3D Response Calculations with M3D-C1

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GENERAL ATOMICS

3D Response is an Important Issue for ITER

- **ELM Suppression**
  - Resonant Magnetic Perturbations (RMP)
  - QH-Mode
- **Fast Ion Loss**
- **Divertor Particle/Heat Flux**
- **Mode Locking**

Outline

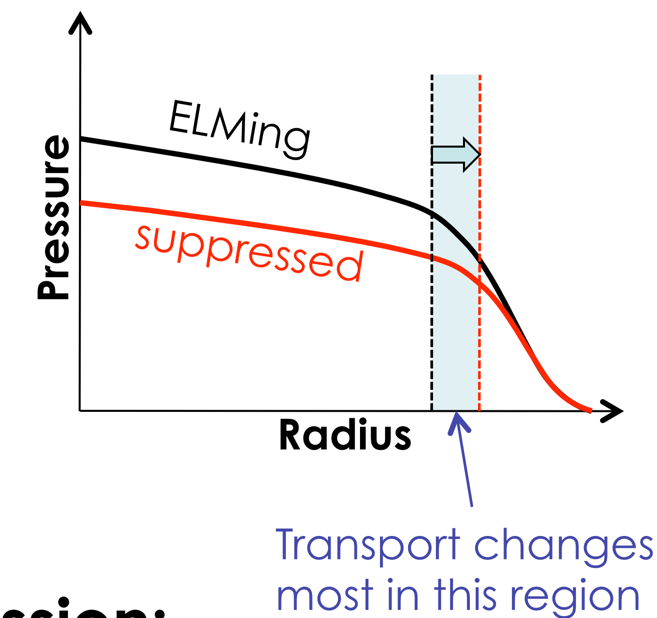
- **RMP ELM suppression: hypothesis and unresolved questions**
  – Transport limits pedestal, but how?

- **Efforts to validate models**
  – Modeling can reproduce large observed edge "displacements"

- **Future directions and opportunities**

Hypothesis for RMP ELM Suppression: RMP-Driven Transport Limits the Pedestal Width

- **Pedestal width is reduced (at low collisionality)**
  - Reduced width is consistent with ideal peeling/ballooning stability
  - Particle confinement is degraded; temperature is not reduced



- **Main questions for RMP ELM suppression:**
  - What is mechanism of additional transport?
  - What determines q95 windows, thresholds (β, ν^*, density)?
  - How much must confinement be degraded?

Experimental Results Are Inconclusive in Determining Internal Response

- **Magnetic topology / 3D structure is difficult to measure**
  - Internal measurements have no toroidal resolution
  - Islands are probably small; dominated by other effects
- **Can flip n=3 fields**
  - Will shift x-points to o-points
  - Inconclusive results: no clear "signature" of islands
- **Can rotate phase of n=2 fields**
  - Will sweep structures past diagnostics
  - Error fields lead to significant phase-dependence of response

Modeling is Necessary to Make Sense of Experimental Results

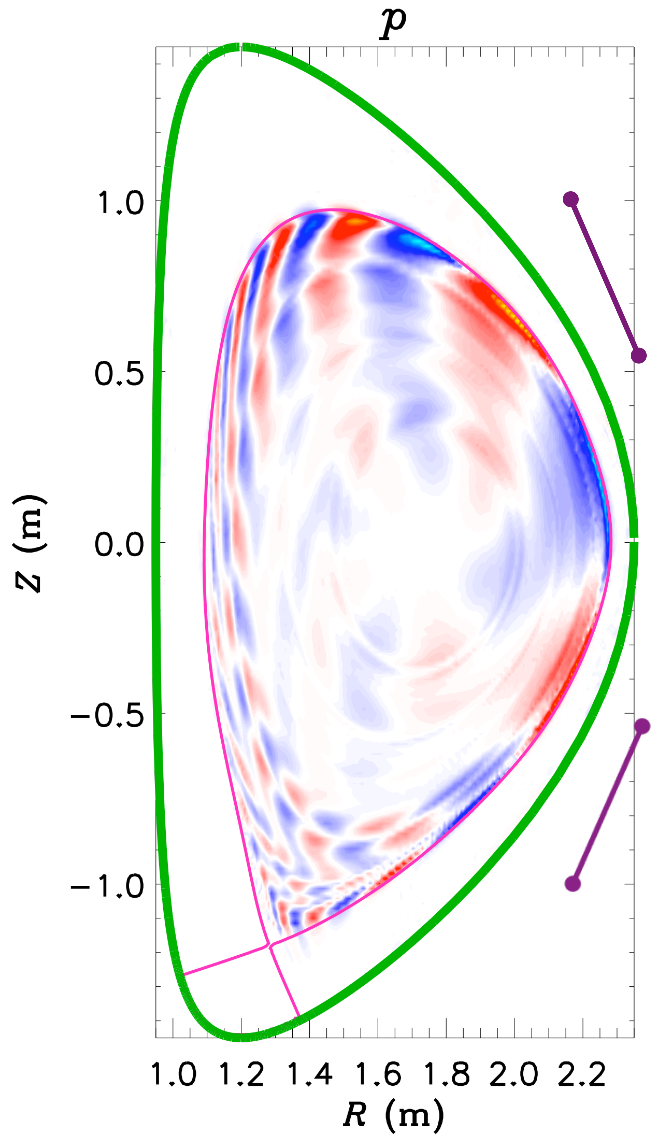
- **What is the expected internal magnetic response?**
  - How does magnetic response depend on plasma parameters?

- **How does magnetic response affect transport?**
  - Islands/stochasticity?
  - Flutter? Turbulence? Convection?

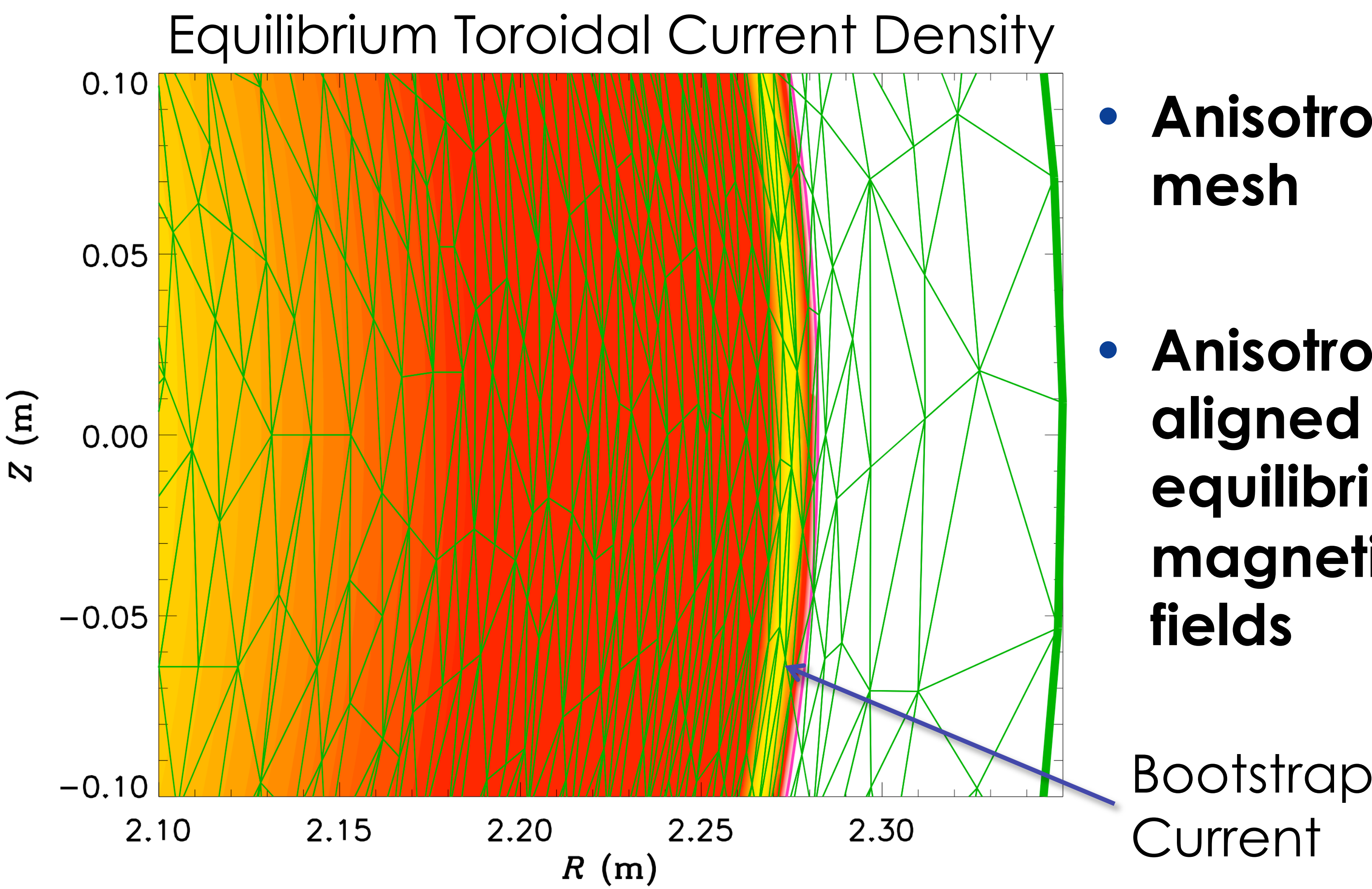
- **Models must be benchmarked against measureable response**
  - Magnetic probe data
  - Internal measurements (TS, BES, x-ray, etc.)

M3D-C1 is Being Used to Calculate Two-Fluid 3D Response

- **Boundary Conditions:**
  - Normal component of "vacuum fields" from I-coils, C-coils, etc.
  - Can read fields from TRIP3D
    - Real coil geometry & error fields
- **Linear calculations:**
  - Time-independent equations
  - Single toroidal mode number
  - ~2-4 cpu hrs
- **Nonlinear calculations:**
  - Run until "quasi-steady state"
  - ~5k-10k cpu-hrs



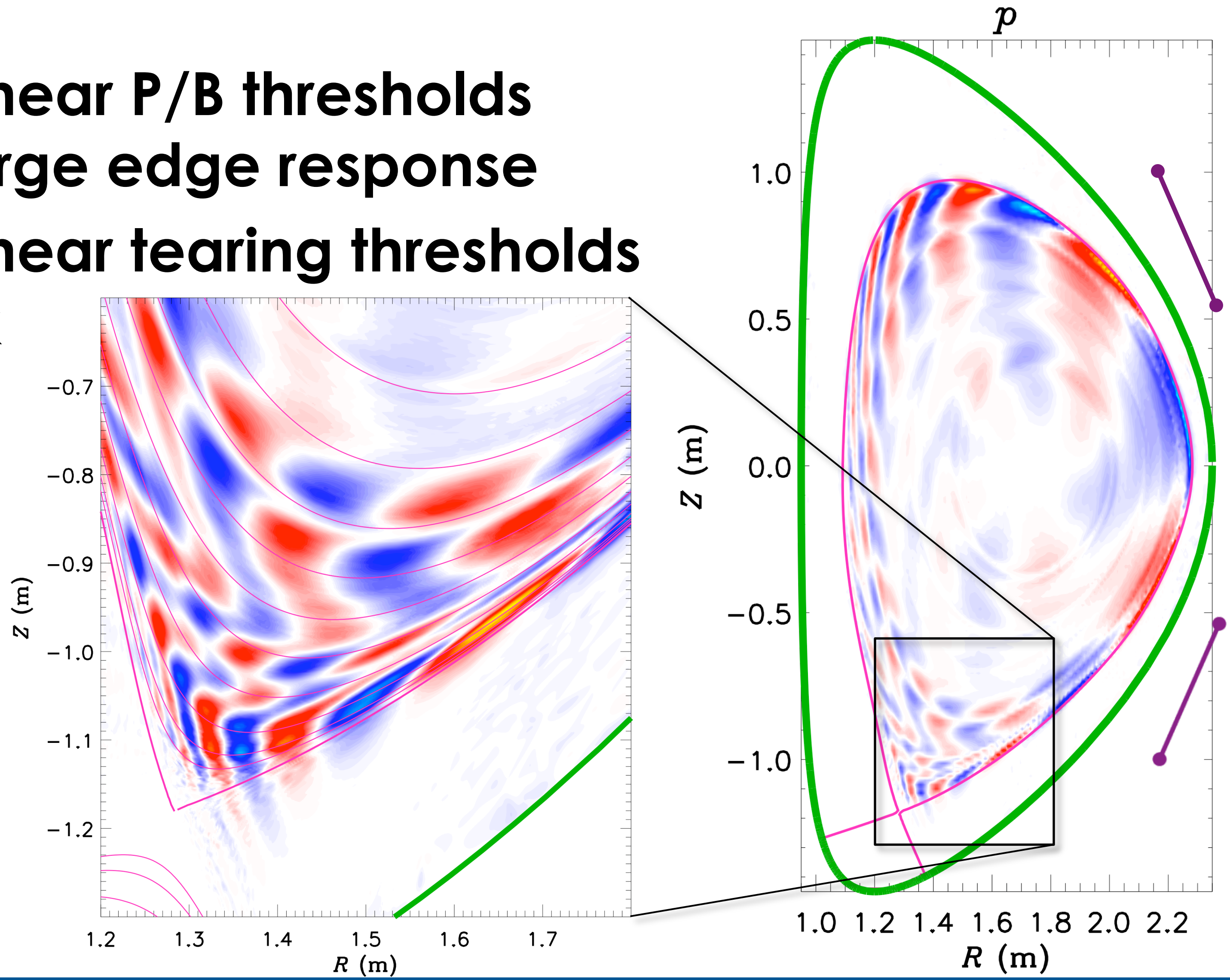
Radial Resolution in Pedestal Region is Typically a Few Millimeters



- **Anisotropic mesh**
- **Anisotropy aligned with equilibrium magnetic fields**

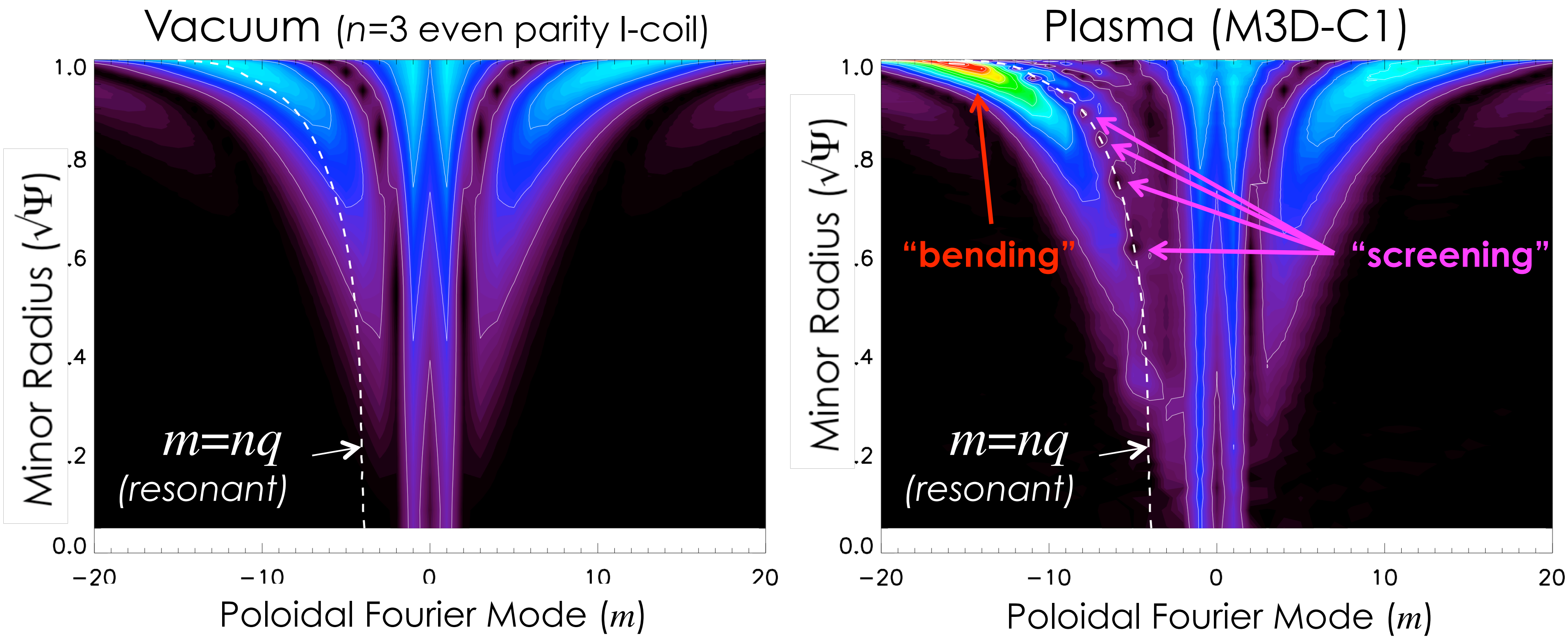
Response Is Typically Similar to Least-Stable Mode

- **Plasmas near P/B thresholds exhibit large edge response**
- **Plasmas near tearing thresholds may lock**



Magnetic Field is Strongly Affected By Plasma Response

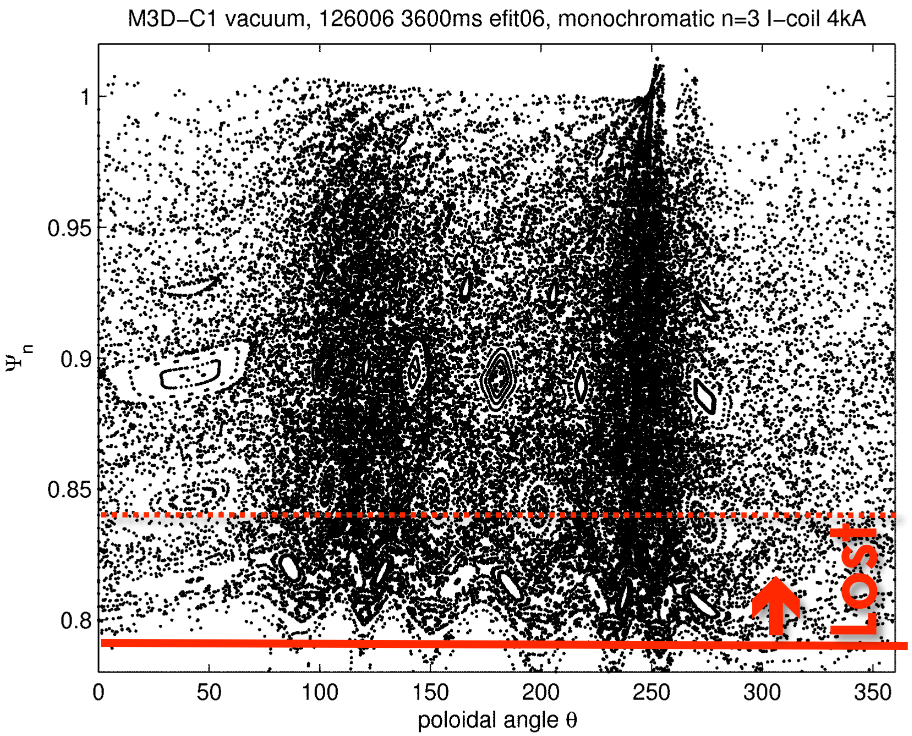
- **Plasma response significantly modifies fields**
  - Reduces resonant components (island screening)
  - Amplifies non-resonant components (kink excitation/bending)
- **Both effects have significant transport implications**



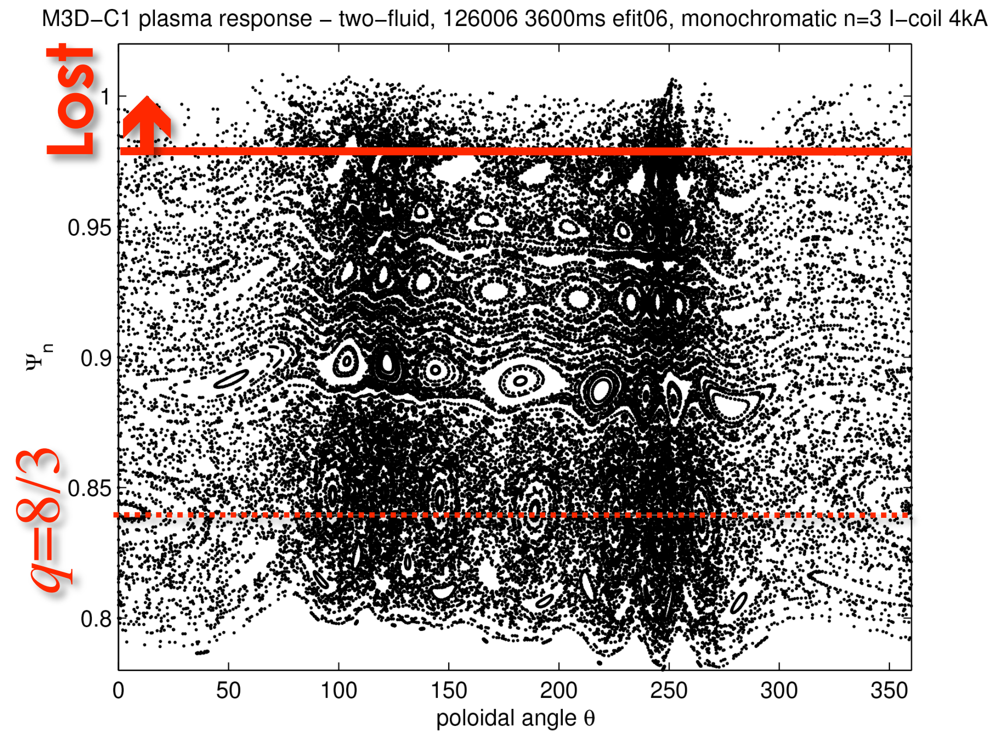
Normal Field $(\hat{\mathbf{r}} \cdot \mathbf{B})_{mn}$ from even parity n=3 I-coils

Plasma Response Significantly Affects Edge Topology, Even When Screening is Not Complete

Vacuum

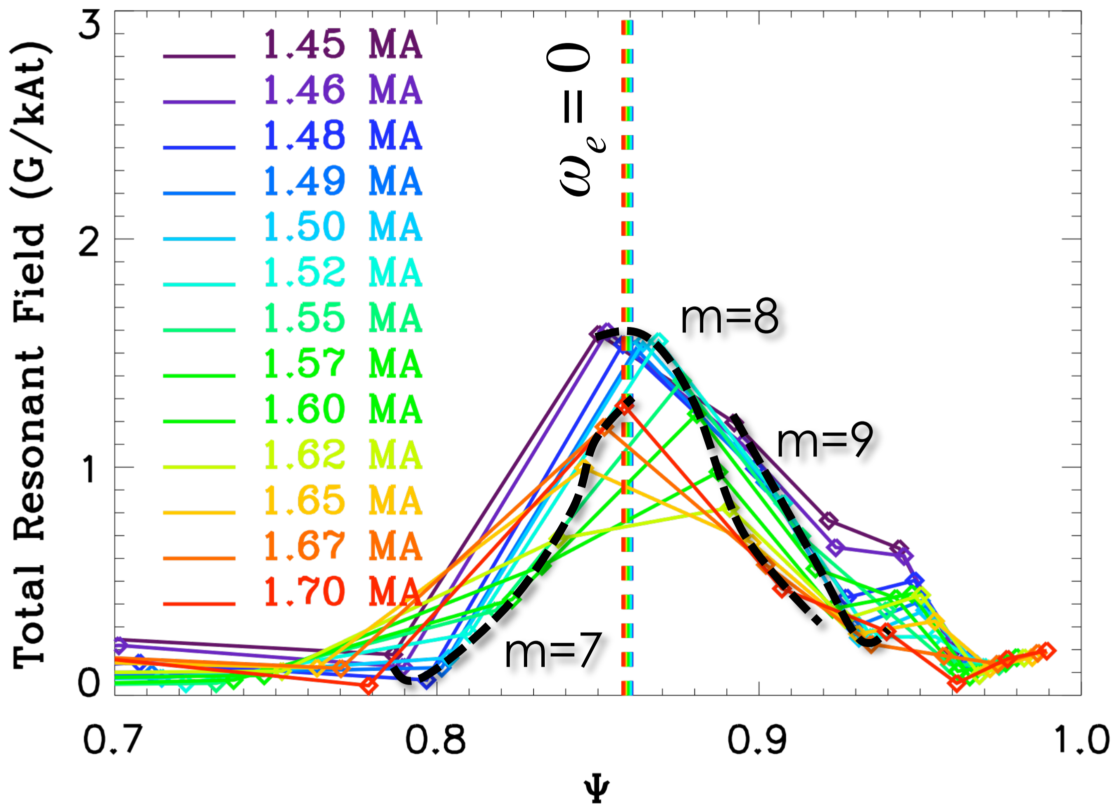


Plasma

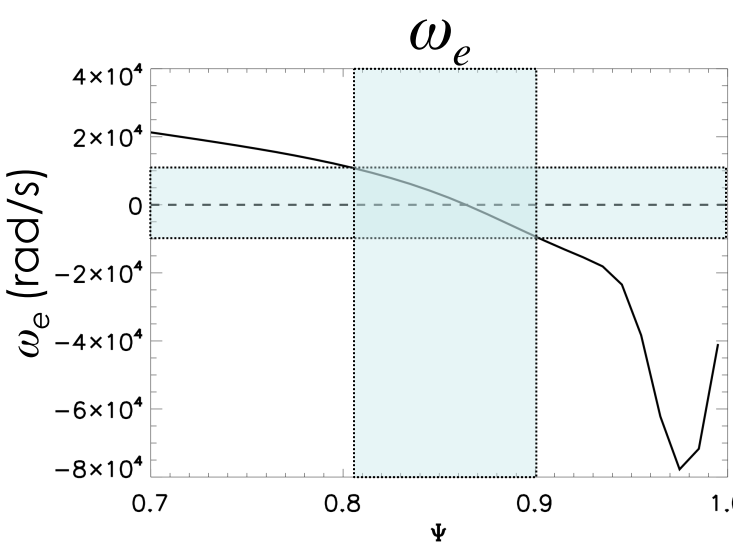


- **Modeling shows both imperfect screening and a reduction in stochasticity (from vacuum level) when plasma response is included**
  - Vacuum: even fields lines starting at Ψ=.80 can be lost
  - Plasma: only field lines starting outside of Ψ=.97 are lost
- **Large island occurs where perpendicular electron rotation vanishes**

Perpendicular Electron Rotation Plays Important Role In Tearing Response

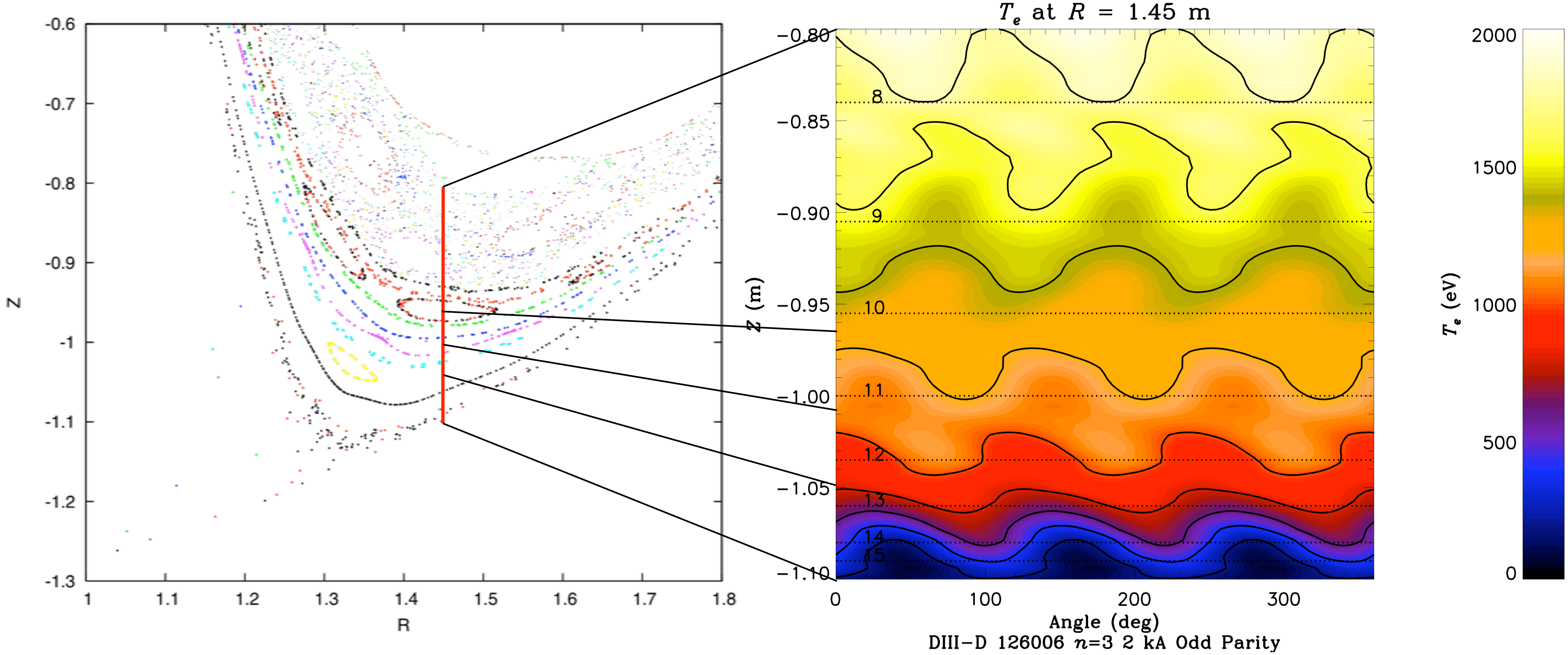


I_p scan
n=3 I-coil fields



- **Width of peak in $\omega_e = 0$ is ~10 krad/s**
- **This implies islands can open easily near top of pedestal**
  - Experiments show hints of "island-like structures" (maybe), but measurement/interpretation is difficult

In Model, Temperature Inversions are Correlated with Islands

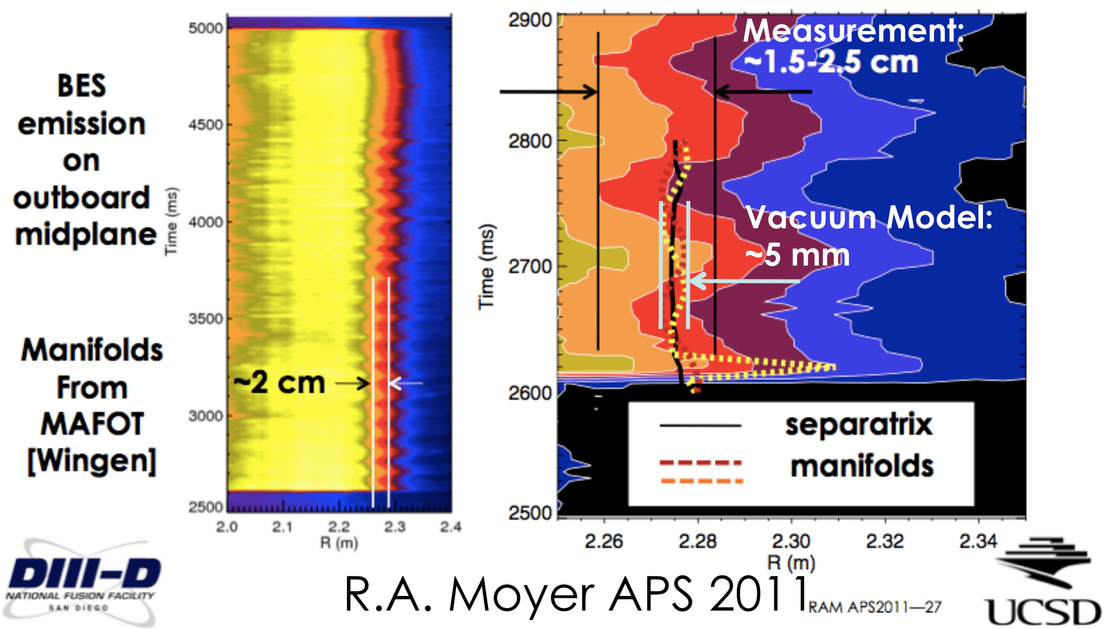


- **Correlation is not perfect; nonlinear effects will modify profiles**
- **Experimental results are subtle and complicated by error fields**
  - n=0 response is phase-dependent

Edge Displacements Represent a Clear Empirical Result to Compare with Modeling

- **Experiments with applied 3D fields find large (~2 cm) displacements of edge profiles**

- **It is generally believed (but not proven) that these displacements are 3D (helical), not *n*=0**

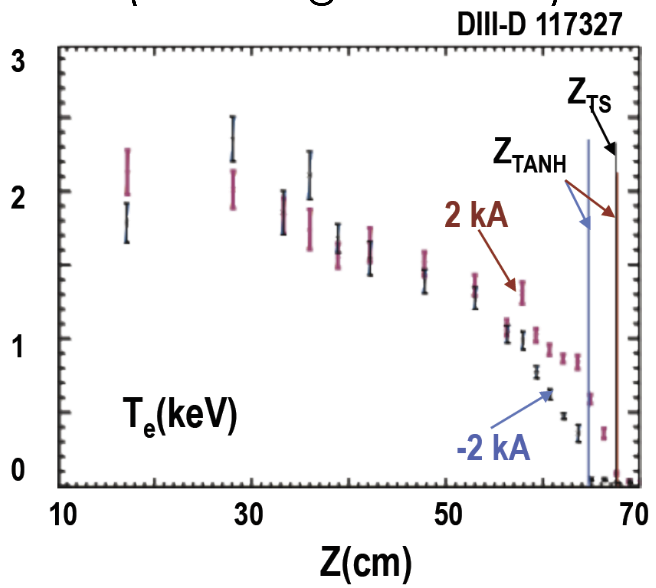


- **Displacements are too large to be explained by vacuum modeling**

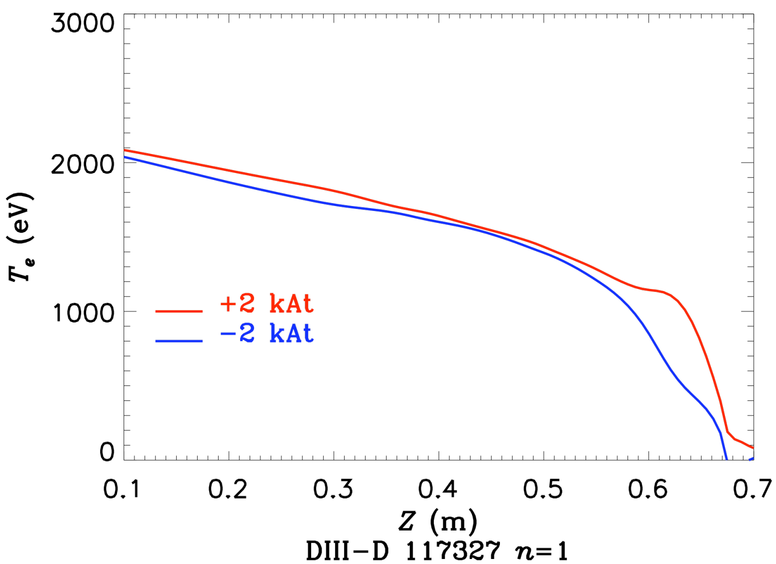
Modeling Shows Quantitative Agreement with Observed Edge Temperature Displacement

- **Pedestal measurements clearly show displacements of 1—4 cm in edge when 3D fields are applied**
  - Vacuum modeling predicts separatrix perturbations of a few mm
  - Linear plasma response modeling shows helical perturbations of comparable magnitude to experiment

Experiment
(Rotating n=1 I-coil)



Model (M3D-C1)



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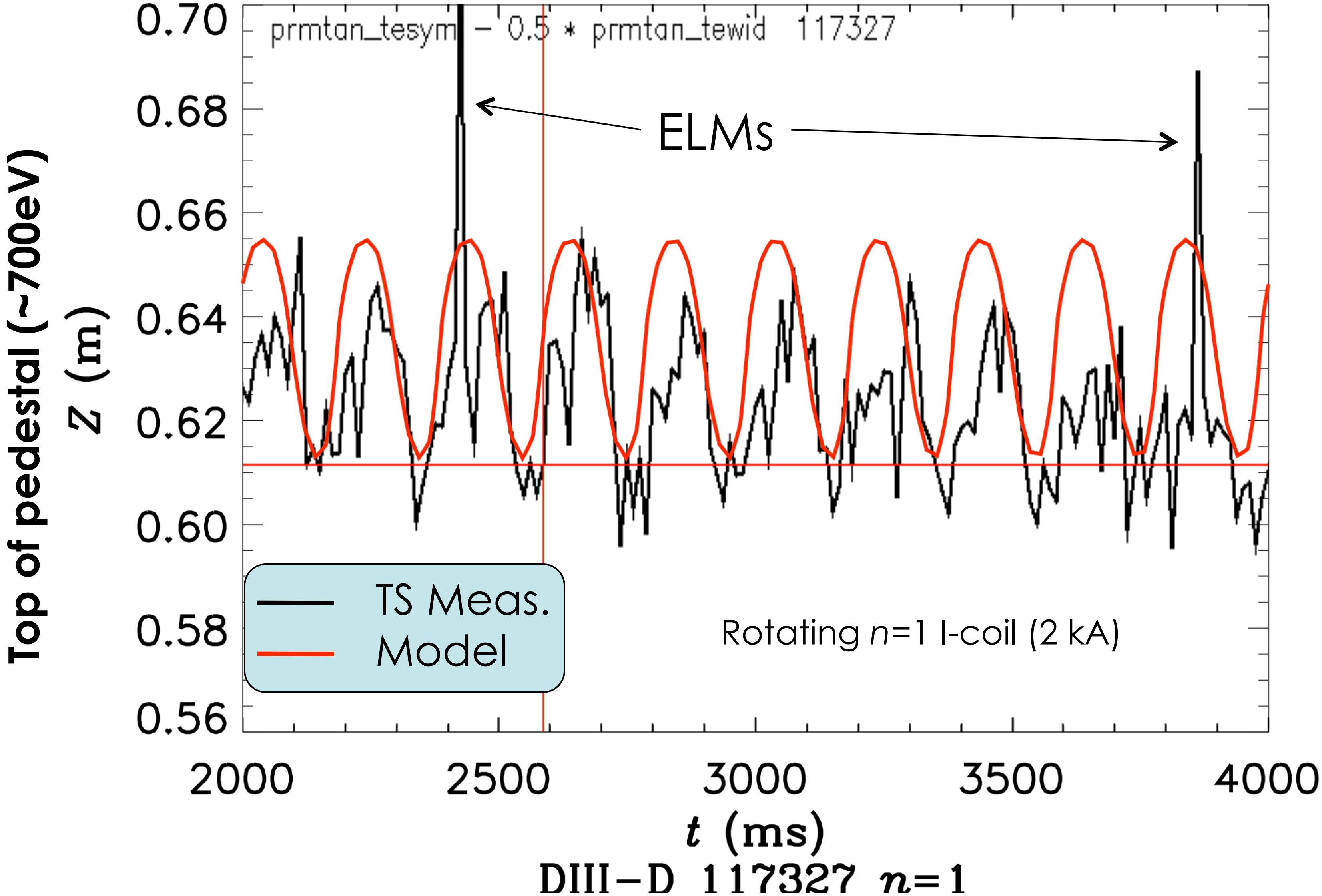
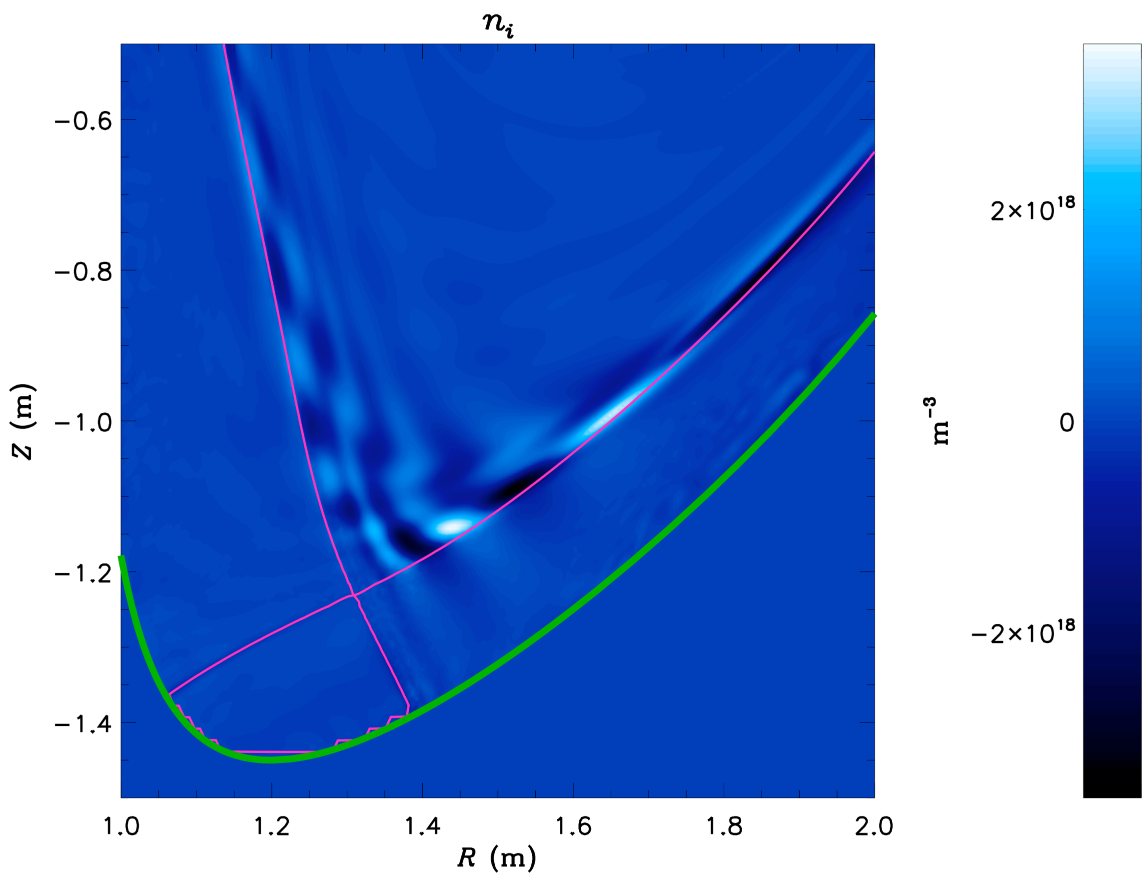


2D Imaging Will Also Provide Basis for Validation

- **New x-ray camera will probe response near x-point**

- **Will impurities collect inside islands and increase x-ray signal?**

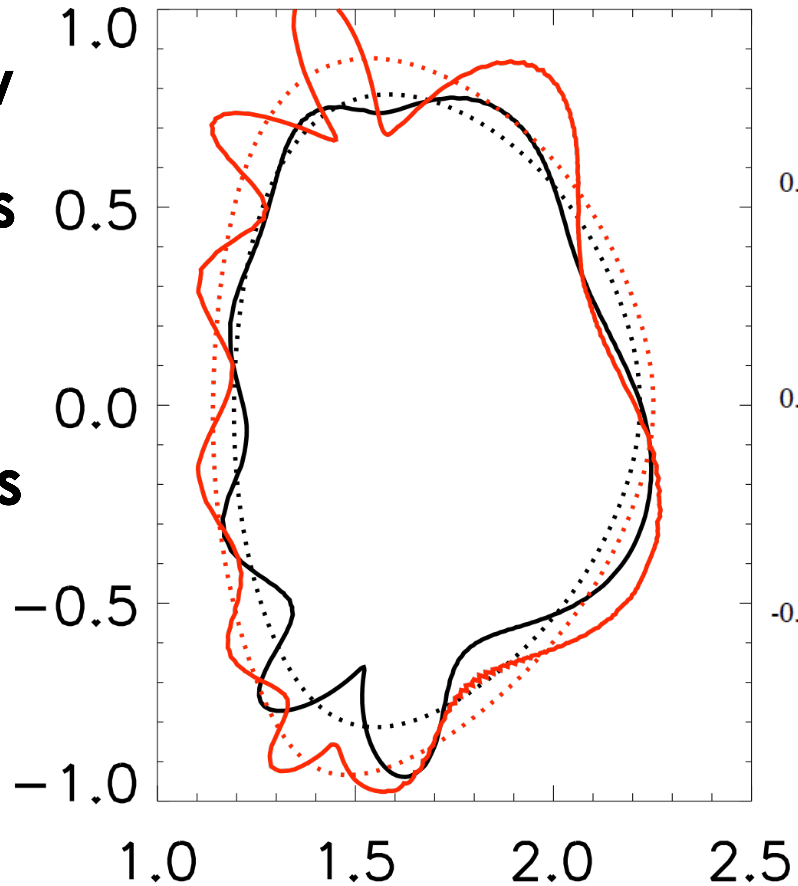


Not All Codes Agree on Displacements

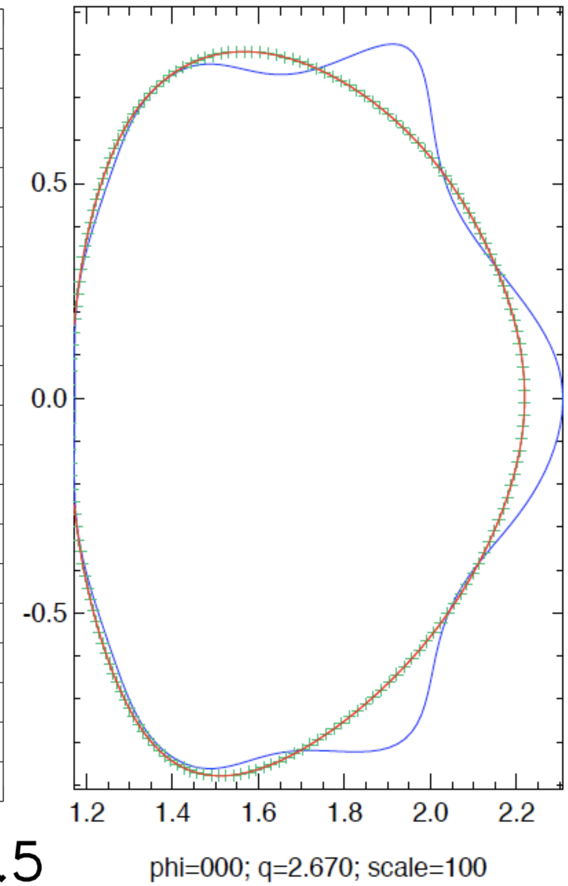
- **Linear codes (IPEC, MARS, M3D-C1) show "kink-like" displacements**
- **VMEC (Ideal, nonlinear) response looks different**

Normal "displacement": $\xi_n = -\delta T / T_0'$

Linear M3D-C1 "Displacement"

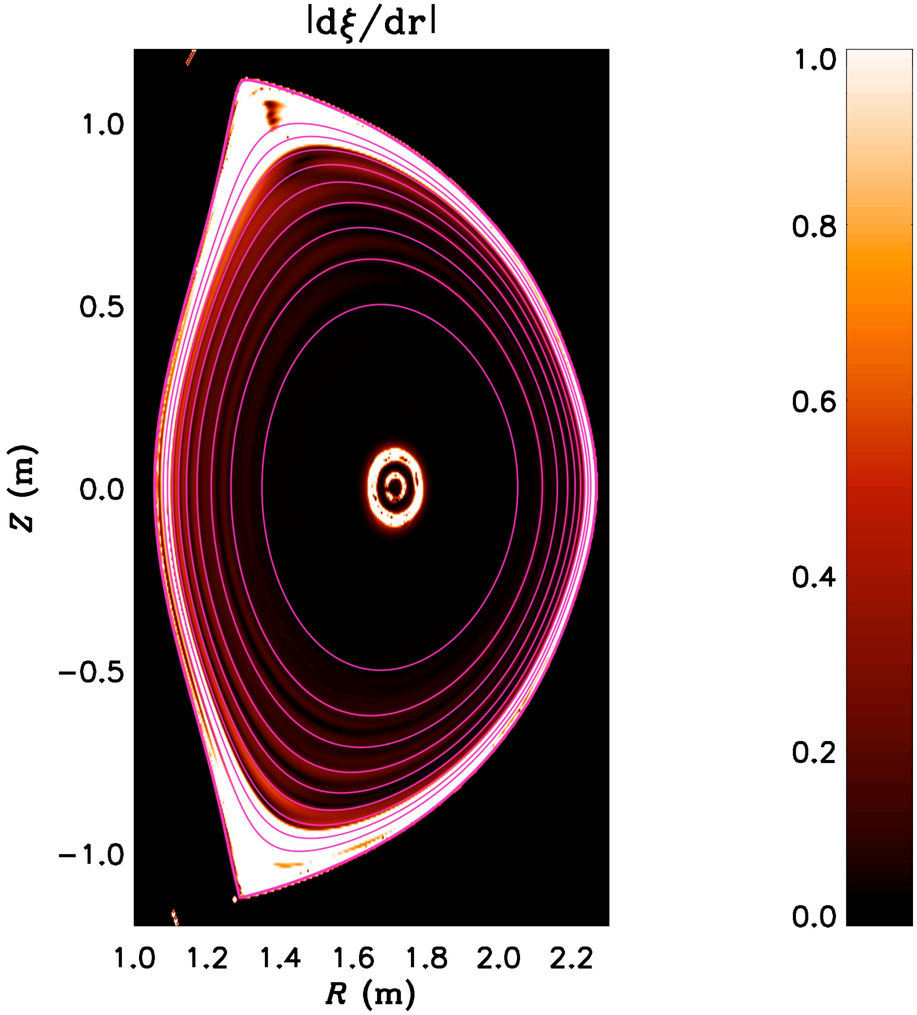


VMEC



Response Violates Ideal-MHD Linear Assumption Through Much of Edge

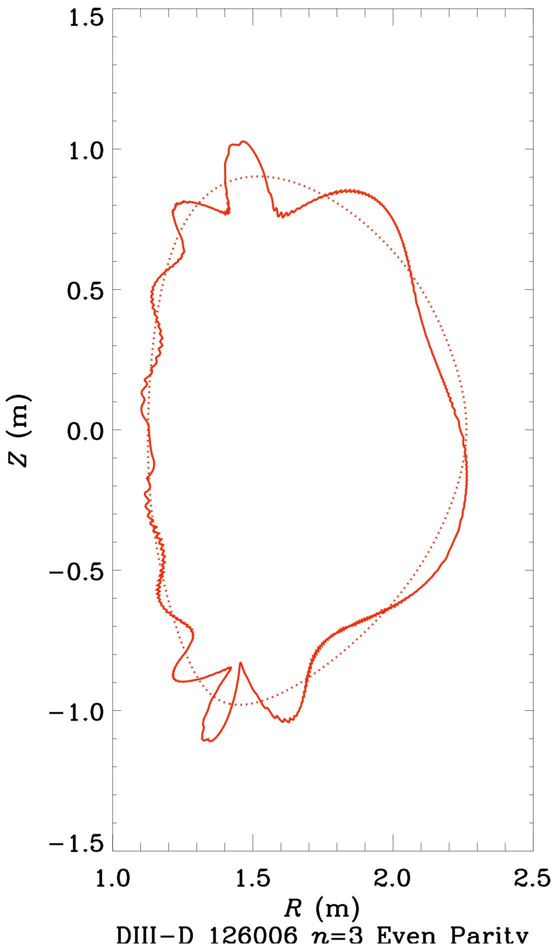
- **Nearby surfaces overlap if $\partial\xi_n / \partial r < -1$**
- **This condition is violated in edge for typical I-coil currents**
- **We can't trust linear "displacements" or perturbed T in this region**
- **Magnetic response may be okay for non-ideal calculations**



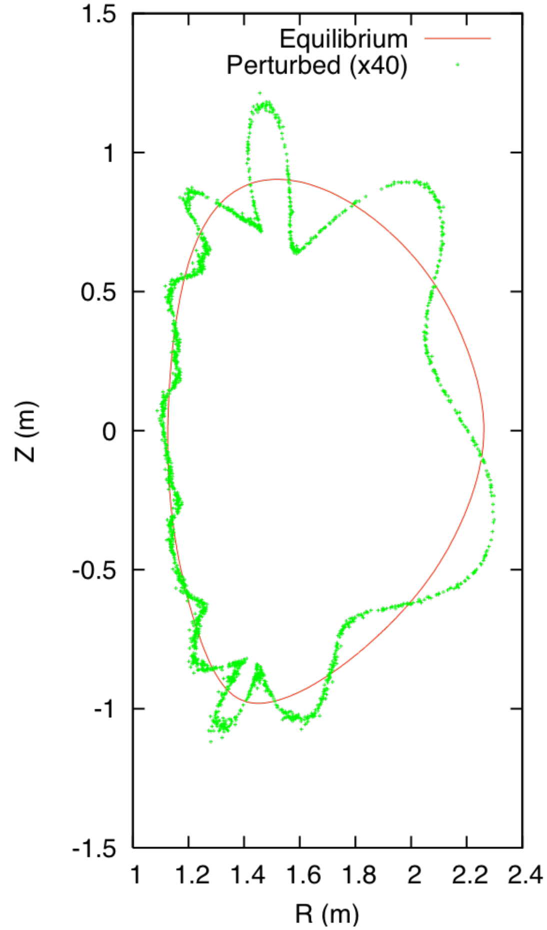
5 kA even parity I-coil

M3D-C1 Calculations Suggest Linearity is Not Source of Discrepancy

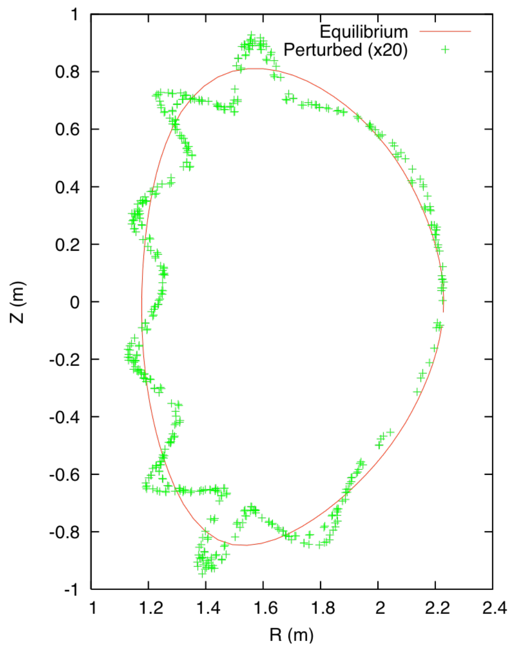
Linear "displacement"



Linear Poincaré



Nonlinear Poincaré



Opportunities For Extended-MHD Contributions

- Transport in 3D Fields
  - **Particle/Heat Flux** to divertor, PFCs
    - TRIP3D now reads M3D-C1 output
  - **Hot ion transport**
    - ORBIT now reads M3D-C1 output
  - **Flutter**, 3D gyrokinetics, etc.

- Nonlinear EHO simulations: **can ITER achieve QH mode?**
  - Why does EHO saturate and not just become an ELM?
  - How/when is EHO driven by coils?

- Torque Calculations
  - How much will 3D fields slow rotation → locking

Summary

- **RMP ELM suppression is plausibly due to 3D-induced transport limiting the pedestal**
- **Detailed experimental data is being produced to test hypotheses**
  - Data is inconclusive; modeling is needed
- **Modeling appears to agree well with observable 3D response**
  - Beta dependence of external magnetics signal
  - Helical displacement of edge profiles
- **Many questions and opportunities remain**

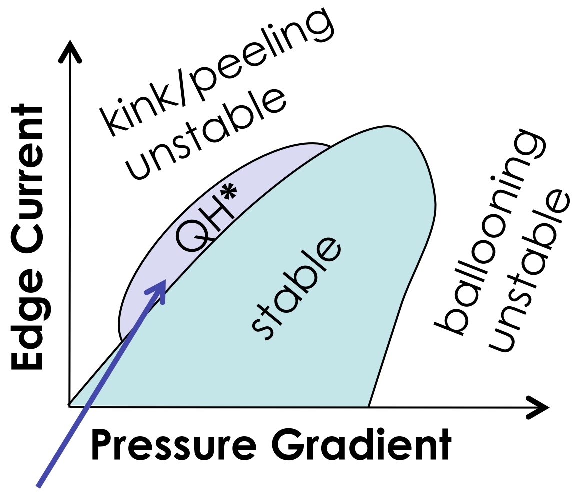
Extra Slides

In QH-Mode EHO Holds Profiles Close to Stability Thresholds

- **Current hypothesis of QH-Mode is strongly influenced by Peeling/ Ballooning theory**
  - Edge rotation shear drives edge kink unstable
  - Edge mode (EHO) saturates
  - EHO drives transport, holding profiles below stability threshold
  - Profiles remain close to stability limit → little confinement degradation

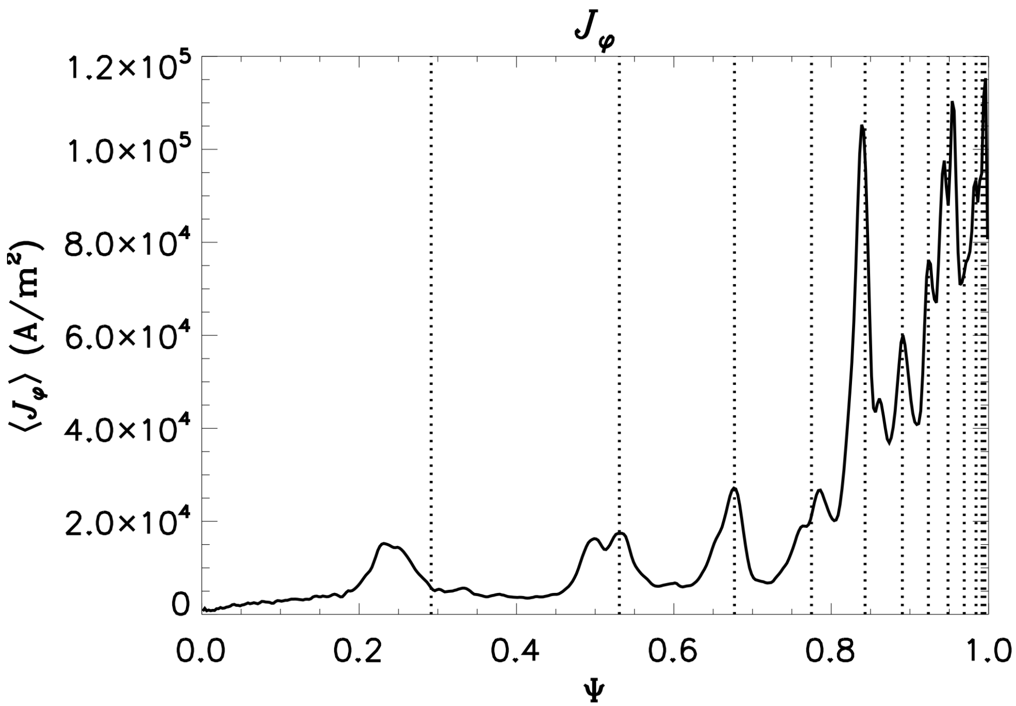
- **Given this understanding, QH-Mode in ITER looks promising**
  - ITER pedestal will be kink/peeling unstable (EPED)
  - Rotation shear can be driven by coils

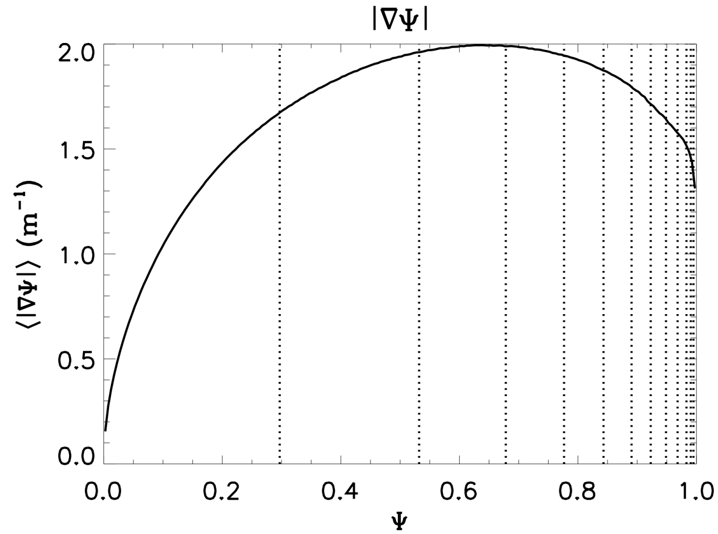
- **EHO is a saturated MHD mode**
  - *n* ~ 2—5
  - Linearly unstable → requires nonlinear modeling
  - "Location" of mode is not certain
  - Mode rotates (i.e. it isn't locked)

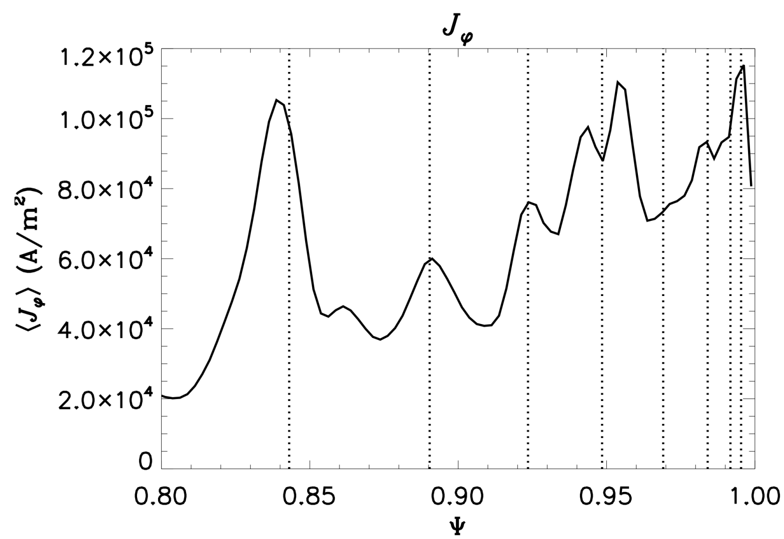


* necessary to be here for QH, but not sufficient!

Boundary Layers in Edge Are Roughly ~1 cm







Two-Fluid Model Implemented in M3D-C1

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{u}) = 0$$

$$n\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \Pi$$

$$\frac{\partial p}{\partial t} + \mathbf{u} \cdot \nabla p = -\Gamma p \nabla \cdot \mathbf{u} - \boxed{\frac{d_i}{n}\mathbf{J} \cdot \left(\Gamma p_e \frac{\nabla n}{n} - \nabla p_e\right)}$$

$$-(\Gamma - 1)\nabla \cdot \mathbf{q}$$

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

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta \mathbf{J} + \boxed{\frac{d_i}{n}(\mathbf{J} \times \mathbf{B} - \nabla p_e)}$$

$$\Pi = -\mu\left[\nabla \mathbf{u} + (\nabla \mathbf{u})^T\right]$$

$$\mathbf{q} = -\kappa \nabla p - \kappa_{\|} \mathbf{b}\mathbf{b} \cdot \nabla\left(\frac{p_e}{n}\right)$$

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

$$\Gamma = 5/3$$

$$p_e = p/2$$

- Two-fluid terms scale with ion skin depth (d_i)
- Time-independent equations may be solved directly for linear response