What's New in M3D-C1

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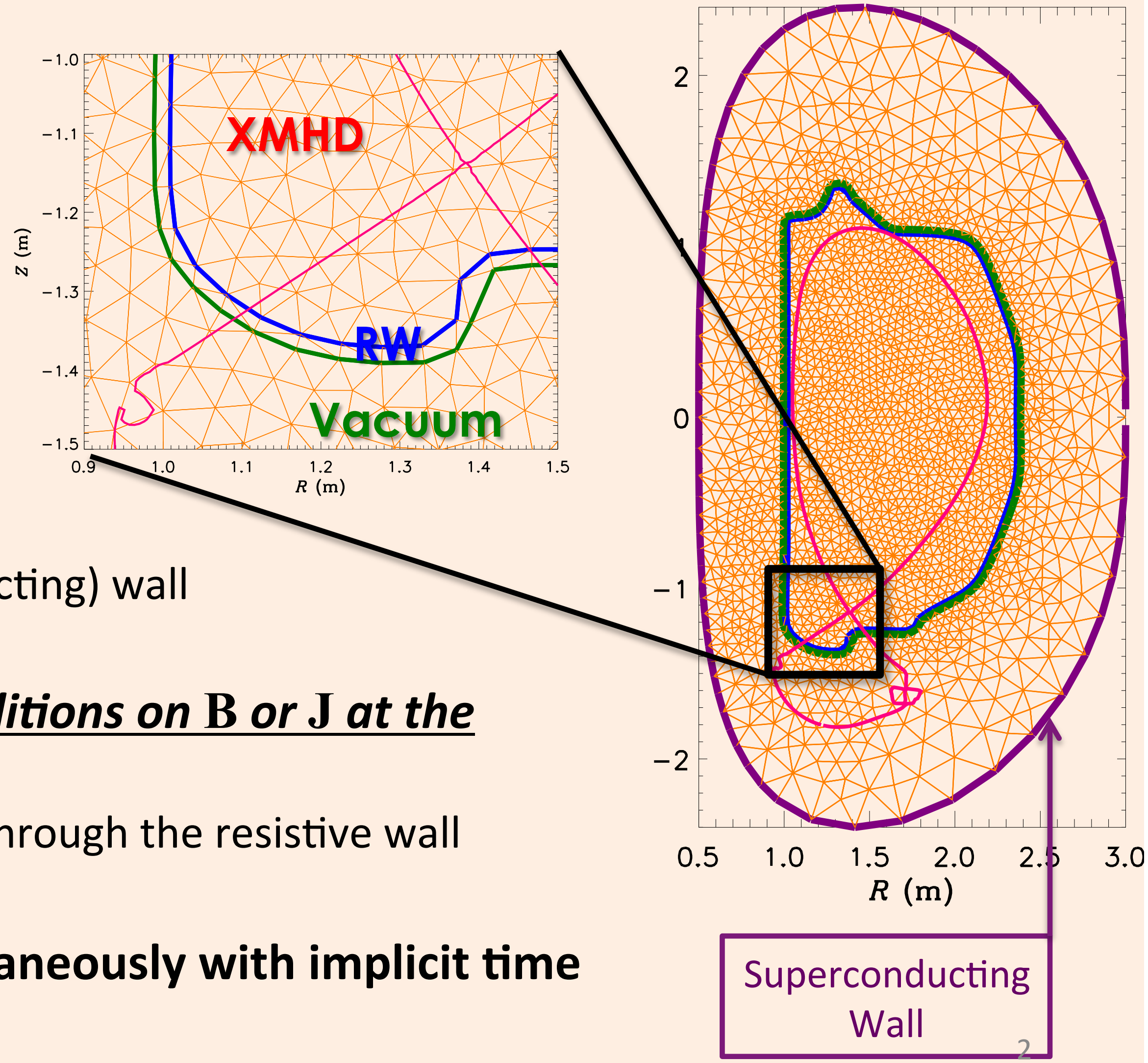
Resistive Wall Model In M3D-C1 Includes Wall Inside Simulation Domain

- **3 regions inside domain:**
  - XMHD (Extended MHD, includes open field-line region)
  - RW ($\mathbf{E} = \eta_W \mathbf{J}$)
  - Vacuum ($\mathbf{J} = 0$)

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

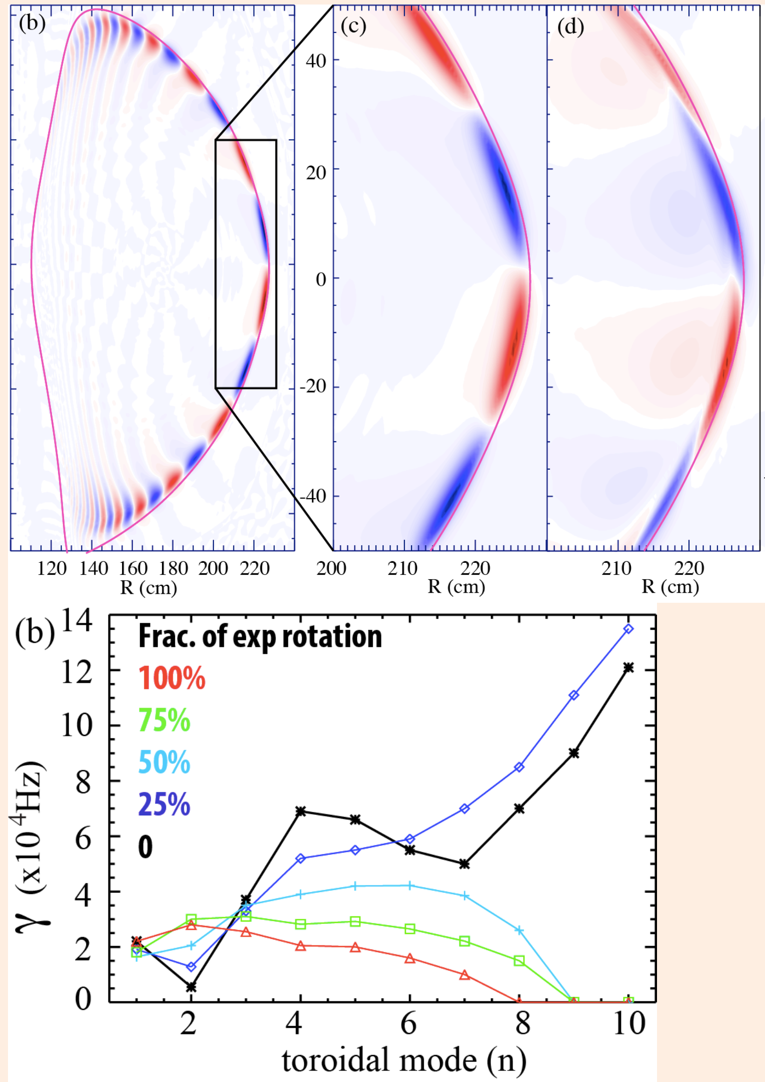
- ***<u>There are no boundary conditions on $\mathbf{B}$ or $\mathbf{J}$ at the resistive wall</u>***
  - Current can flow into and through the resistive wall

- **All regions advanced simultaneously with implicit time step**



Linear Modeling of Edge Instabilities in QH-Mode Discharges (Xi Chen)

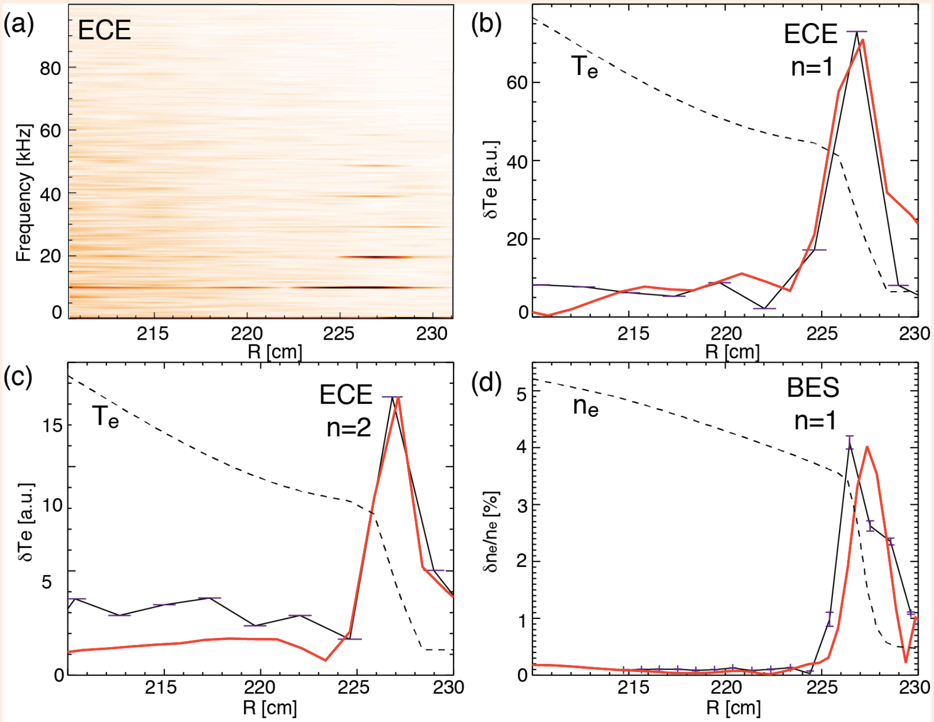
- **Linear stability of QH-Mode discharge in DIII-D is analyzed**
  - This shot / time has coherent EHO
- **Both ELITE and M3D-C1 find unstable edge modes, even at low *n***
- **M3D-C1 is used to explore dependence of growth rate on rotation**
  - Stabilizing at high n, destabilizing to n=2 in this case

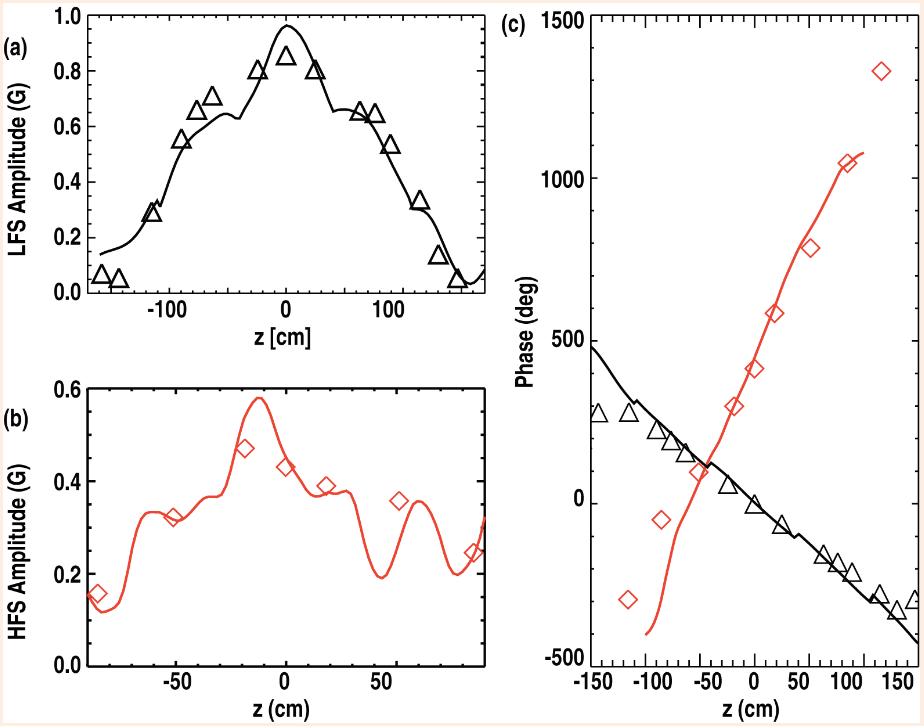


X Chen, KH Burrell, NM Ferraro, *et al.* Submitted to *Nucl. Fusion*

Linear Modeling of Edge Instabilities in QH-Mode Discharges (Xi Chen)

- **Eigenmode calculated by M3D-C1 agrees well with experimental observations of EHO structure**



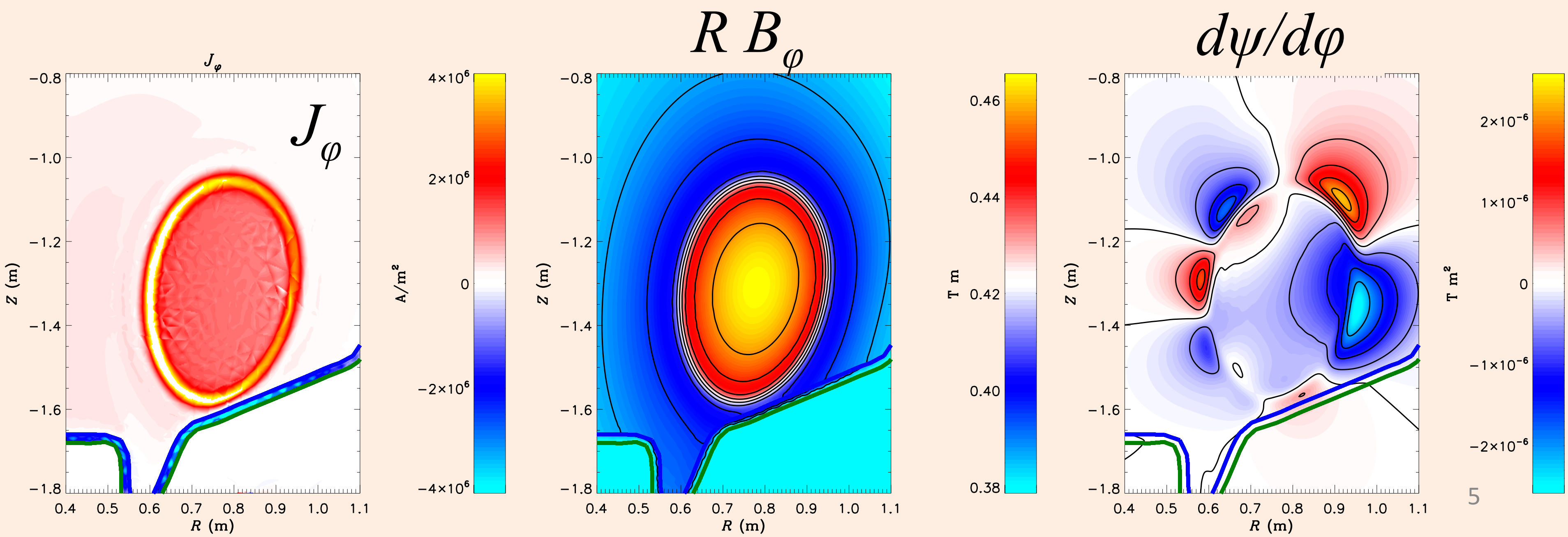


X Chen, KH Burrell, NM Ferraro, *et al.* Submitted to *Nucl. Fusion*

Nonlinear Disruption Modeling (David Pfefferlé)

- **Modeling seeks to explore magnitude and toroidal distribution of currents in the wall**

- **Can run VDE simulation in 2D until q_{edge} ~ 2, then switch to 3D**



In “Hot VDE,” q_{edge} Drops Until Plasma Becomes Unstable to n > 0 MHD

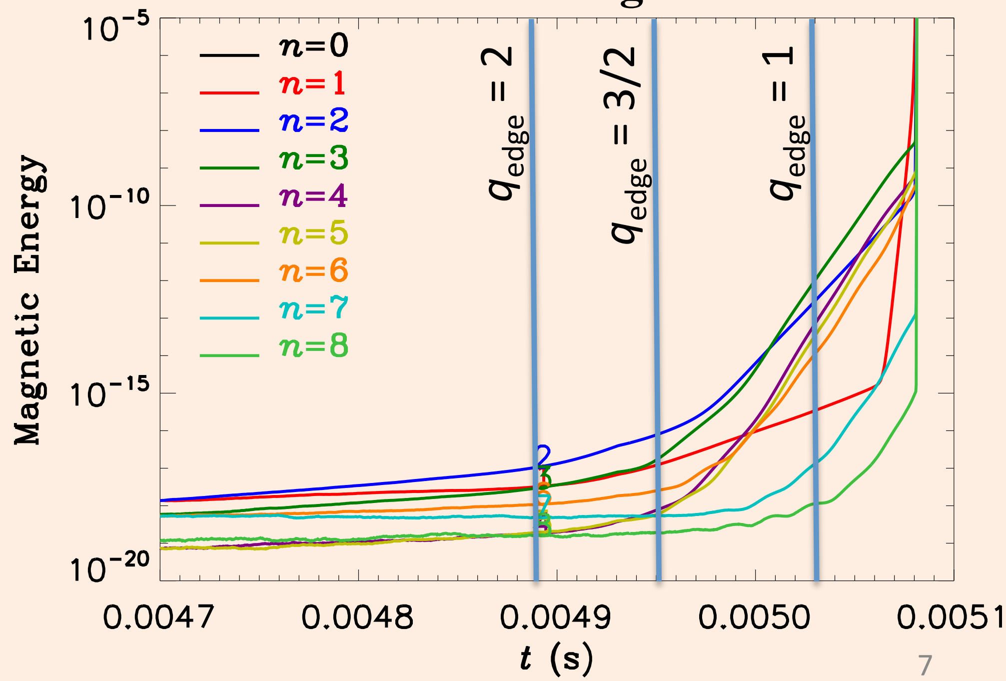
- **Two competing effects determine q_{edge} once plasma is limited:**
  1. q_{edge} drops as plasma shrinks and is scraped off by limiter
  2. q_{edge} rises because of resistive decay of I_P

- **In <u>cold-VDE</u> (TQ happens before VDE), resistive decay is fast and q_{edge} rises**
  - Plasma remains stable to $n > 0$ MHD

- **In <u>hot-VDE</u> (no TQ before VDE), resistive decay is slow and q_{edge} drops**
  - Plasma eventually becomes unstable to $n > 0$ MHD
  - $n > 0$ instability potentially causes strong Halo currents, wall forces, and TQ

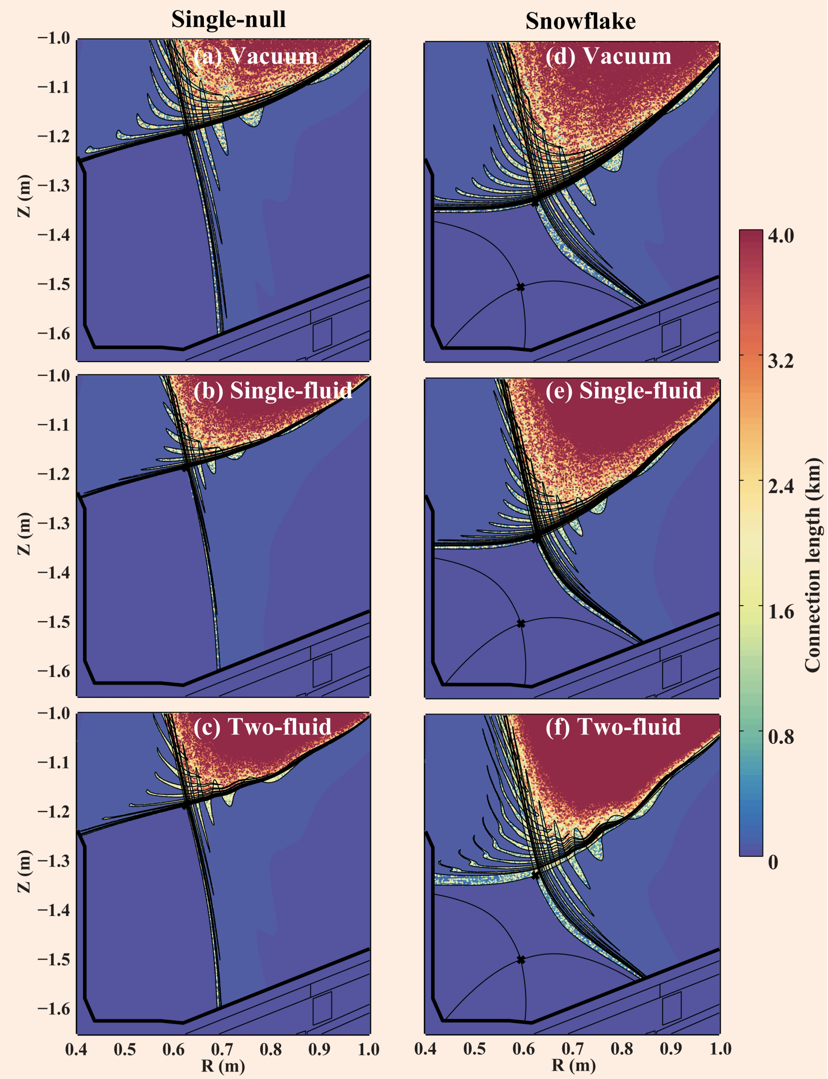
In Hot-VDE Simulation of NSTX, $q_{\mathrm{edge}} < 1$ Before Non-Axisymmetry is Significant

- Non-axisymmetric modes start growing when $q_{\mathrm{edge}}=2$, but are still at small amplitude when $q_{\mathrm{edge}}=1$
- q_0 is still > 1, so shear is reversed when $q_{\mathrm{edge}}=1$
- Plasma is more stable than expected
  - Need to explore different τ_W, SOL temperatures



3D Perturbed Equilibria in Snowflake Geometry (Gustavo Canal)

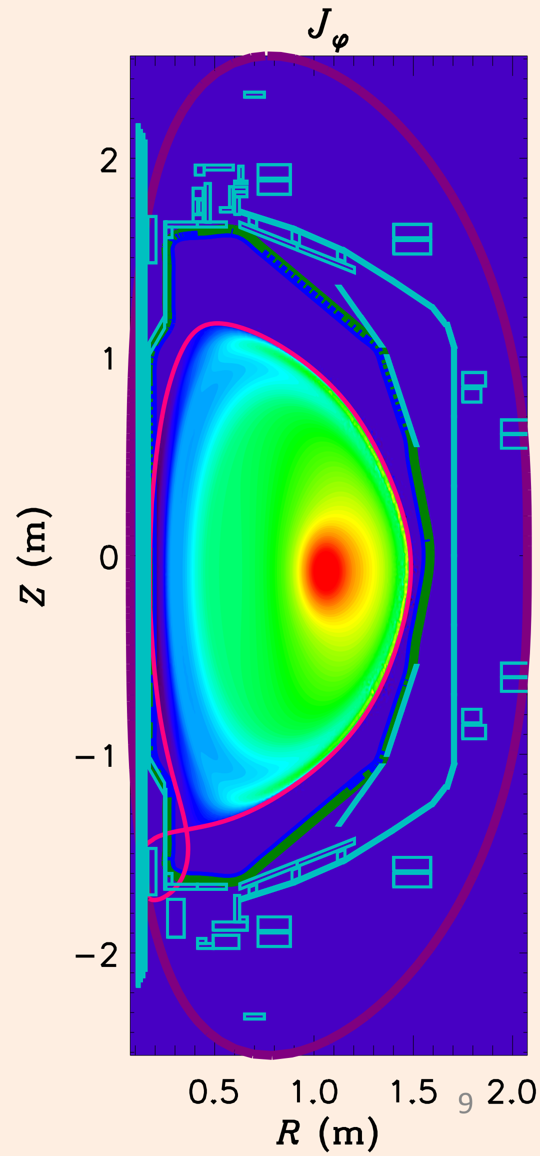
- **M3D-C1 Grad-Shafranov solver was improved to allow good snowflake equilibria**
- **3D response calculations in snowflake geometry show more stochasticity, larger lobes**
- **Effect is attributed to weaker Bpol**
  - Smaller perpendicular part from toroidal rotation
  - Larger lobes for given perturbation



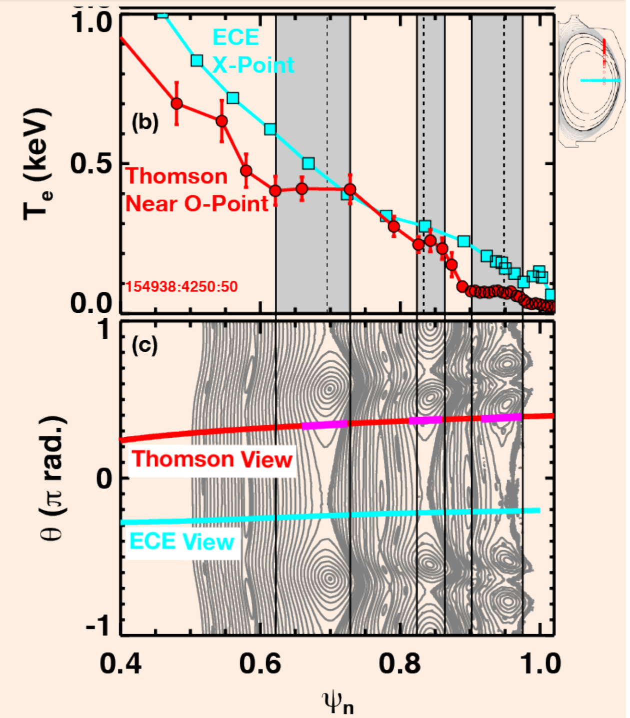
GP Canal, NM Ferraro, TE Evans, *et al.* In preparation.

Accurate Free-Boundary NSTX(-U) Equilibria Require Vessel Currents

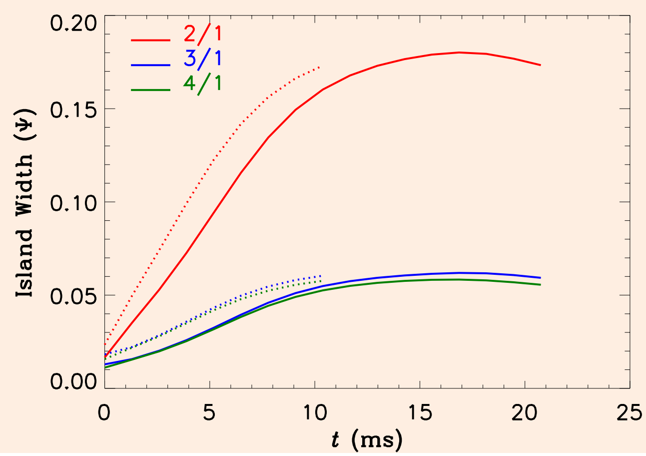
- **In NSTX(-U), eddy currents in vessel strongly contribute to shape**
- **Snowflake equilibria are very sensitive due to small B_{pol} over large area**
  - Also sensitive to SOL currents
- **We now read "coil" definitions and currents from device & signal files used by EFIT**



Understanding Penetrated Error Fields Requires Nonlinear Modeling



- **DIII-D experiments highlighted shortcomings of linear response in modeling post-penetrated state of plasma**
  – Island is large compared to resistive layer width
  – Island size is observed to be essentially independent of amplitude of error field
  – Island appears to lock ion rotation, not electron rotation



- **Nonlinear modeling of island saturation is underway**
  – Finds saturated island size is independent of error field
  – Case also being investigated using Siesta and HINT

Pellet Modeling for ELMs and Disruption Mitigation

- **New capability to pack mesh toroidally to better resolve pellet**
  - Demonstrated capability to resolve realistic pellet cloud (~ 1 cm)

- **Initial calculations are underway**
  - Benchmarking evolution of cold particle cloud with PRL code (S. Diem & L. Baylor)
  - Implementation of P. Parks model of pellet ablation for ELM triggering calculations (A. Fil)

Summary

- **User base of M3D-C1 is now expanding rapidly, and being applied to diverse set of problems**

- **Code development is focusing on ways to improve disruption modeling**
  - Resistive wall, halo currents
  - Pellets, radiation

- **3D response / equilibrium work is ongoing**
  - Linear response is mature but still improving
  - Now exploring nonlinear response and penetration

- **Lots of plans and data for validation; need some code benchmarking too!**

Extra Slides

Full, Compressible, Two-Fluid Model is Implemented in XMHD Region

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

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

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

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

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

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

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

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

$$\Gamma = 5/3$$

$$n_e = Z_i n_i$$

- **(R, φ, Z) coordinates → no coordinate singularities in plasma**

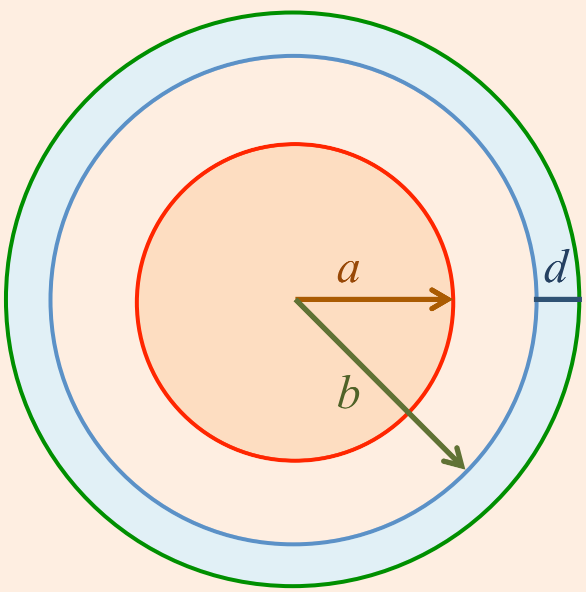
- **Three modes of operation:**
  - Linear, time-dependent (**linear stability**)
  - Linear, time-independent (**perturbed equilibrium**)
  - Nonlinear, time-dependent (**nonlinear dynamics**)

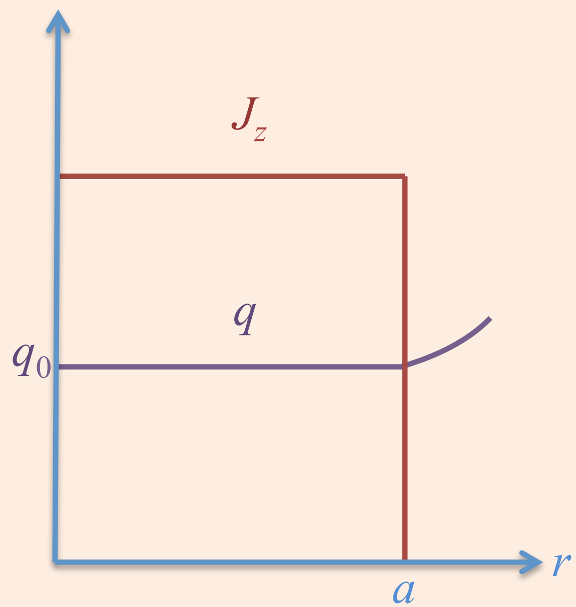
Resistive Model Verified Against Analytic Resistive Wall Mode Result

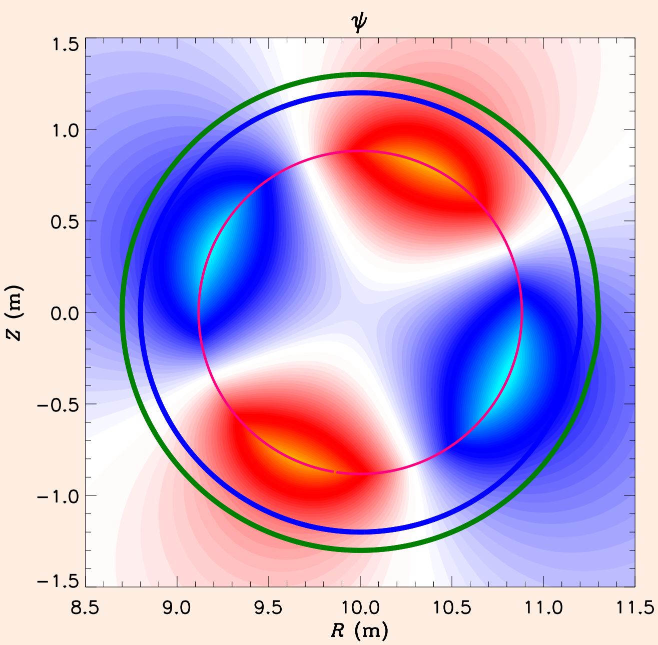
- **Circular cross-section, cylindrical plasma with constant q, current density (J_z) and mass density (ρ_0) (Shafranov equilibrium)**

- **Analytic thin-wall solution provided by Liu *et al.* *Phys. Plasmas* 15, 072516 (2008)**

Wall time: $\tau_W = \mu_0 bd/(2\eta_W)$
Alfven time: $\tau_A = (\mu_0 \varrho_0)^{1/2} R_0/B_0$





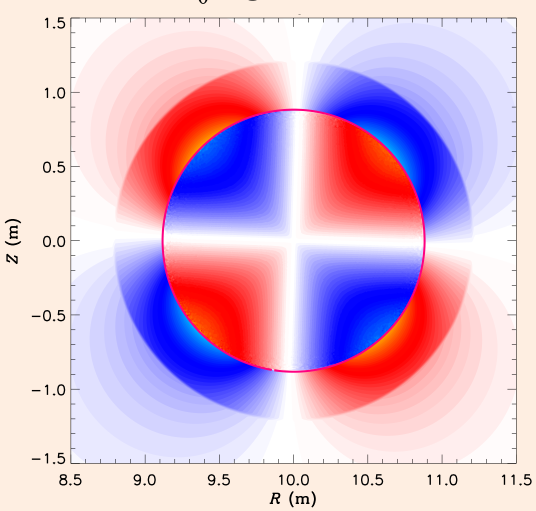


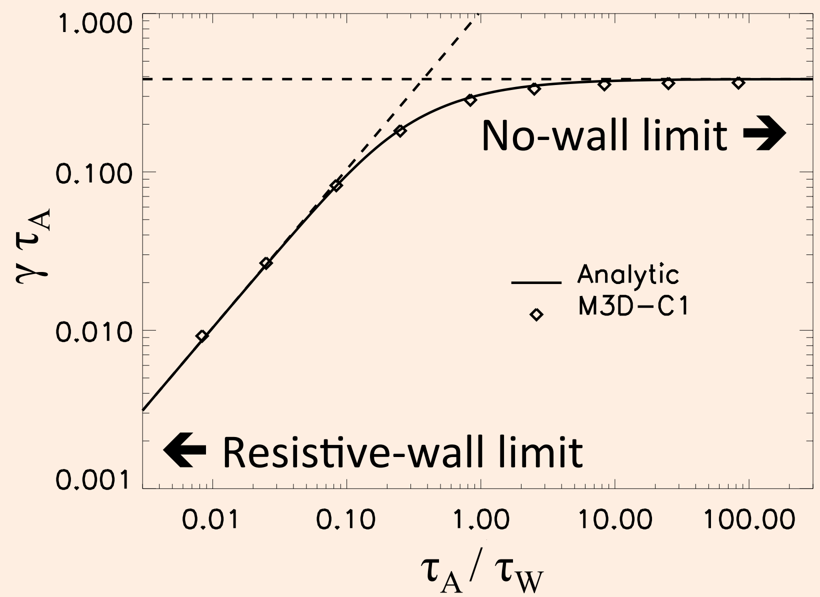
RWM Benchmark: M3D-C1 Agrees with Analytic Result

- **Growth rate calculated using linear, time-dependent calculation**

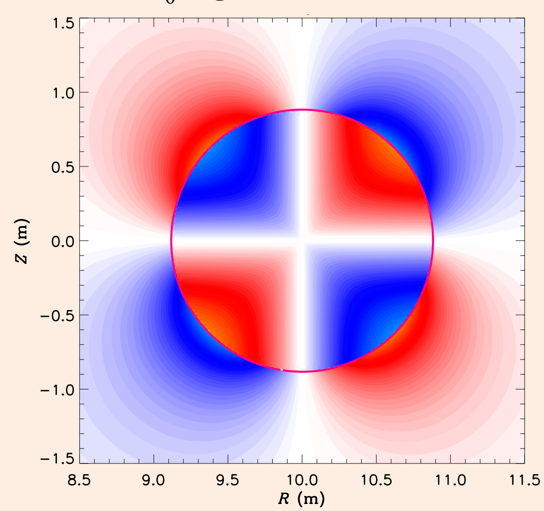
- **M3D-C1 agrees with analytic growth rate in both resistive-wall ($\tau_A \ll \tau_W$) and no-wall ($\tau_W \ll \tau_A$) limits**

Resistive-Wall Limit
B_θ Eigenfunction





No-Wall Limit
B_θ Eigenfunction



M3D-C1 Model Verified For Arbitrary Wall Thickness

- **Allowing arbitrary wall thickness leads to straightforward modification of Liu *et al.* (thin wall) dispersion relation**

$$\frac{\nu}{m-nq_0} - \frac{1}{1-(a/b)^{2\mu}F} = \frac{(\gamma\tau_A)^2}{2}\frac{q_0^2}{(m-nq_0)^2}$$

$$\mu = |m| \qquad \alpha = \sqrt{2\gamma\tau_W b/d}$$

$$\nu = \mathrm{sgn}(m) \qquad \beta = (1+d/b)\alpha$$

<u>General solution</u>

$$F = \frac{I_{\mu-1}(\beta)K_{\mu-1}(\alpha) - I_{\mu-1}(\alpha)K_{\mu-1}(\beta)}{I_{\mu-1}(\beta)K_{\mu+1}(\alpha) - I_{\mu+1}(\alpha)K_{\mu-1}(\beta)}$$

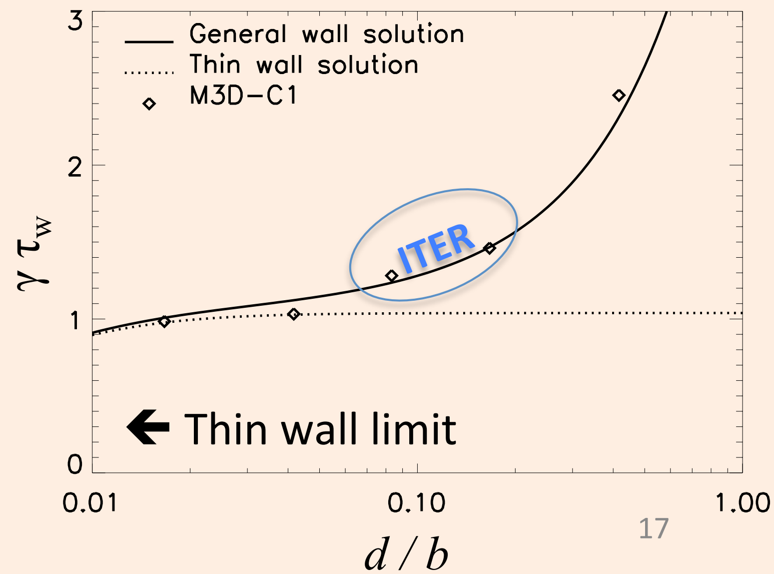
<u>Thin wall ($d \ll b$)</u>

$$F \rightarrow \frac{\gamma\tau_W}{\gamma\tau_W + \mu}$$

- **In thick wall, skin depth limits eddy current depth**
  - Weaker eddy currents than in thin wall approximation, which assumes radially uniform current in wall

- **M3D-C1 model in good agreement with analytic results for arbitrary wall thickness**

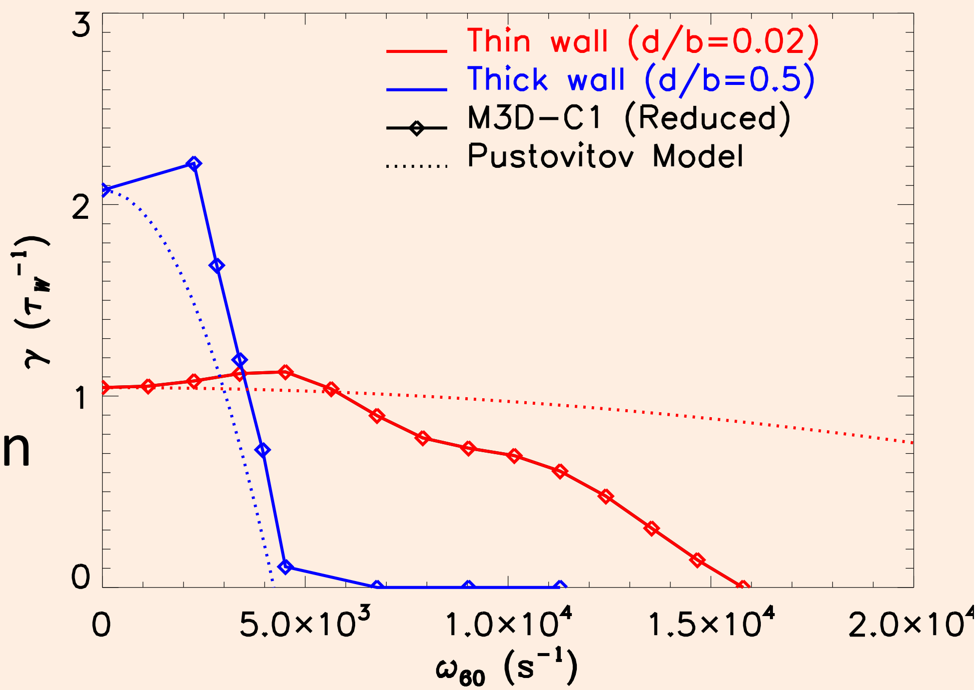
- **In ITER, $(\gamma\tau_W)(d/b) \sim 0.2$ ***
  - Growth rates ~ 20—50% larger than thin wall solution



* F. Villone et al. *Nucl. Fusion* **50**, 125011 (2010)

Rotational Stabilization of RWM Observed

- **Reduced-model calculations show stabilization of RWM by toroidal rotation**
  - $\omega \sim p$
- **Qualitative agreement with Pustivitov model***
  - Growth rate falls off roughly as $(\omega/\omega_{crit})^2$
  - Pustivitov model derived in thick wall limit with uniform rotation



*Pustivitov *Nucl. Fusion* **53** (2013) 033001