RMP Modeling

by

N.M. Ferraro

Presented at the

CEMM Meeting

Providence, Rhode Island

October 28, 2012

We Need a Predictive Model for Plasma Response to 3D Fields in Tokamaks

- **Effects of 3D fields need to be evaluated for ITER:**
  - RMP ELM suppression
  - Changes in particle/heat flux to wall
    - Edge displacements
    - Divertor footprints
  - Fast ion transport
  - Mode locking

- **We now have the tools and the measurements to evaluate our capabilities to model some of these things**
  - Modeling of edge displacements generally finds good agreement with experiment

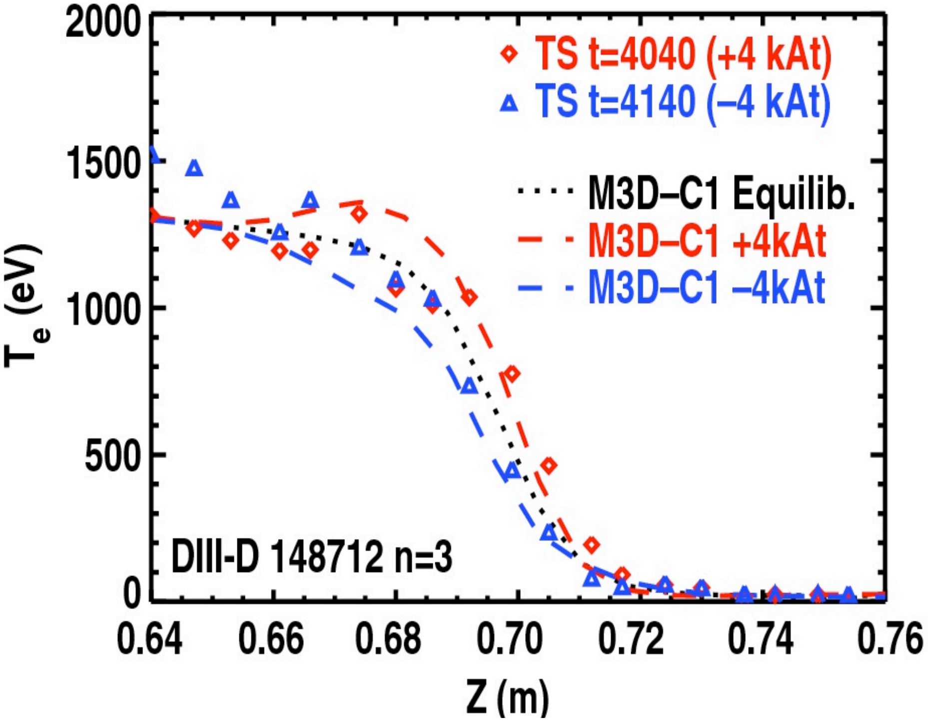
- **Transport in 3D fields is next step towards predictive models**

Edge Displacement

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

- **T_e and n_e profiles are "displaced" by the application of 3D fields**

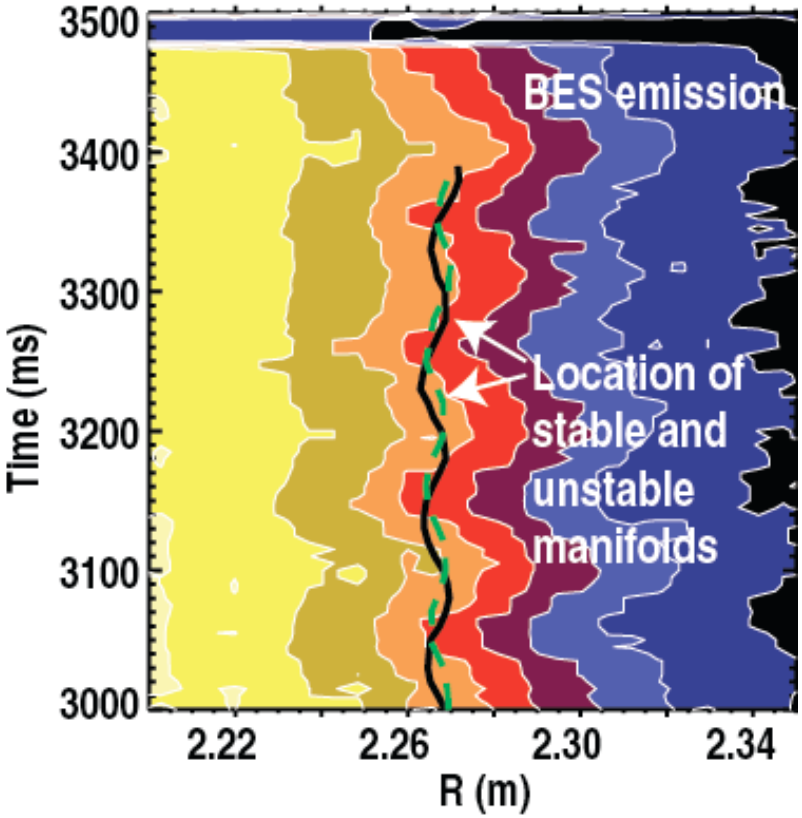
- **Edge displacements are a robust feature of 3D plasma response**
  - Provide a measurement for validating codes
  - Provide an indication of internal plasma response
  - May cause problems in ITER
    - Focus of ITPA WG (Chapman)



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

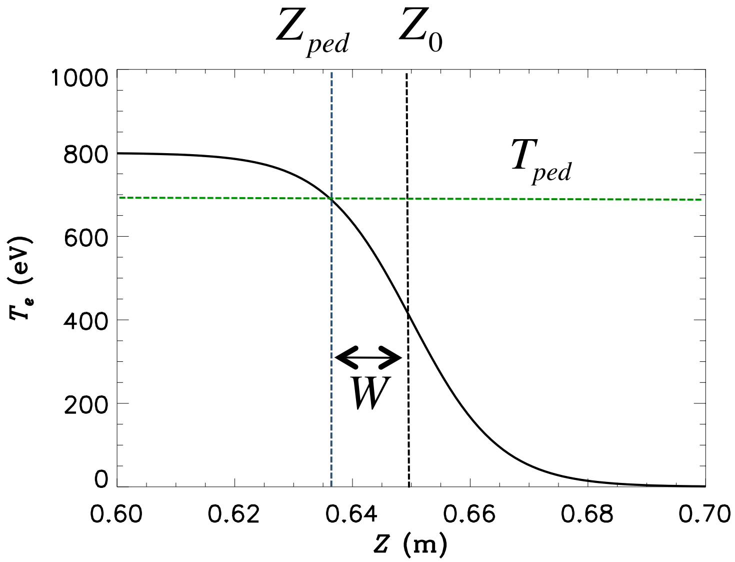
Rotating *n*=1,2 Fields Sweeps Structures Past Diagnostics

- **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)



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

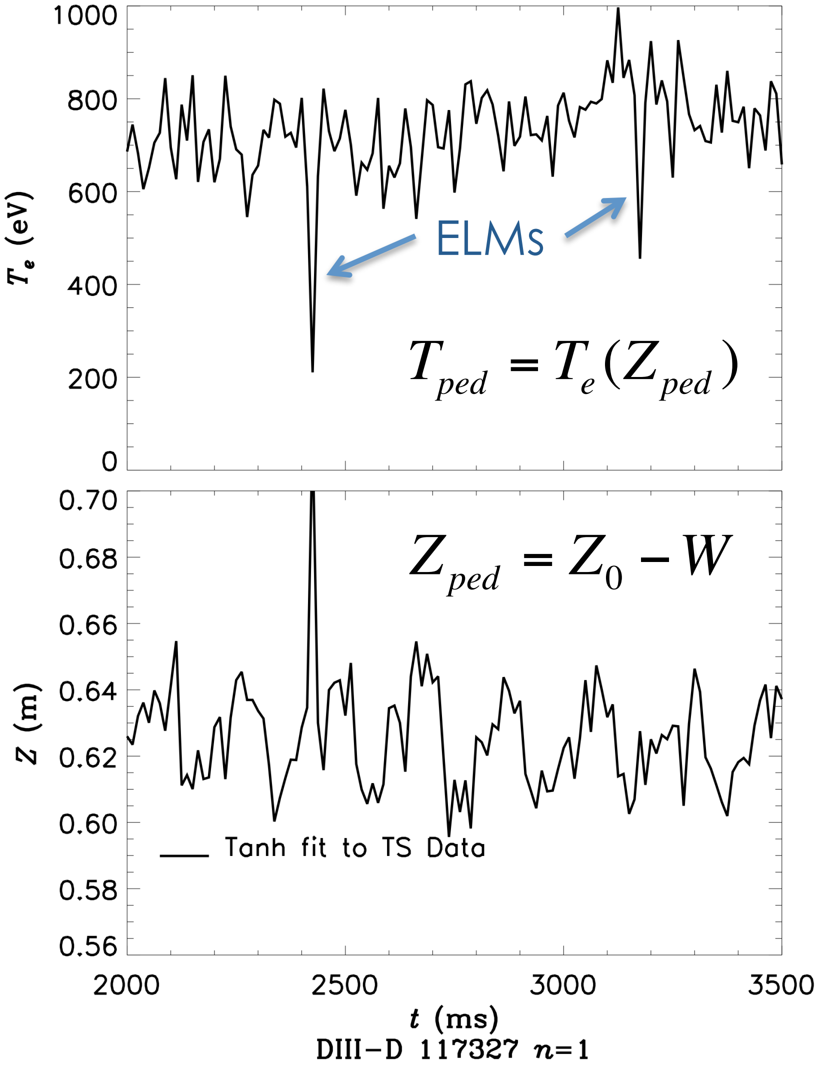
Displacement Can Be Quantified By The Change In The Location Of The Pedestal Top



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

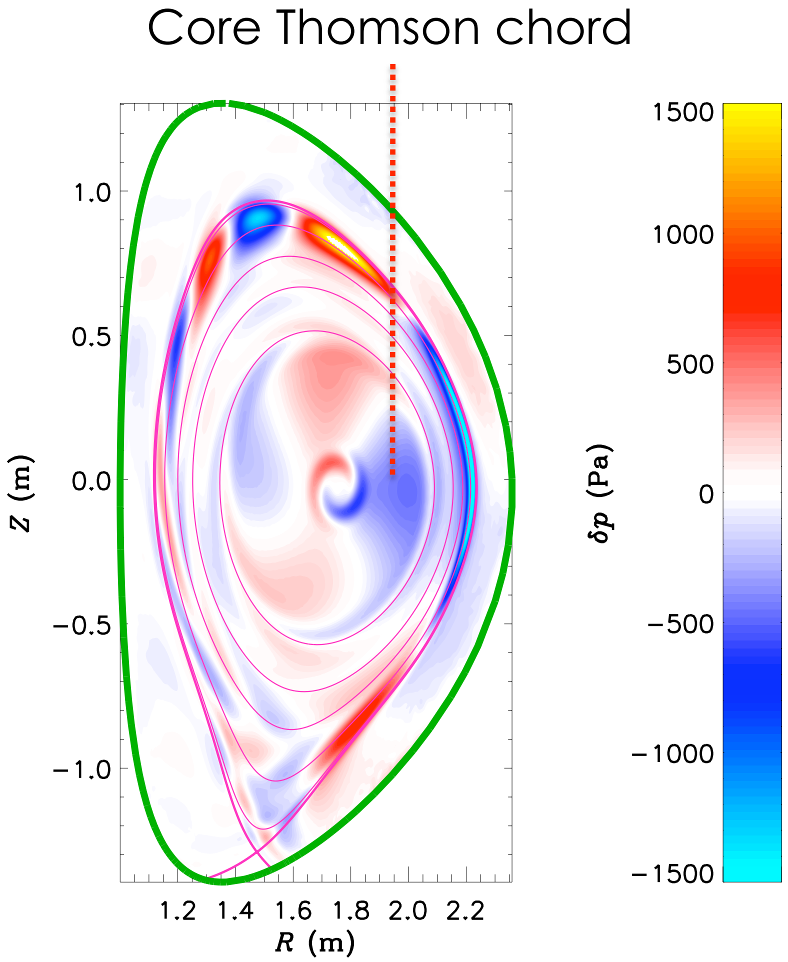
$$T_e(Z) = \frac{T_0}{2}\left[1-\tanh\left(\frac{Z-Z_0}{W}\right)\right]$$

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



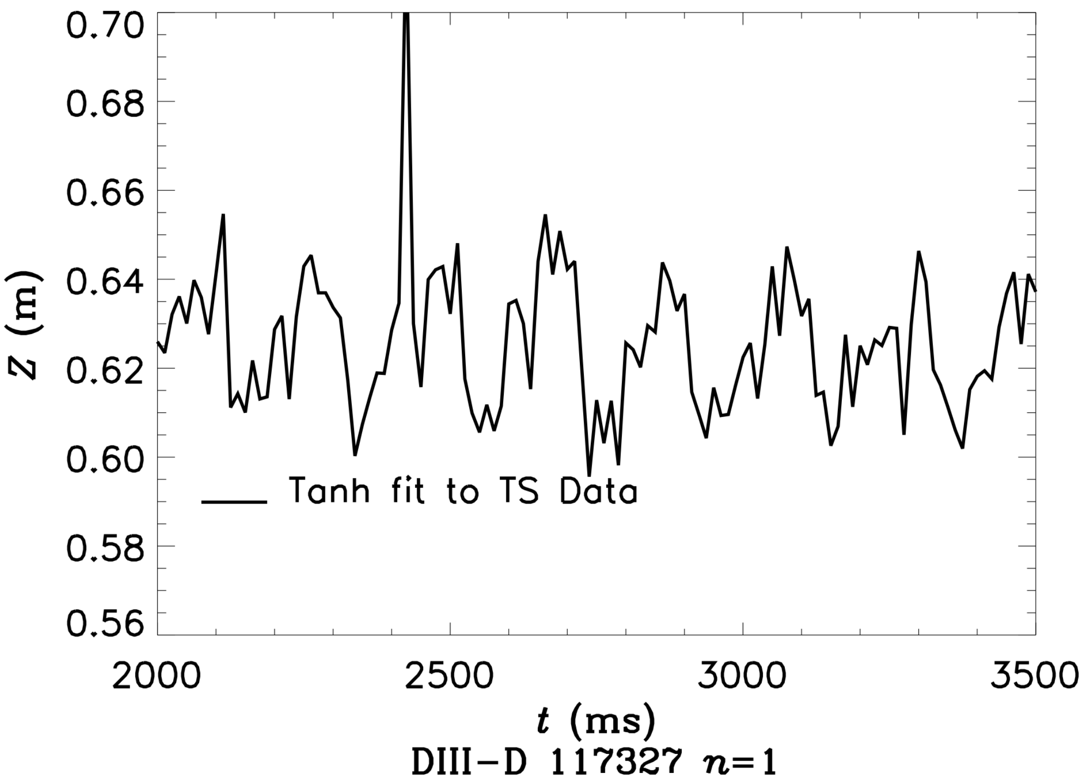
Time-Independent Response is Calculated as Boundary-Value Problem

- **Boundary Conditions:**
  - Normal component of magnetic field is fixed equal to applied field
  - No-slip, no pressure perturbation
- **Linear time-independent solution is solved directly (not by initial value calculation)**



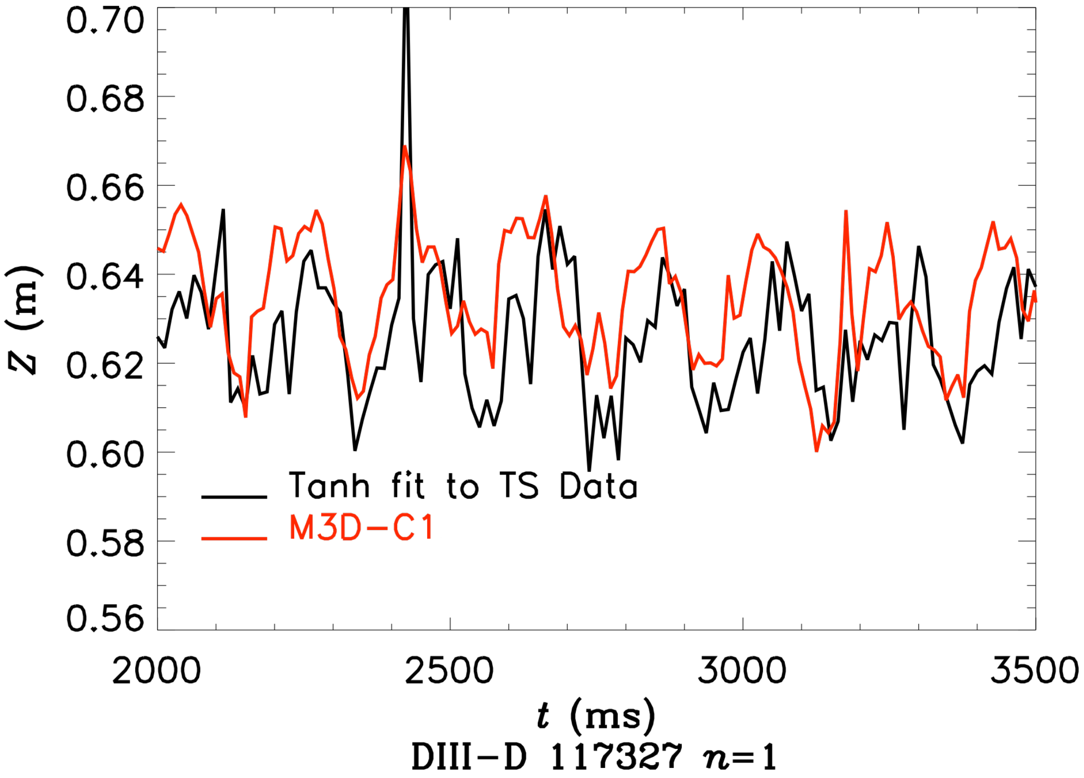
Two-Fluid Modeling Reproduces Phase and Magnitude of Displacement

- **In the experiment, the peak-to-peak displacement is ~4 cm**
- **Vacuum modeling finds few mm**



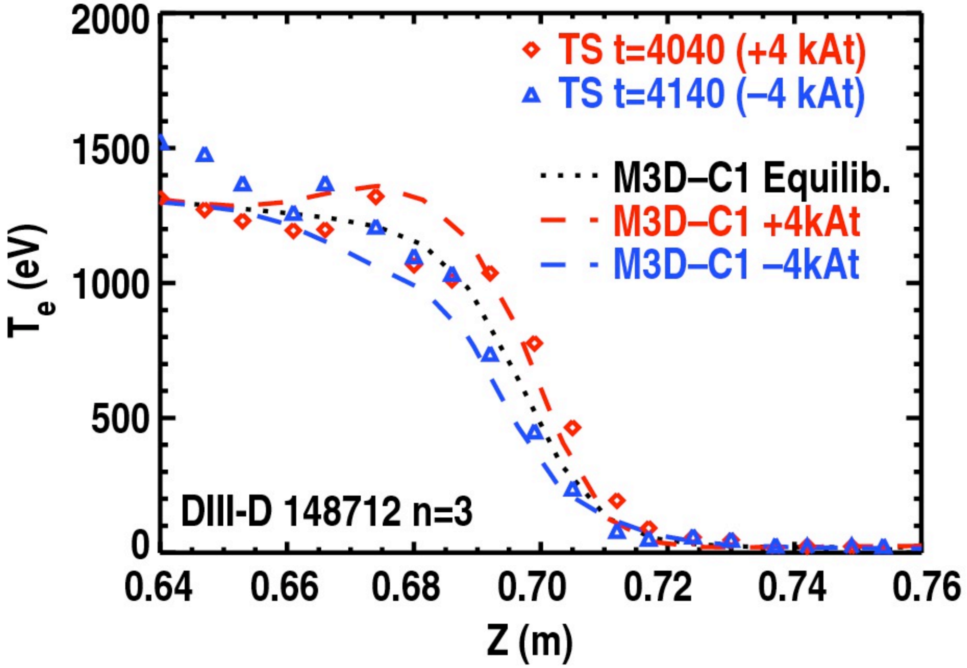
Two-Fluid Modeling Reproduces Phase and Magnitude of Displacement

- **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

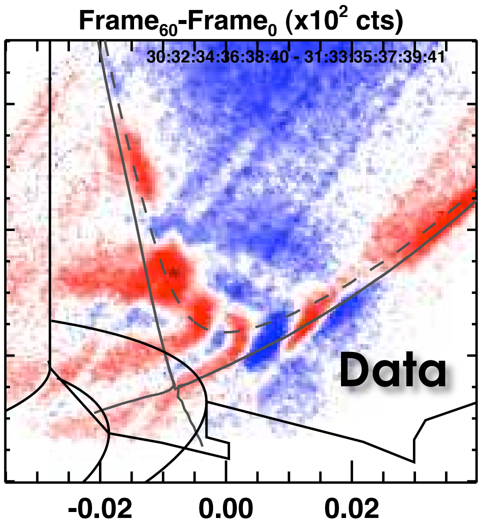
- ***n*=3 fields cannot be rotated on DIII-D, but can be flipped**
- **Flipping *n*=3 fields yields displacement of ~1—2 cm**



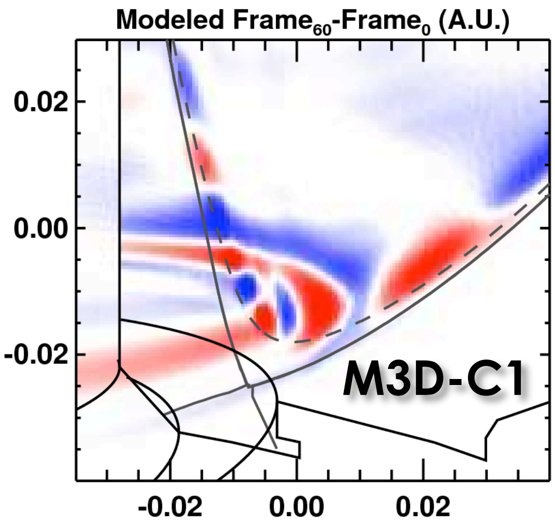
- **M3D-C1 finds agreement through much of pedestal**

X-Ray Data Reveals Field-Aligned 3D Structure

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



$\text{Frame}_{60}\text{-Frame}_{0}$ ($\times 10^2$ cts)



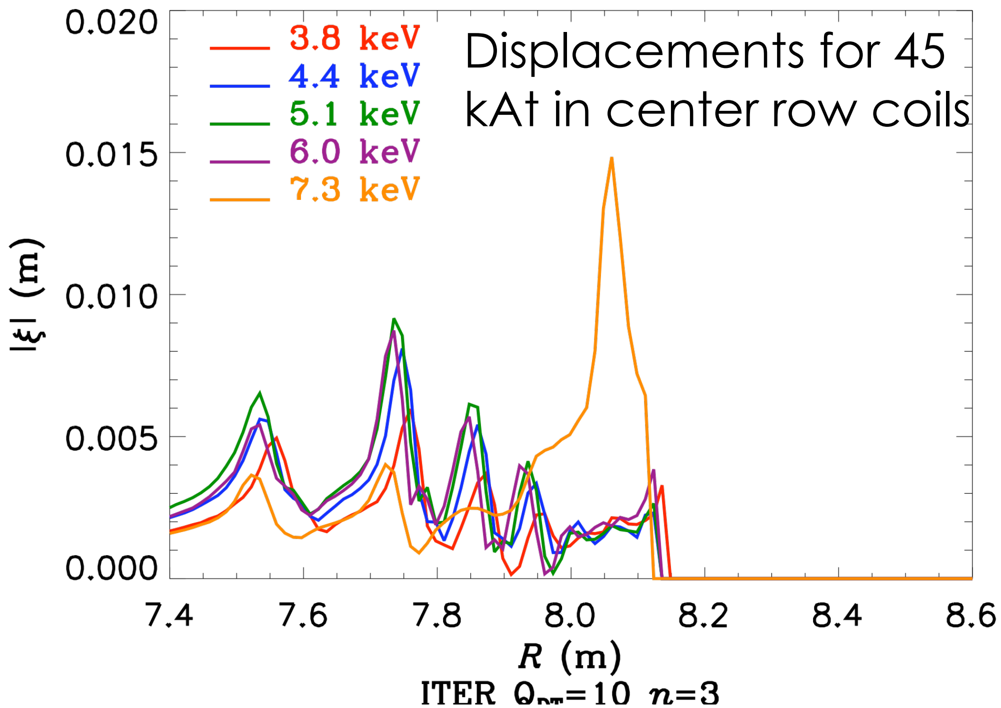
Modeled $\text{Frame}_{60}\text{-Frame}_{0}$ (A.U.)

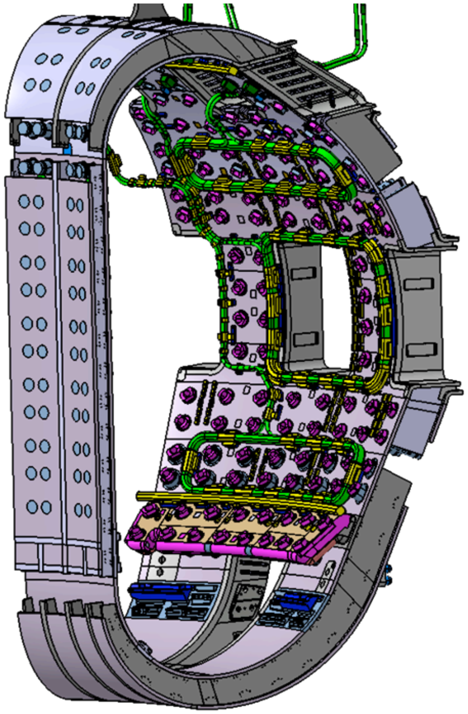
- **The poloidal structure is strongly indicative of a <u>field-aligned helical response</u>**

- **Modeling agrees qualitatively with poloidal structure of response**

- **Radial localization indicates driven peeling-ballooning response**

Preliminary Results Show Moderate Displacements for ITER

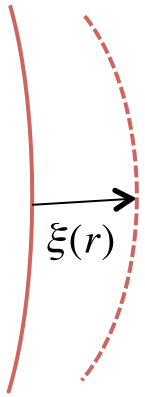




- **Midplane edge displacements are found to be ~1/2 cm in Q_{DT}=10 scenarios with 45 kAt in the center row**
  - Only center row considered (found to have strongest coupling)
  - ITER Q_{DT}=10 scenarios have ~10 cm outer gap

Linear Results Appear to be Valid In These Cases

- **“Displacement” may be defined by movement of isotherms:**



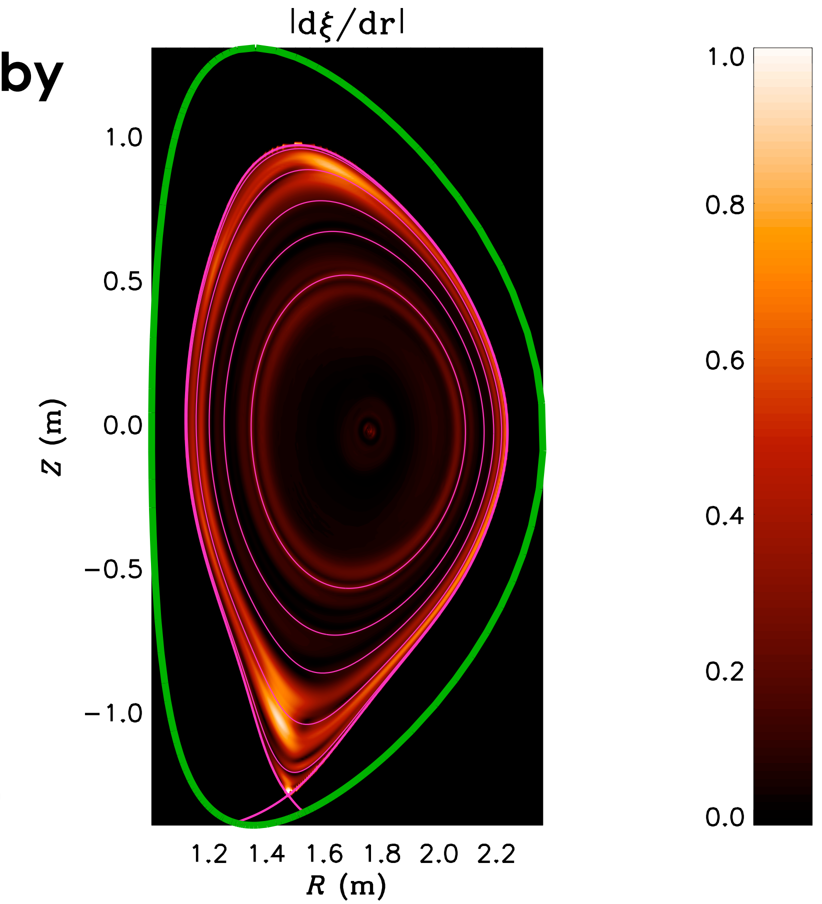
$$T_0(r+\xi) + \delta T(r+\xi) = T_0(r)$$

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

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

- **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

Transport in 3D Fields

Predictive Modeling of Requires Calculation of Transport in 3D Fields

- **Transport in 3D fields is necessary for predictive modeling**
  - Fast ion loss
  - Torque from RMP
  - RMP ELM suppression

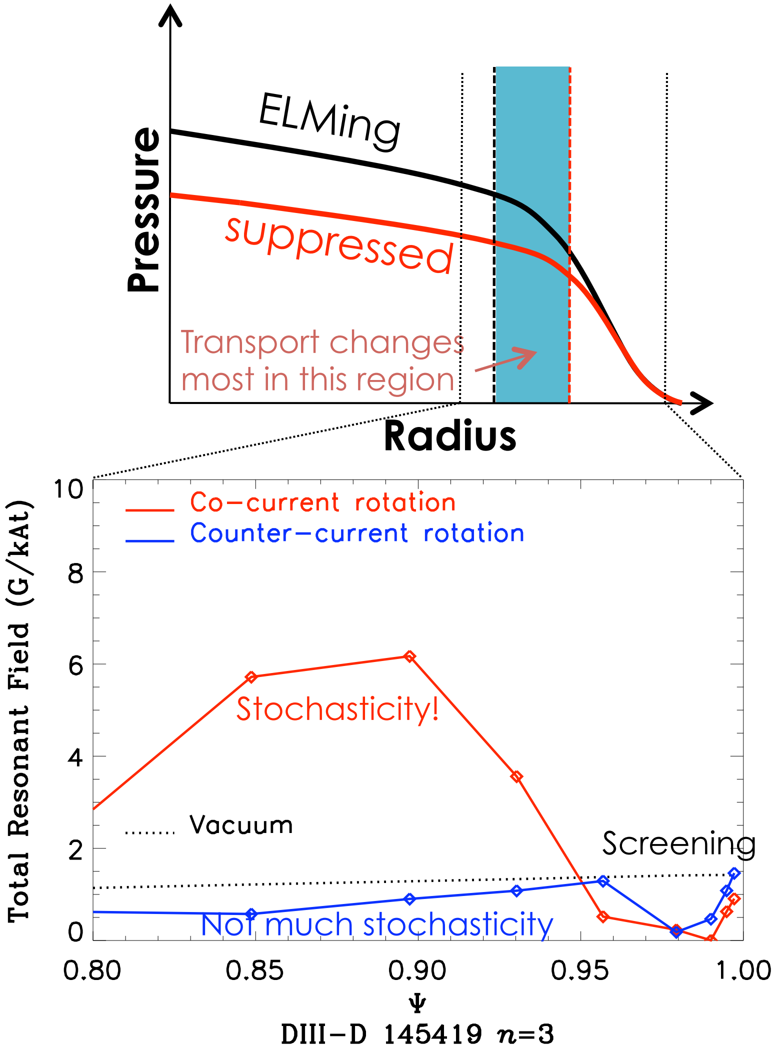
- **New tools and interfaces are being developed for this purpose using fields from M3D-C1**
  - Single-particle orbit calculations (ORBIT-RF, SPIRAL)
    - Choi GP8.00098
  - NTV torque calculations (Cole, Callen)
    - McCubbin JP8.00016
  - Flutter transport calculations (Callen)
    - Raum JP8.00017
  - Ballooning mode stability (Bird)

Island Formation at Pedestal Top is a Promising Hypothesis for RMP ELM Suppression

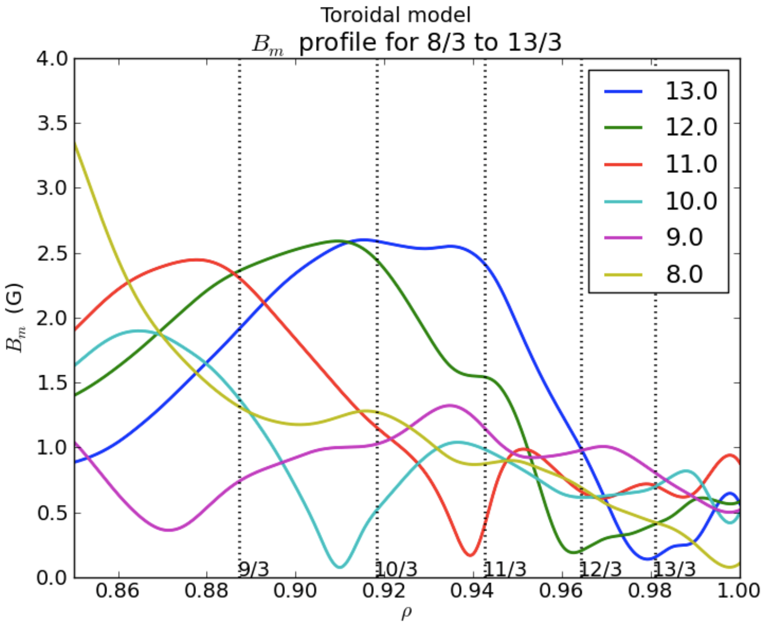
- **Hypothesis: RMP ELM suppression is achieved by limiting pedestal width**
  - Confinement is degraded by 3D fields at top of pedestal

- **Does response at top of pedestal cause ELM suppression?**
  - With co-current rotation, a large response is expected at pedestal top (where ω_e crosses zero)
  - RMP ELM suppression not definitively observed with counter-current rotation (since ω_e never crosses zero)

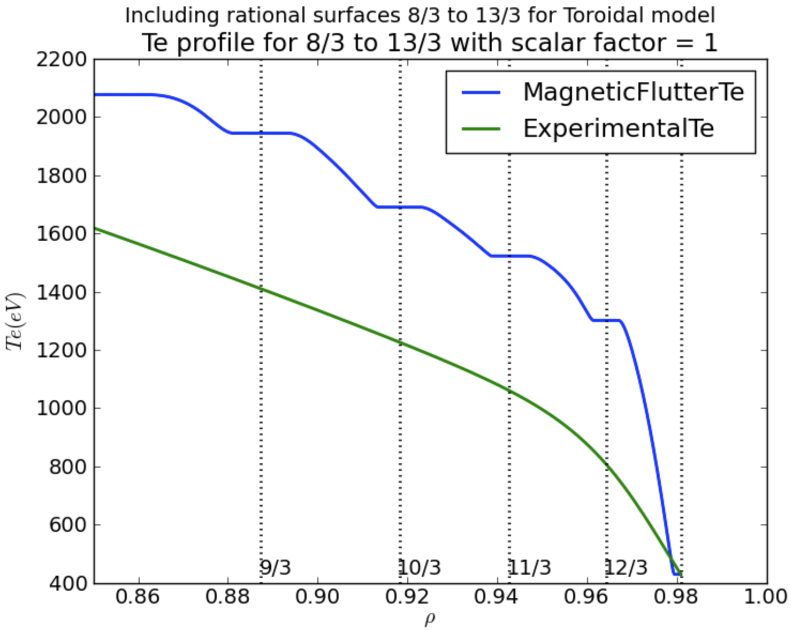
- **What is the source of the additional transport?**



Flutter Transport Calculations Show Enhanced Thermal Transport Near Pedestal Top


Toroidal model

B_m profile for 8/3 to 13/3


Including rational surfaces 8/3 to 13/3 for Toroidal model

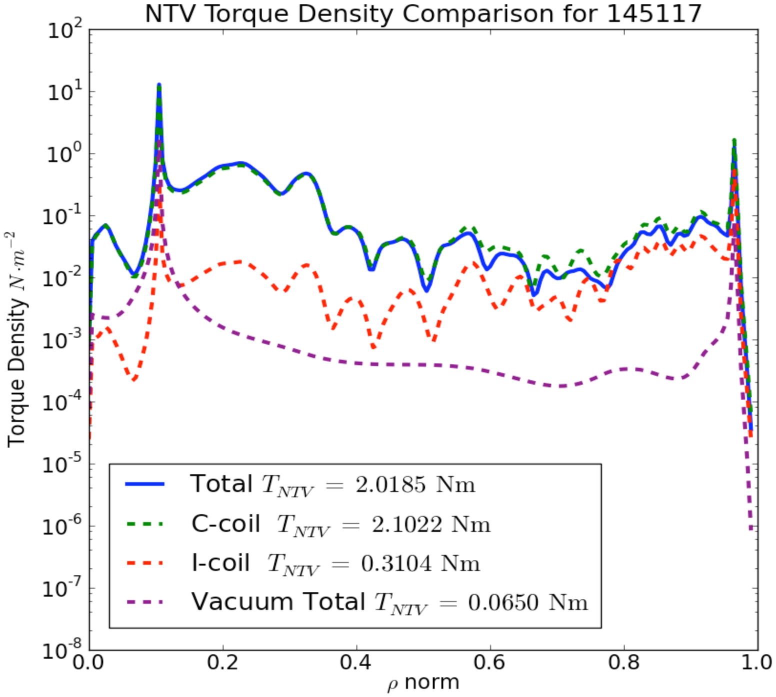
Te profile for 8/3 to 13/3 with scalar factor = 1

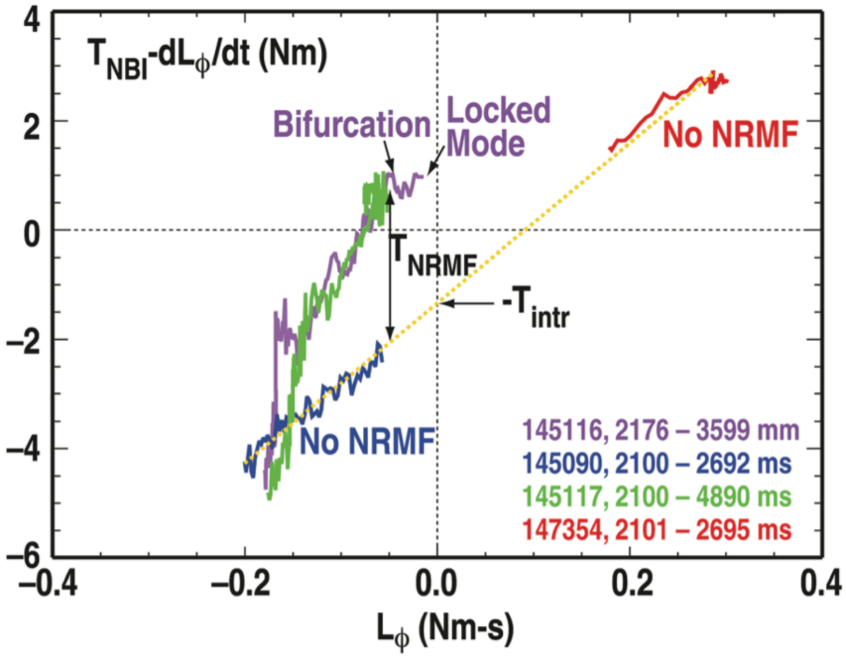
- **Magnetic response from M3D-C1 can serve as basis for transport calculations**
  - – TRIP3D → parallel thermal transport
  - – ORBIT-RF / SPIRAL → fast ion transport
  - – New post-analysis tools for NTV & flutter transport
  - – 3D KBM stability

Raum JP8.00017
Callen BP8.00160

NTV Calculation Using M3D-C1 Fields Finds Agreement with Experiment

- **Evaluating Cole's formula for NTV finds:**
  - 0.065 Nm using vacuum fields
  - 2.0185 Nm using plasma response





- **Both experiment and previous calculations using IPEC response find 2—3 Nm**

McCubbin JP8.00016

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)**

- **Transport calculations in 3D fields are being integrated with M3D-C1 calculations**

Extra Slides

Two-Fluid Model Implemented in M3D-C1

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

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

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

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

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

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

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

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

$$\Gamma = 5/3$$

$$p_e = p/2$$

- Two-fluid terms scale with ion skin depth (d_i)
- Time-independent equations may be solved directly for linear response
- Boundary conditions: normal B from external coils is held constant at boundary