Modeling Edge Plasma Response to 3D Fields in DIII-D

by

N.M. Ferraro,

T.E. Evans, M.J. Lanctot, L.L. Lao, A.D. Turnbull,
R.A. Moyer,[1] R. Nazikian,[2] D.M. Orlov,[1] M.W. Shafer,[3] E.A. Unterberg[3]

[1] University of California, San Diego
[2] Princeton Plasma Physics Laboratory
[3] Oak Ridge National Laboratory

Presented at the

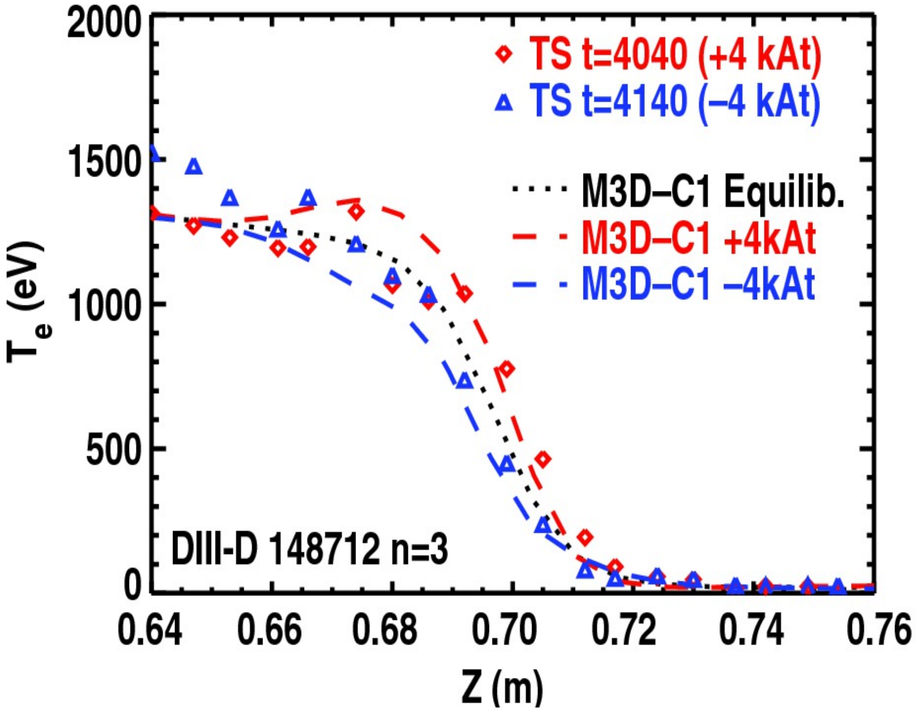
54th Annual APS Meeting
Division of Plasma Physics
Providence, Rhode Island

October 29 — November 2, 2012

Measurements of Edge Response to 3D Fields Are Generally in Good Agreement With Two-Fluid Modeling

- **3D fields have significant impact on tokamak performance**
  - ELM suppression, pump-out, braking, etc.
- **Edge displacements are a robust feature of 3D plasma response**
  - Provide a measurement for validating codes
  - Provide an indication of internal plasma response

T_e profile is “displaced” by 3D fields



- **We find generally good agreement between two-fluid modeling (M3D-C1) and measurements of edge response**

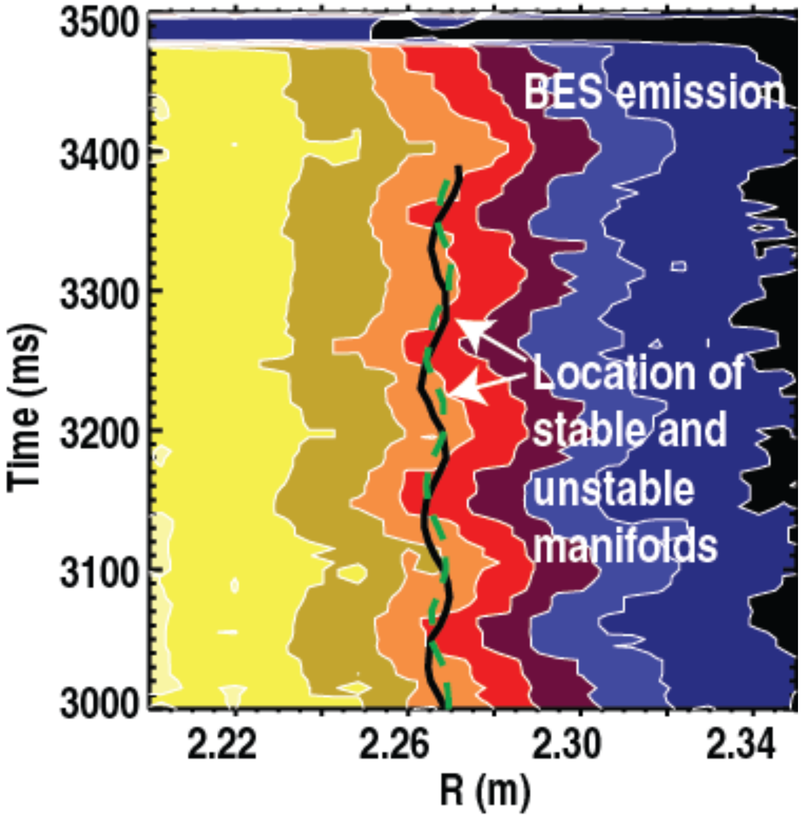
Rotating *n*=1,2 Fields Sweeps Structures Past Diagnostics

- **On DIII-D, the toroidal phase of *n*=1 and *n*=2 fields can be smoothly rotated**

- **Displacement is phase dependent**

- **Two possibilities**
  - Displacement is 3D
  - Displacement is 2D, but phase dependent (*i.e.* there are significant error fields)

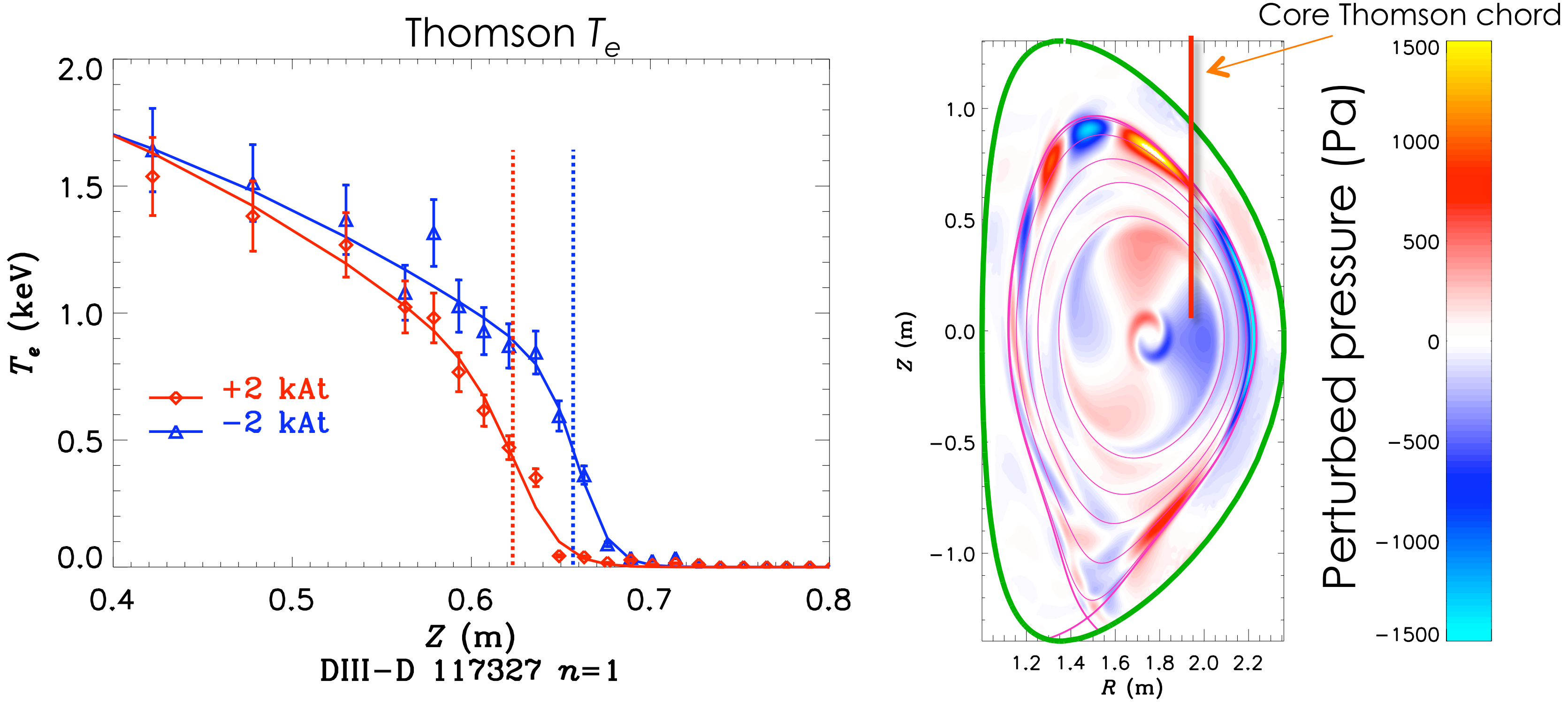
Beam Emission Spectroscopy



- **Measured displacement is generally larger than calculated displacement of separatrix manifolds from vacuum fields**

Large Displacements Also Observed Along Core Thomson Chord

- **Measurements show significant (2–4 cm) displacements of edge *n* and *T* profiles when *n*=1 3D fields are applied**



- **Separatrix displacements due to vacuum fields are only ~few mm**

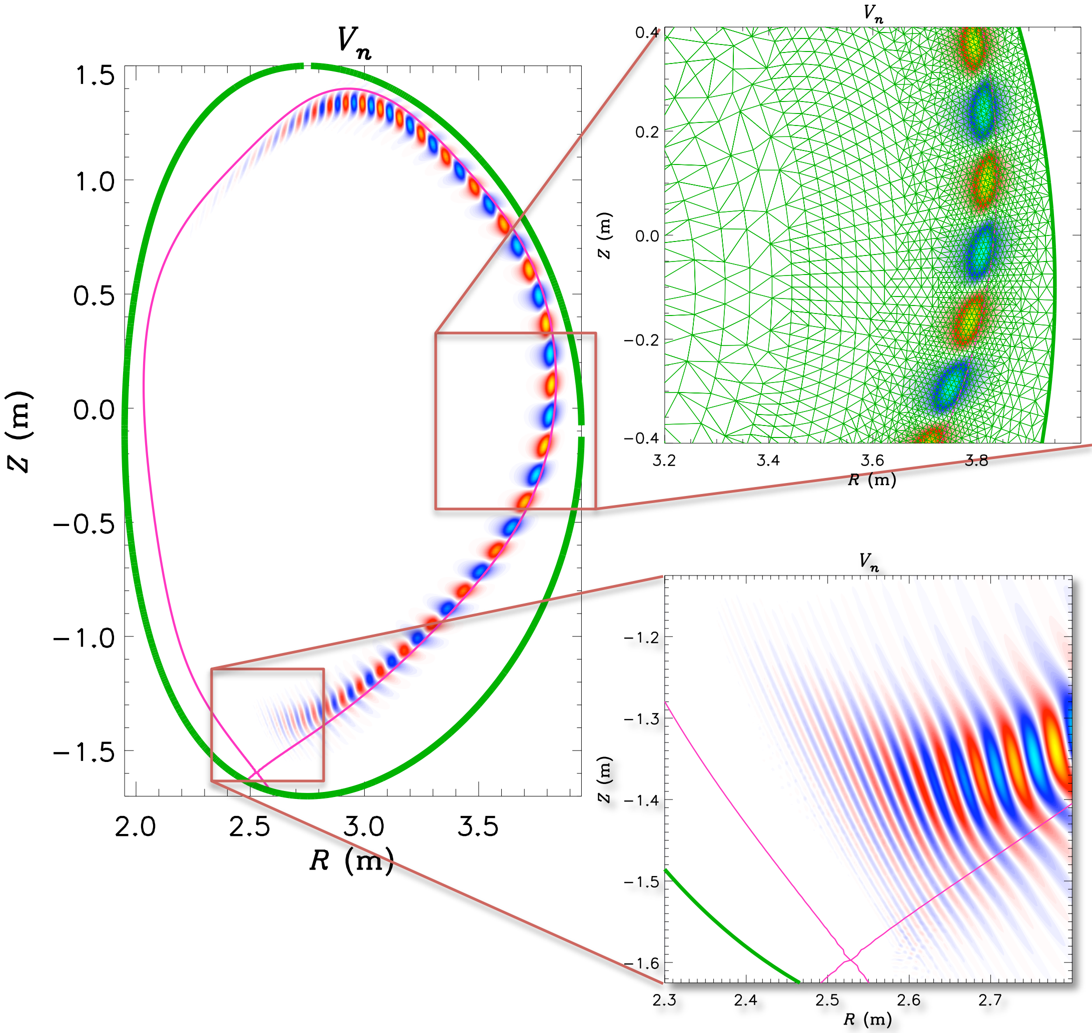
Linear Plasma Response to 3D Fields is Modeled with M3D-C1

- **<u>M3D-C1 ≠ M3D</u>**

- **Model includes**
  - Two-fluid effects
  - Realistic resistivity
  - Scrape-off layer
  - Diverted geometry

- **Mesh can be packed anisotropically**

- **Can solve linear or nonlinear response**
  - Here we consider linear response



DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

Two-Fluid Model Implemented in M3D-C1

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

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

$$\frac{\partial p}{\partial t} + \mathbf{u} \cdot \nabla p = -\Gamma p \nabla \cdot \mathbf{u} - \boxed{\frac{d_i}{n}\mathbf{J} \cdot \left(\Gamma p_e \frac{\nabla n}{n} - \nabla p_e\right)}$$
$$-(\Gamma - 1)\nabla \cdot \mathbf{q}$$

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

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

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

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

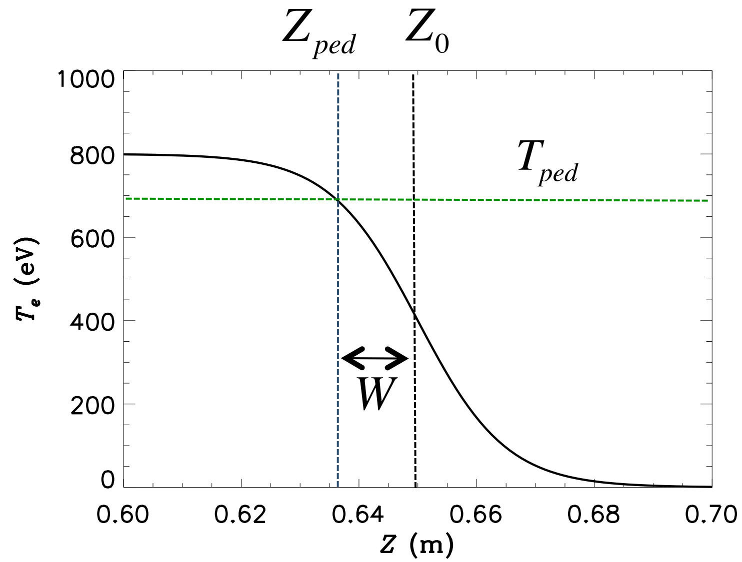
$$\mathbf{J} = \nabla \times \mathbf{B}$$

$$\Gamma = 5/3$$

$$p_e = p/2$$

- Two-fluid terms
- Time-independent equations may be solved directly for linear response
- Boundary conditions: normal B from external coils is held constant at boundary

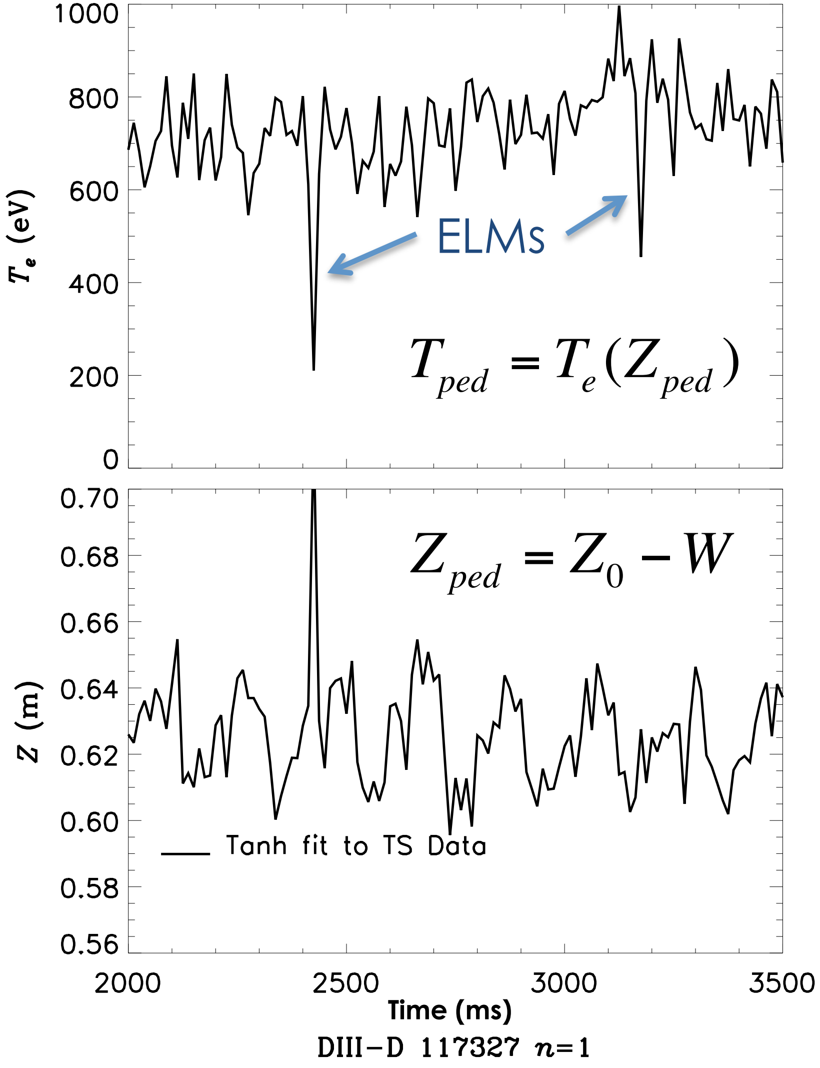
Displacement Can Be Quantified By The Change In The Location Of The Pedestal Top



- **Pedestal top Z_{ped} is defined by tanh fit to data**

$$T_e(Z) = \frac{T_0}{2}\left[1-\tanh\left(\frac{Z-Z_0}{W}\right)\right]$$

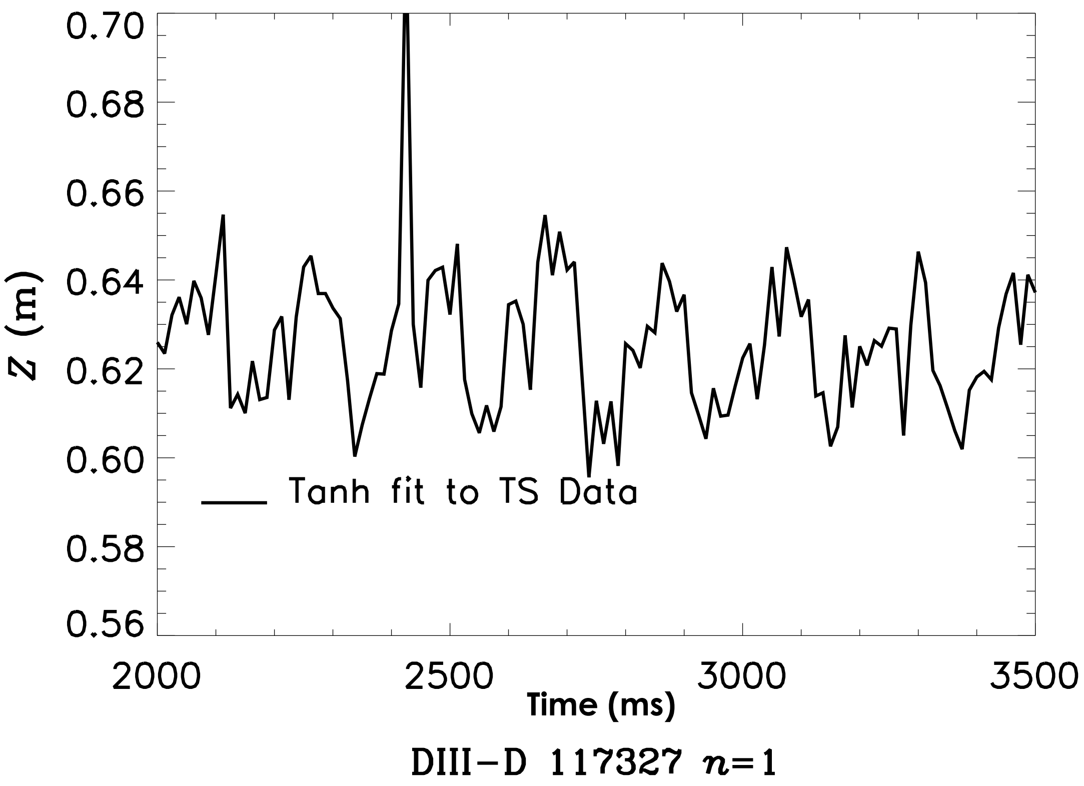
- **Z_{ped} oscillates with phase of applied field (5 Hz)**
- **Little change in T_{ped}**



Two-Fluid Modeling Reproduces Phase and Magnitude of Displacement

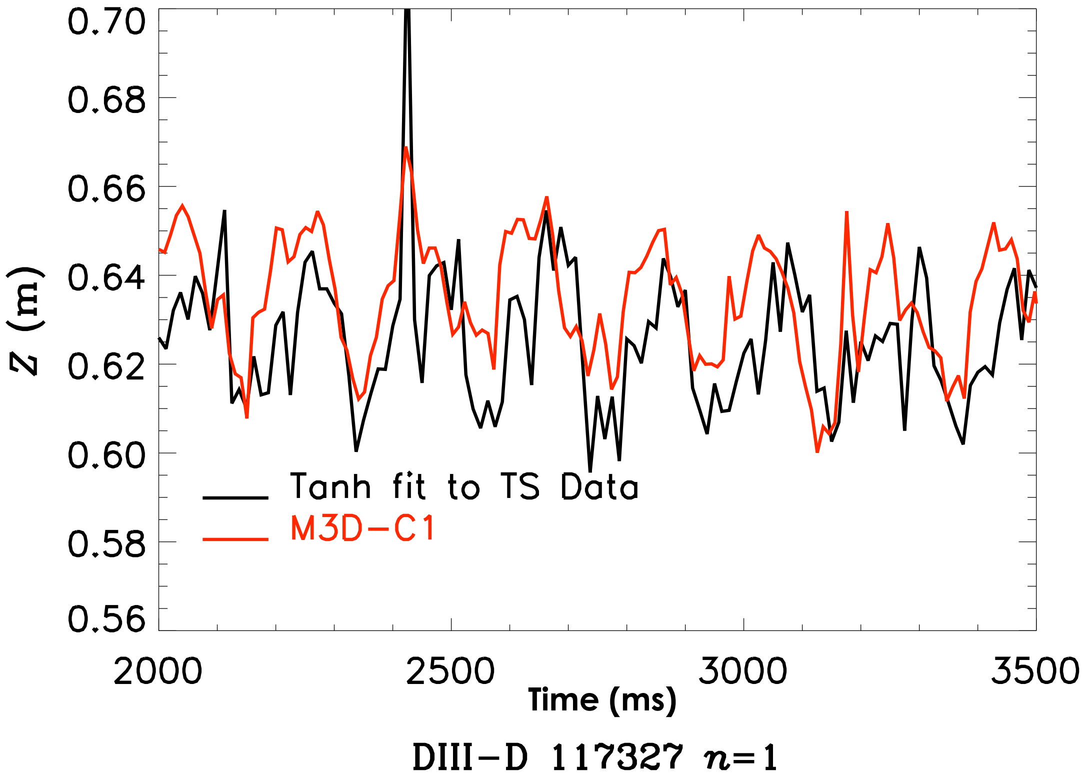
- **In the experiment, the peak-to-peak displacement is ~4 cm**

- **Vacuum modeling finds few mm**



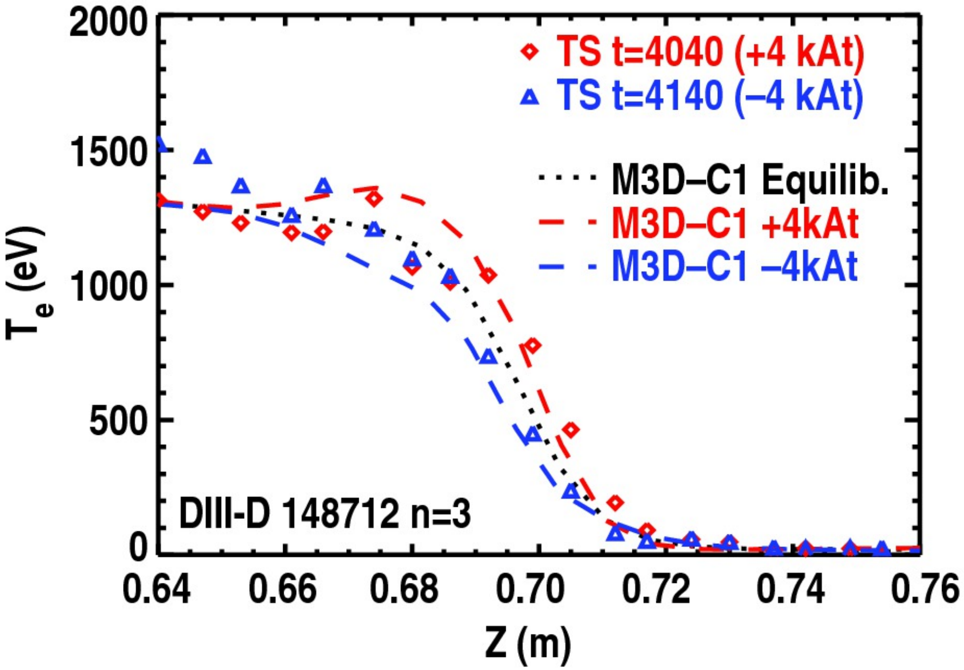
Two-Fluid Modeling Reproduces Phase and Magnitude of Displacement

- **In the experiment, the peak-to-peak displacement is ~4 cm**
- **Vacuum modeling finds few mm**
- **M3D-C1 Modeling finds good agreement in phase and magnitude of displacement**



n=3 Fields Yield Smaller Displacements Than *n*<3

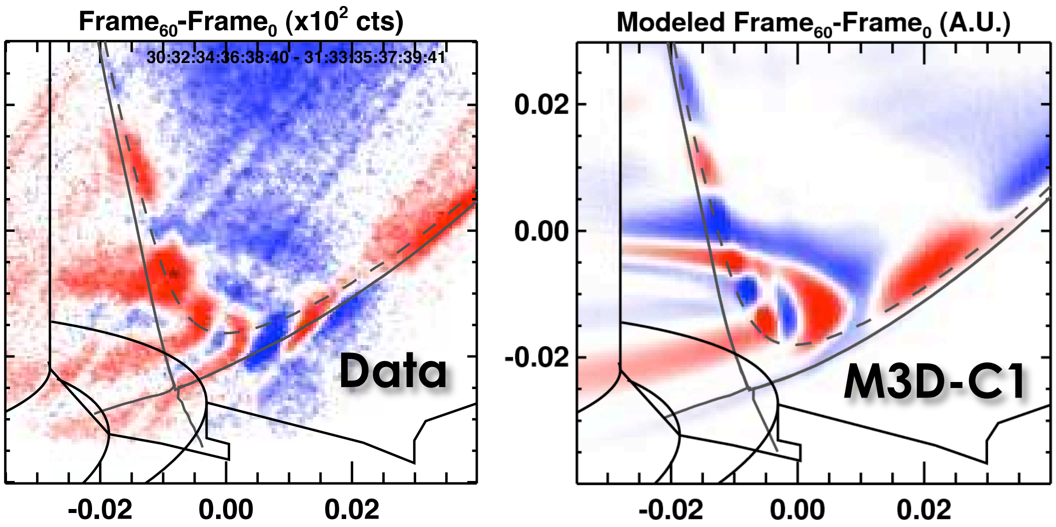
- ***n*=3 fields cannot be rotated on DIII-D, but can be flipped**
- **Flipping *n*=3 fields yields displacement of ~1—2 cm**



- **M3D-C1 finds agreement through much of pedestal**

X-Ray Data Reveals Field-Aligned 3D Structure

- Data is obtained by flipping I-coil fields and taking difference between signals



Frame$_{60}$-Frame$_0$ (x10^2 cts)

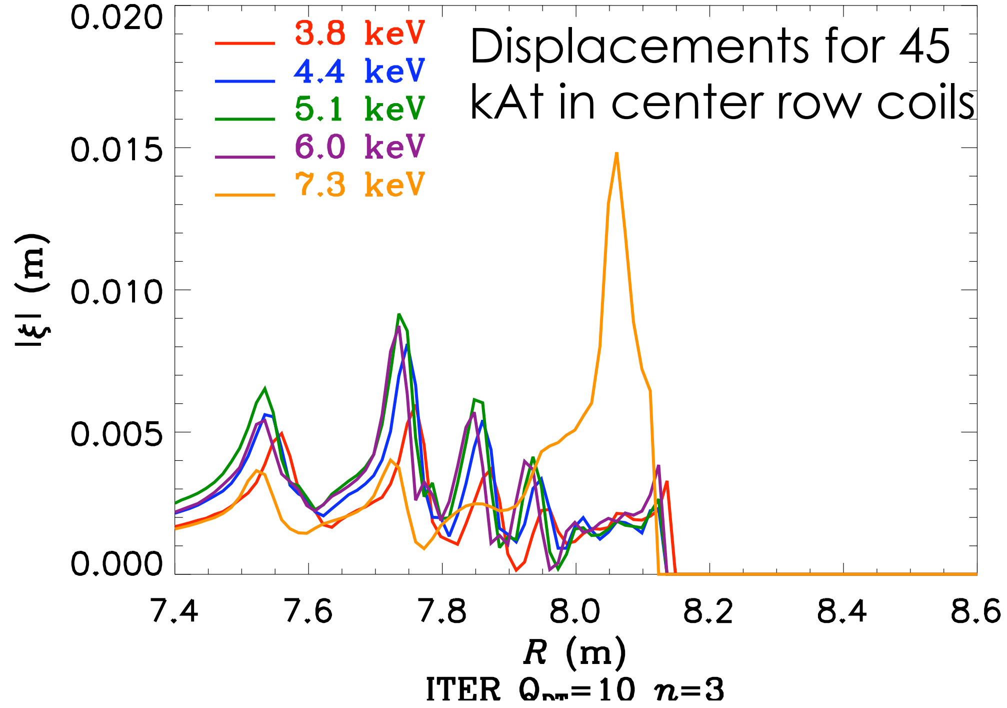
Modeled Frame$_{60}$-Frame$_0$ (A.U.)

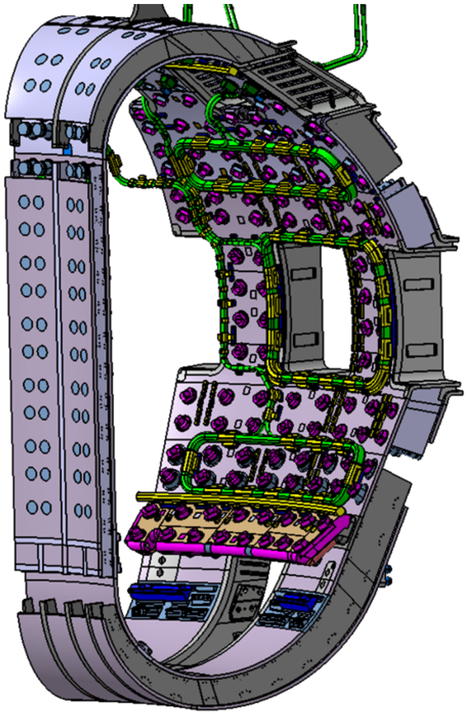
- The poloidal structure is strongly indicative of a <u>field-aligned helical response</u>

- Modeling agrees qualitatively with poloidal structure of response

- Radial localization indicates driven peeling-ballooning response

Preliminary Results Show ~1 cm Midplane Displacements for ITER

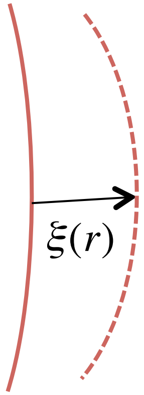




- **Midplane edge displacements are found to be ~1/2 cm in Q_{DT}=10 scenarios with 45 kAt in the center row**
  - Only center row considered (found to have strongest coupling)
  - ITER Q_{DT}=10 scenarios have ~10 cm outer gap

Linear Results Appear to be Valid In These Cases

- **"Displacement" may be defined by movement of isotherms**



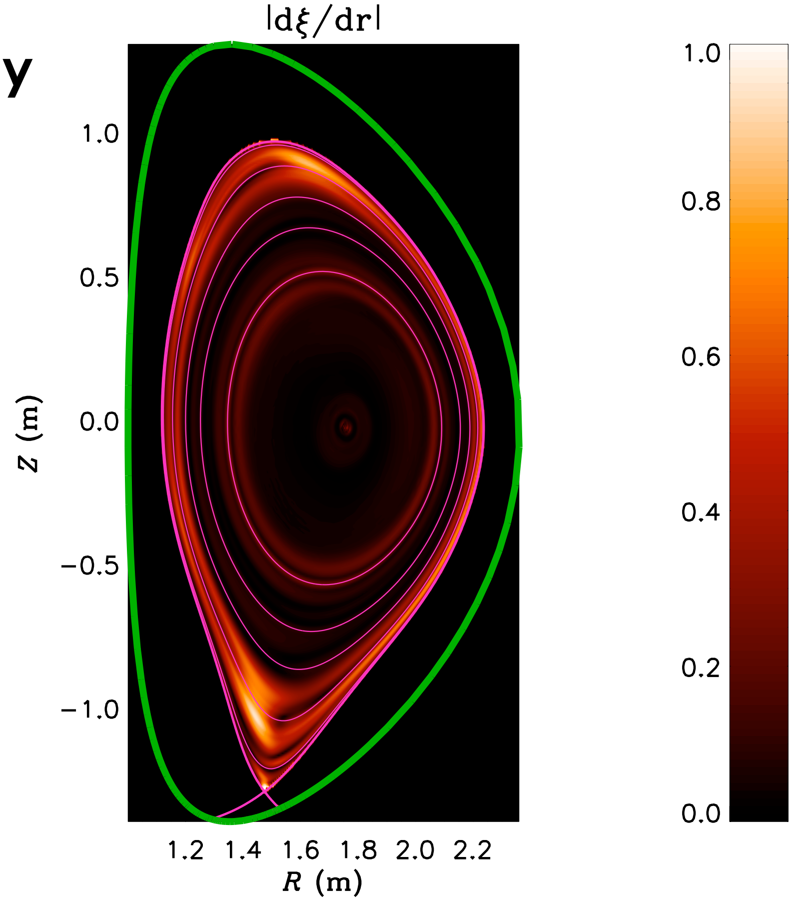
$$T_0(r+\xi) + \delta T(r+\xi) = T_0(r)$$

$$\left[T_0(r) + \frac{dT_0}{dr}\xi\right] + \delta T(r) = T_0(r)$$

$$\xi = -\frac{\delta T}{dT_0/dr}$$

- **Overlap of adjacent surfaces is possible, especially near mode-rational surfaces, edge, & x-point**

Overlap criterion: $\left|\frac{d\xi}{dr}\right| > 1$



DIII-D 117327 *n*=1

Summary

- **Plasma response calculations yield good agreement with experimental measurements of edge displacement**

- **Edge displacements are largely helical, not (just) axisymmetric**
  - M3D-C1 response is purely helical, and agrees with experiment
  - X-ray data shows clear helical response

- **Displacements may be strongly enhanced by plasma response (*i.e.* stable mode driven to finite amplitude)**

- **This tool will help us extrapolate to ITER with some confidence**