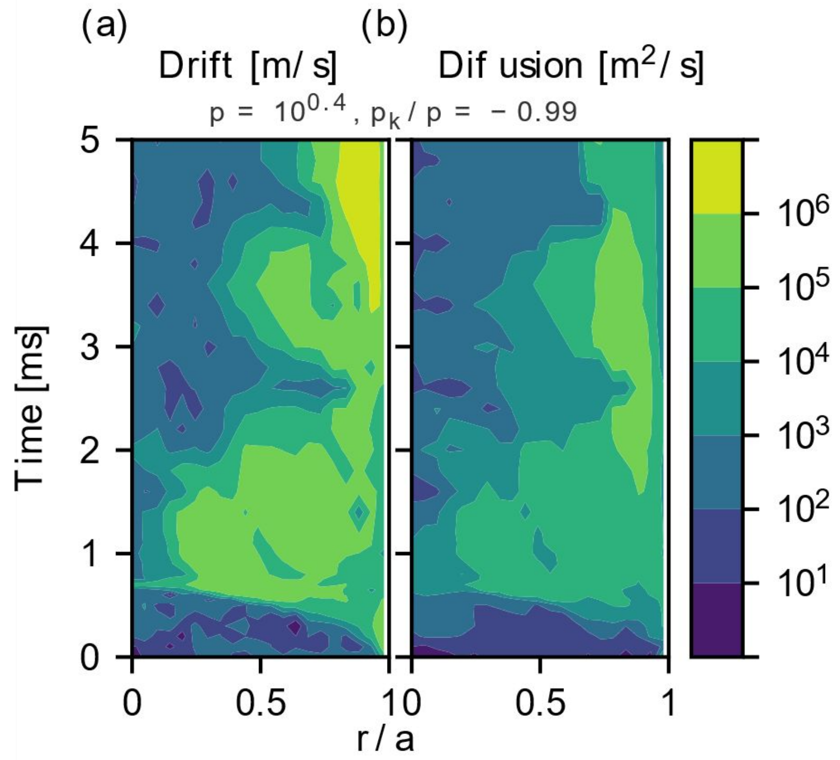
3D fields imposed at the NIMROD simulation boundary are taken from a COMSOL calculation



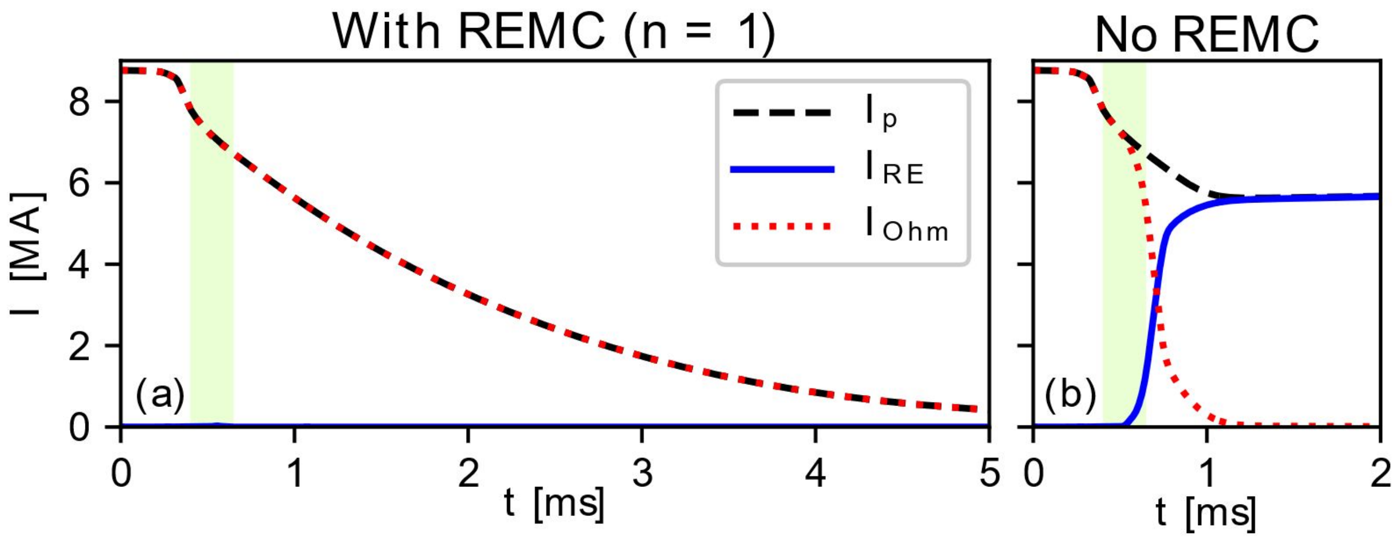
SPARC

Full RE current suppression predicted with multi-code workflow*

***R.A. Tinguely *et al* 2021 *Nucl. Fusion* 61 124003**



- 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



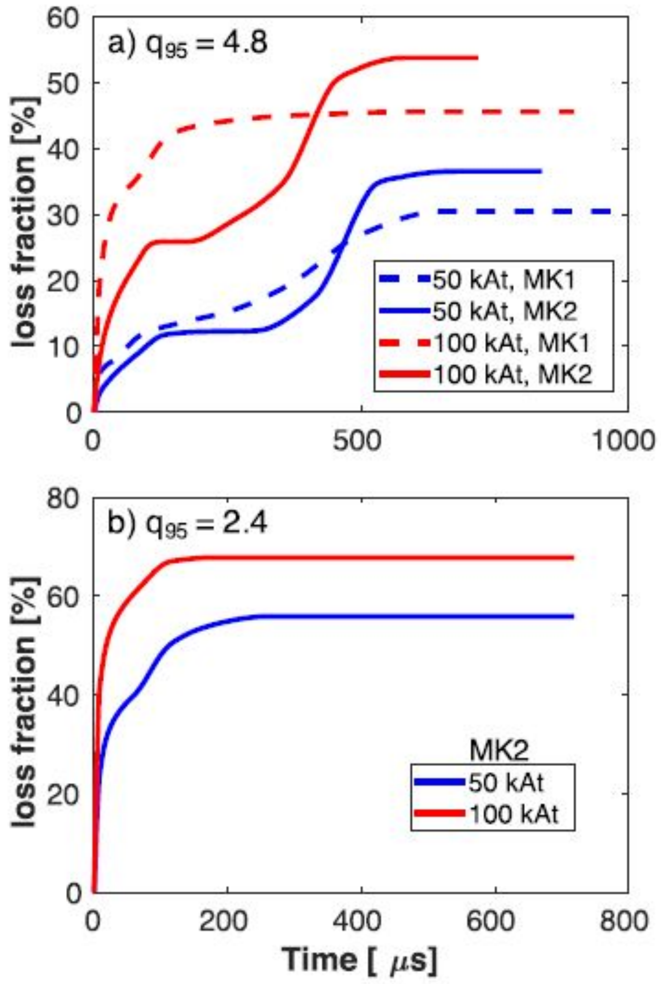
See also: Izzo, V. A., et al, *Nuclear Fusion* (2022): 096029 & Tinguely, R. A., et al, *Plasma Phys. and Control. Fusion* (2023): 034002.

DIII-D REMC nonlinear modeling with NIMROD followed MARS linear response modeling

- 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.

D.B. Weisberg , C. Paz-Soldan , Y.Q. Liu, A. Welander and C. Dunn, Nucl. Fusion **61** (2021) 106033



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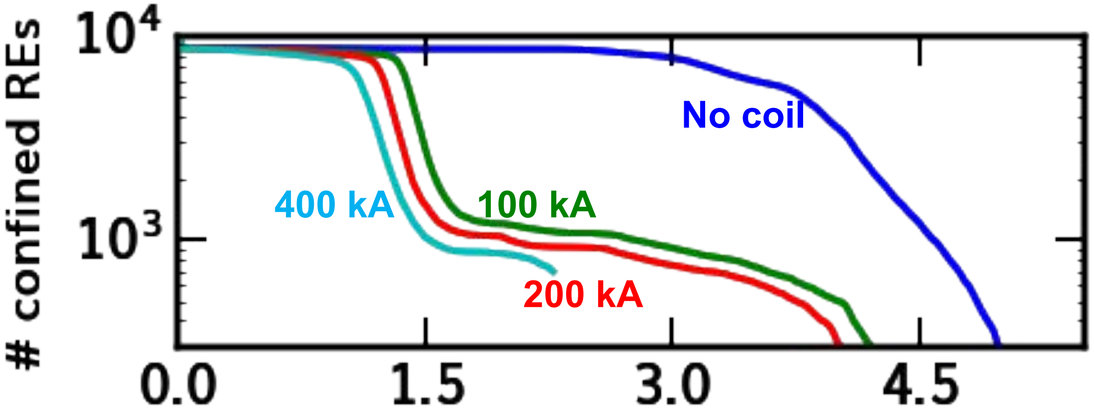
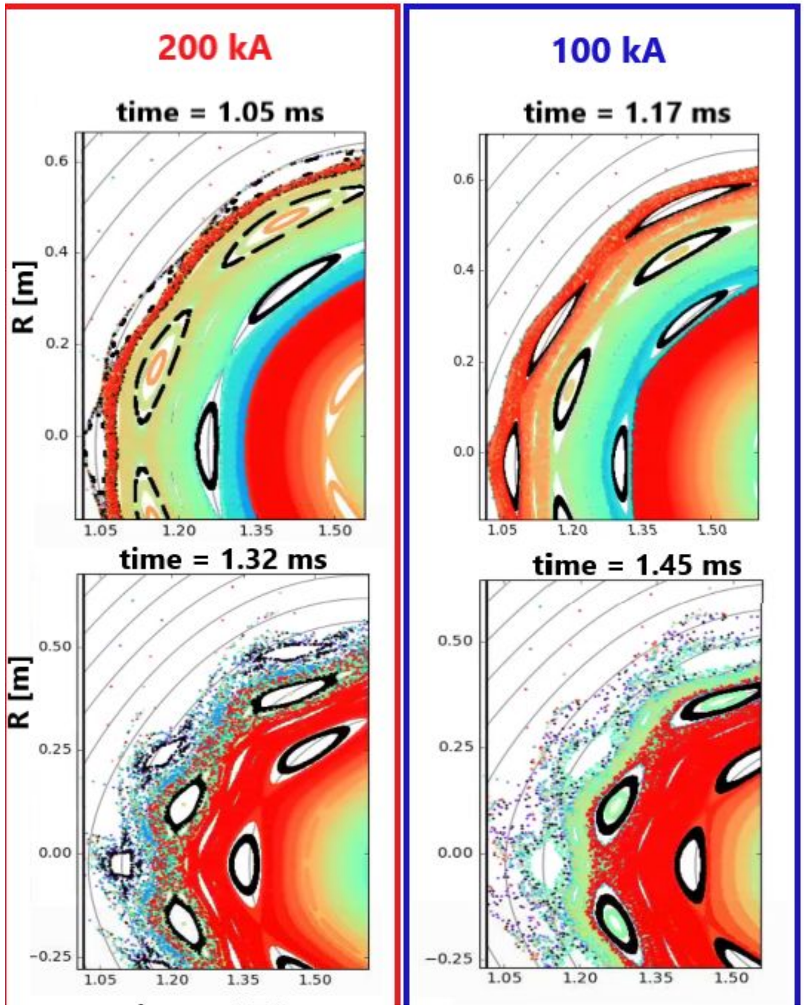
Nonlinear modeling shows higher (~90%) loss fractions, insensitivity to coil current

- Use vacuum fields w/ linear ramp and maximum currents of 100kA and 200kA to match mid-CQ currents of 50 &100kA from linear response modeling





- In each case, island overlap occurs when q at the edge crosses a threshold (q=8). Stochasticity propagates inward.

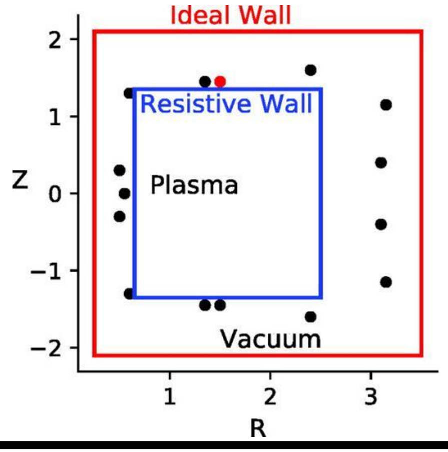
Some limitation to the current modeling

- These simulations used a perfectly conducting wall placed inside the limiter location
  - Close conducting wall can have a stabilizing effect and underpredict RE losses

1

Sovinec, Carl R., and K. J. Bunkers ,*Plasma Physics and Controlled Fusion* (2019): 024003.

Bunkers, K. J., and C. R. Sovinec *Physics of Plasmas*, (2020).



- NIMROD includes multiple resistive wall models, <u>but wall location is constrained by the fact is not straightforward to include the coil within the gridded domain</u>

2

Alternate resistive wall has no outer vacuum region, uses Green's function code by D. Barnes– but does not yet include n=0 component… work on this is in progress

The n=0 component will be important for q-profile evolution, vertical motion, etc.

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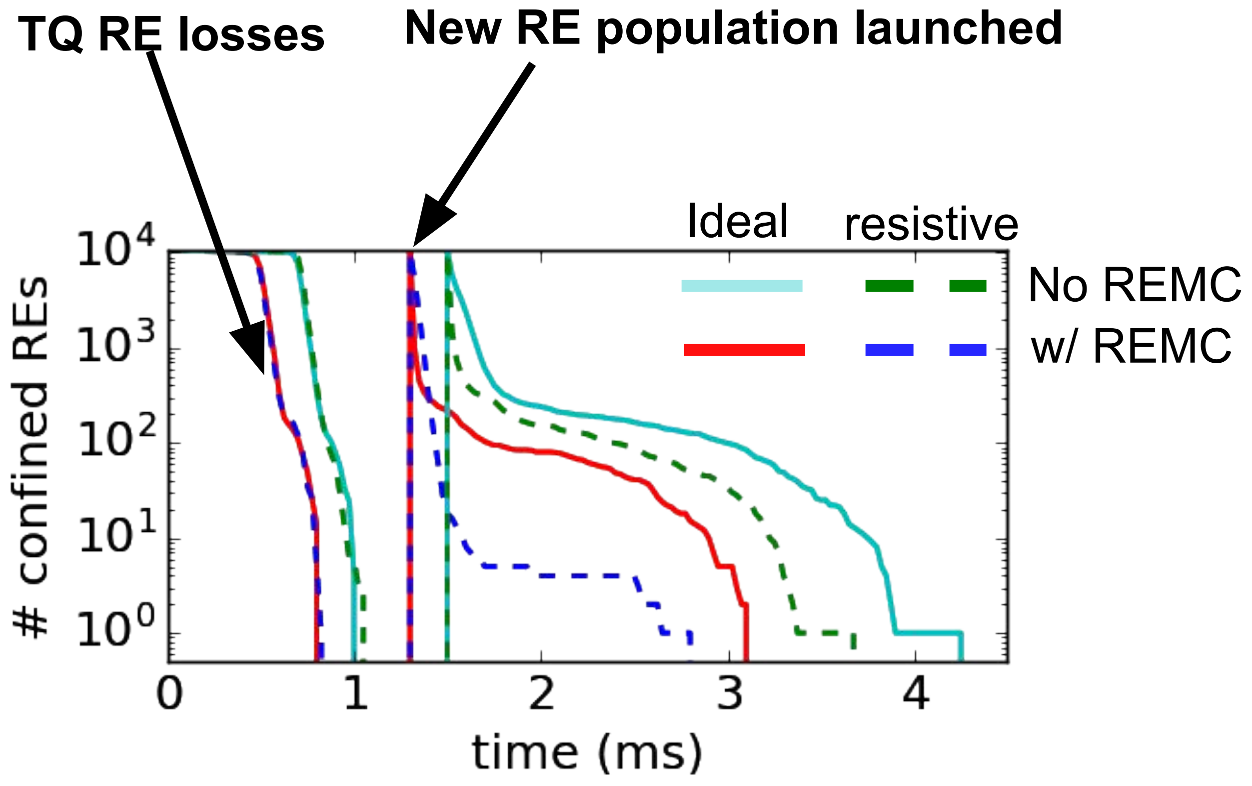
- Model improvements for the DIII-D REMC: resistive wall, ThinCurr, extended boundary

1 2 3

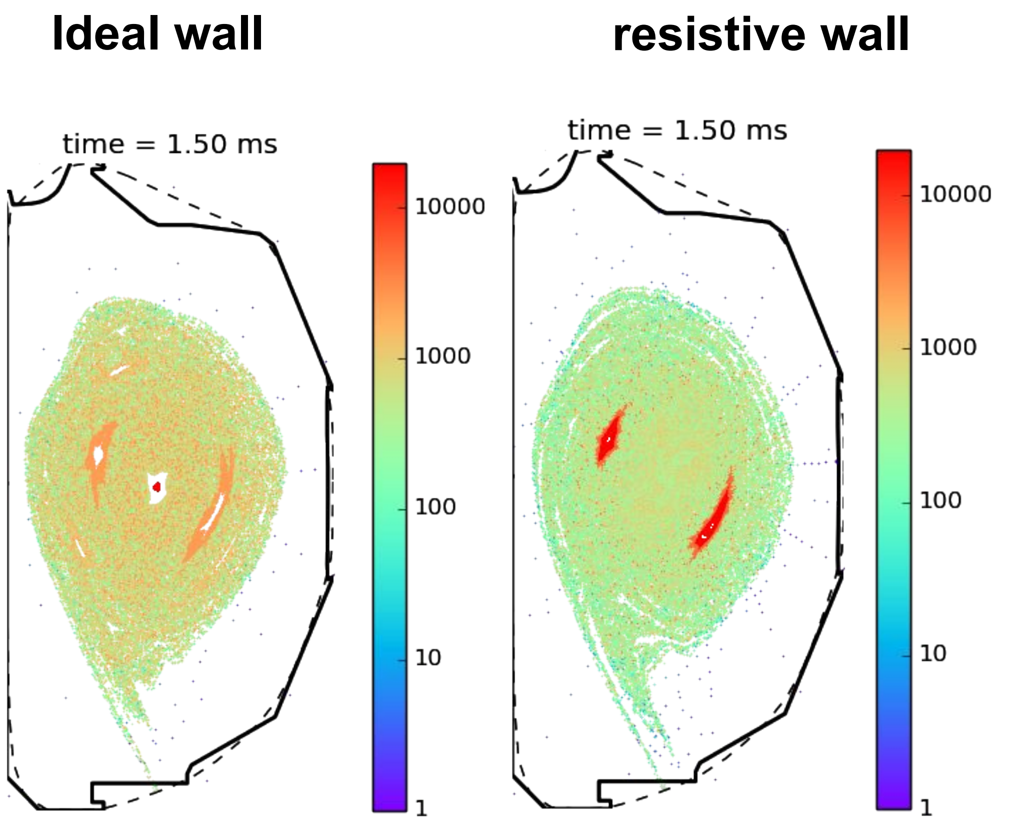
Summary

Green's function n>0 model tested for DIII-D REMC with LSN shape equilibria

1



Cases with REMC



- Somewhat surprising that the boundary condition is having this kind of effect on the reformation of small islands in the core

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Resistive wall allows plasma to modify spectrum of applied fields

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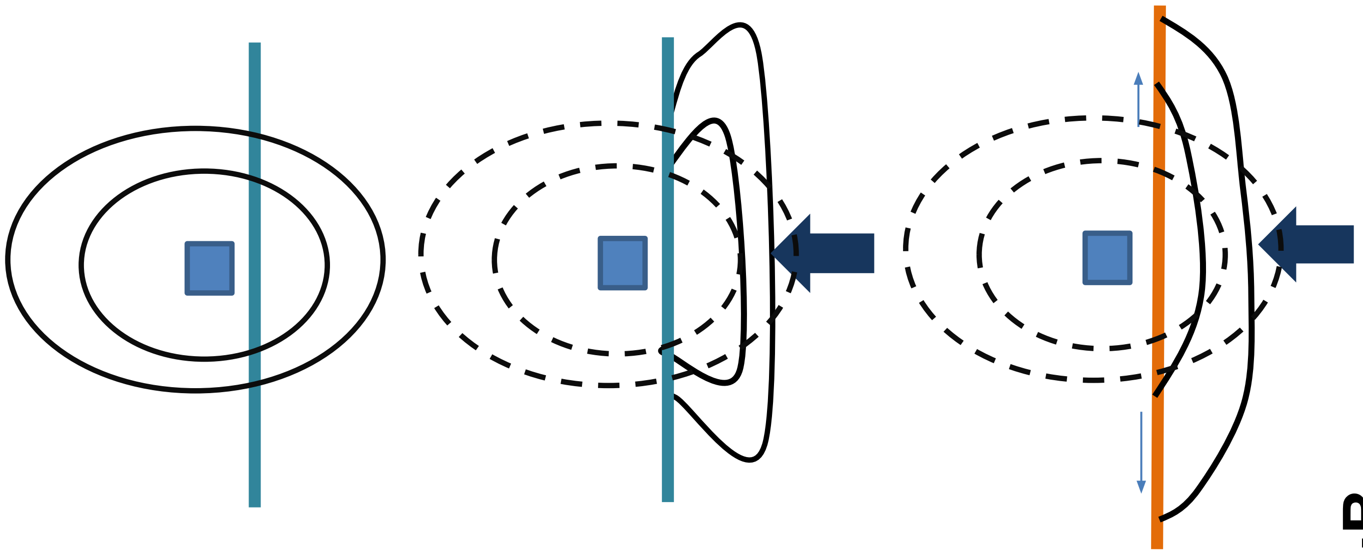
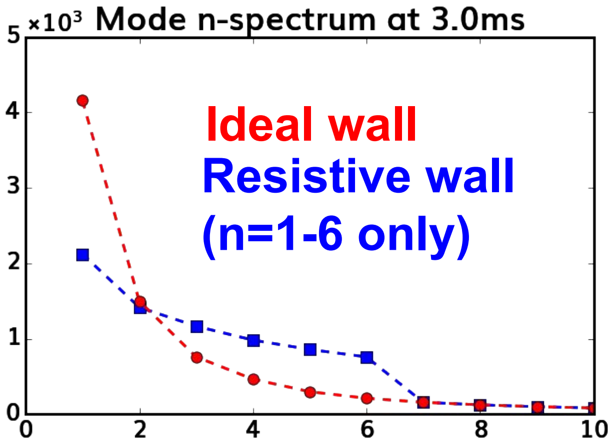
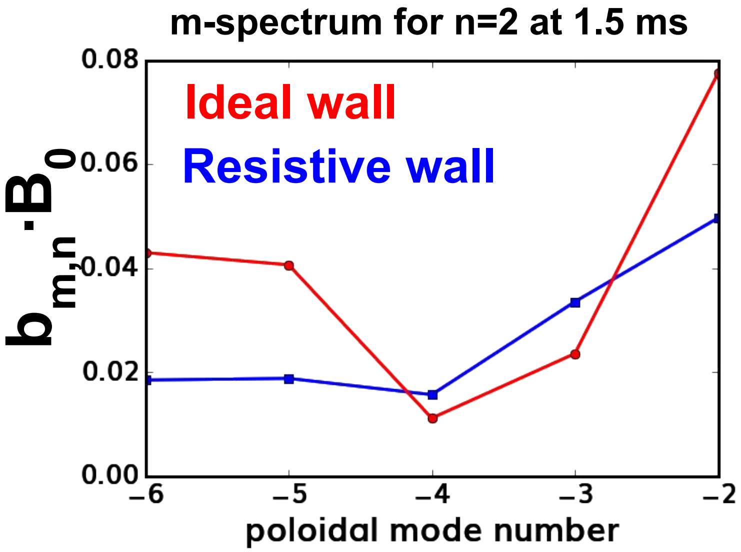


- Poloidal and toroidal mode spectrum tends to broaden/flatten as field-lines spread



- Flattening of toroidal mode spectrum



- Flattening of n=2 poloidal mode spectrum

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ThinCurr* models 3D conducting structures as a series of coupled circuit equations

❷

Physics governed by inductance/resistance

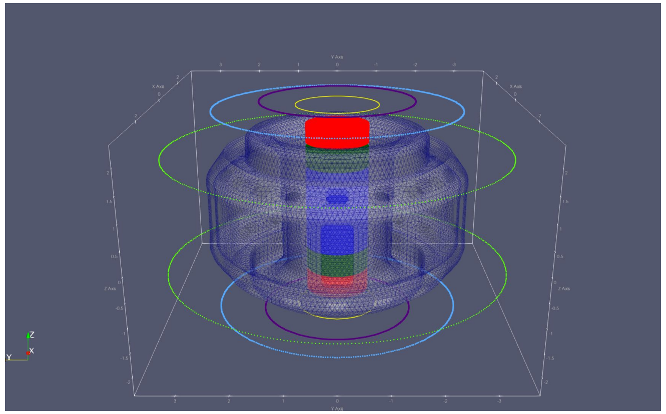
$$L_{i,j}\frac{\partial I_i}{\partial t} + R_{i,j} I_i = V_j(t)$$

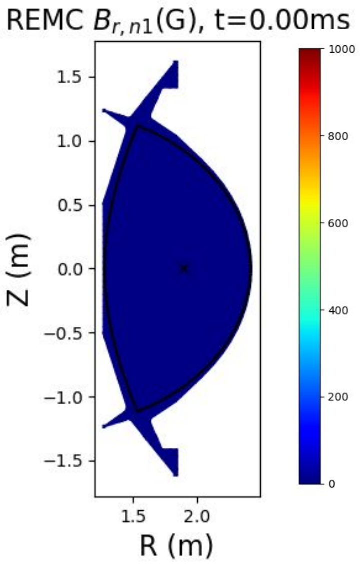
Additional currents/voltages can be included

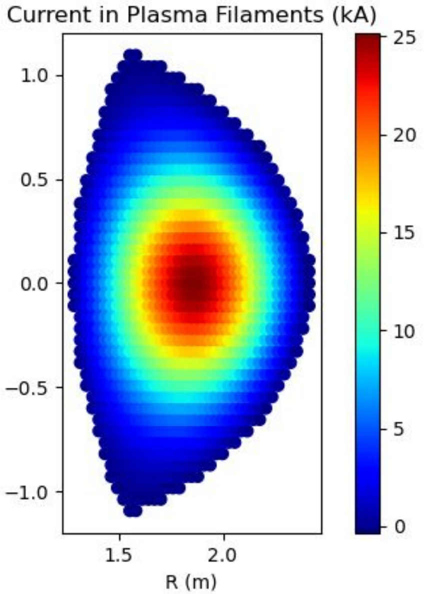
- Filament coils ($I(t)$ or $V(t)$)
- Plasma "modes" (eg. DCON)

Magnetic fields can be calculated anywhere in space or time

- Sensor signals with eddy currents
- Lorentz forces on structures
- Discontinuities in $\boldsymbol{B} \times \hat{\boldsymbol{n}}$ at surfaces





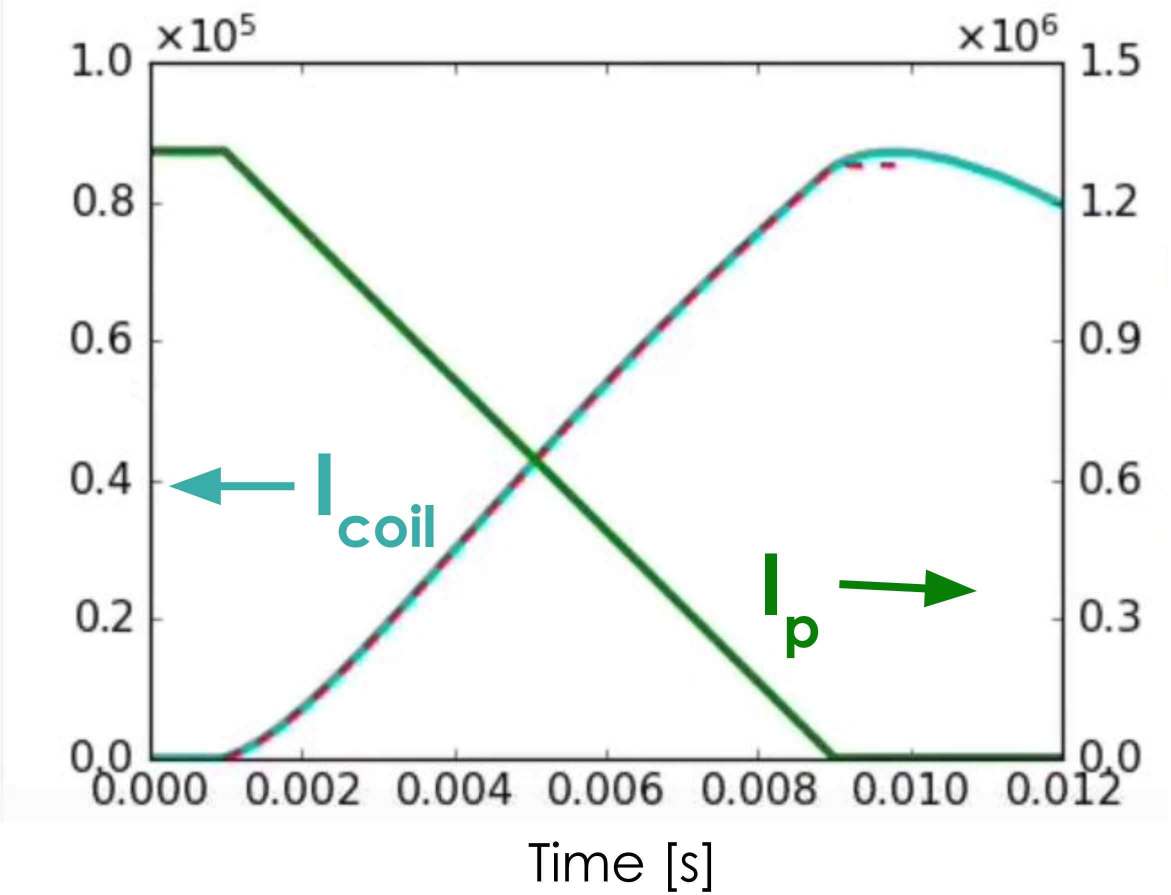


*See talk by Chris Hansen at this workshop

ThinCurr calculation replaces vacuum fields for coil/vessel response

2

- As with COMSOL modeling for SPARC, linear plasma current ramp down is prescribed
- Response of coil and surrounding conducting structures is calculated
- Non-linear I_c vs. I_p used in NIMROD



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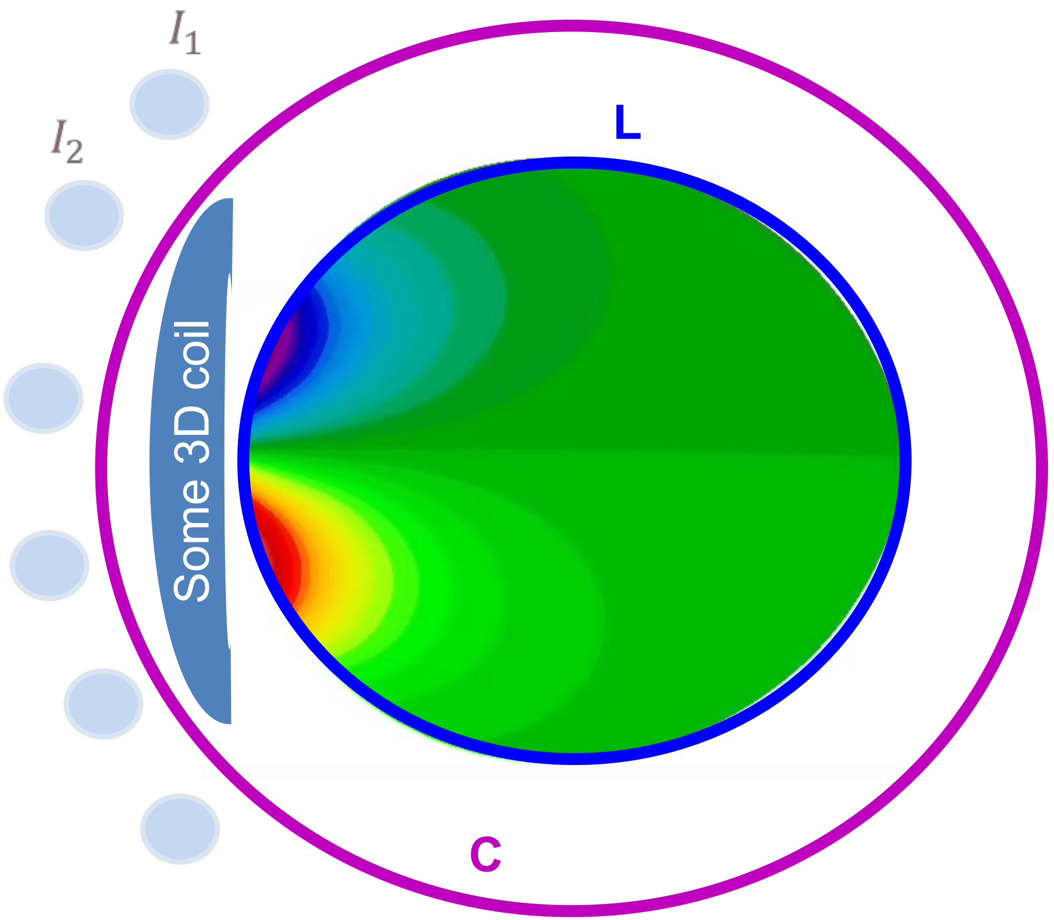
Can we move the wall farther away by finding an equivalent set of boundary fields?*

3



For *each Fourier component*, assume m toroidal current loops arranged around the larger wall.

$$x = \begin{bmatrix} I_1 \\ . \\ . \\ . \\ I_m \end{bmatrix}$$

$$A_L x = b_n^L$$

Known b_n on each segment of limiter wall

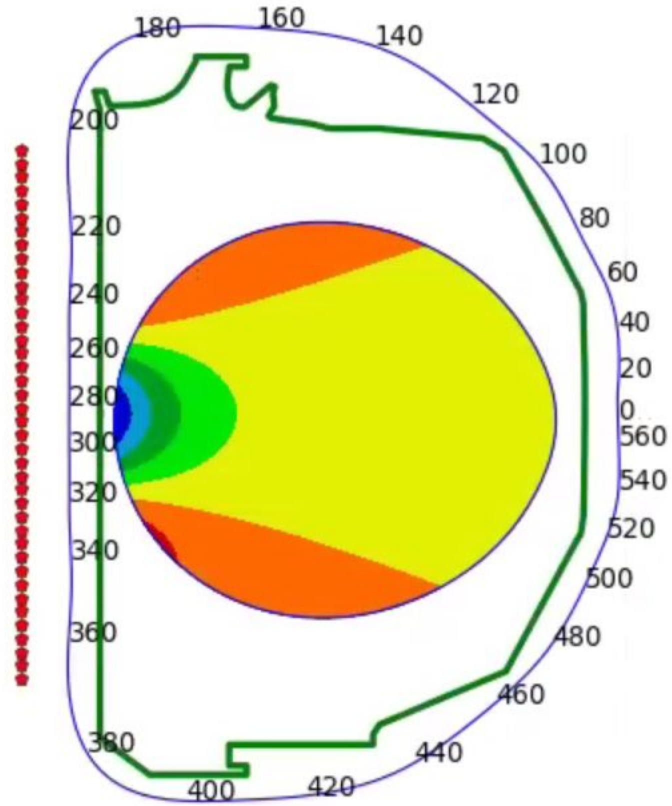
$$A_C x = b_n^C$$

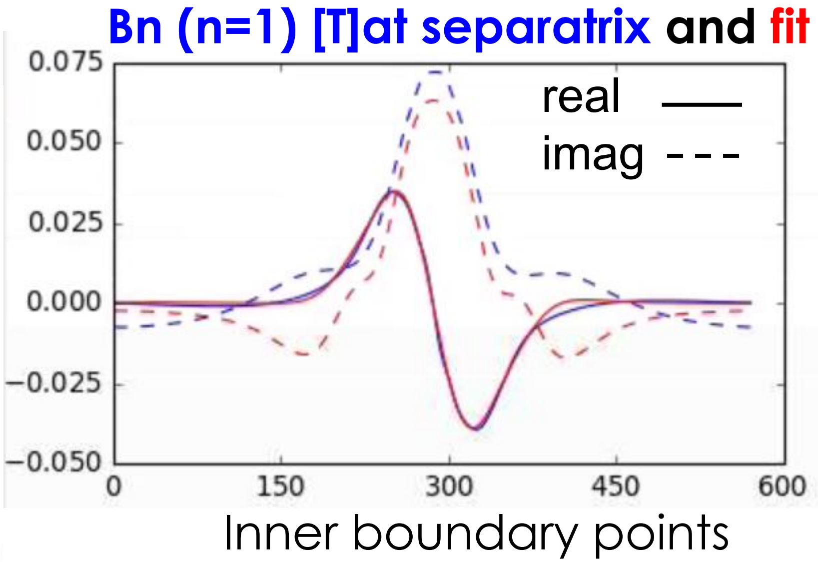
Unknown b_n on each segment of conducting wall

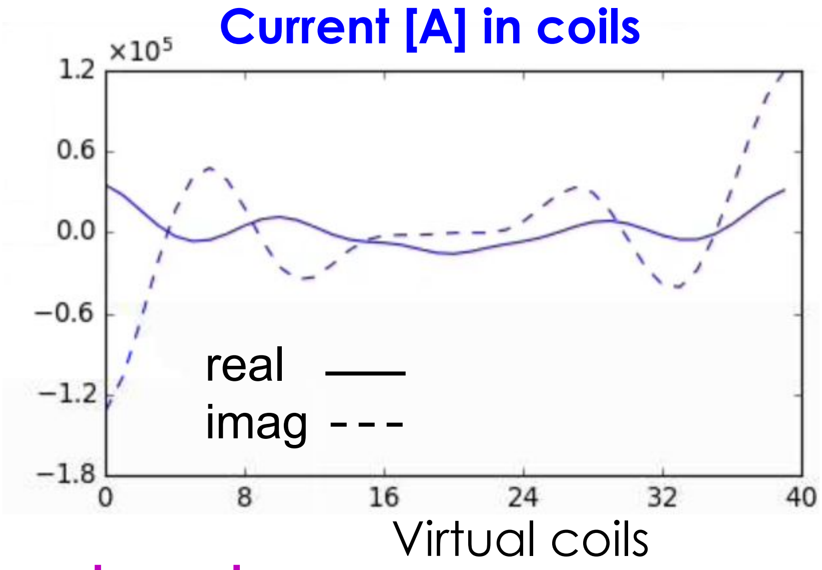
$$A_C A_L^{-1} b_n^L = b_n^C$$

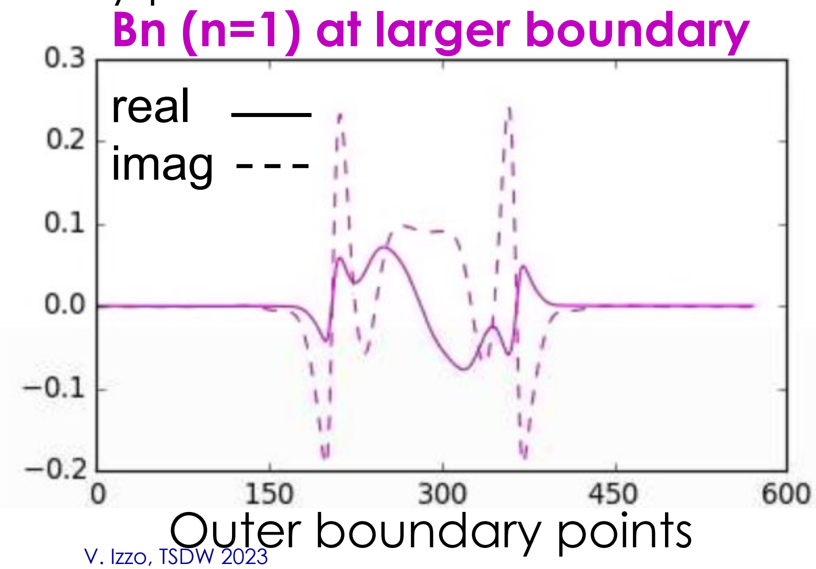
*credit suggestion from R. Sweeney

Under-determined solution gives well behaved reasonable fits (room for optimization)









Results with extrapolation from original vacuum fields

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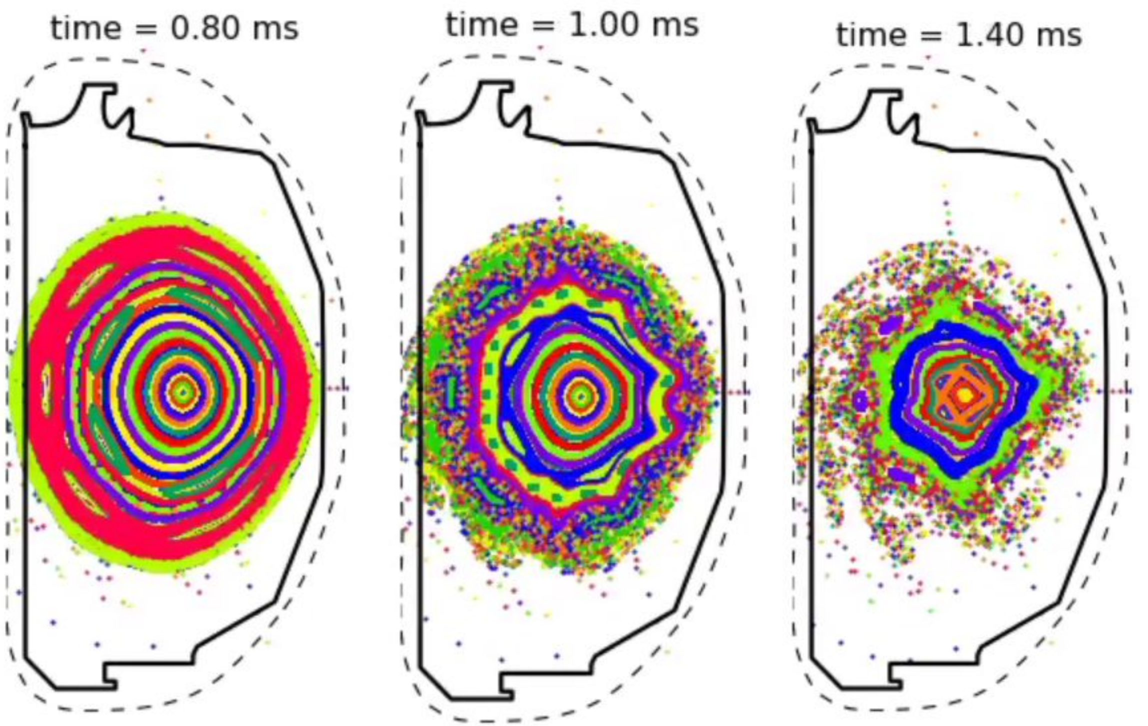

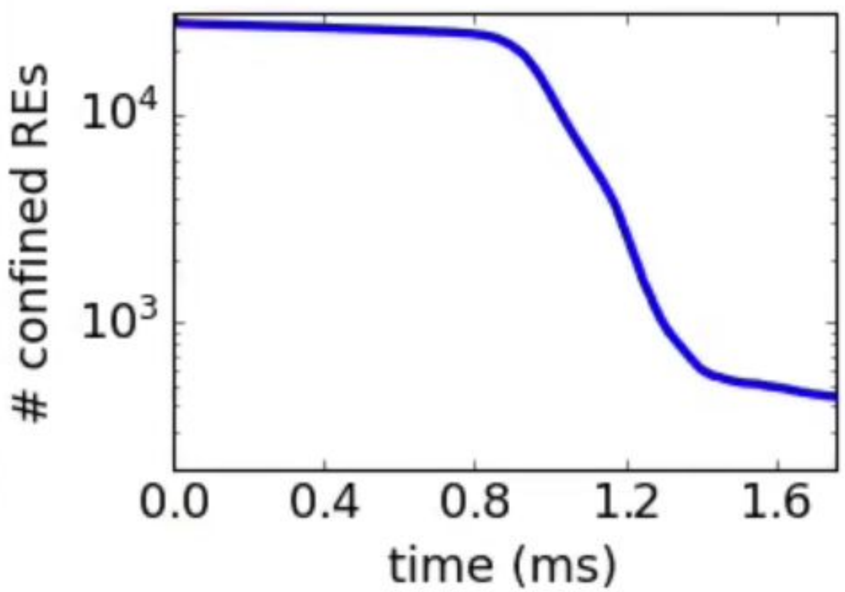

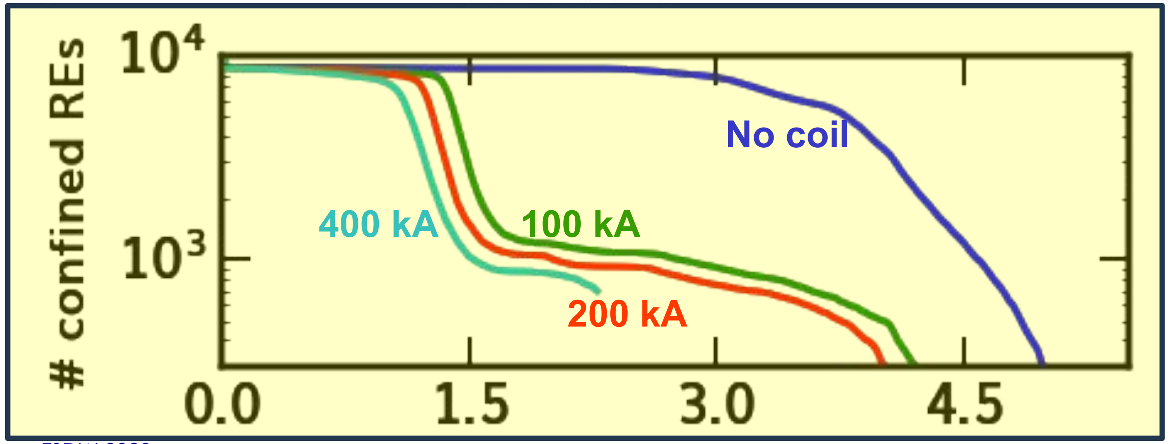

- Simulation with larger wall has slightly earlier RE loss and larger loss fraction

Results with extrapolation from ThinCurr fields, n>0 resistive wall at larger boundary

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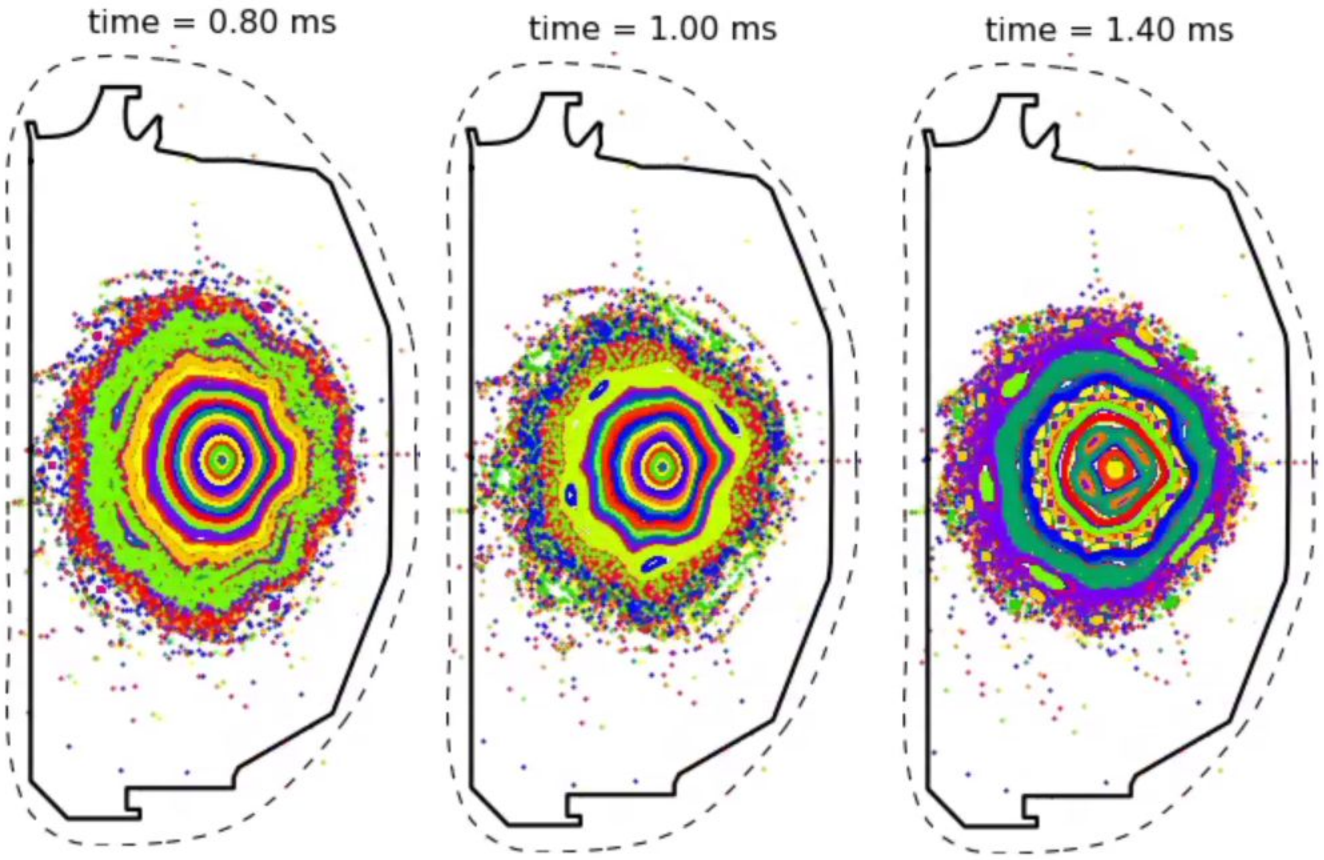
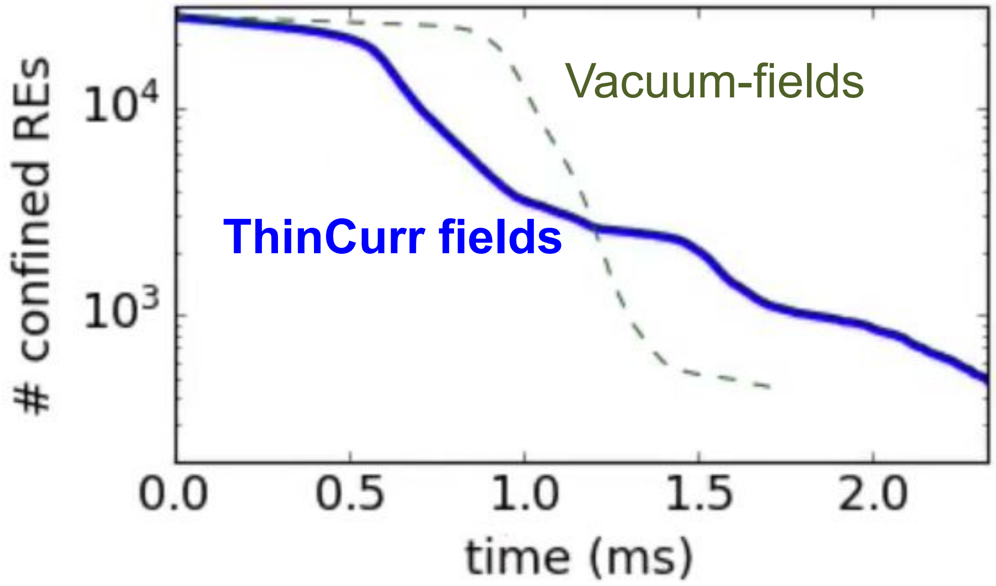


- ThinCurr fields have a different spectrum (n=2 amplitude is closed to n=1)
- Earlier, but also more gradual losses



- A number of checks to verify the general validity of this method are still needed.

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Summary (1)

- Nonlinear, ideal-wall modeling of REMCs for DIII-D and SPARC indicates these coils successfully suppress RE avalanche growth

- Modeling for DIII-D is being extended and improved in various ways: inclusion of resistive wall (n>0 for now); ThinCurr calculates response of coil and conducting structures; Larger boundary implemented with "equivalent normal fields" boundary condition

Summary (2)

- With geometry for both REMCs essentially frozen, modeling is focused on improving fidelity in preparation for validation in 2025-2026

- Additional model improvements desirable: n=0 resistive wall (using either RW model), close coupling of coil response model, more fully integrated RE transport calculation

- High-fidelity, validated modeling capability for REMCs can aid in FPP designs to build a disruption resilient tokamak