VDEs and Resistive Wall Instabilities with M3D-C1

by
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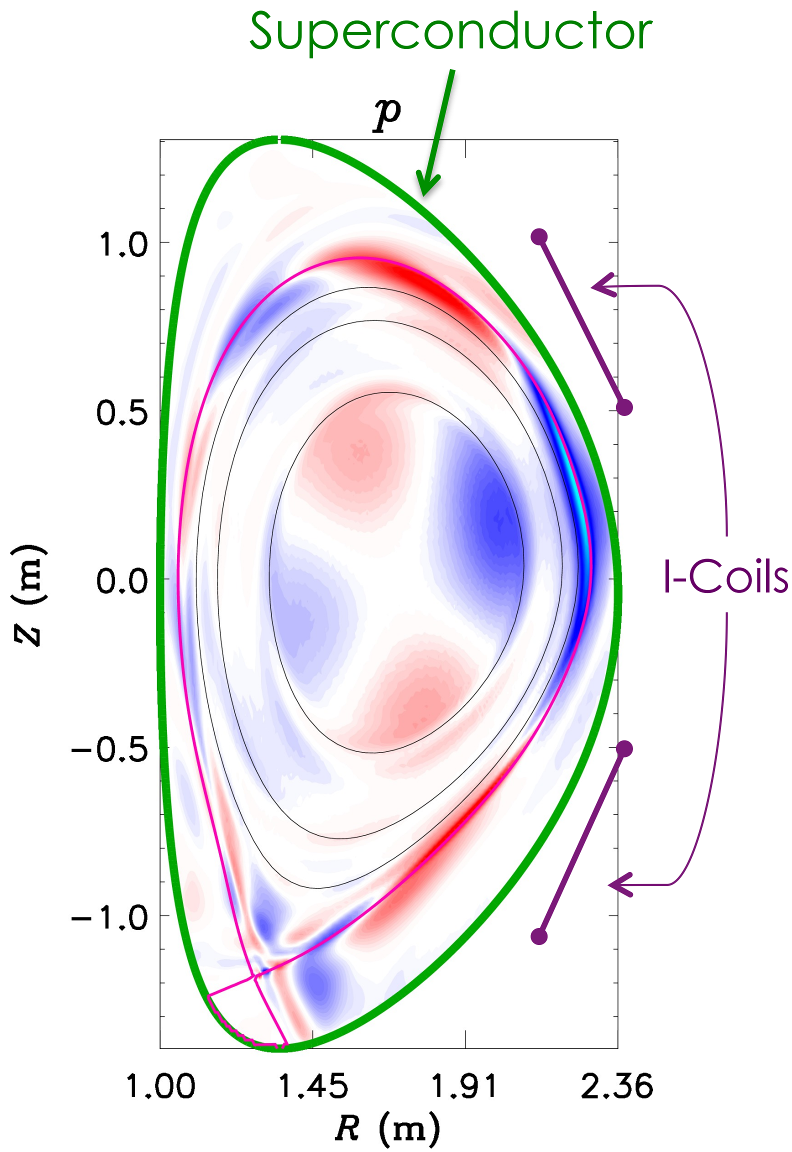
Presented at the
Theory and Simulation of Disruptions Workshop

Princeton, NJ
July 10, 2014

Previous M3D-C1 Calculations Required Conducting Boundary Within PF Coils

- **Affects stability & plasma response**
  - Especially $n = 0$, $n = 1$
- **Shields magnetic probes from plasma response**
  - Plasma response outside of conductor is zero
- **Implementing resistive wall boundary conditions was challenging**
  - All boundary nodes become coupled; hurts parallel scalability
  - Extant RW codes are spectral

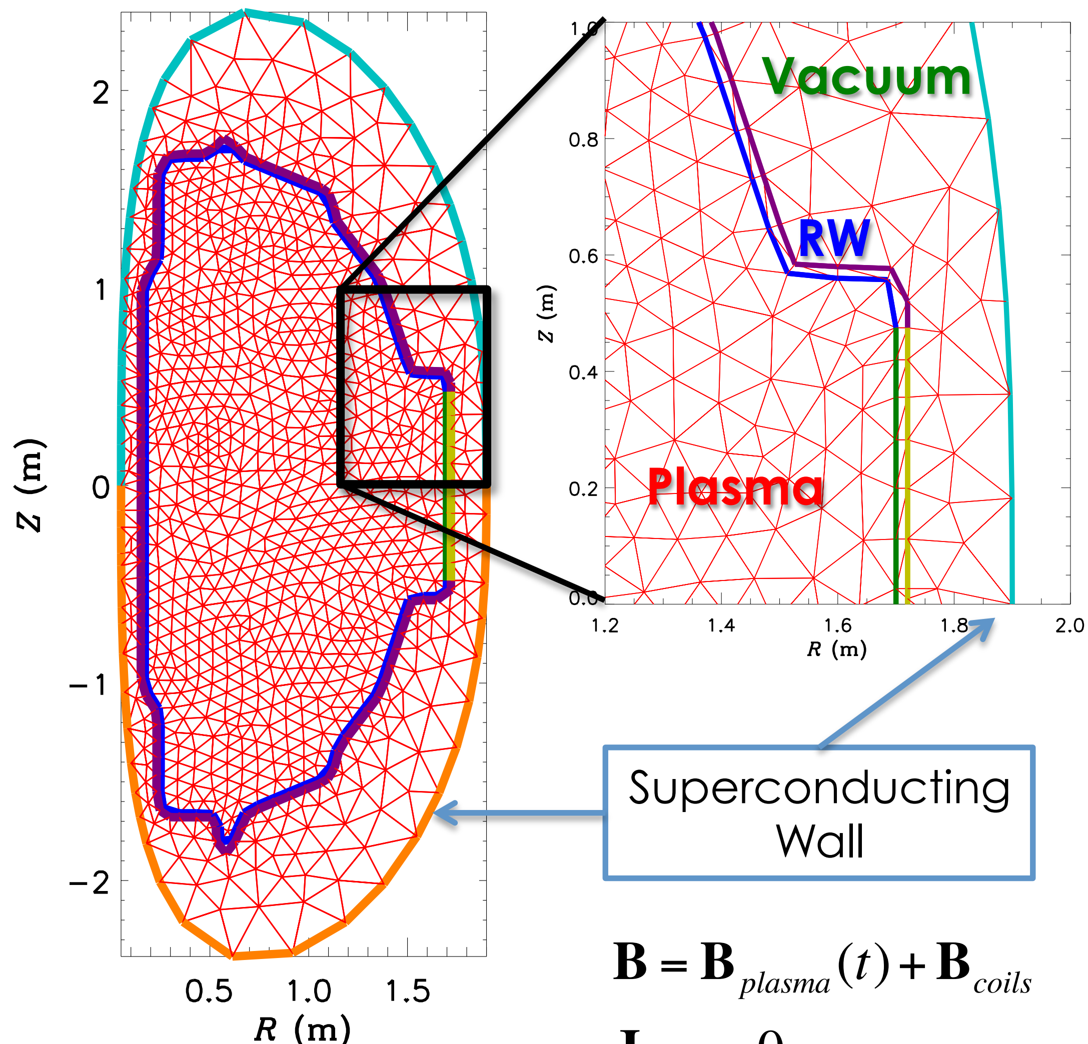


New Resistive Wall Capability In M3D-C1

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

- **Boundary conditions:**
  - $\mathbf{v}$, 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



$$\mathbf{B} = \mathbf{B}_{plasma}(t) + \mathbf{B}_{coils}$$

$$\mathbf{J}_{coils} = 0$$

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Advantages and Disadvantages of Including Resistive Wall In Domain

- **Advantages:**
  - Computation is more scalable than using RW BCs for implicit step
    - RW BCs couple all finite elements touching the boundary
  - Can add time/space dependent physical attributes of wall
    - Resistivity, temperature
  - Can allow current to flow into and out of wall
- **Disadvantages:**
  - Bigger matrices
    - But non-MHD regions do not make matrices more poorly conditioned
  - Still need a conducting boundary somewhere
    - This could be a problem in STs like NSTX-U

Two-Fluid Model is Implemented in "Plasma" Region

$$\frac{\partial n}{\partial t} + \nabla\cdot\left(n_i \mathbf{v}\right) = 0$$

$$n_i m_i \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = \mathbf{J}\times\mathbf{B} - \nabla p - \nabla\cdot\Pi_i$$

$$\frac{\partial p}{\partial t} + \mathbf{v}\cdot\nabla p + \Gamma p \nabla\cdot\mathbf{v} = -\frac{1}{n_e e}\mathbf{J}\cdot\left(\Gamma p_e \frac{\nabla n_e}{n_e} - \nabla p_e\right) - \left(\Gamma - 1\right)\nabla\cdot\mathbf{q}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\mathbf{E}$$

$$\mathbf{E} = -\mathbf{v}\times\mathbf{B} + \eta\mathbf{J} + \frac{1}{n_e e}\left(\mathbf{J}\times\mathbf{B} - \nabla p_e\right)$$

$$\Pi_i = -\mu\left[\nabla\mathbf{v} + \left(\nabla\mathbf{v}\right)^T\right] + \Pi_i^{gv} + \Pi_i^{\parallel}$$

$$\mathbf{q} = -\kappa\nabla T_i - \kappa_{\parallel}\mathbf{bb}\cdot\nabla T_e$$

$$\mathbf{J} = \nabla\times\mathbf{B}$$

$$\Gamma = 5/3$$

$$n_e = Z_i n_i$$

- **Ion viscosity model optionally includes Braginskii gyroviscosity, parallel viscosity (poloidal flow damping)**

- **Open field line region of "plasma" region is treated as low-temperature, low-density plasma**

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- **Ion viscosity model optionally includes Braginskii gyroviscosity, parallel viscosity (poloidal flow damping)**
- **Open field line region of "plasma" region is treated as low-temperature, low-density plasma**
- **VDE calculations here use a single-fluid model**

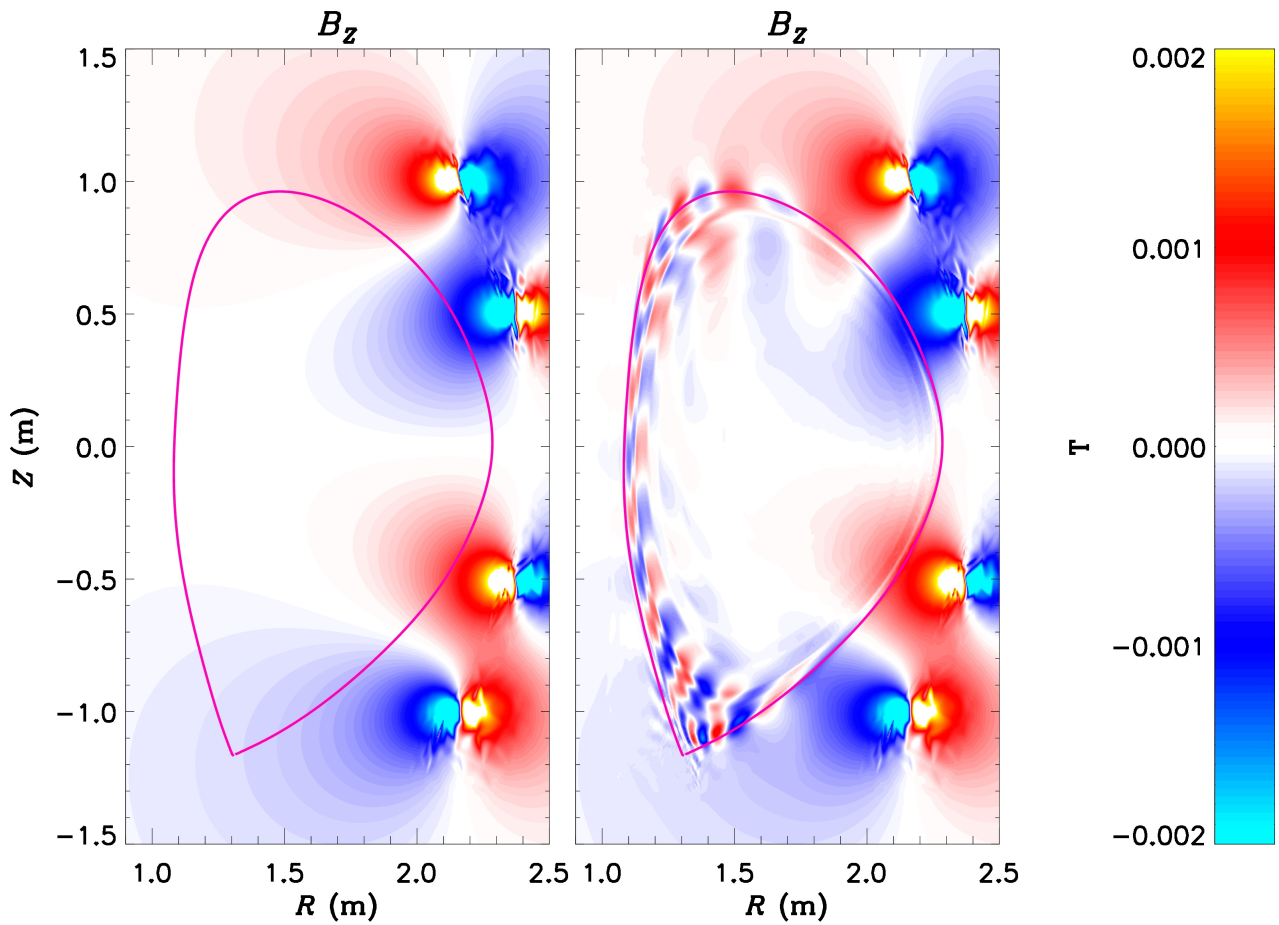
“Free Boundary” 3D Response

Resistive Wall Capability Allows "Free-Boundary" 3D Response Calculations

- **(Technically fixed-boundary, but now conducting wall is very far from plasma and outside PF coils)**

- **In zero-frequency response, there are no eddy currents**
  - Resistive wall can still play a role: currents can flow through wall

- **Free-boundary response allows direct comparison with new MP data**



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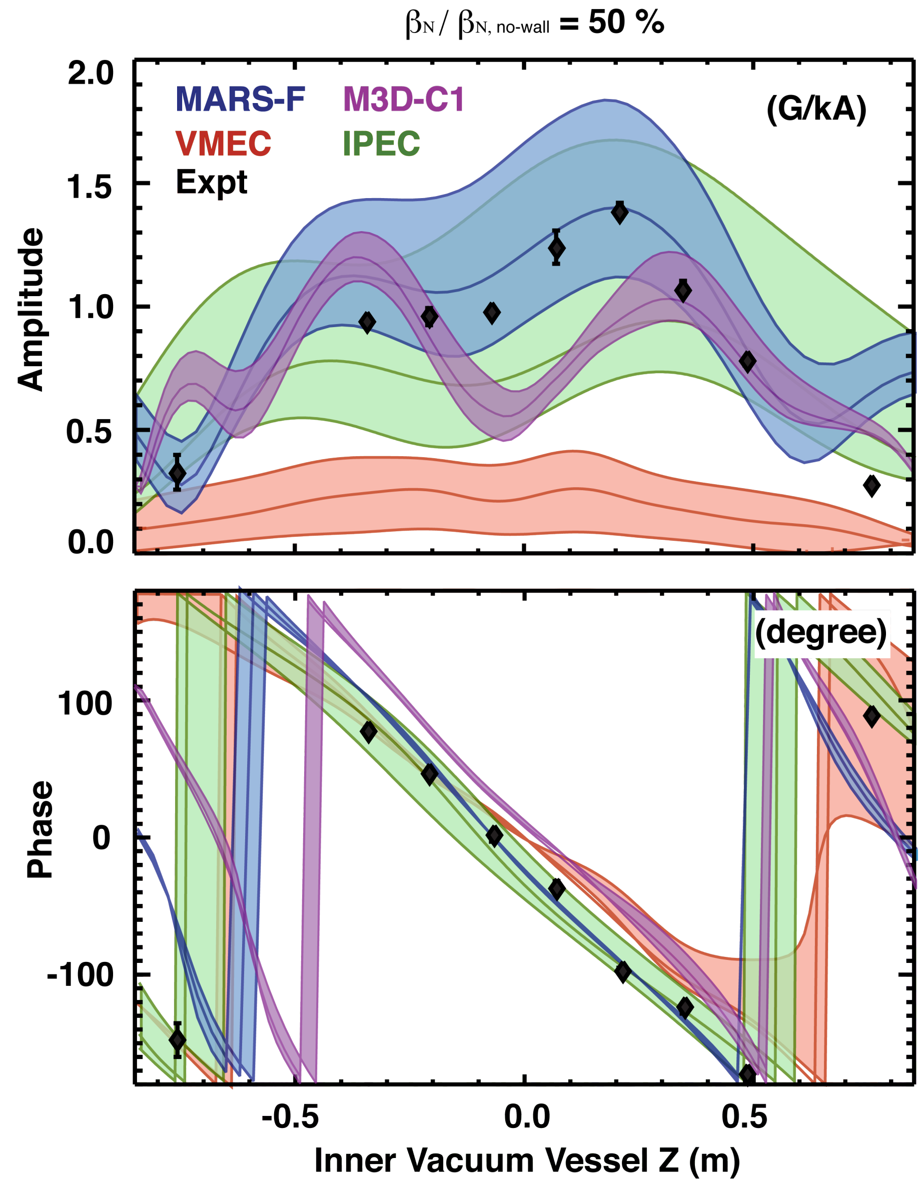
Preliminary Free-Boundary Calculations Show Encouraging Agreement With Experimental Data

- **Free-Boundary 3D response calculated with several codes**
  - IPEC, MARS-F: linear, ideal
  - M3D-C1: linear, two-fluid, resistive
  - VMEC: nonlinear, ideal

- **Calculated values are in decent agreement with measurements**

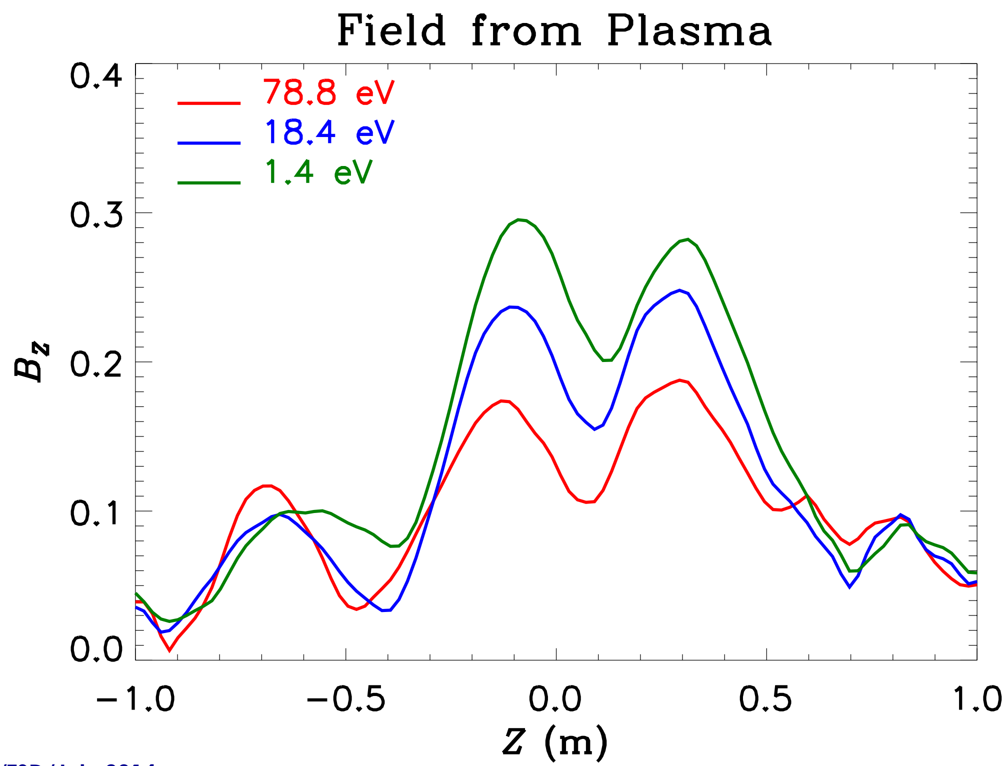
- **Different codes show different sensitivities to bootstrap current**
  - M3D-C1 seems least sensitive, probably because there is no "q_{edge}"



Courtesy J. King

Inclusion of Open Field Line Region Introduces Additional "Free Parameters" in M3D-C1 Model

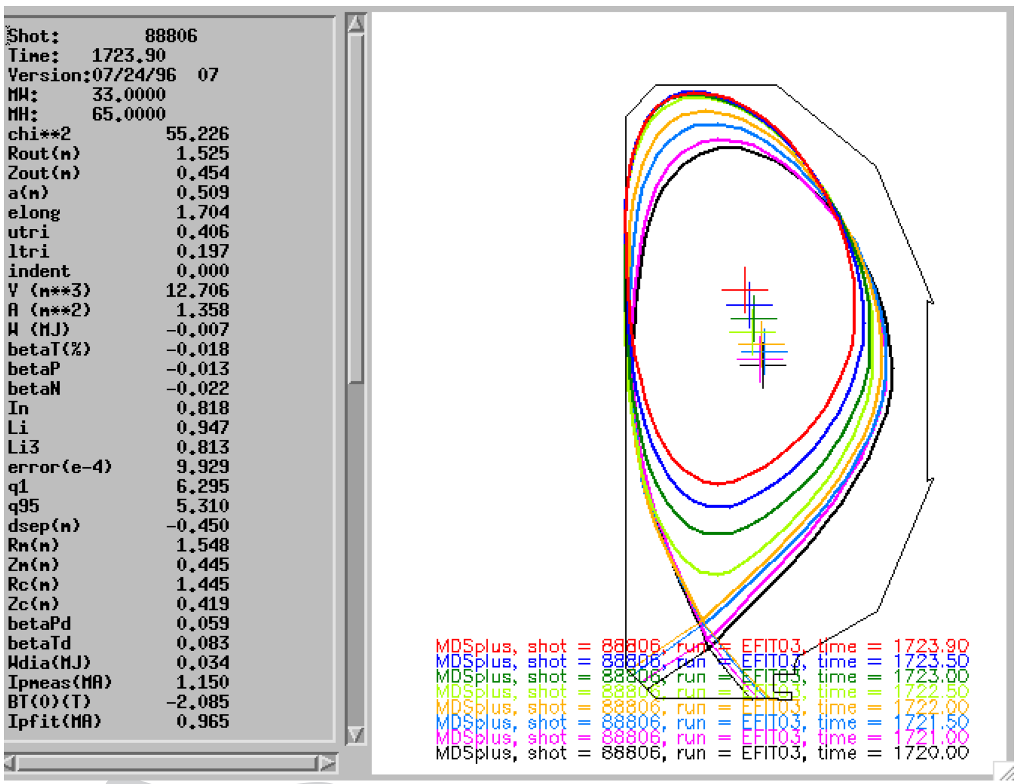
- **Because M3D-C1 models open field-line region as a plasma, the parameters of this region can affect the response**
- **Magnetic probe response is especially sensitive to the resistivity of this region**
- **Density is much less important**
- **Validation is ongoing, and is helping to refine the models**

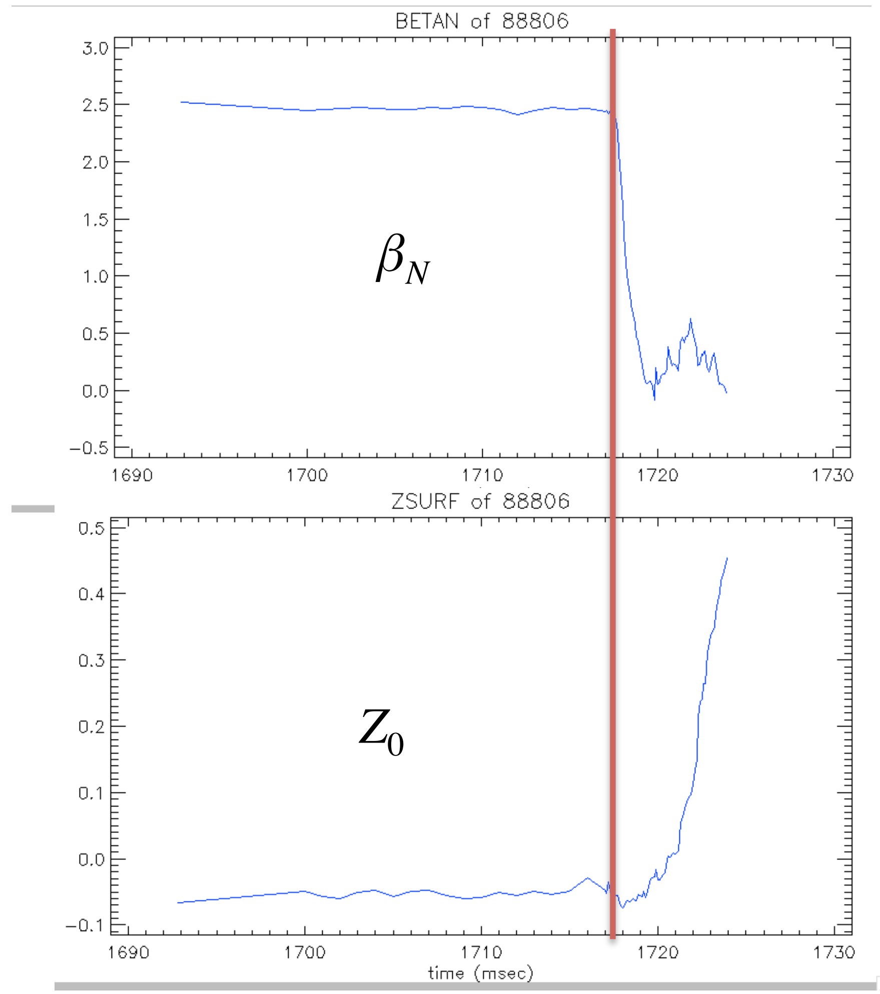


Vertical Displacement Events

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
  - Timescale ~ 3 ms





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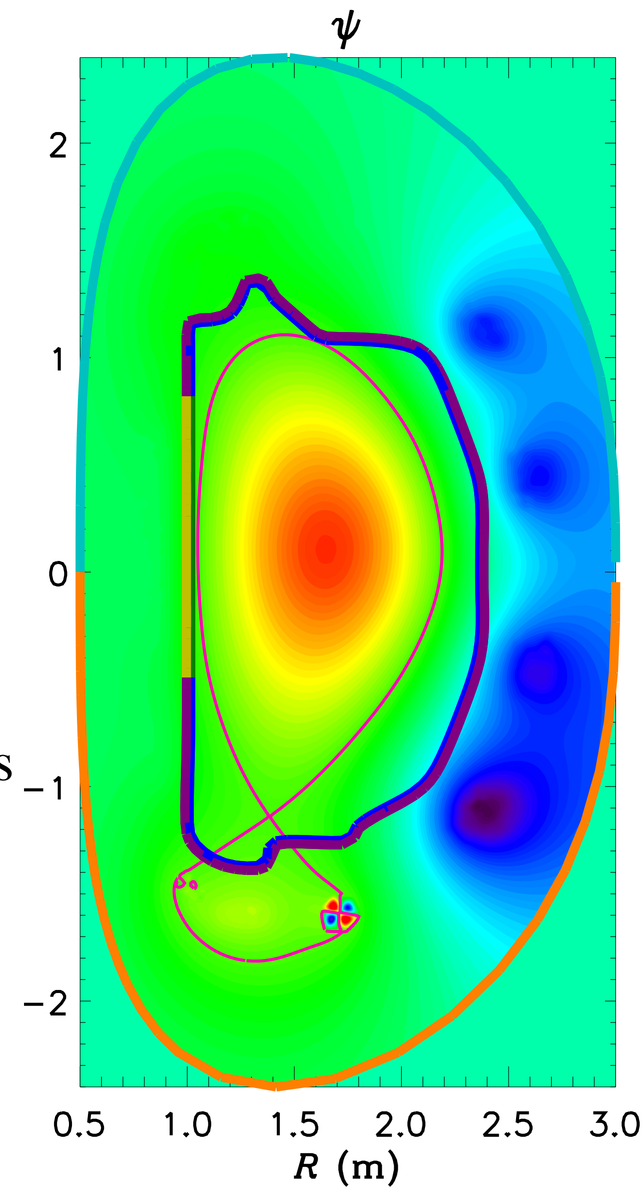
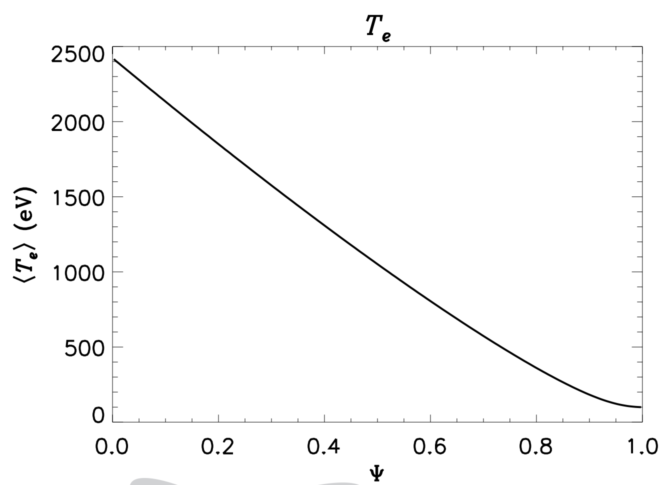
Nonlinear Calculation Initialized From EFIT Reconstruction

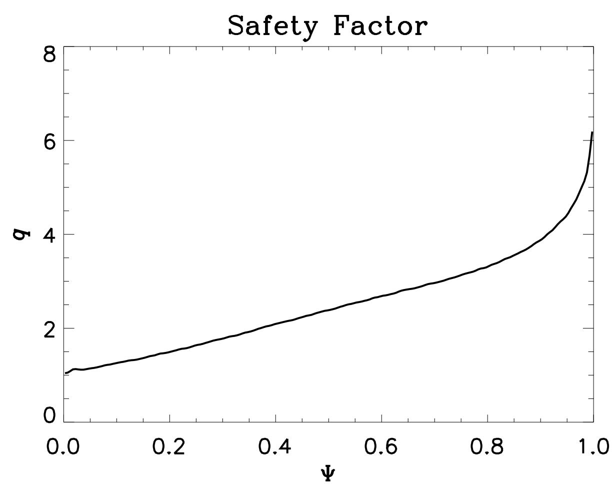
- **M3D-C1 was initialized using the reconstructed equilibrium just before TQ ($t = 1720$ ms)**
  - Equilibrium is re-solved on M3D-C1 grid
- **Nonlinear $n = 0$ calculation uses fairly realistic plasma parameters**
  - Spitzer resistivity: $S_0 \approx 6.8\times10^{-7}$
  - Anisotropic thermal conductivity: $\chi_{\parallel}/\chi_{\perp} = 10^6$
  - Anomalous perp. transport: $100 < \chi_{\perp} < 800 \text{ m}^2/\text{s}$
- **RW approximates first wall, not vacuum vessel here; using "modern" first wall, different from old experiment**

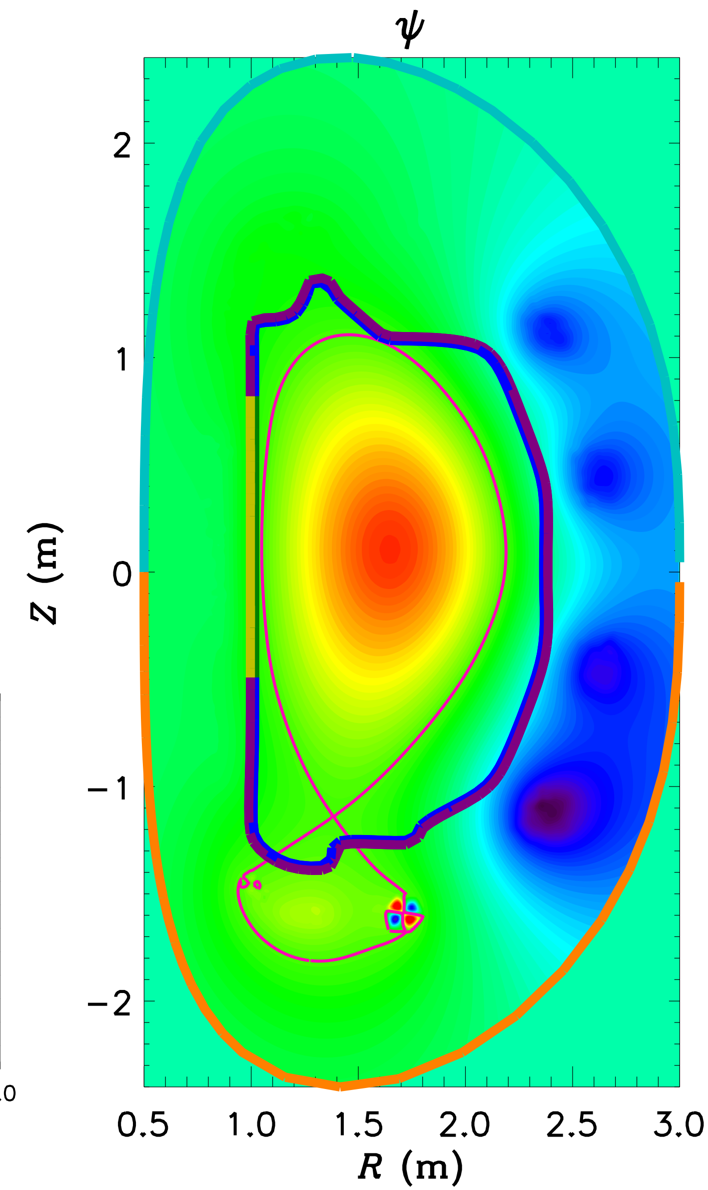


These Calculations Are A "First Try"; Not Suitable For Quantitative Validation

- **Simulations done at low resolution**
  - 5059 elements, ~320k DOFs
- $T_{SOL} \approx 100$ eV → $\eta_{SOL} \approx 1.6\times10^{-6}\ \Omega$ m
- **Single-Fluid, no sources**
- **Wall is uniform thickness (2 cm), resistivity**

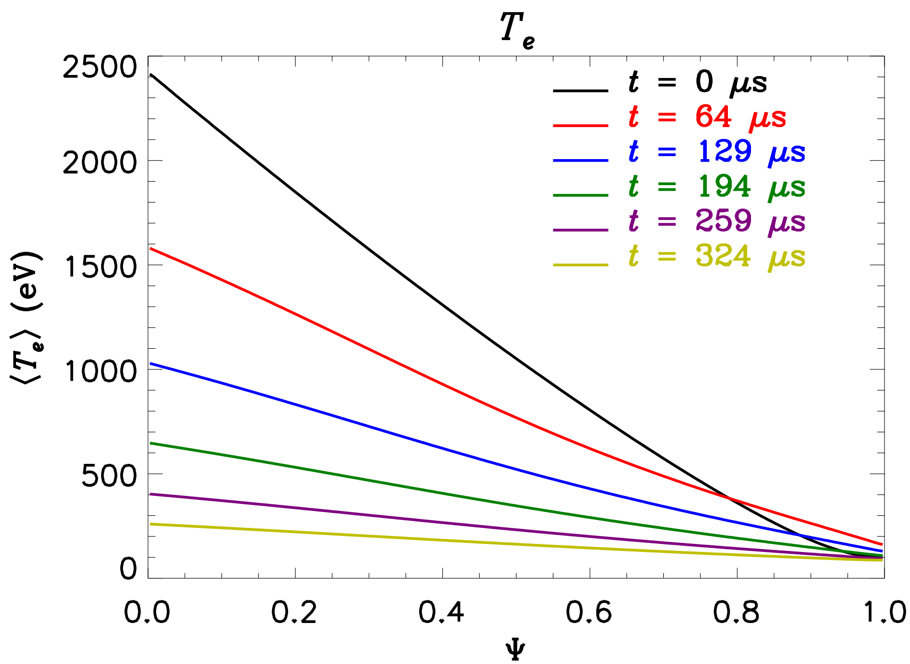






Simulations Include Thermal Quench Stage

- **A thermal collapse happens on ~$100\ \mu s$ timescale, due to large perpendicular thermal conductivity**
  - Not caused by any MHD activity or convective transport



- **At some point during the TQ, the plasma becomes vertically unstable**

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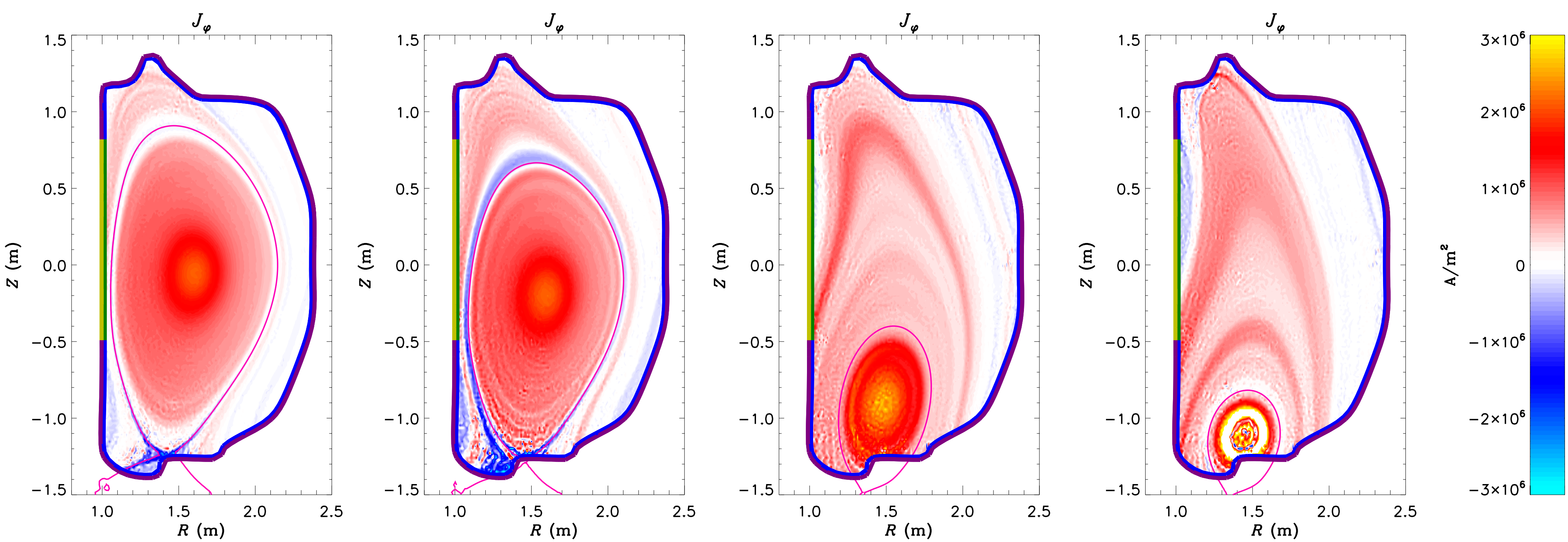
Calculation Shows Vertical Displacement Into Lower Divertor

- **Both co-I_P and counter-I_P currents are seen in the open field-line region**

- **Plasma always moves to lower divertor, unlike in experiment**
  - Maybe due to different wall configuration?

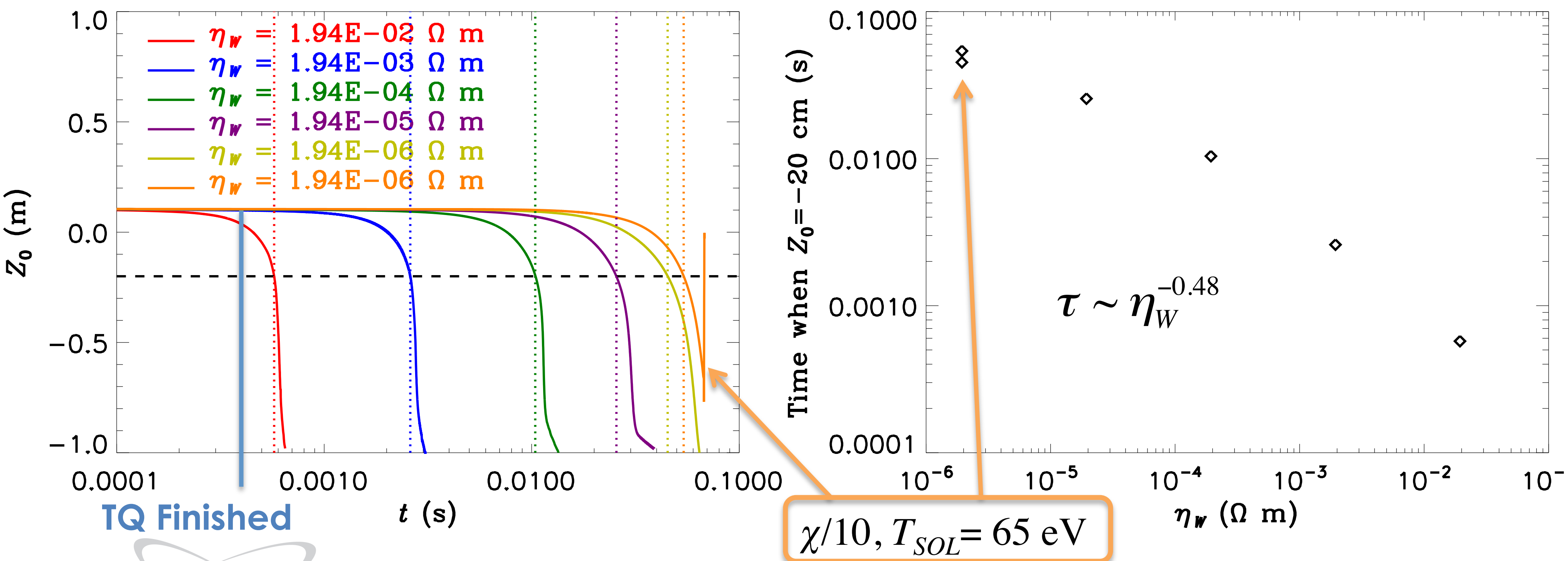


$t = 2.27$ ms $t = 2.59$ ms $t = 2.92$ ms $t = 3.24$ ms

Timescale of VDE Scales Inversely with $(\eta_W)^{1/2}$

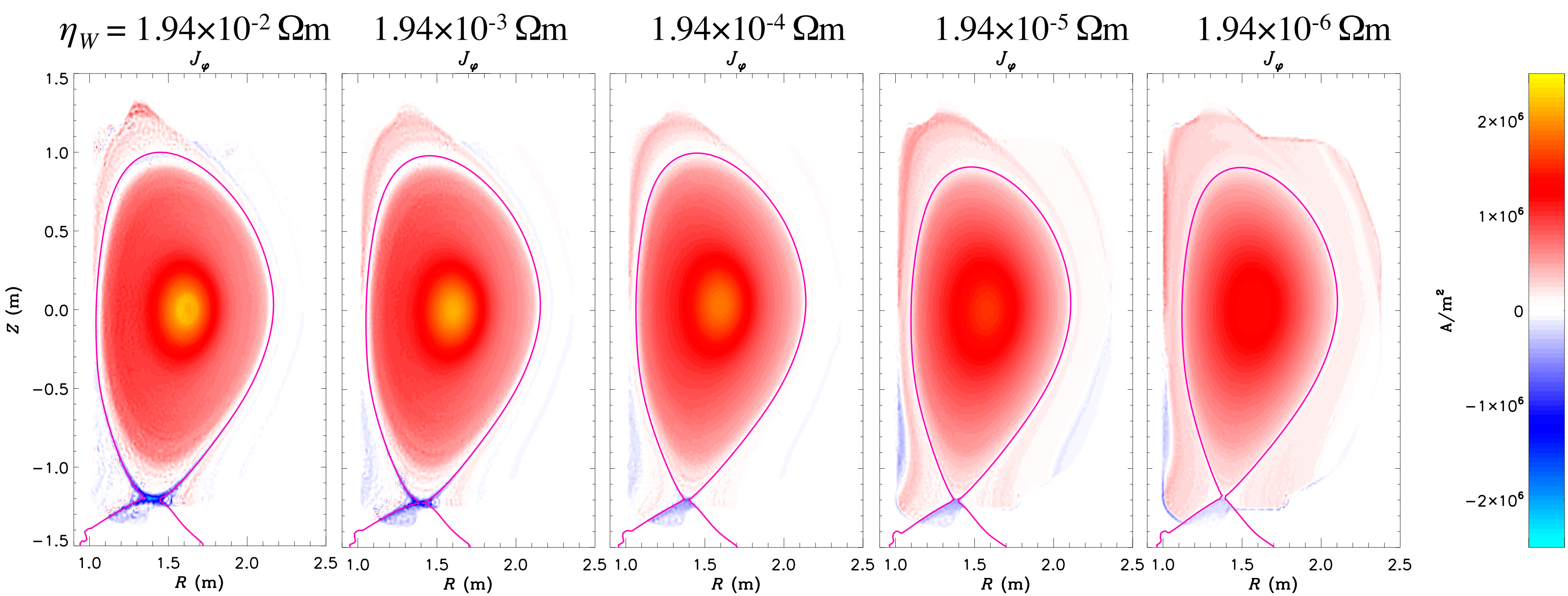
- **Given wall thickness** $\delta = 2$ cm **and a poloidal scale length** $d =$ 50 cm, **resistive wall diffusion times range from** ~6.5 ms **to** ~0.65 μs
- **VDE timescale is longer than resistive wall time**
  - Doesn't seem strongly affected by T_{SOL}; need more cases

$$\tau_W = \frac{\mu_0 d \delta}{\eta_W}$$



Currents in Wall and Open Field-Line Region Change with η_W

- At early stage of VDE, currents in the wall are stronger at lower η_W
- Counter-I_P currents are significantly stronger at higher η_W



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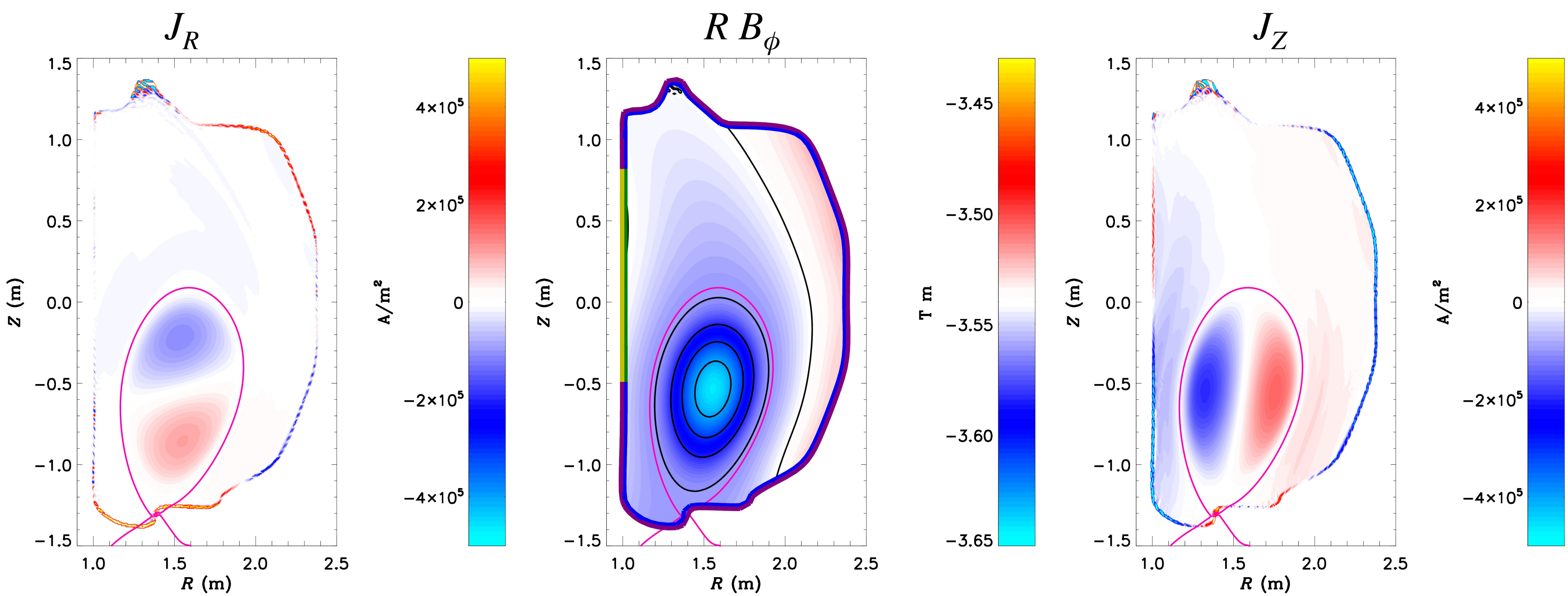
Wall Currents are Mostly Inductive

- **Poloidal currents are present in the open field-line region**
  - Gradients in $R\,B_\phi$ imply poloidal currents
  - Current flows from plasma to wall to ensure $\nabla \cdot \mathbf{J} = 0$
- **Poloidal wall currents are consistent with excluding toroidal flux**



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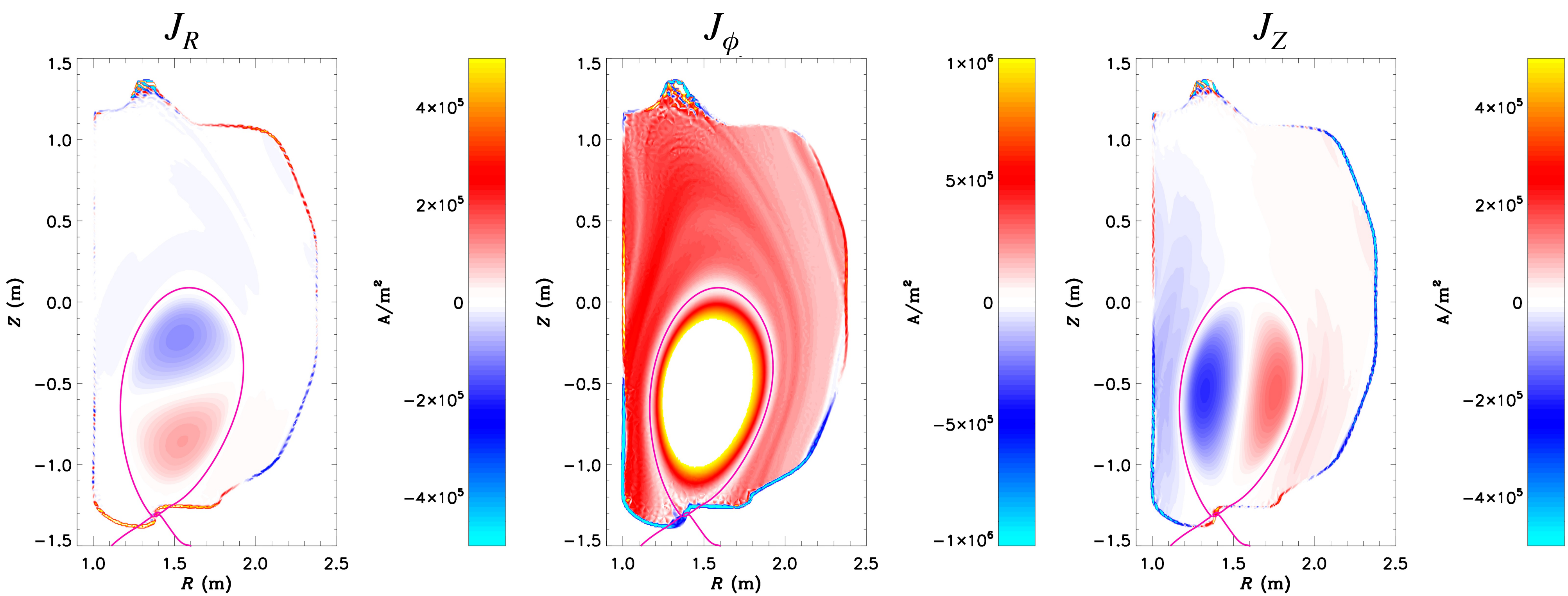
Wall Currents are Mostly Inductive

- **Toroidal currents are also present in the open field-line region**
  - Magnitude may be an artifact of high T_e in the open field-line region

- **Toroidal wall currents are consistent with excluding poloidal flux**



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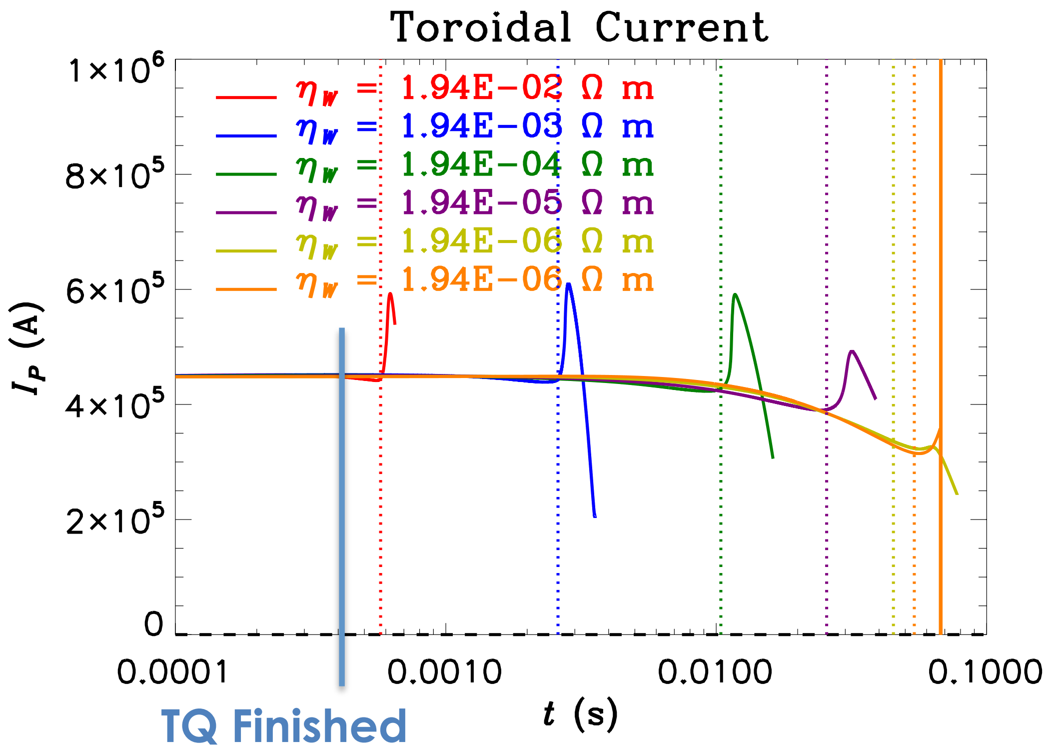
Current Spikes Observed Before Current Quench; Associated with Vertical Motion of Plasma

- **Current spike onset is correlated with vertical motion of plasma, unlike TQ**



- **"I_P" here only includes all toroidal current in the plasma region, but not in the resistive wall**

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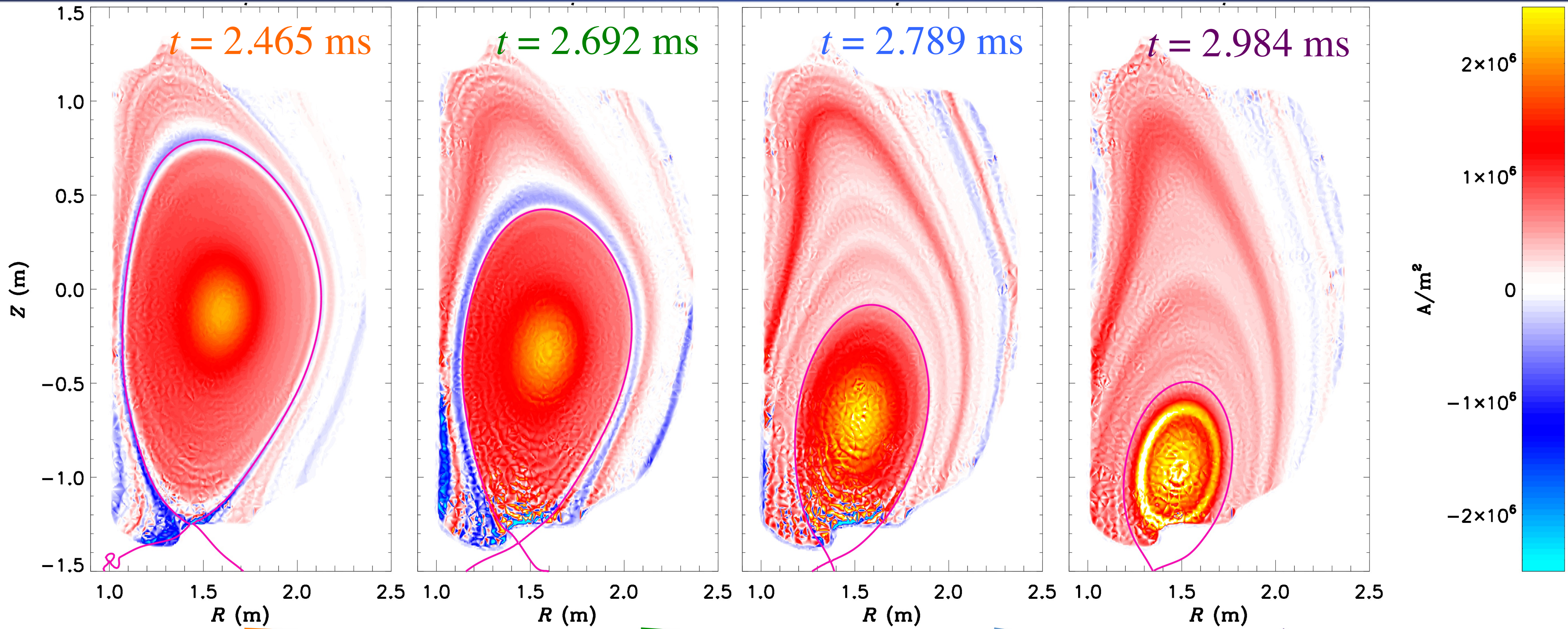
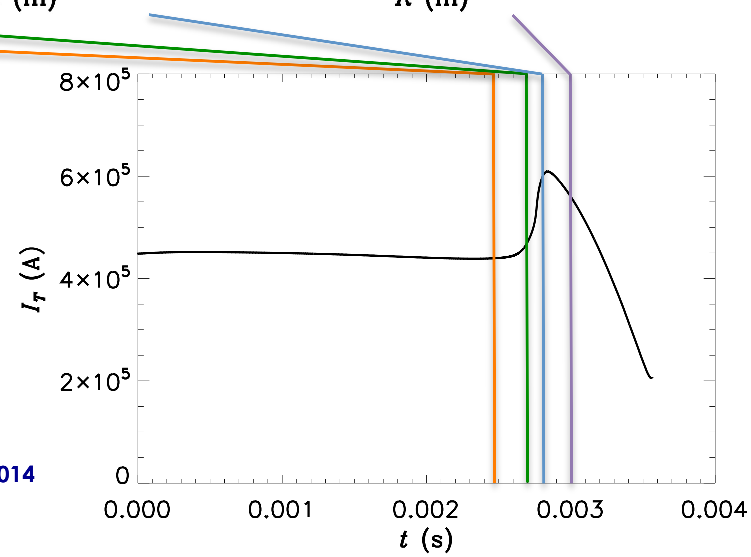
Current Spike is Associated With Loss of Counter-I_P Current In Open Field-Line Region



$\eta_W = 1.94{\times}10^{-3}\ \Omega\ \mathrm{m}$

- **Plasma undergoes rapid contraction during current spike**



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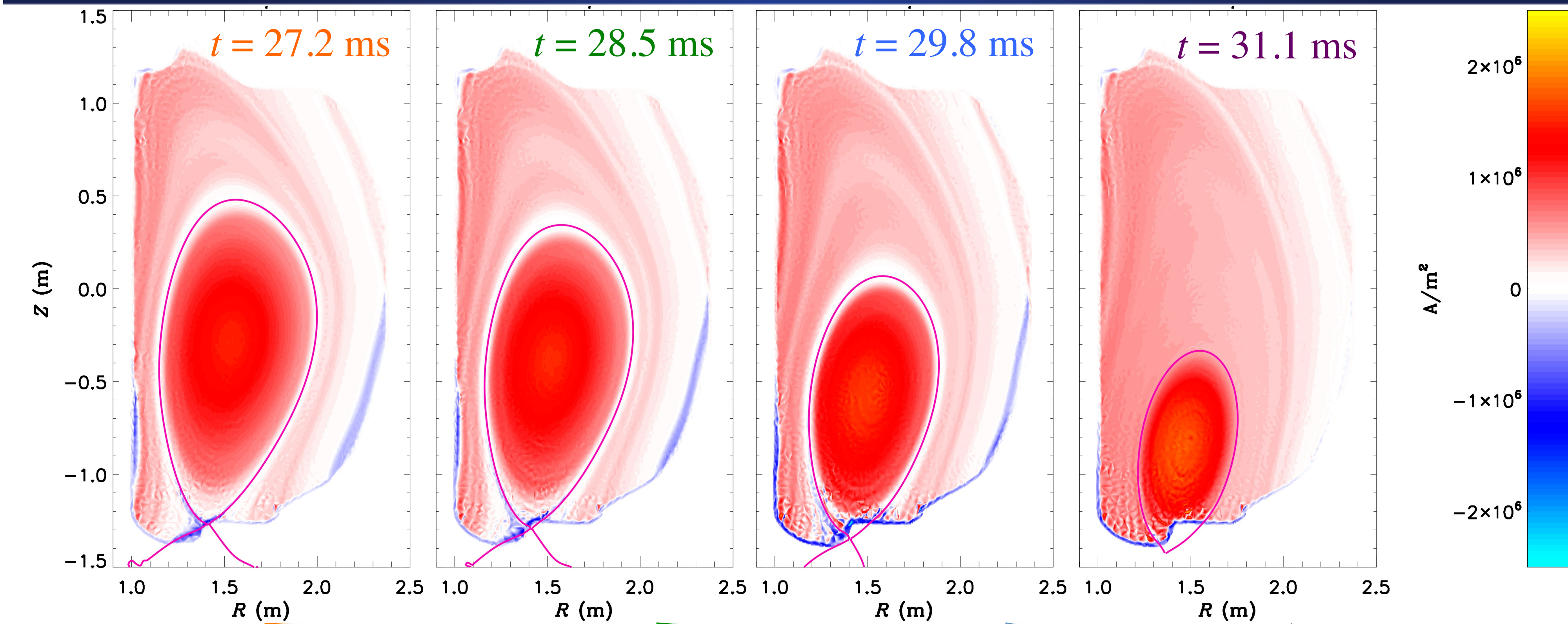
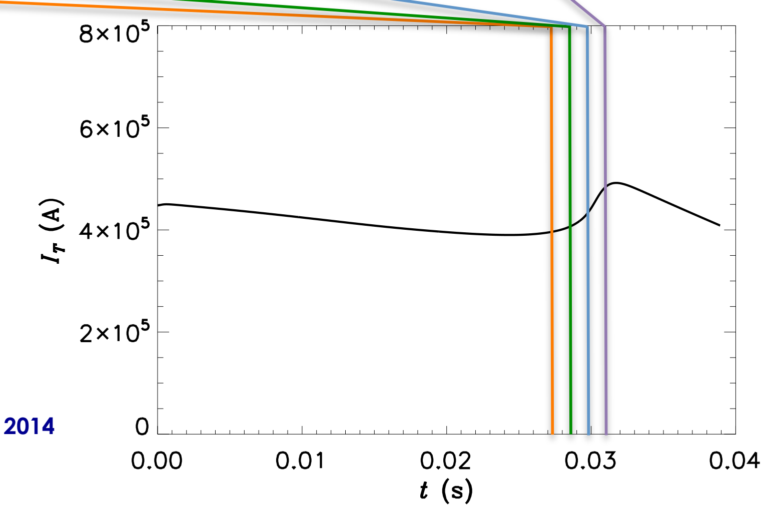


$$\eta_W = 1.94\times10^{-6}\ \Omega\ \mathrm{m}$$



- **Plasma undergoes rapid contraction during current spike**

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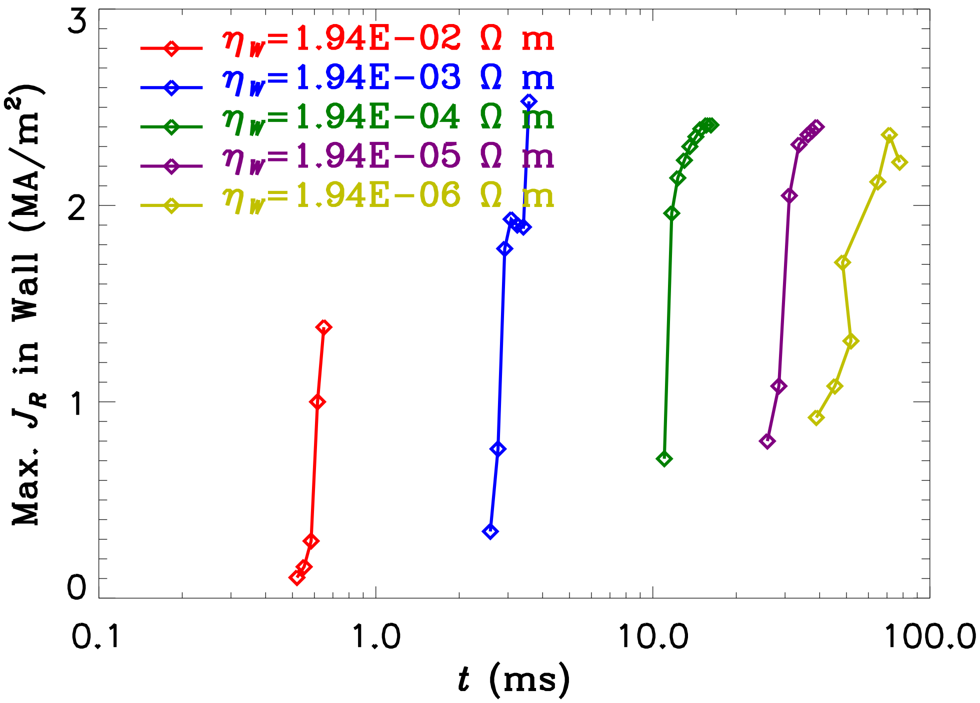
Max Poloidal Current in Wall Depends Weakly on η_W

- **Maximum J_R occurs very late in VDE, when plasma is limited by lower divertor**
- **Maximum J_R is roughly $2–2.5\ \mathrm{MA/m^2}$ in this case**
  - Corresponds to $F_Z \sim 500\ \mathrm{kN}$ over ~$50\ \mathrm{cm}$ of the lower divertor



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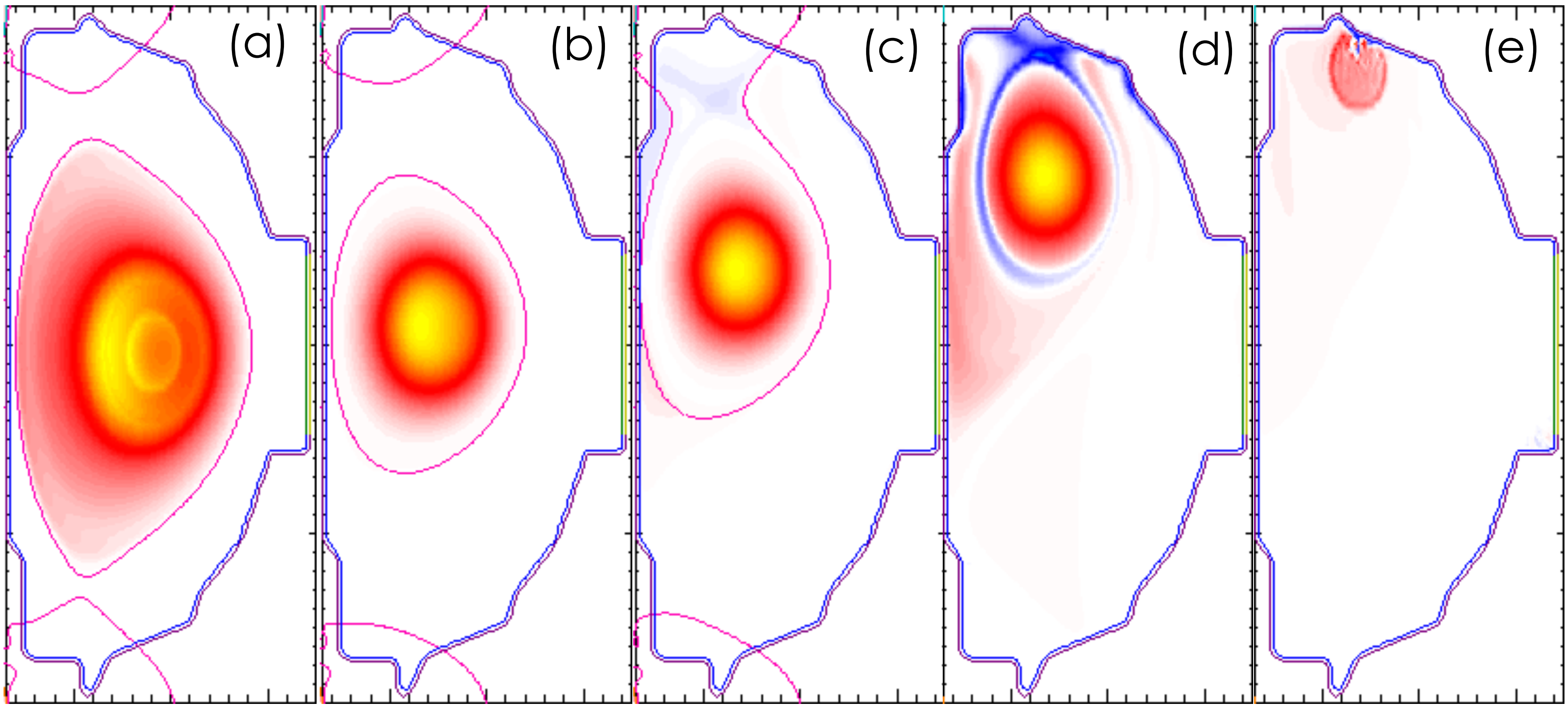
VDEs Also Simulated for NSTX; Results Similar to DIII-D Simulations

- **NSTX case also shows co-current and counter-current current density in the open field-line region**



Toroidal current density at 5 times in VDE simulation

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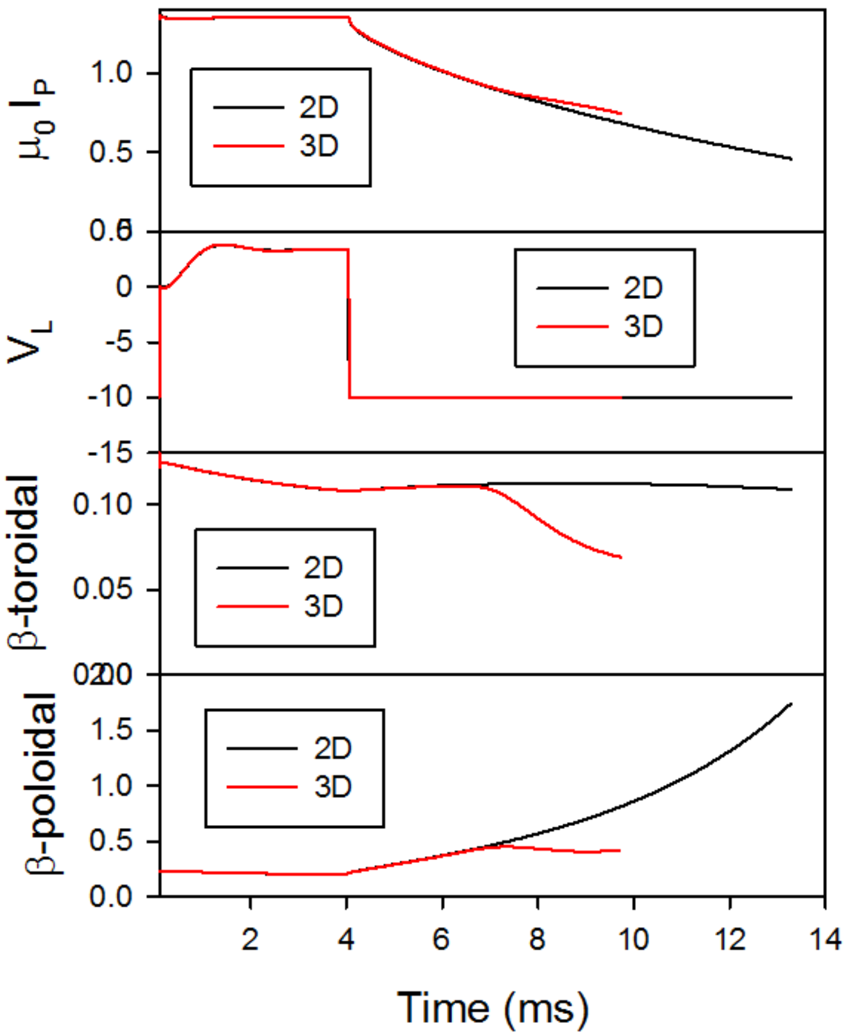
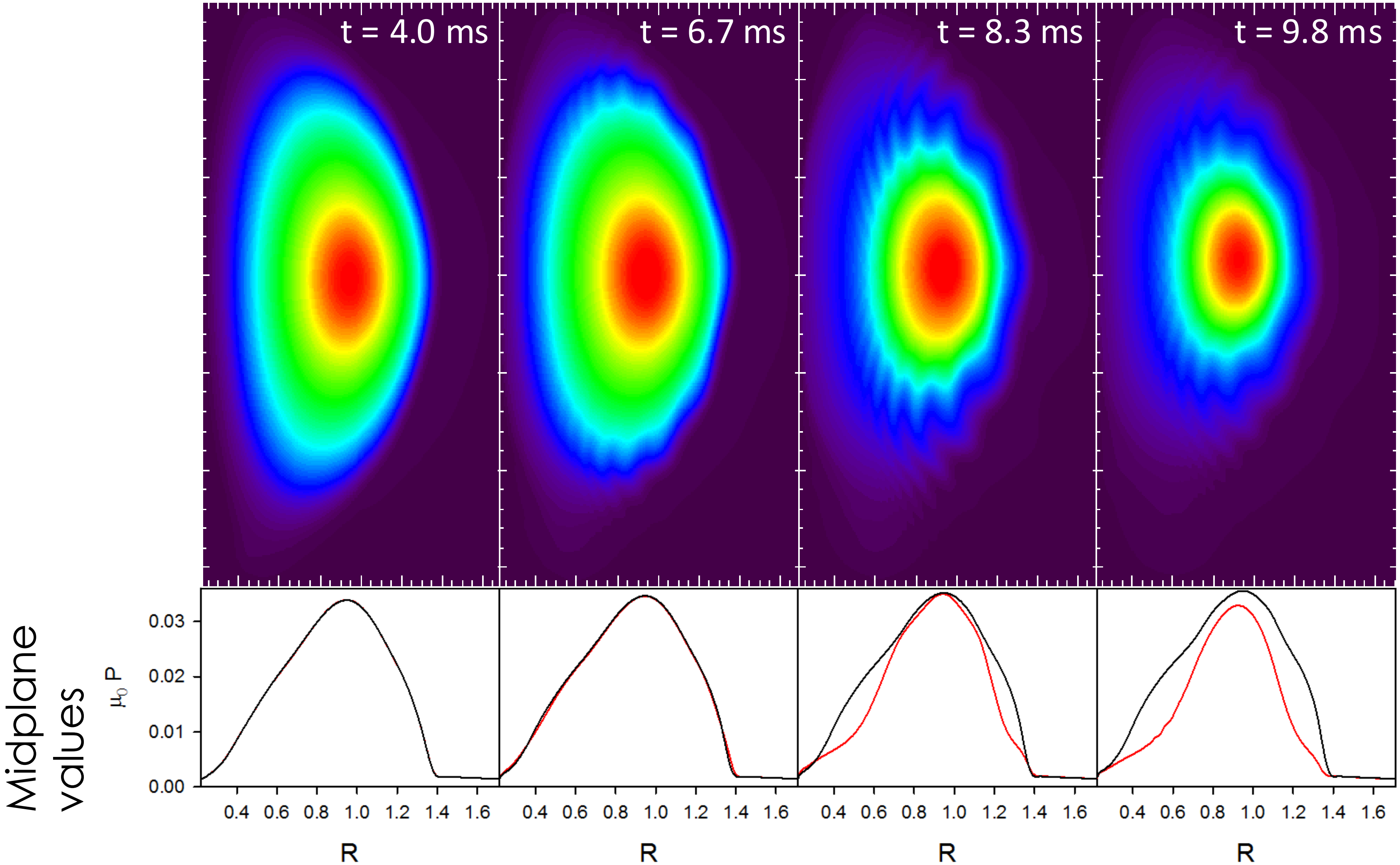
Disruptions From V_L Reversal Are Being Explored



- At the end of the discharge, the loop voltage in NSTX is rapidly reversed to quench the OH coils
- Experimentally, this often leads to a disruption
- We are trying to reproduce this with M3D-C^1 using realistic parameters
- Difference in 2D and 3D behavior is due to 3D instabilities

Edge Mode Found in Reversed-V_L Simulation



Pressure in 2D (black) and 3D (red) at 4 times

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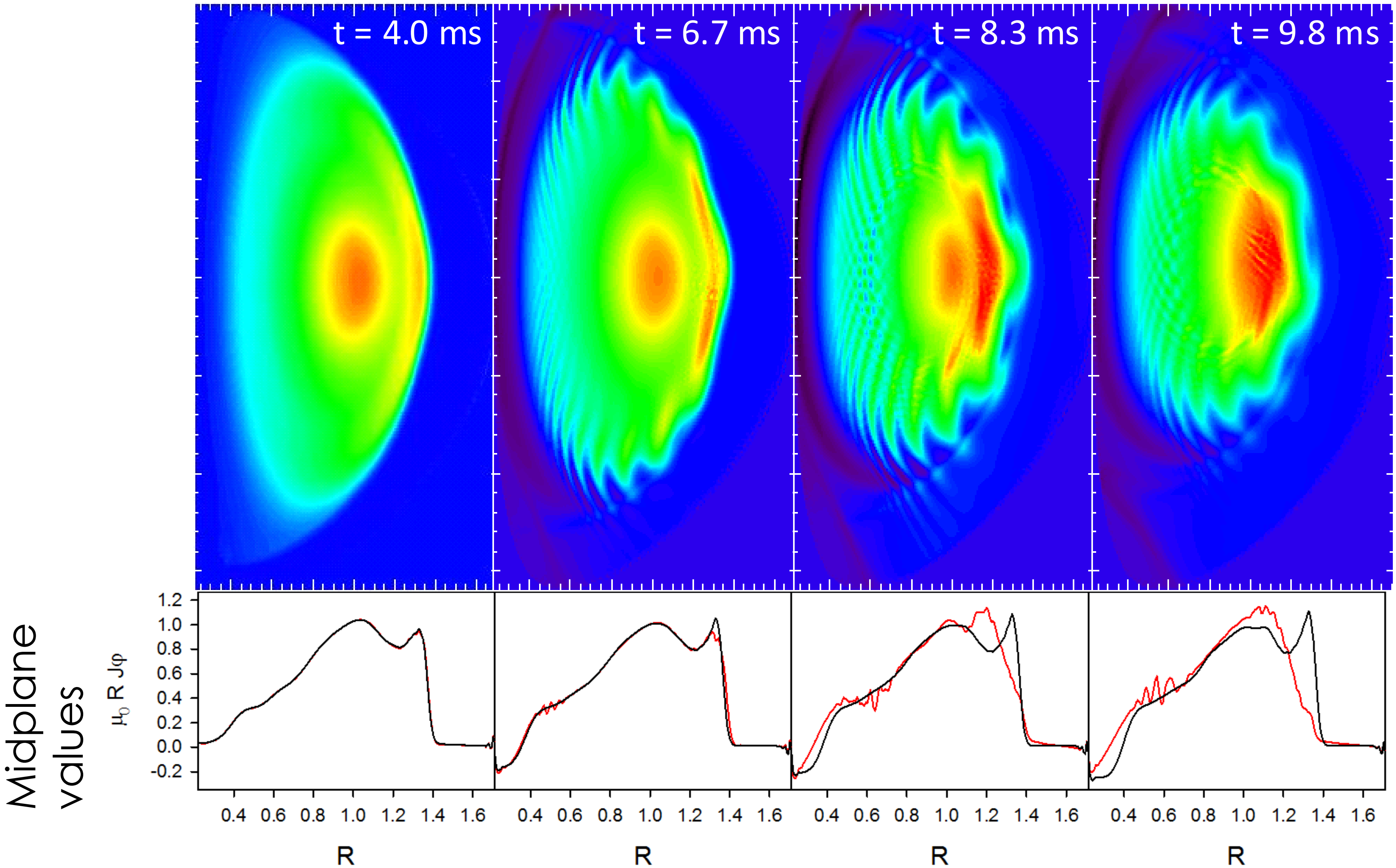


Toroidal current density in 2D (black) and 3D (red) at 4 times

Summary

- **"Free-Boundary" response using resistive wall model is being validated using new 3D magnetic probes**
  - Agreement is encouraging
  - Results sensitive to treatment of open field-line region, especially resistivity; other sensitivities are being explored

- **VDEs successfully simulated in DIII-D and NSTX-U**
  - Axisymmetric, single-fluid
  - Spitzer resistivity, realistic parameters

- **Currents are observed in the wall and open field-line region**
  - At early stages of disruption, wall currents are larger at low η_W
  - At late stages of disruption, wall currents depend weakly on η_W
  - Current spike is observed, and is associated with contraction of plasma and loss of counter-I_P current (not TQ)

Future Work Will Focus on Quantitative Validation and 3D Effects in Disruptions

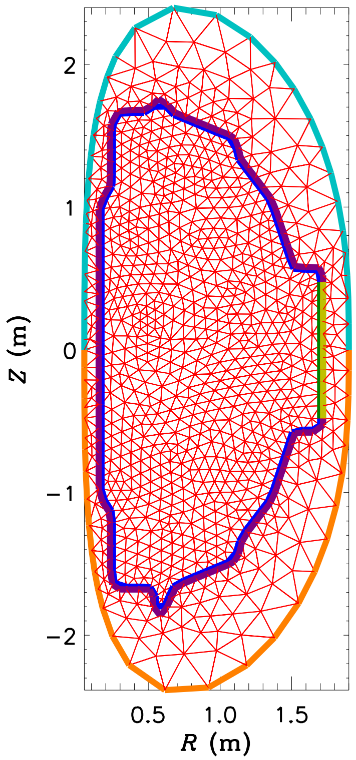
- **Need cases with lower boundary T_e**
  - Will faster current decay reverse wall current direction?
- **Non axisymmetric instabilities during disruption may lead to sideways forces, enhanced transport**
- **First step: linear stability analysis of 2D evolving equilibrium**
  - Very fast
  - Will show onset, but not saturation / dynamics of n > 0 instability
- **Next step: fully nonlinear 3D**
  - This will be possible soon, but expensive
  - Nonlinear evolution will be necessary to quantify forces, etc.

Extra Slides

VDE Calculations Also Successfully Simulated for NSTX

- **Position of outer boundary can still strongly affect stability**

VDE Stable



VDE Unstable