Resistive Wall Model in M3D-C1

by

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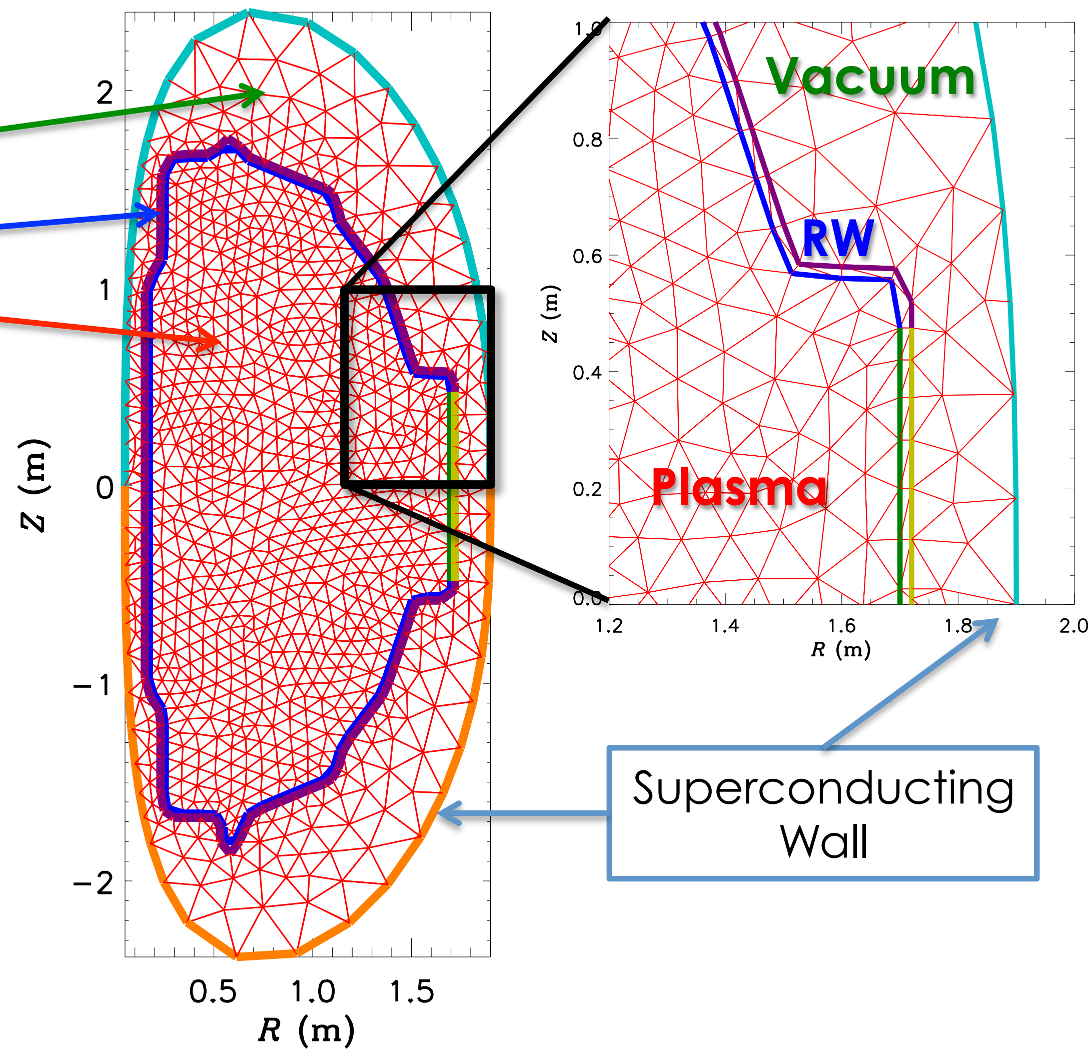
New Resistive Wall Capability Has Been Implemented in M3D-C1

- **3 regions inside domain:**
  - Vacuum ($\mathbf{J} = 0$)
  - RW ($\mathbf{E} = \eta_W \mathbf{J}$)
  - Plasma (Extended MHD)

- **BCs:**
  - $\mathbf{v}$, p, n set at inner wall
  - $\mathbf{B}$ set at outer (superconducting) wall

- ***<u>There are no boundary conditions on $\mathbf{B}$ or $\mathbf{J}$ at the resistive wall</u>***
  - Current can flow into and through the wall



Advantages and Disadvantages of Including Resistive Wall In Domain

- **Advantages:**
  - Computation is more scalable than using RW BCs
    - RW BCs couple all finite elements touching the boundary
  - Can add time/space dependent physical attributes of wall
    - Resistivity, temperature
  - Can treat non-thin walls
    - Can also be done in principle with RW BCs, but not yet implemented

- **Disadvantages:**
  - Bigger matrices
    - But non-MHD regions do not make matrices more poorly conditioned
  - Need to include PF coils inside domain
  - Still need a conducting boundary somewhere
    - This could be a problem in STs like NSTX-U

Some Algorithmic Changes Required for RW Model

- **Poloidal field coils are now inside domain**
  - PF coil fields must be treated separately (inconsistent with J=0 equation in vacuum) → new terms!
    - $\mathbf{J}\times\mathbf{B} \rightarrow \mathbf{J}_{plas}\times\mathbf{B}_{tot}$

- **GS Solve can no longer be fixed boundary**
  - PF coil fields must be treated separately again
  - Need coil current data from "a" or "m" eqdsk files
  - GS solve is much less stable, requires feedback stabilization
    - Added proportional controllers on R_{axis} and Z_{axis}

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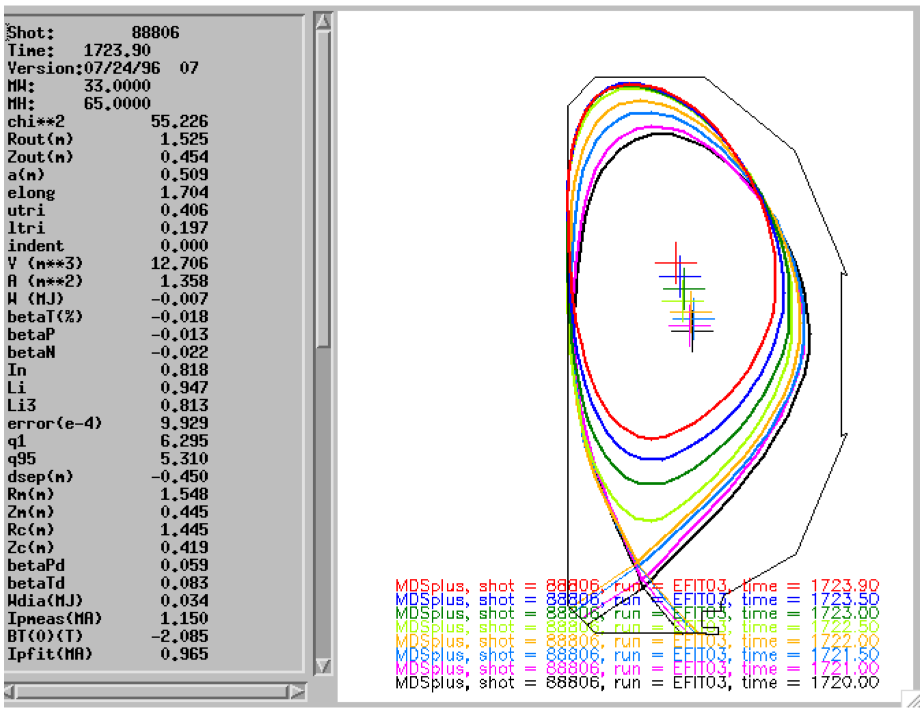
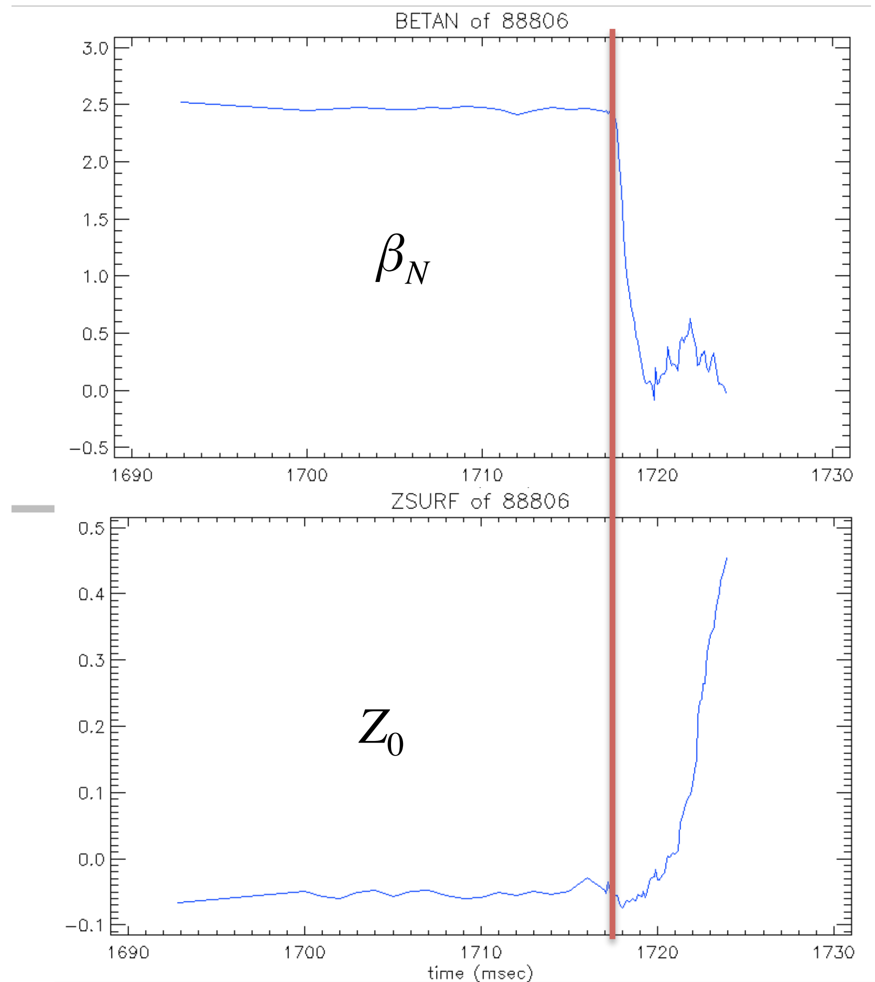
Vertical Displacement Events (VDEs)

Nonlinear Calculation Recovers $n = 0$ Instability In DIII-D VDE Discharge

- **DIII-D discharge 088806 disrupted due to gas injection**
  - Vertical stability was lost shortly after thermal quench (TQ)
  - Timescale ~ 3 ms



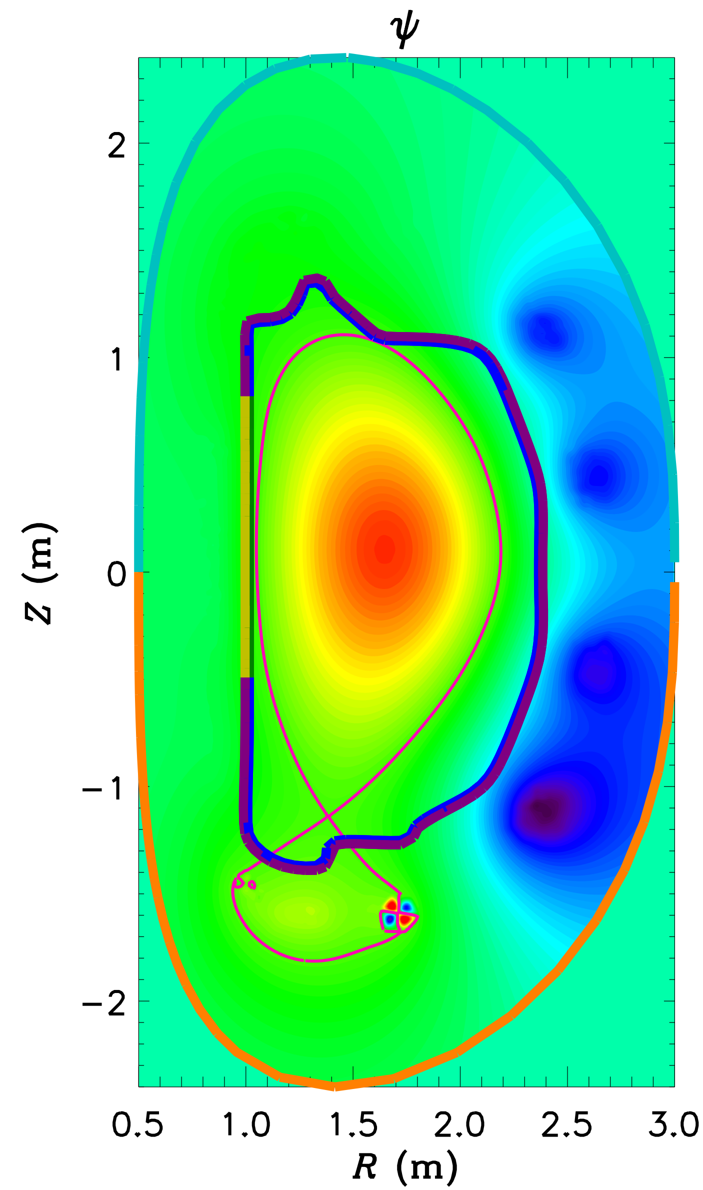


Nonlinear Calculation Recovers $n = 0$ Instability In DIII-D VDE Discharge

- **M3D-C1 was initialized using the reconstructed equilibrium just after TQ ($t = 1720$ ms)**
  - Equilibrium is re-solved on M3D-C1 grid

- **Nonlinear $n = 0$ calculation uses realistic plasma parameters**
  - Spitzer resistivity
  - Anisotropic thermal conductivity
  - Anomalous perp. transport

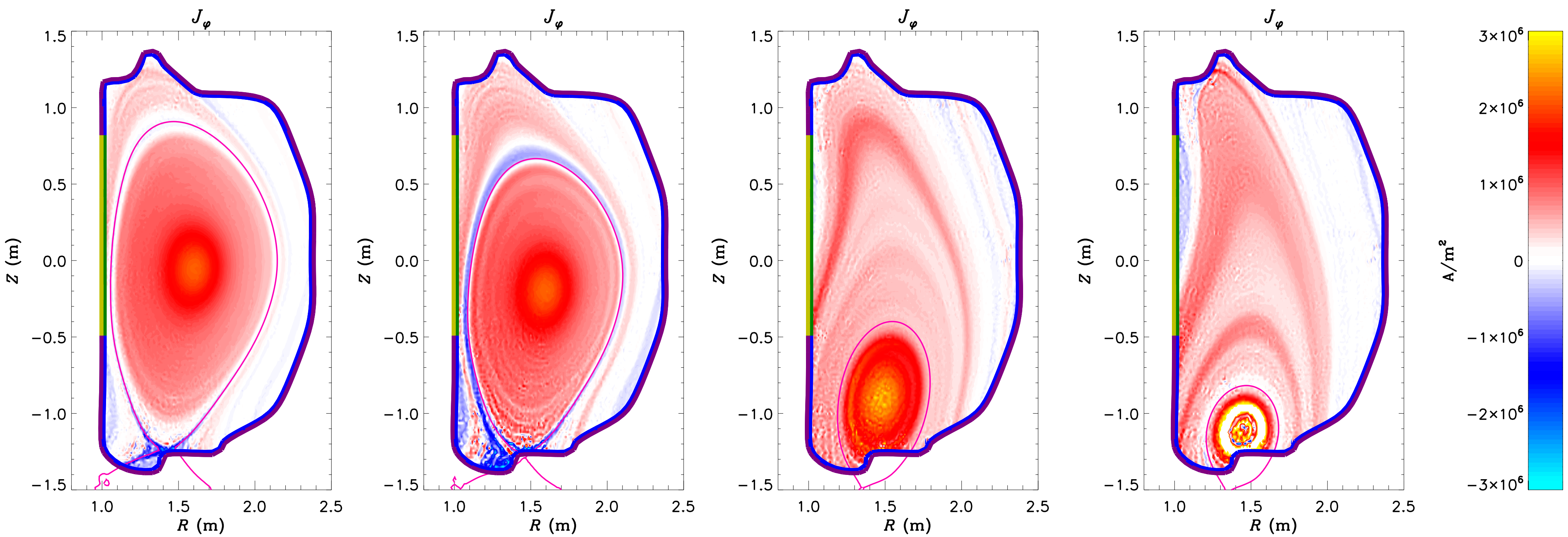
- **RW approximates first wall, not vacuum vessel here; using "modern" first wall, different from old experiment**



Calculation Shows Vertical Displacement Into Lower Divertor

- **Initial results from low-resolution calculation with large wall resistivity ($\eta_W = 1.9\times10^{-3}$ Ω-m)**

- **Both Halo (co-current) and Hiro (counter-current) currents are found**
  - Unclear how these will scale with η_W



$t = 2.27$ ms $t = 2.59$ ms $t = 2.92$ ms $t = 3.24$ ms

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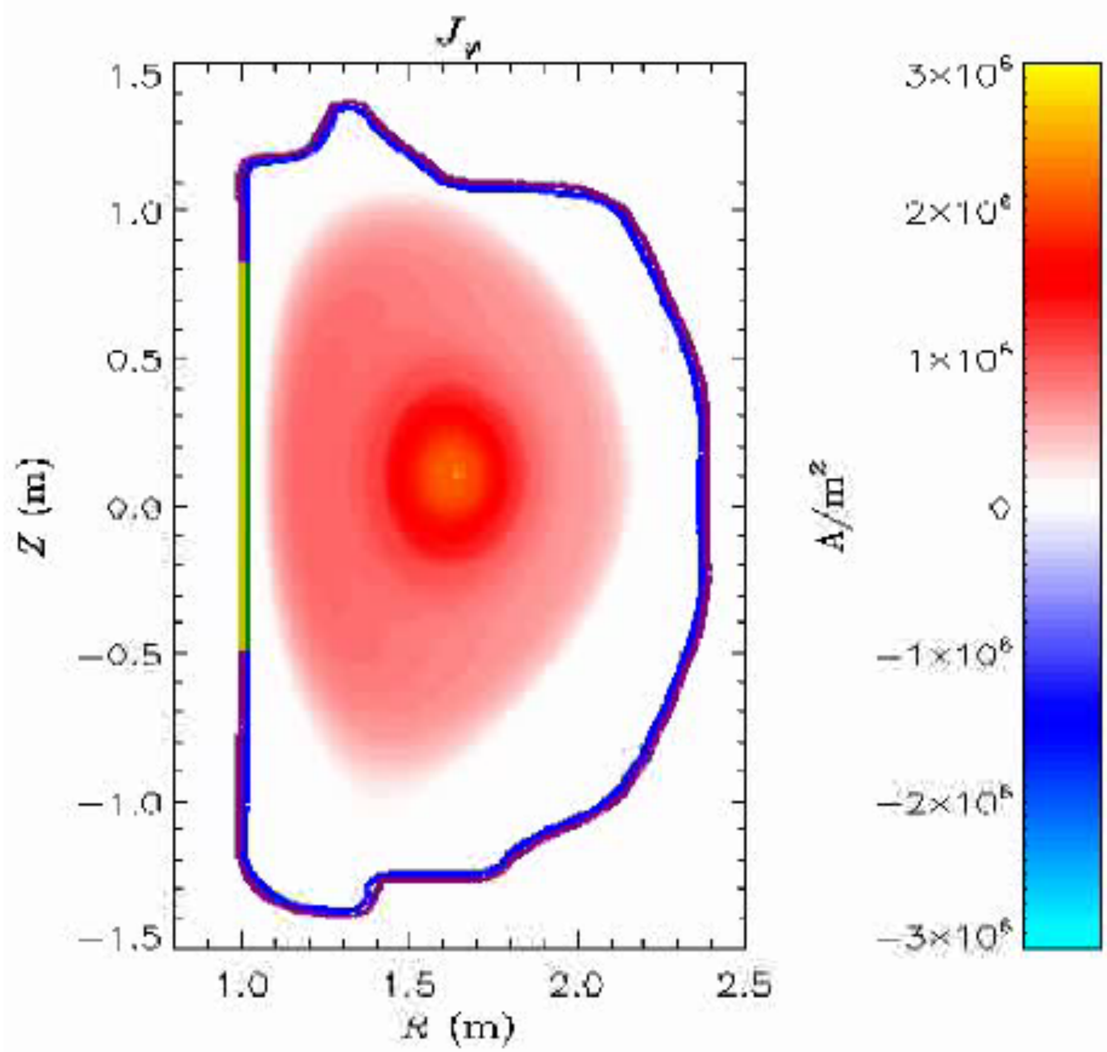
Calculation Shows Vertical Displacement Into Lower Divertor



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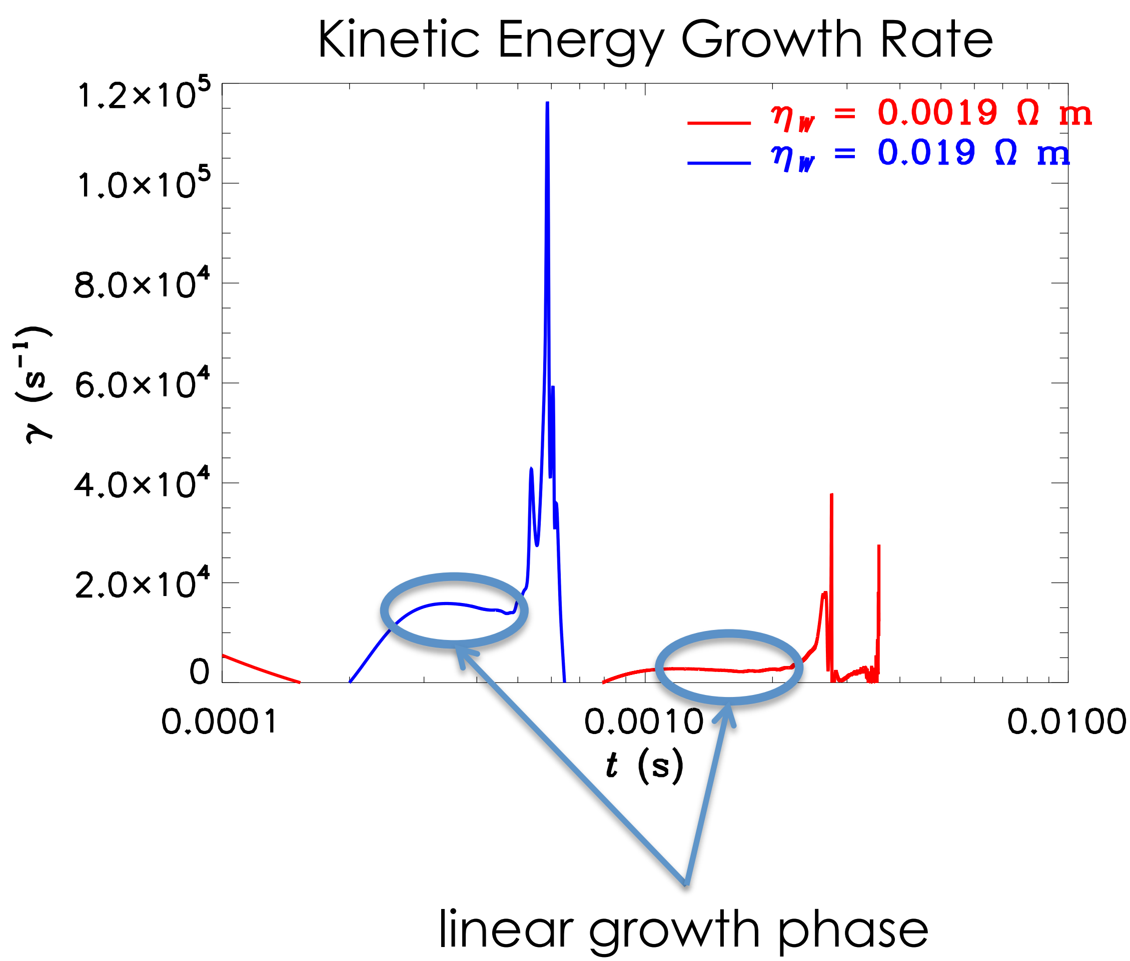
Linear Growth Rate of VDE Scales with Wall Resistivity

- **VDE is faster, more violent as η_W is increased**
- **Increasing η_W by factor of 10 increases growth rate by factor of ~6**
  - $\gamma \sim \eta_W^{0.78}$
  - ~ 2 ms from onset of linear growth to hit wall at $\eta_W = 1.9\times10^{-3}$ Ω-m
- **More cases are needed to determine scaling!**



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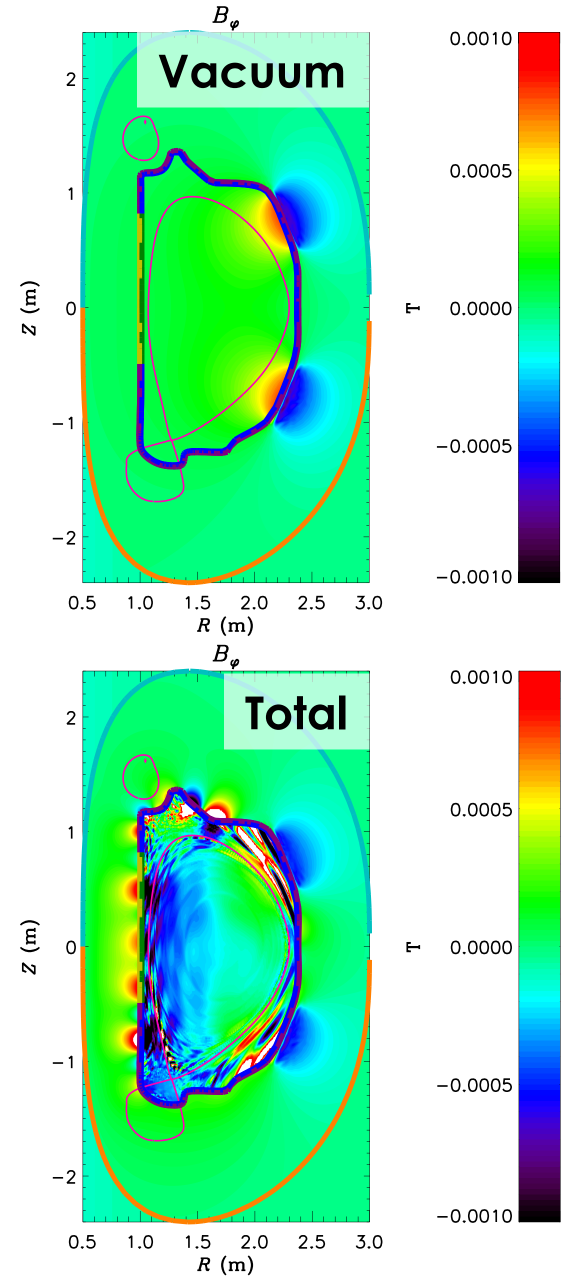
3D Response

M3D-C1 Can Solve Time-Independent Linear Plasma Response To Applied 3D Fields

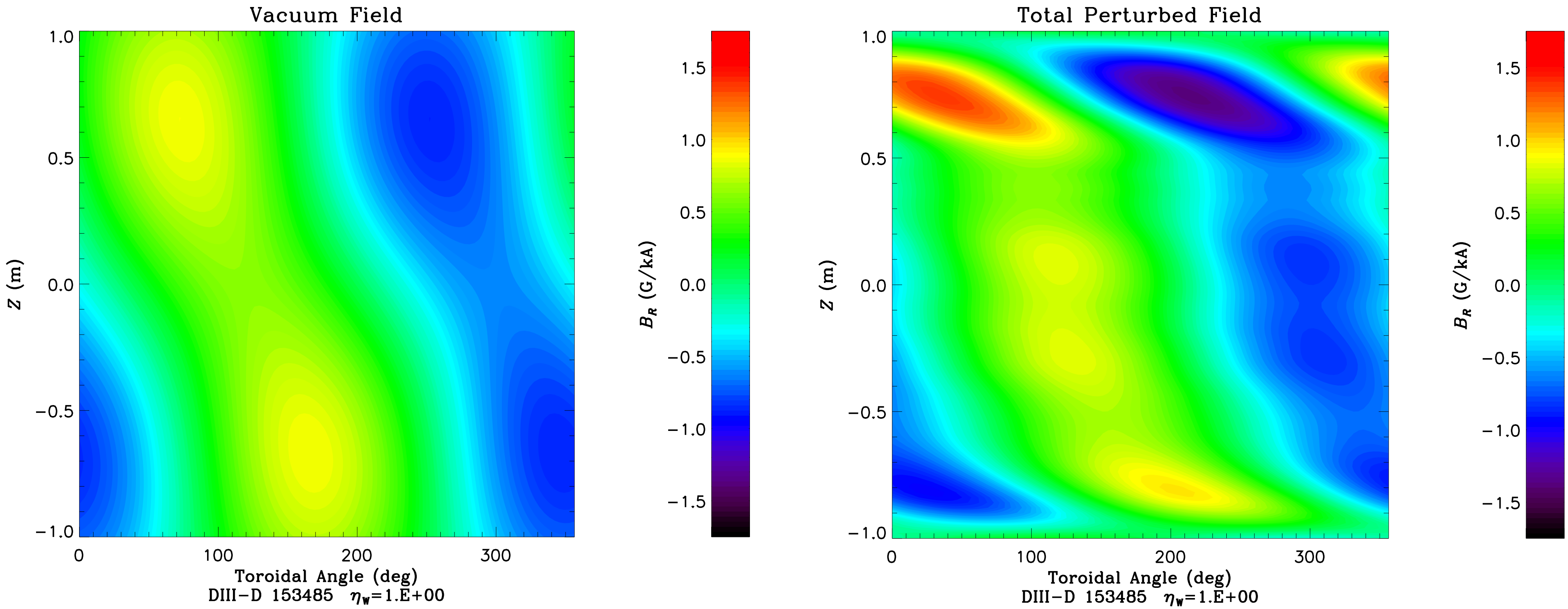
- **M3D-C1 directly solves inhomogeneous linear system to obtain time-independent response**
  - Linear system is poorly conditioned; solved by LU factorization

- **With resistive wall, time-independent solution includes plasma response and eddy currents in the wall**



M3D-C1 Calculations With Resistive Wall Show Fields Due to Plasma Response Near or Beyond Wall

B_R at R = 0.98 m



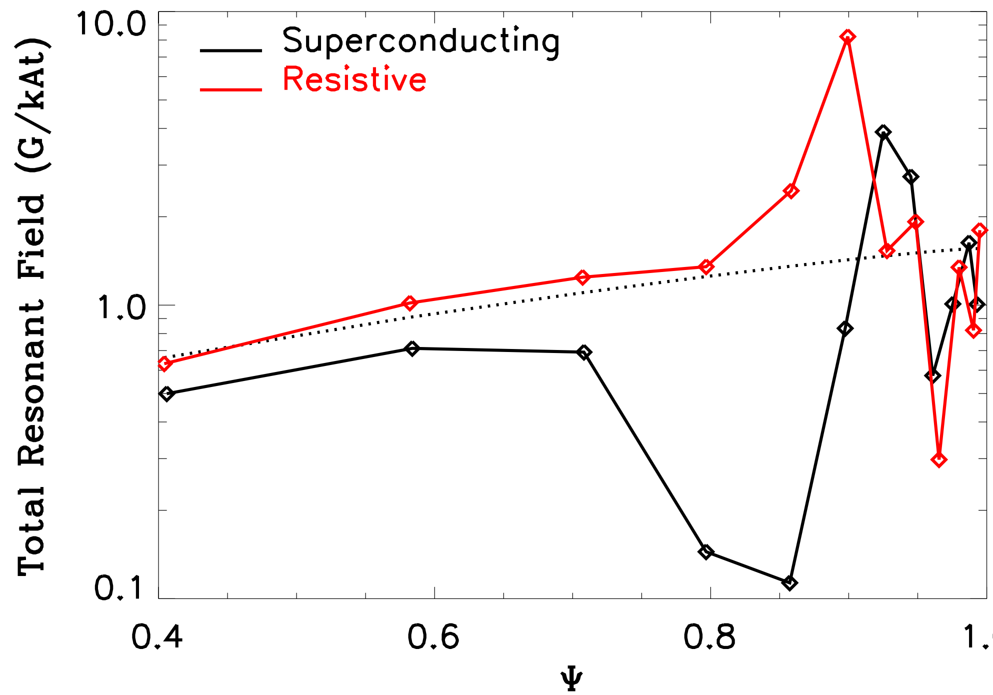
- **The extent to which magnetics data reveals internal structures has not yet been explored with M3D-C1**

Internal Plasma Response is Changed Quantitatively By Resistive Wall

- **Screening is generally found to be stronger in the case with the superconducting wall**
  - External kinks and tearing modes are stabilized by wall

- **Amplification at pedestal top (near $\omega_e = 0$) persists**

- **Presumably, finite-frequency response decreases with lower η_W**
  - Stable external kinks are moved farther from marginal stability
  - This has not yet been quantified with M3D-C1



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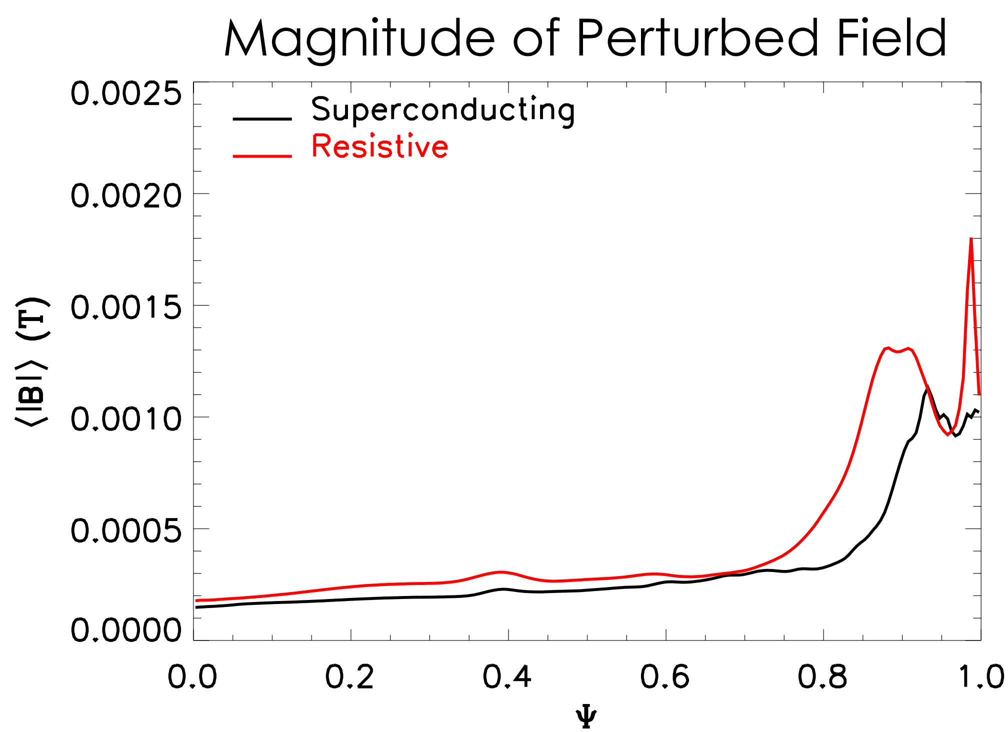
Resistive Wall Increases Internal Response

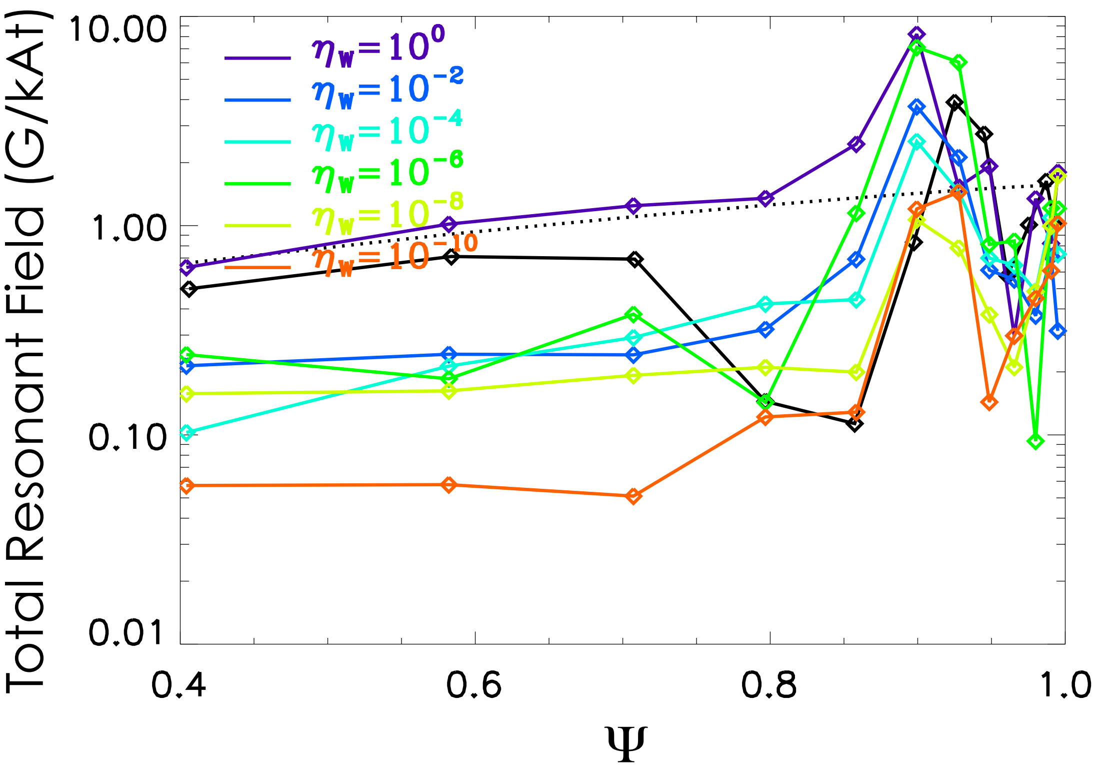
- **External kinks and tearing modes are stabilized by superconducting wall**
- **Effect on torques, fast ion transport have not been quantified**
- **Resistive vs. Superconducting results should converge in high-frequency limit**



Unexpected Behavior: Time-Independent Response Depends on Wall Resistivity

- **The time-independent response apparently depends on η_W**
  - Screening generally improves as η_W decreases

- **Why is this happening?**
  - Can't be eddy currents (zero frequency)
  - Could be plasma currents flowing through wall?
  - Bug?



Summary

- A resistive wall model has been implemented in M3D-C1, in which the wall and surrounding vacuum region are included in the computational domain
- Preliminary tests successfully obtain VDEs, RWMs, and time-independent 3D plasma response with RW
- VDE calculations with large η_W show both Hiro and Halo currents
- In linear 3D response, screening is changed quantitatively, but edge screening and amplification at pedestal top remains

Future Work

- **VDE cases will be run at realistic values of η_W to try to make quantitative comparison with experiments**
  - How do wall forces scale with η_W?
  - Will Hiro currents persist at low η_W?
- **RWM calculations will be done for experimentally relevant discharges**
- **3D response calculations can now be compared to magnetic probe data**
  - To what extent can MP data be used to probe internal response?
  - Lots of data from new DIII-D MPs for validation