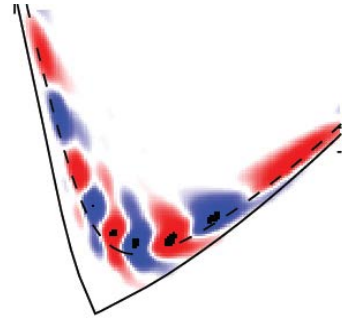
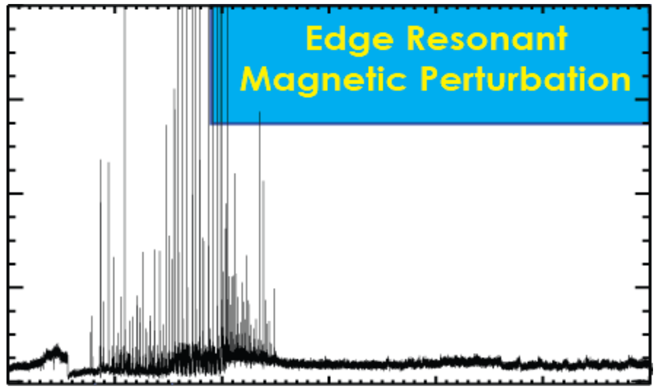
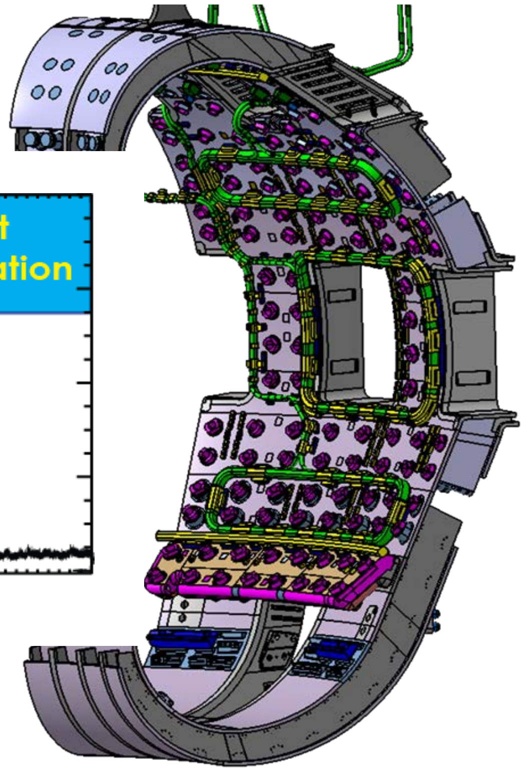
Advances in the Physics Understanding of ELM Suppression Using Resonant Magnetic Perturbations in DIII-D



by

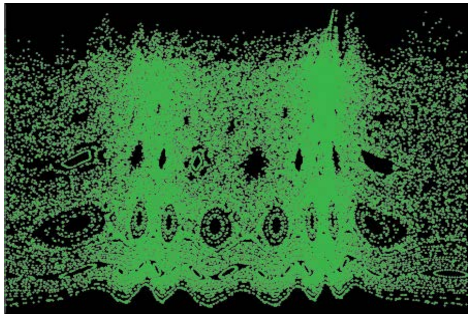
M.R. Wade for the DIII-D ELM Control Task Force





Presented at

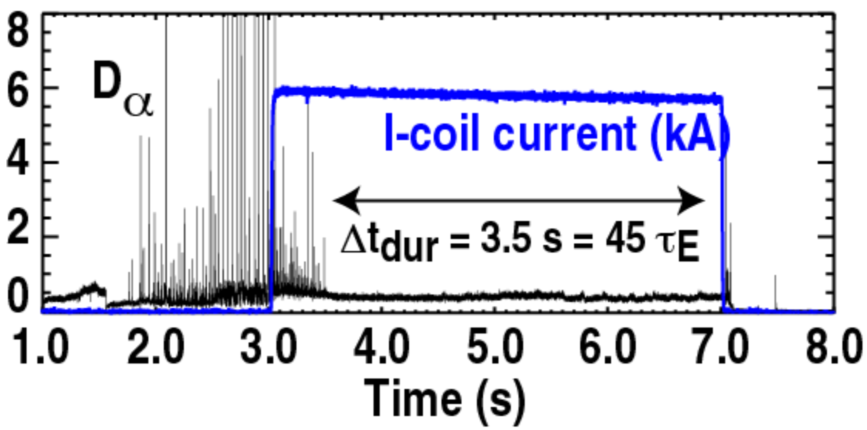
2012 IAEA Fusion Energy Conference San Diego, California



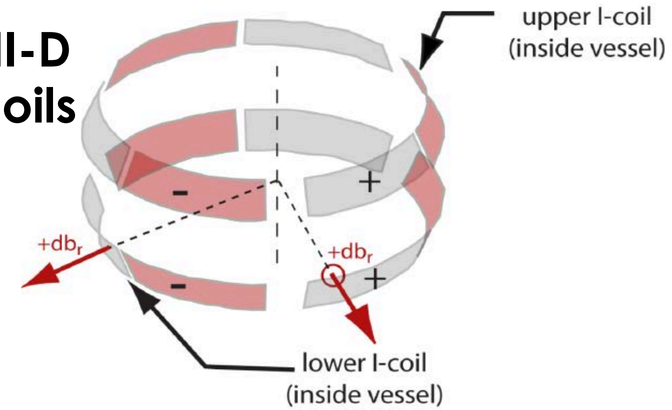
October 8–13, 2012

DIII-D Research Has Increased Confidence in Ability to Achieve RMP ELM Suppression on ITER

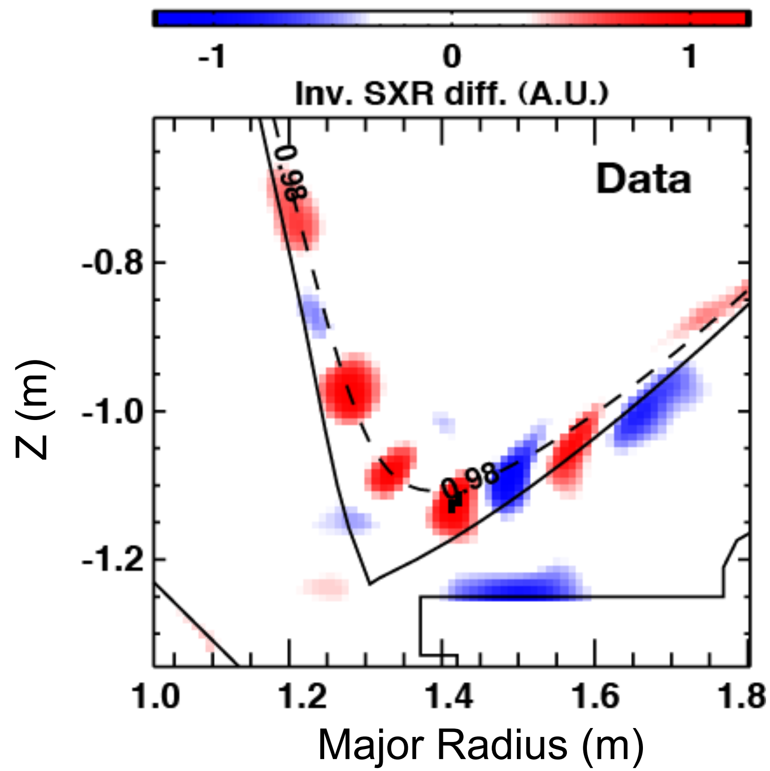
- **ELM suppression operating space expanded to include ITER baseline**



DIII-D I-coils

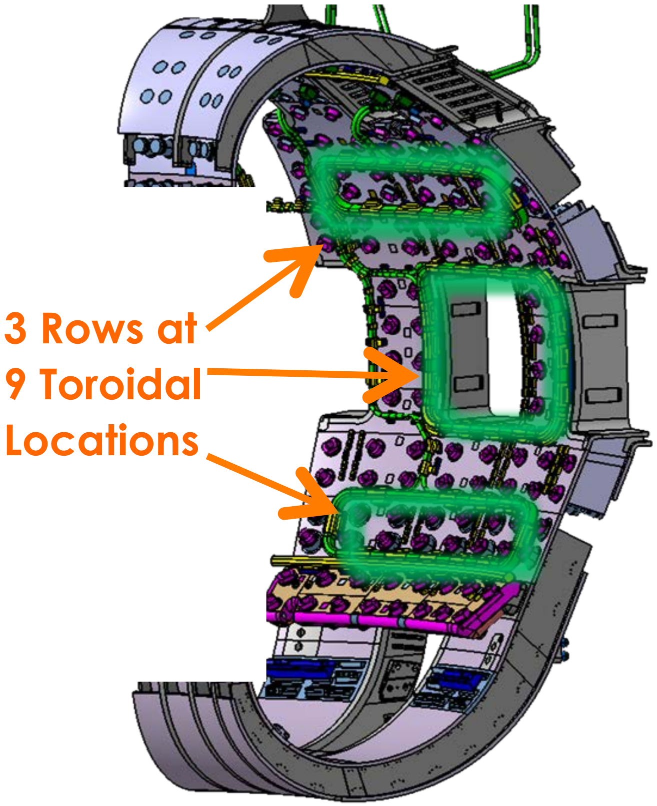


- **Significant advances in physics understanding of RMP effects**

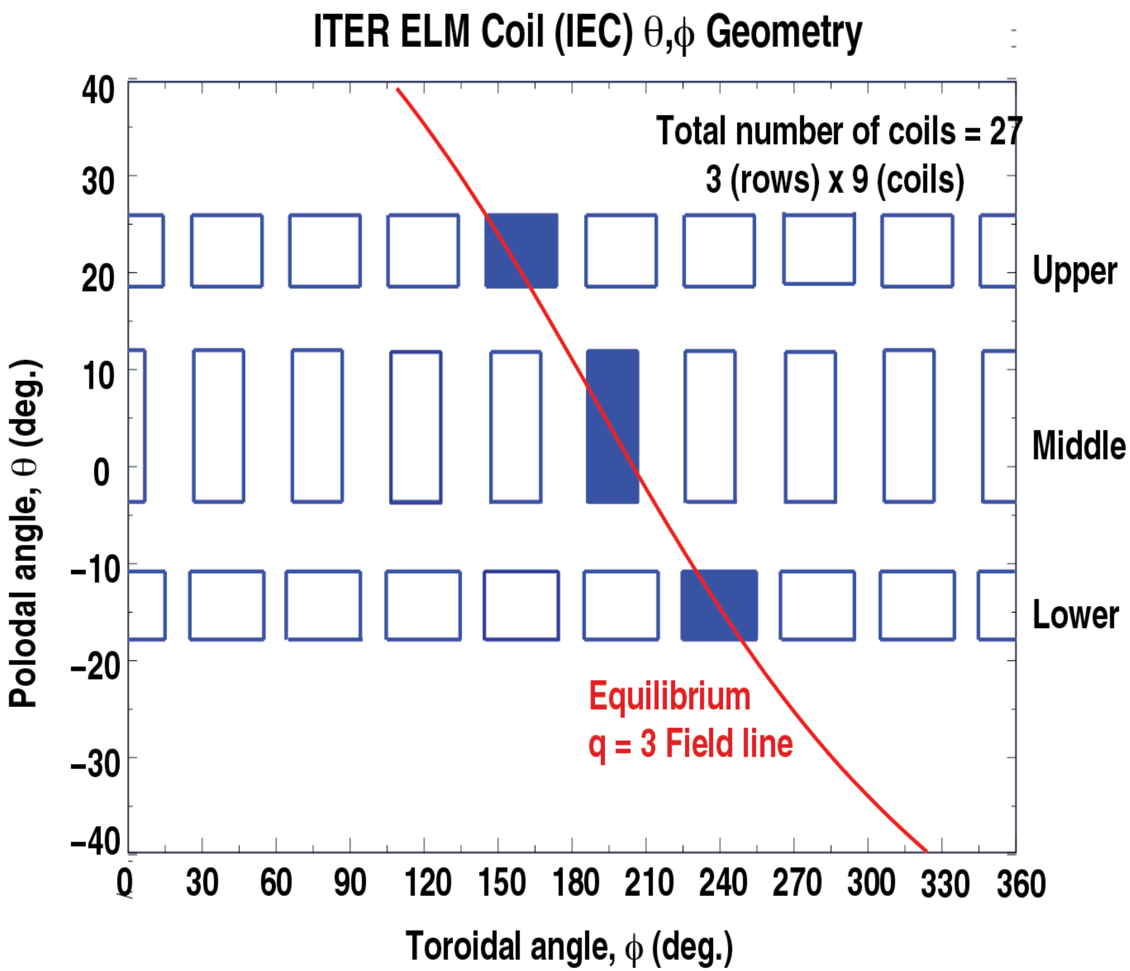


ITER Design Incorporates 3D Coil Set for Producing Magnetic Perturbations Localized in the Edge

ITER ELM Control Coils

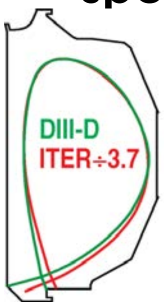


Goal: Generate 3D field that is pitch-aligned to the edge equilibrium field



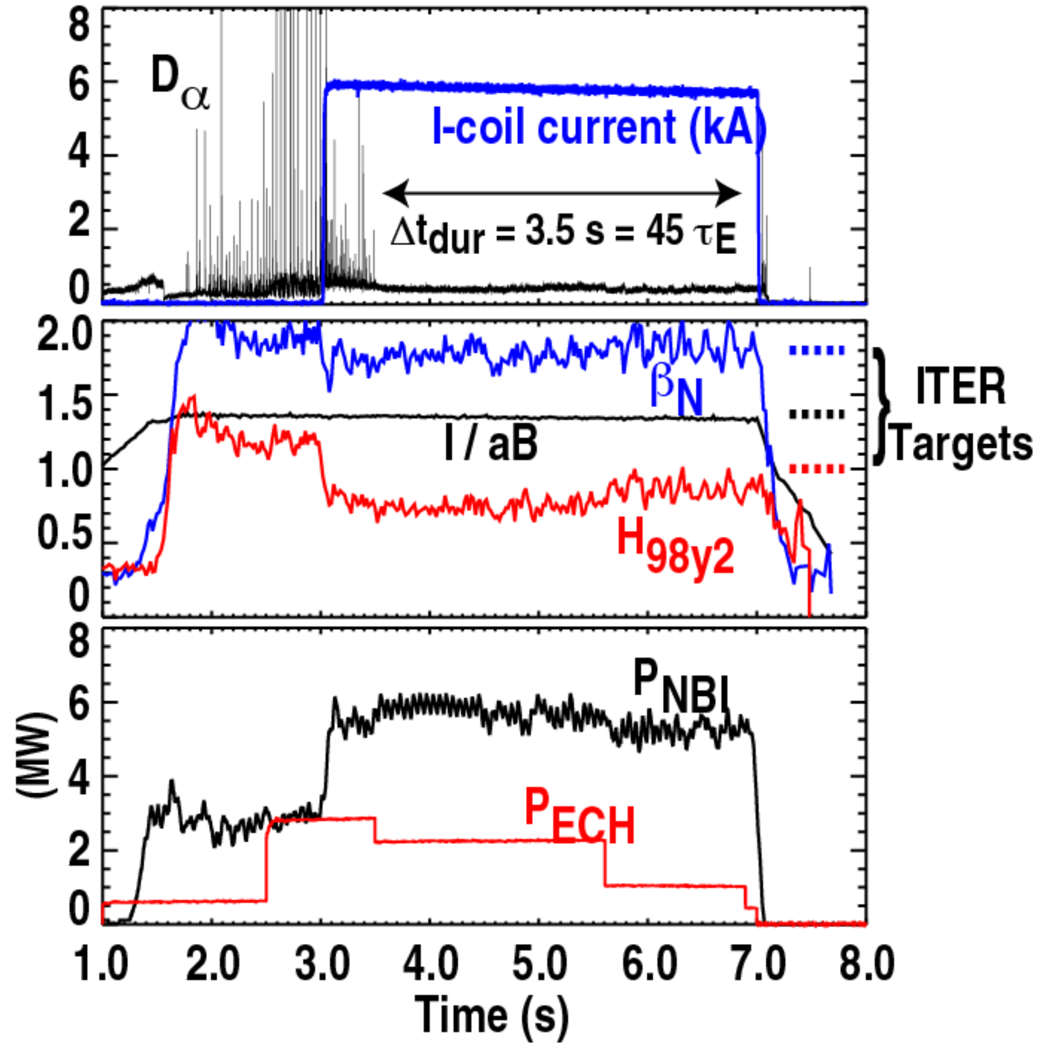
ELM Suppression Sustained for Long Duration in ITER Baseline Scenario

- **Sustained for 3.5 s, limited only by technical limits of power supplies**
- **Approximates ITER baseline specifications closely:**



	I/aB	β_N	H_{98}	$\nu_{*,ped}$
DIII-D	1.40	1.8	0.9	0.12
ITER	1.41	1.8	1.0	0.10

- **Achieved with n=3 RMP from single row of I-coils**

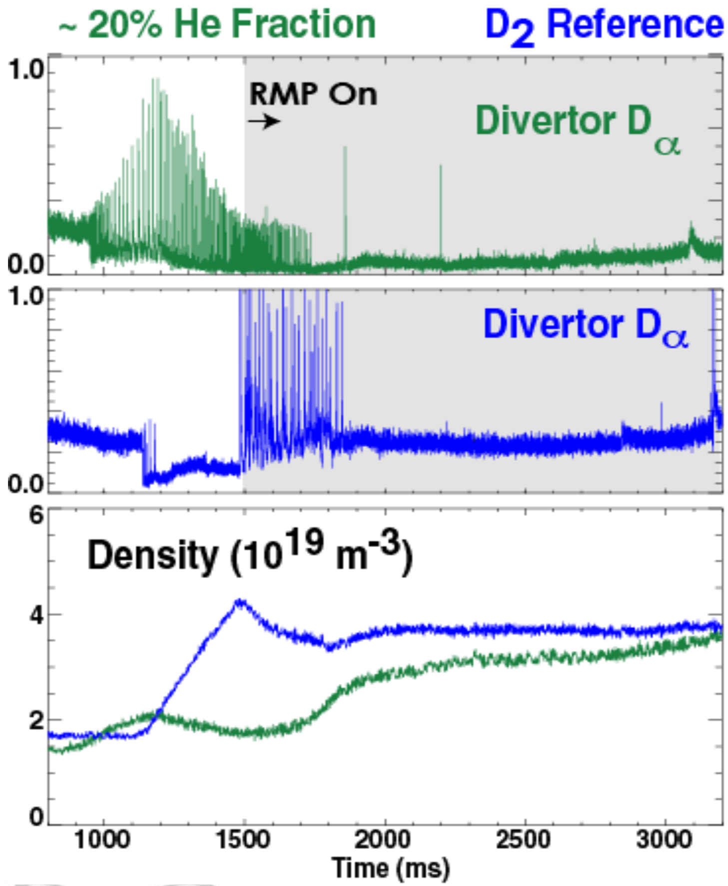


Proof-of-principle that RMP ELM suppression can be achieved in ITER baseline scenario

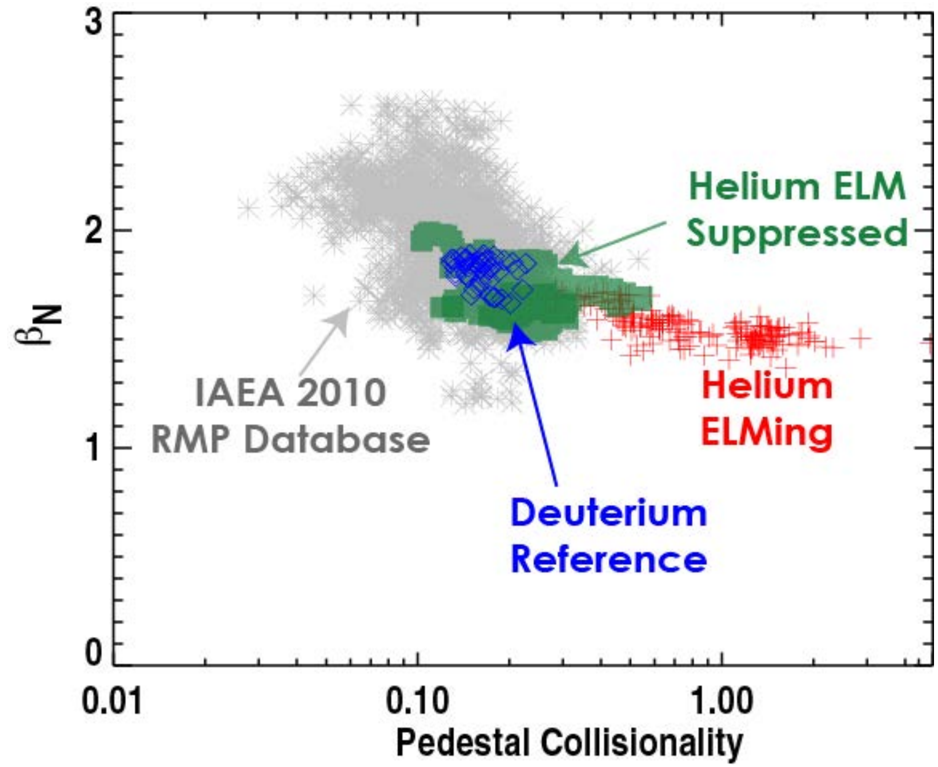
ITER Demonstration

Feasibility of RMP ELM Suppression in ITER Non-Nuclear Phase Demonstrated

- RMP ELM suppression demonstrated in plasmas with up to 25% helium fraction (n_{He}/n_e)



- Transition to ELMs occurs at density and collisionality levels consistent with deuterium database

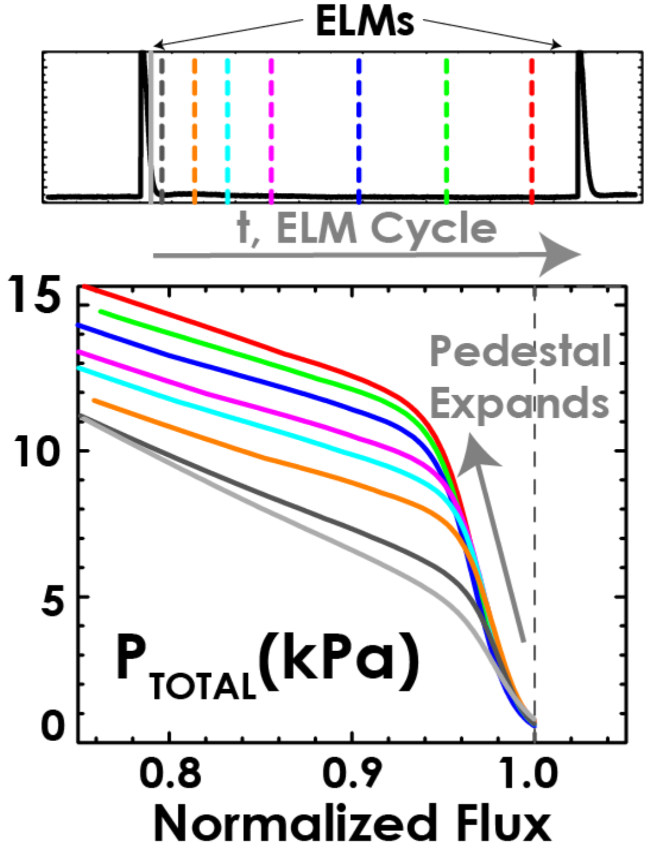


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

ITER Demonstration

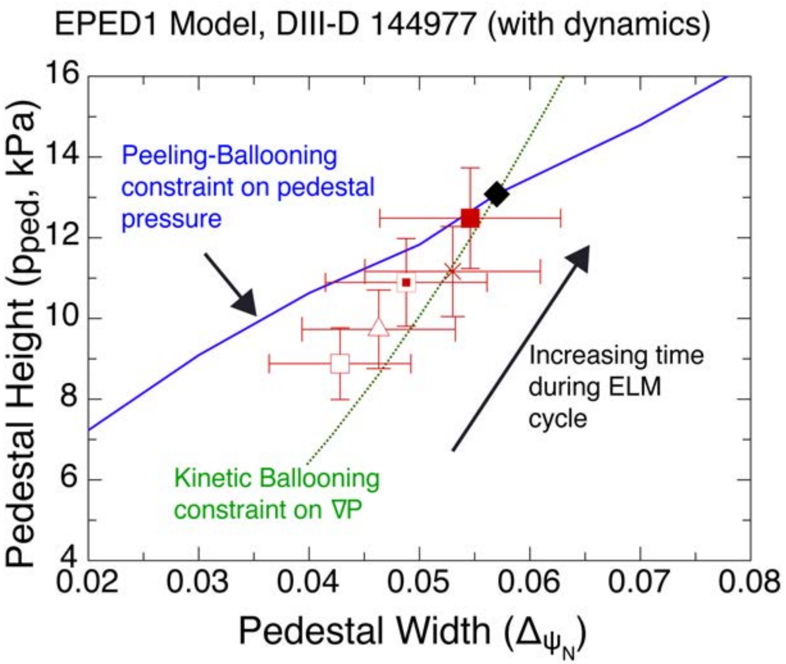
Emerging Model for RMP ELM Suppression

- In non-RMP H-mode, pedestal continues to expand until ELM is encountered



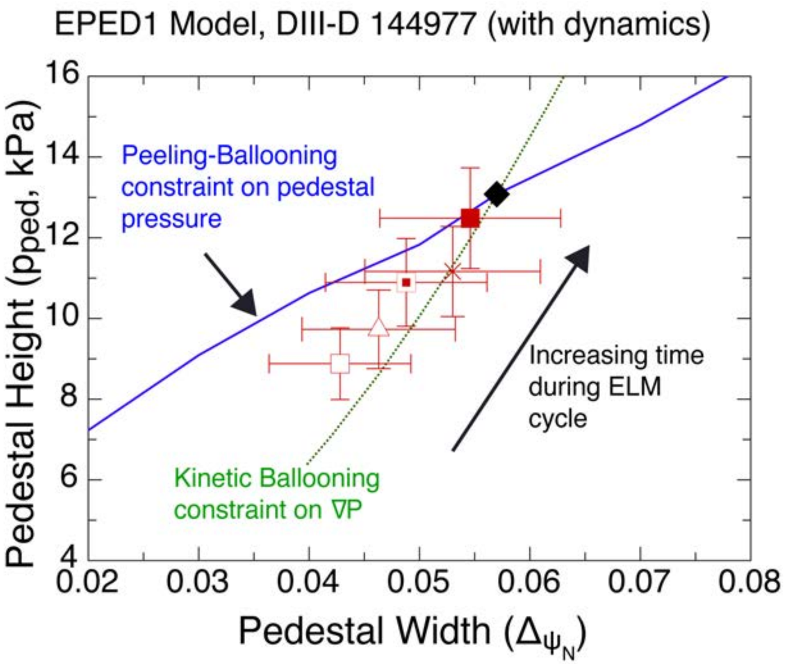
Emerging Model for RMP ELM Suppression

- **In non-RMP H-mode, pedestal continues to expand until ELM is encountered**
  - Consistent with EPED1 model

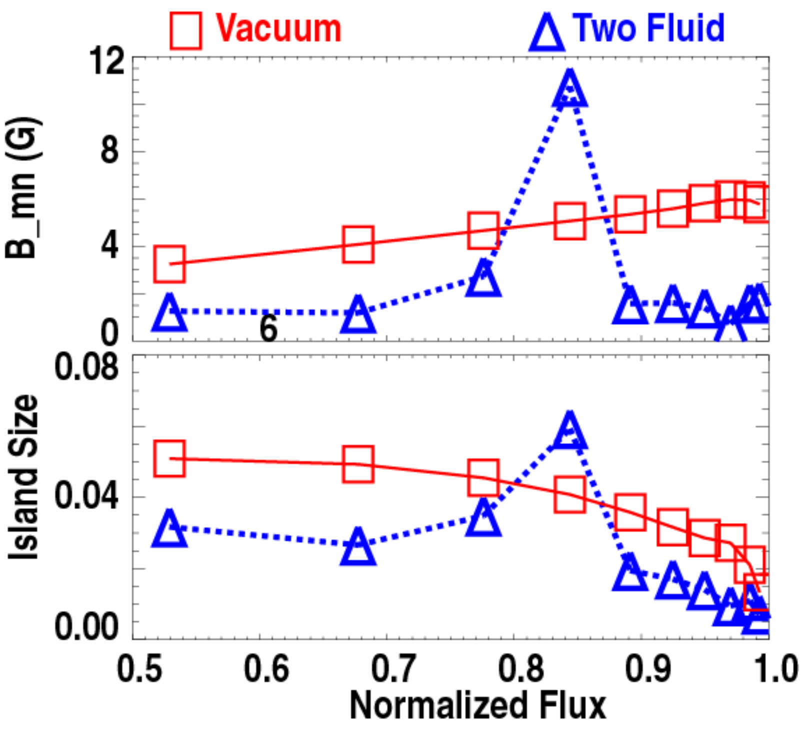


Emerging Model for RMP ELM Suppression

- **In non-RMP H-mode, pedestal continues to expand until ELM is encountered**
  - Consistent with EPED1 model



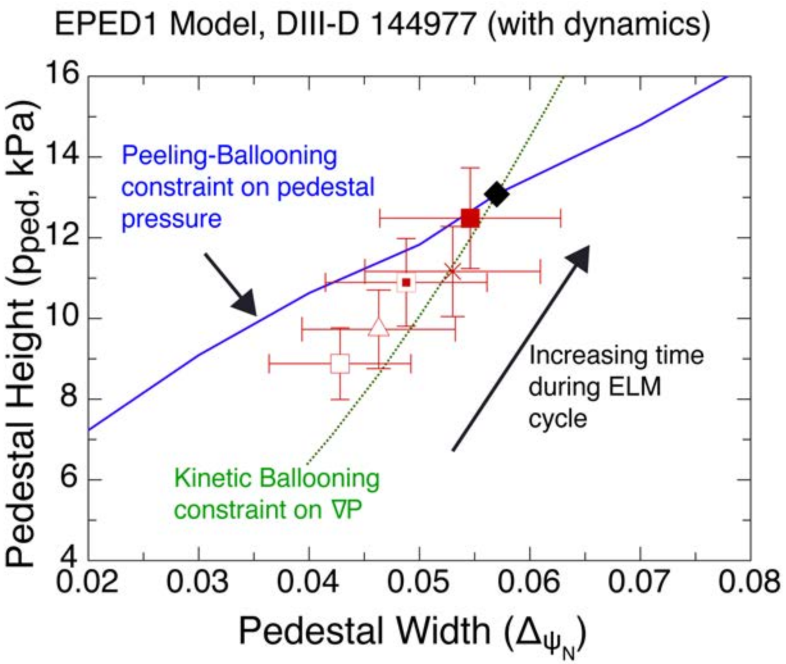
- **Model: MHD response at top of pedestal enhances transport and stops pedestal expansion**



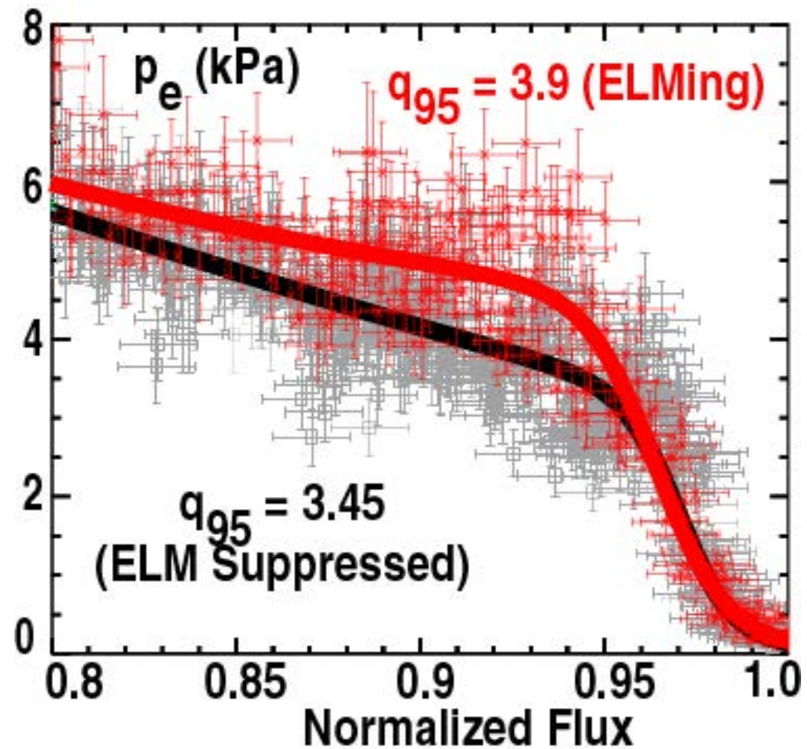
Emerging Model

Emerging Model for RMP ELM Suppression

- **In non-RMP H-mode, pedestal continues to expand until ELM is encountered**
  - Consistent with EPED1 model

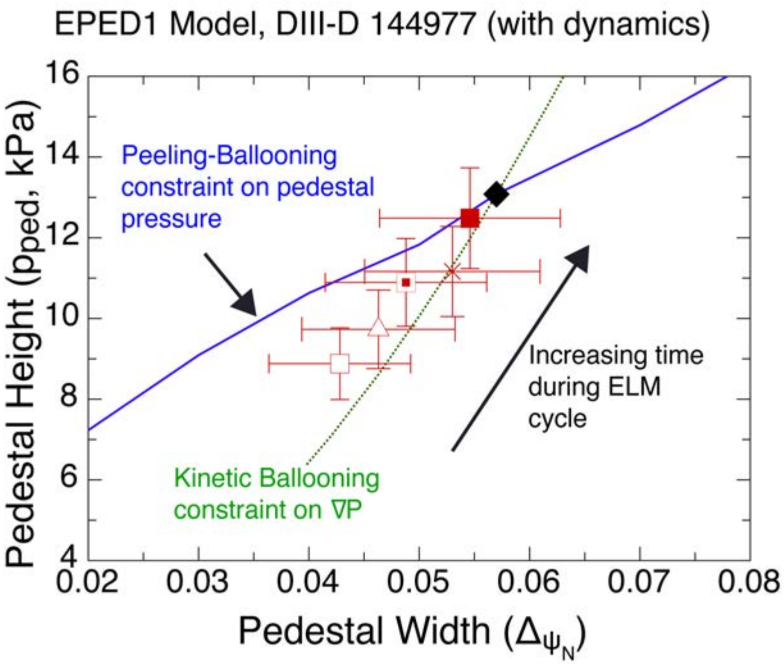


- **Model: MHD response at top of pedestal enhances transport and stops pedestal expansion**

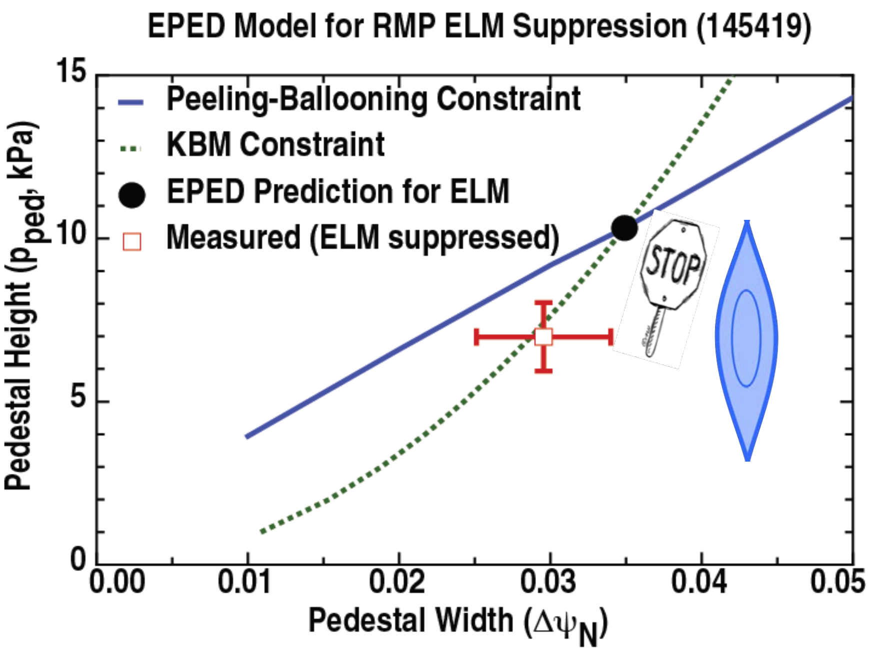


Emerging Model for RMP ELM Suppression

- **In non-RMP H-mode, pedestal continues to expand until ELM is encountered**
  - Consistent with EPED1 model



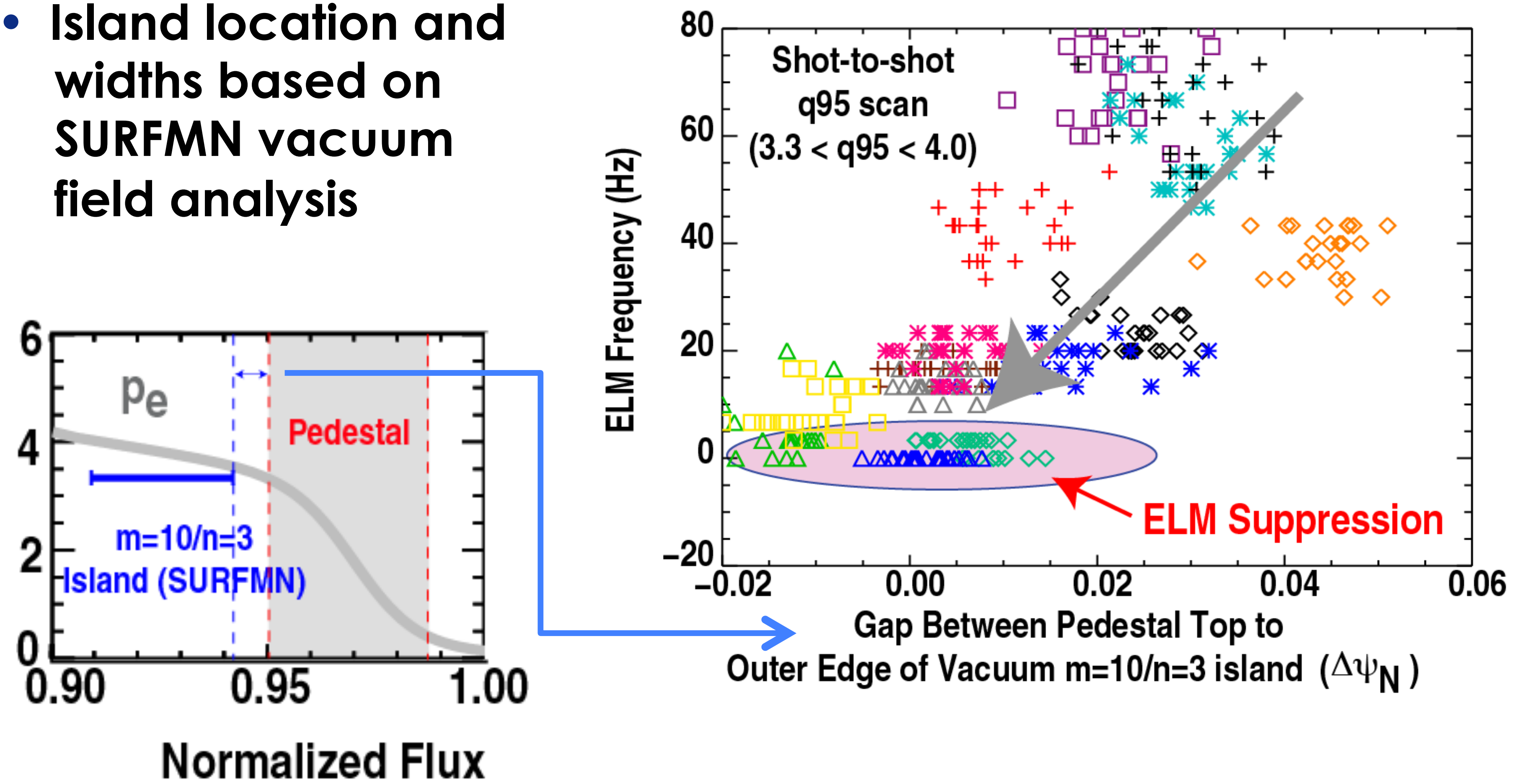
- **Model: MHD response at top of pedestal enhances transport and stops pedestal expansion**
  - Avoiding ELM instability boundary



Emerging Model

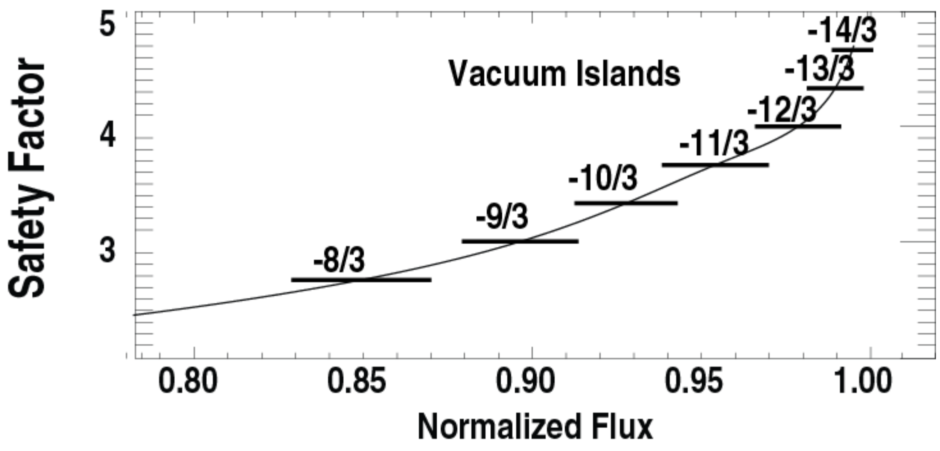
Degree of ELM Mitigation Correlated with Alignment of Pedestal Top and Outer Extent of m=10/n=3 Island

- Island location and widths based on SURFMN vacuum field analysis



Two-Fluid Resistive Codes Predict Shielding Currents on Rational Surfaces Modify Plasma Response Significantly

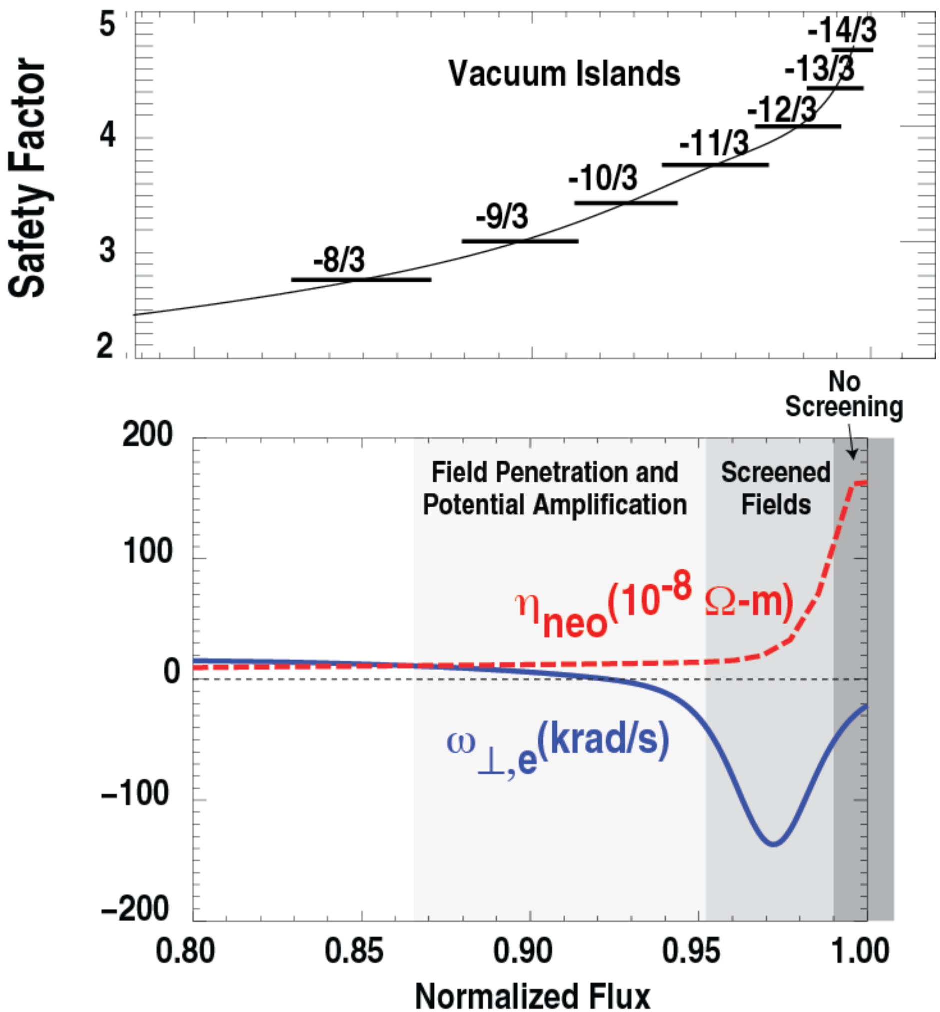
- **In vacuum model, large islands generated in edge region**
- **Applied field shielded by image currents on rational surface if:**
  - Resistivity is small (true everywhere but edge)
  - Sufficient plasma rotation



Two-Fluid Resistive Codes Predict Shielding Currents on Rational Surfaces Modify Plasma Response Significantly

- **In vacuum model, large islands generated in edge region**
- **Applied field shielded by image currents on rational surface if:**
  - Resistivity is small (true everywhere but edge)
  - Sufficient plasma rotation
- **Fields can "penetrate" at low perpendicular electron frequency**

$$\omega_{\perp,e} = \omega_{ExB} + \omega_{e,dia}$$



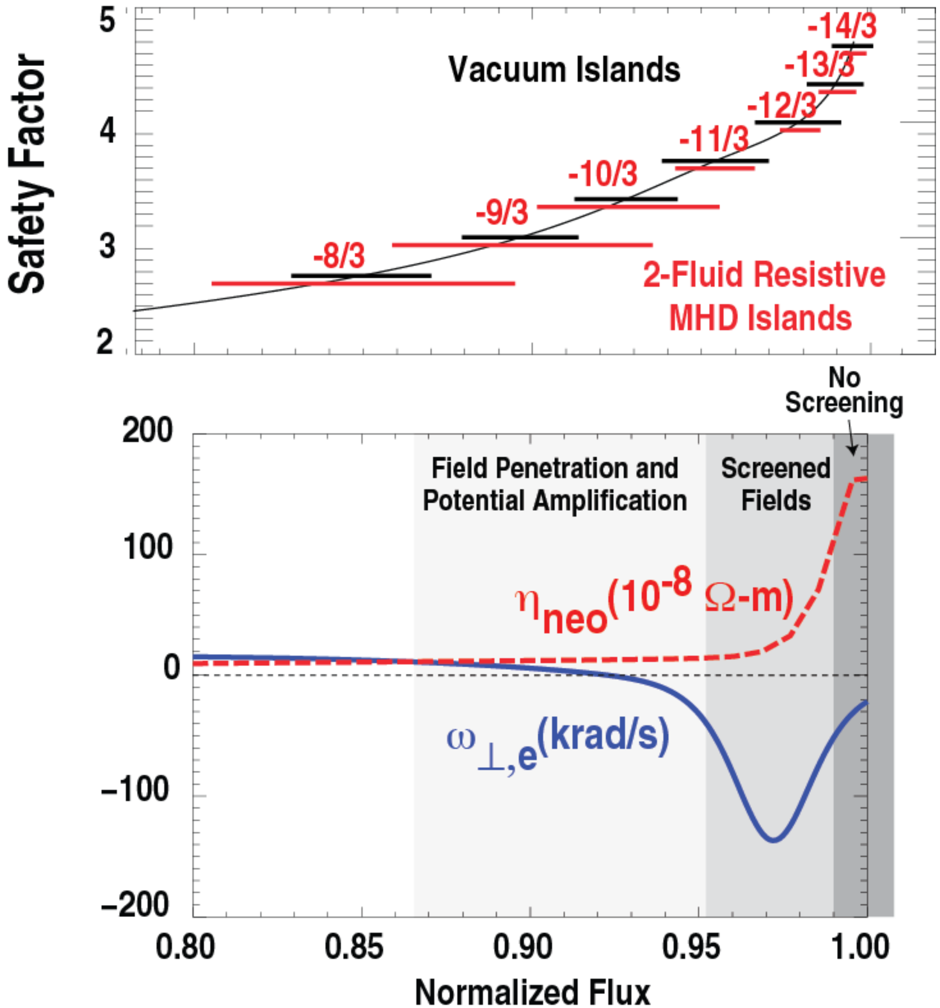
MHD Response - Theory

Two-Fluid Resistive Codes Predict Shielding Currents on Rational Surfaces Modify Plasma Response Significantly

- **In vacuum model, large islands generated in edge region**
- **Applied field shielded by image currents on rational surface if:**
  - Resistivity is small (true everywhere but edge)
  - Sufficient plasma rotation
- **Fields can "penetrate" at low perpendicular electron frequency**

$$\omega_{\perp,e} = \omega_{ExB} + \omega_{e,dia}$$

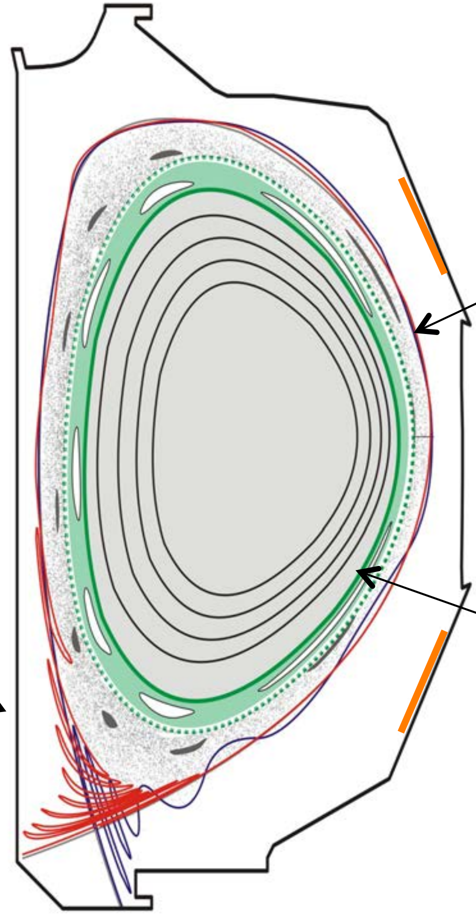
- **2-Fluid model predicts larger islands at top of pedestal, smaller in barrier**



DIII-D NATIONAL FUSION FACILITY SAN DIEGO

MHD Response - Theory

Three Distinct Regions of Plasma Response are Predicted by Two-Fluid Resistive Code M3D-C1



- **High Gradient Region**
  - Screening but distortion of flux surfaces
- **Divertor: Lobe Structures Near X-point**
  - Homoclinic tangles
- **Top of Pedestal**
  - Field penetration leading to possible island formation

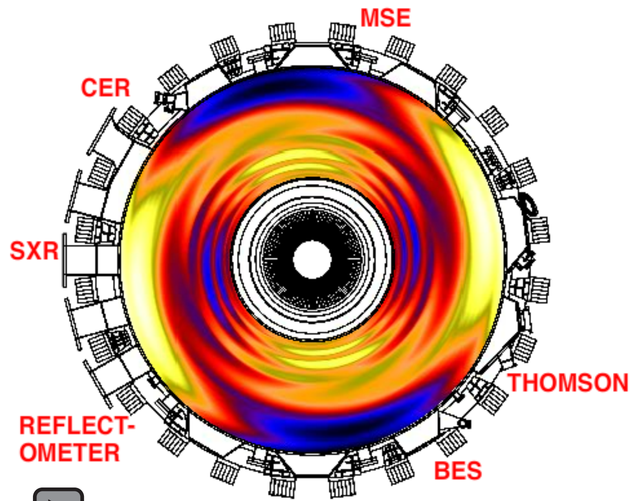
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

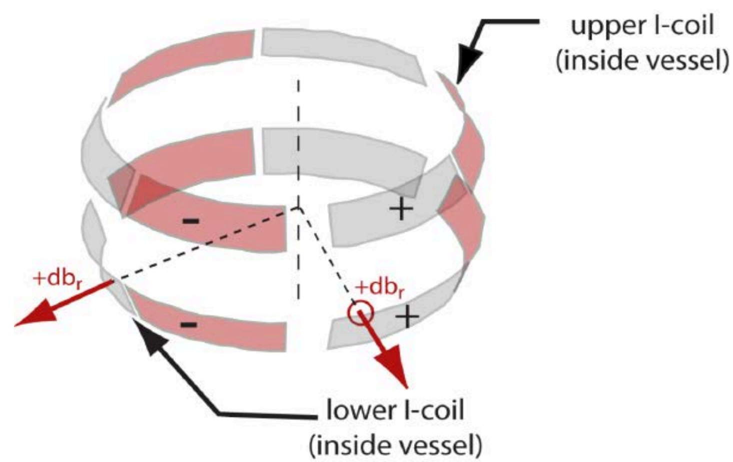
MHD Response - Theory

Toroidal Phase Variations of Applied RMP Used to Rotate Perturbations Across Toroidally Fixed Diagnostics

- **Diagnostic locations are fixed**
  - Can only sample local perturbation
- **However, RMP can be rotated with respect to diagnostics to measure toroidal variation of perturbation**
- **DIII-D I-coil set has 6 coils per row allowing**
  - n=2 Full toroidal rotation
  - n=3 Only two toroidal phases separated by 60^{o} toroidally

Top View **n = 2 B_r at midplane**

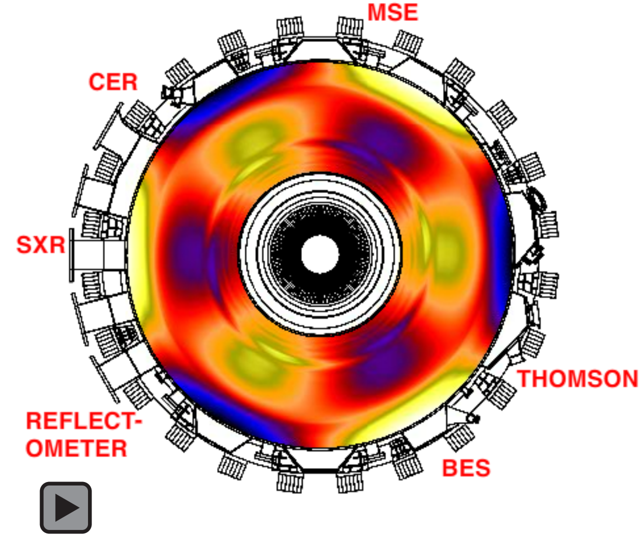


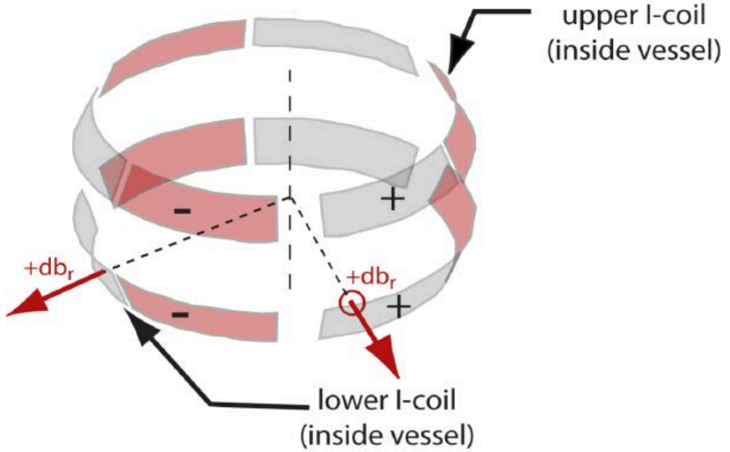


Toroidal Phase Variations of Applied RMP Used to Rotate Perturbations Across Toroidally Fixed Diagnostics

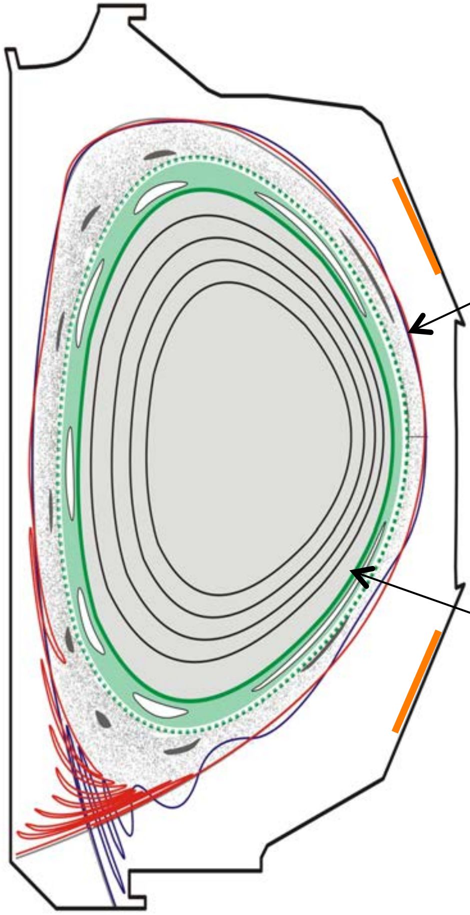
- **Diagnostic locations are fixed**
  - Can only sample local perturbation
- **However, RMP can be rotated with respect to diagnostics to measure toroidal variation of perturbation**
- **DIII-D I-coil set has 6 coils per row allowing**
  - n=2 Full toroidal rotation
  - n=3 Only two toroidal phases separated by 60° toroidally

Top View **n = 3 B_r at midplane**





Three Distinct Regions of Plasma Response are Predicted by Two-Fluid Resistive Code M3D-C1

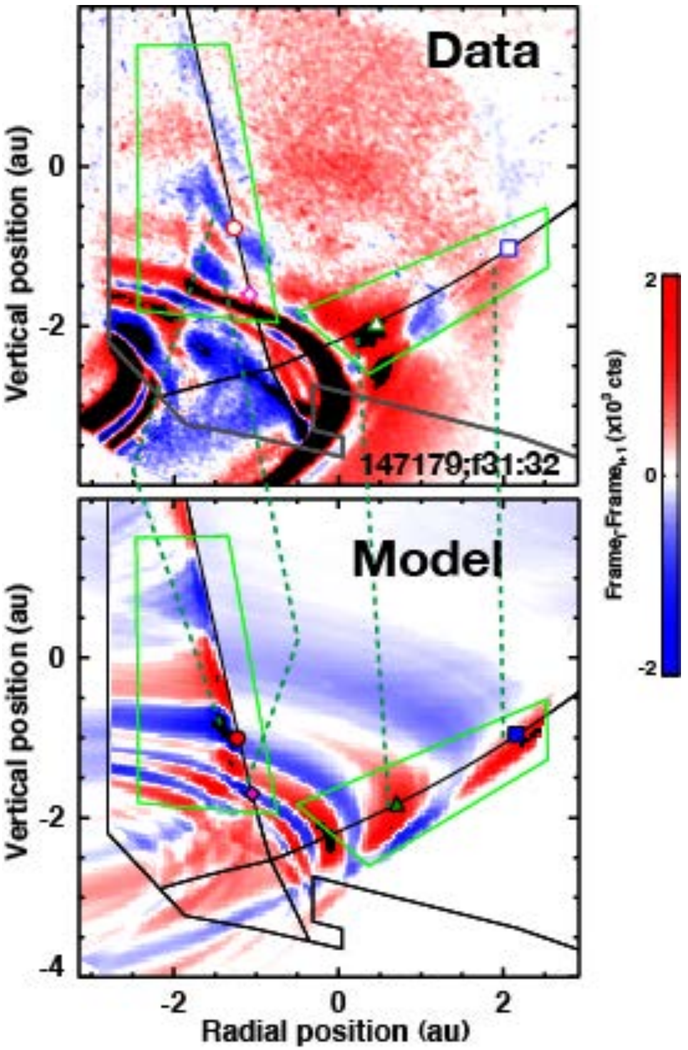


- **High Gradient Region**
  - Screening but distortion of flux surfaces
- **Top of Pedestal**
  - Field penetration leading to possible island formation
- **Divertor: Lobe Structures Near X-point**
  - Homoclinic tangles

MHD Response - Divertor

Vacuum Model Qualitatively Describes Observation of Homoclinic Tangles in Divertor

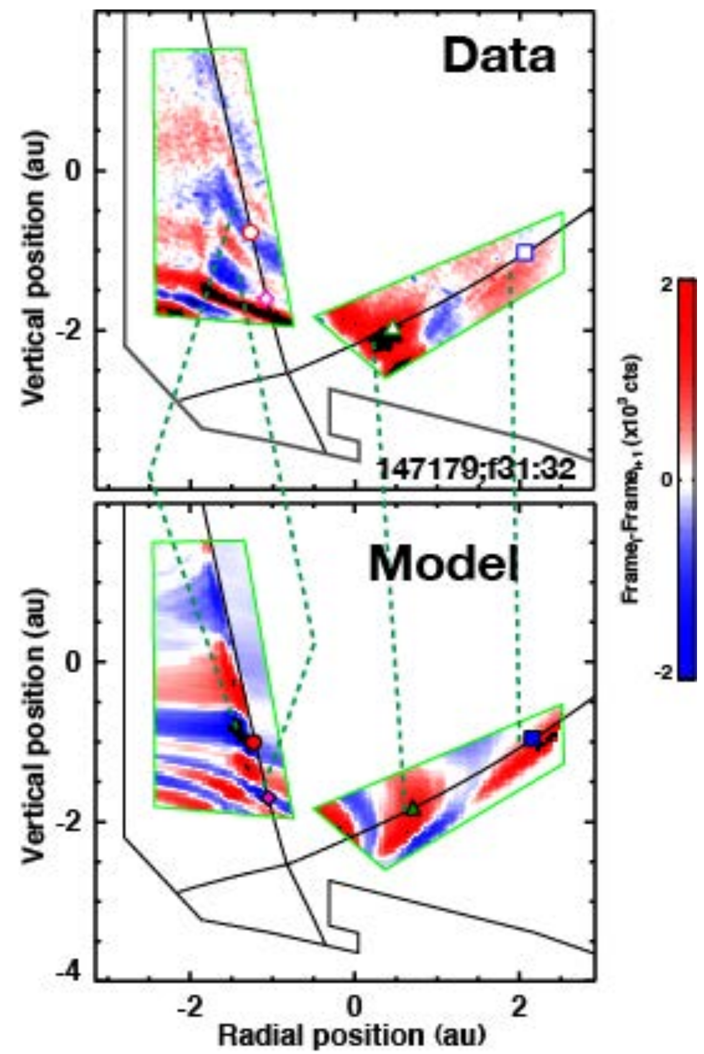
- **Strike-point splitting with q_{95} variation predicted by vacuum model**
- **Extreme soft X-ray imaging detects lobe structures at X-point**
  - Homoclinic tangles
- **Large floating potential detected on divertor probes when predicted lobe location coincident with probe**



MHD Response - Divertor

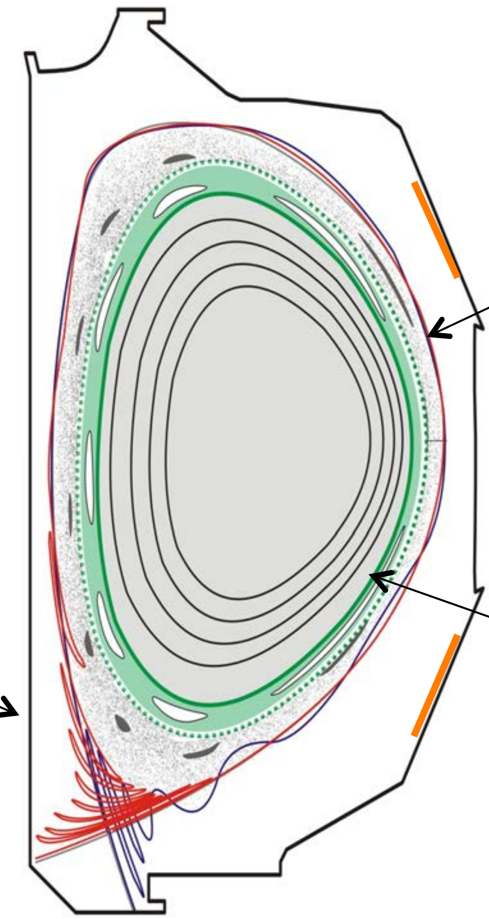
Vacuum Model Qualitatively Describes Observation of Homoclinic Tangles in Divertor

- **Strike-point splitting with q_{95} variation predicted by vacuum model**
- **Extreme soft X-ray imaging detects lobe structures at X-point**
  - Homoclinic tangles
- **Large floating potential detected on divertor probes when predicted lobe location coincident with probe**



MHD Response - Divertor

Three Distinct Regions of Plasma Response are Predicted by Two-Fluid Resistive Code M3D-C1



- **High Gradient Region**
  - Screening but distortion of flux surfaces

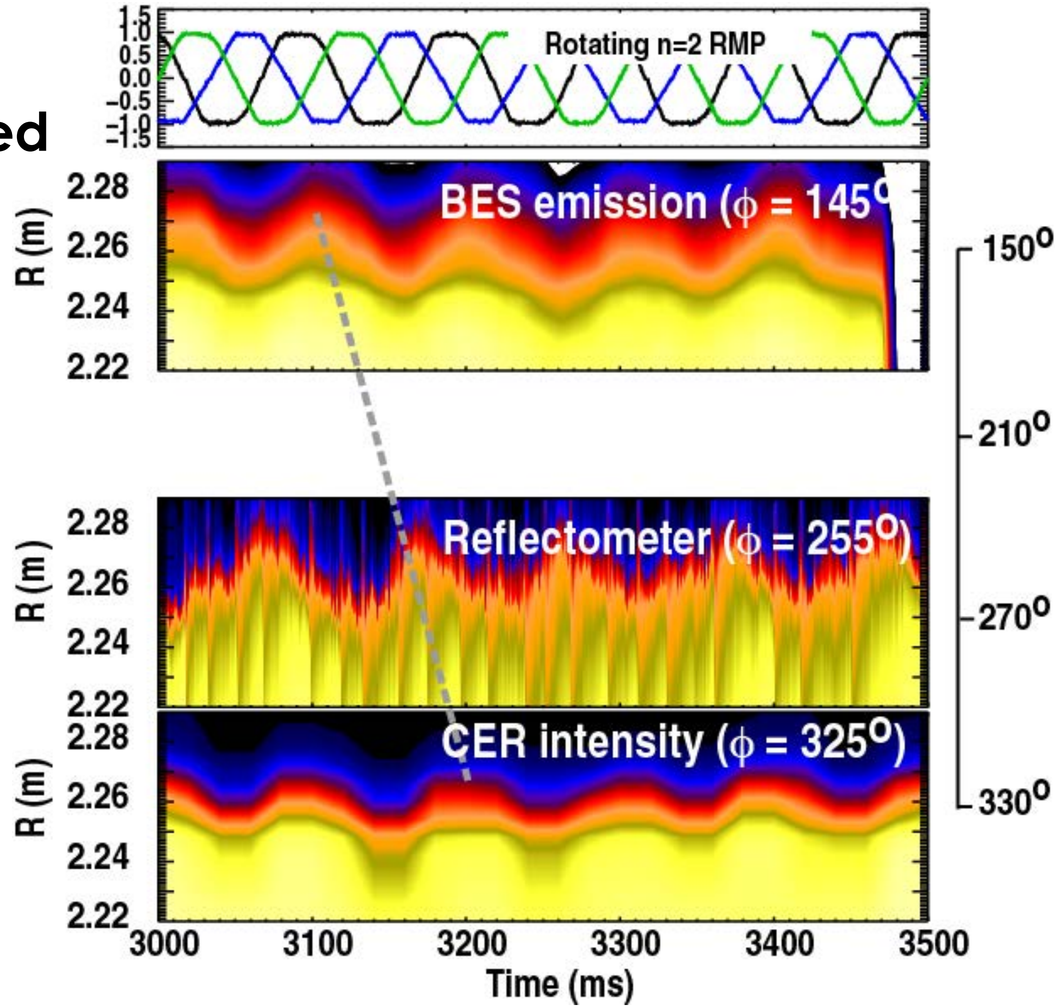
- **Divertor: Lobe Structures Near X-point**
  - Homoclinic tangles

- **Top of Pedestal**
  - Field penetration leading to possible island formation

MHD Response - Edge

Rotating n=2 RMP Produces Synchronous Modulation of Edge Profiles

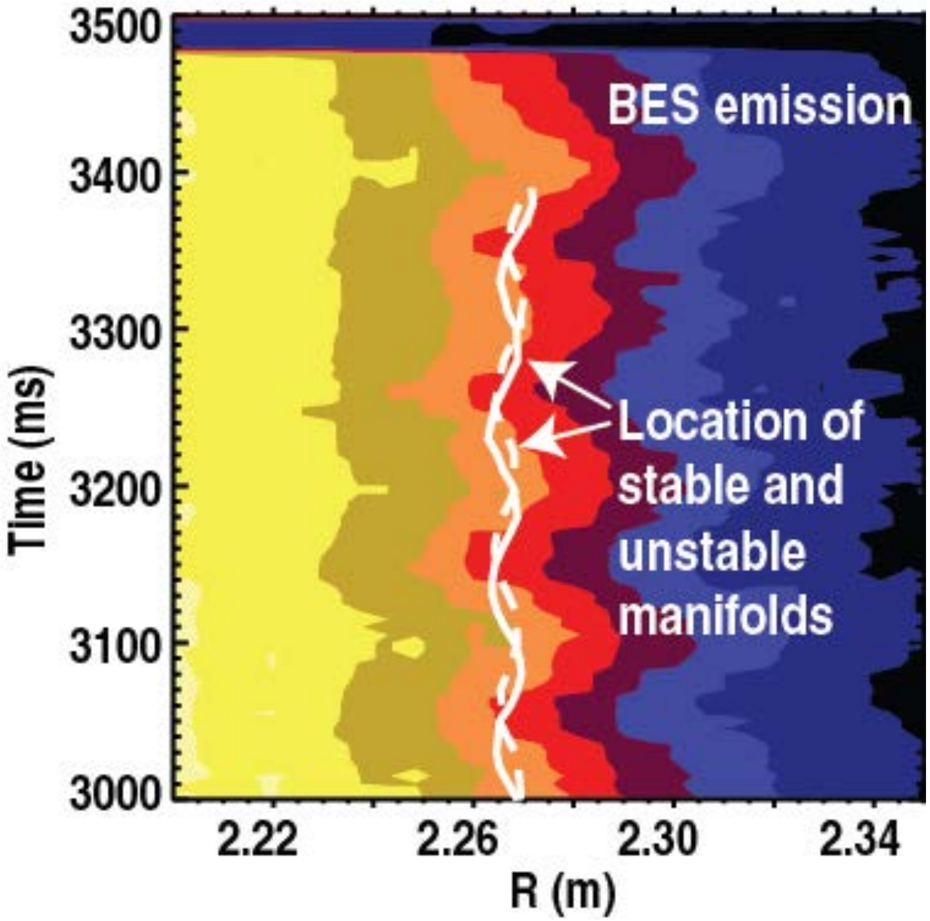
- Significant displacements (~2–3 cm) observed at midplane as n=2 RMP is rotated
- Toroidal variation of measurements confirms n=2 perturbation structure



MHD Response - Edge

Displacement at Midplane Associated with n=2 RMP Much Larger than Vacuum Prediction

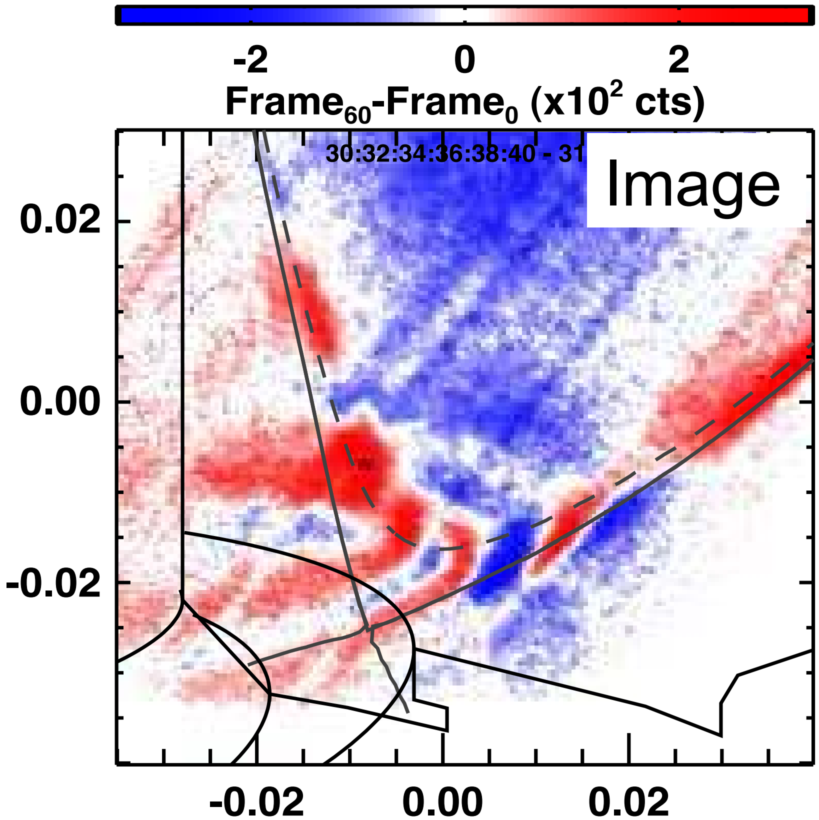
- **Significant displacements (~2–3 cm) observed at midplane as n=2 RMP is rotated**
- **Toroidal variation of measurements confirms n=2 perturbation structure**
- **Size of displacement is factor of 4–5x larger than vacuum prediction**
  - Suggests importance of MHD response to applied field



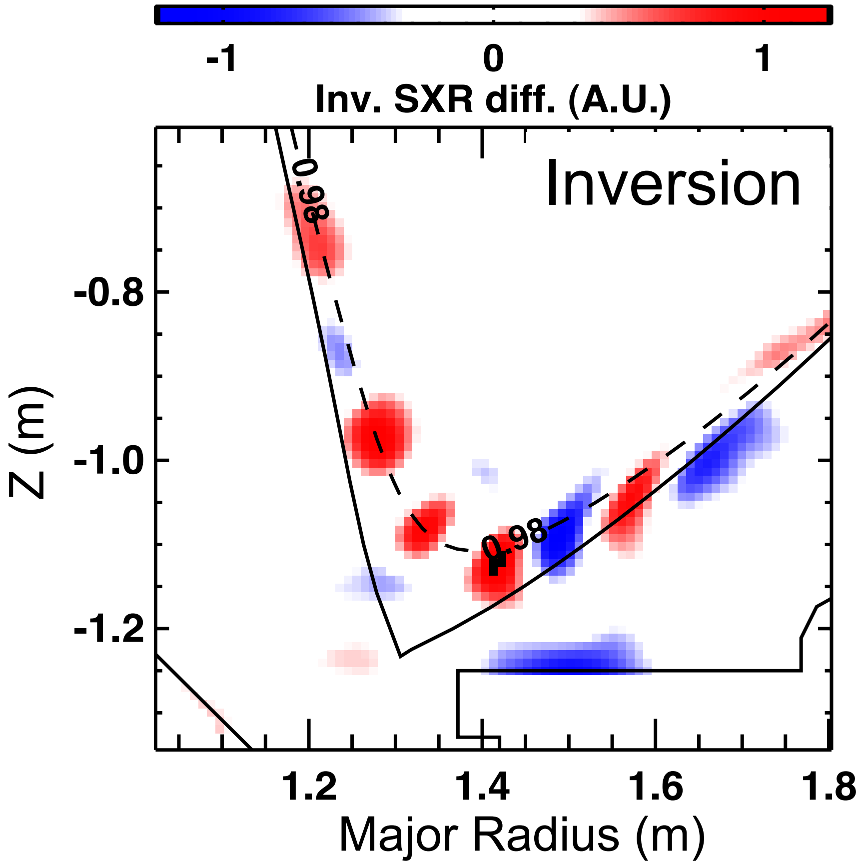
MHD Response - Edge

Higher Energy Filter on Soft X-Ray Imaging System Enables Measurements of Internal Helical Structures

- To accentuate confined plasma emission, high energy (~600 eV) filter used



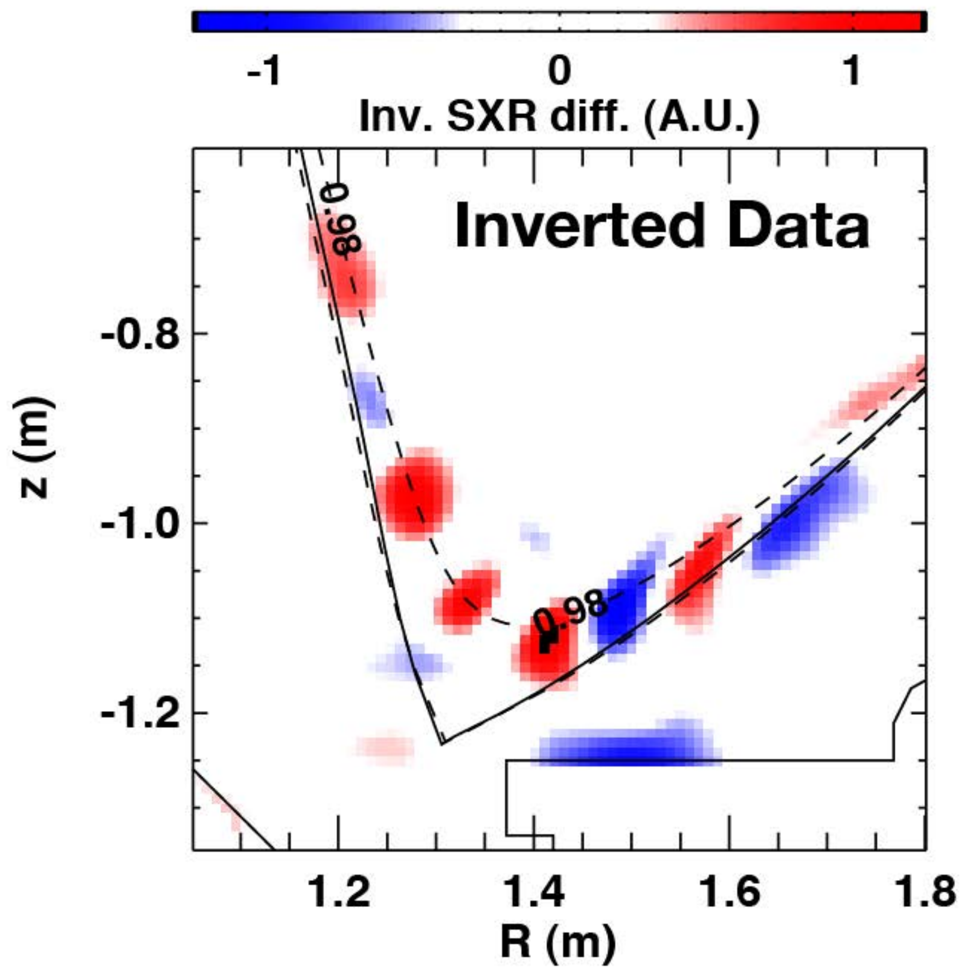
- Tomographic reconstruction reveals internal structures

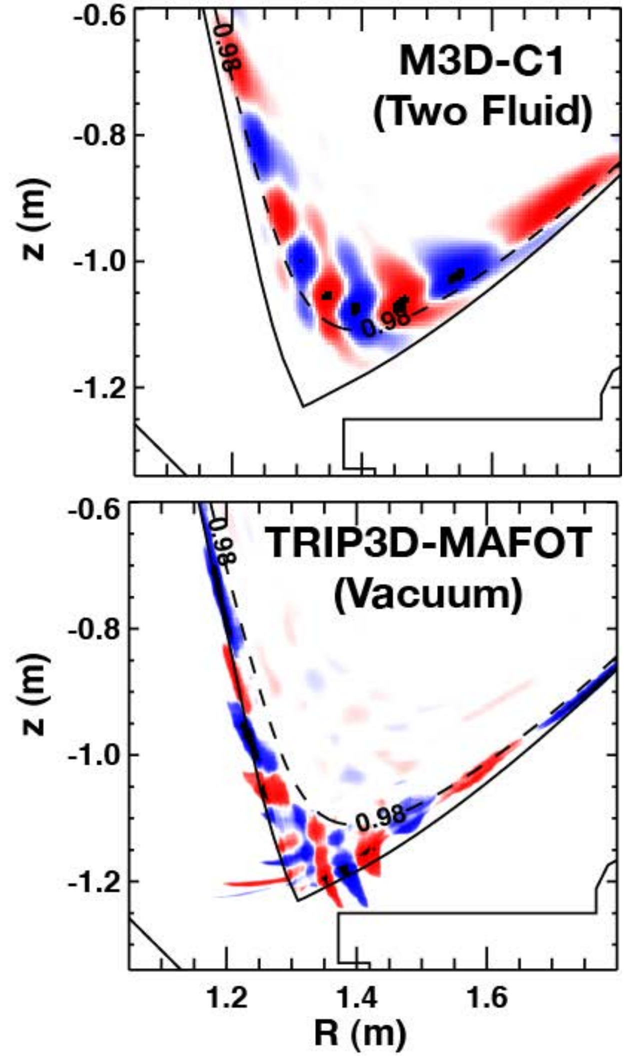


MHD Response - Edge

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Comparison Shows Better Agreement with Two-Fluid Resistive MHD Predictions Compared to Vacuum Predictions



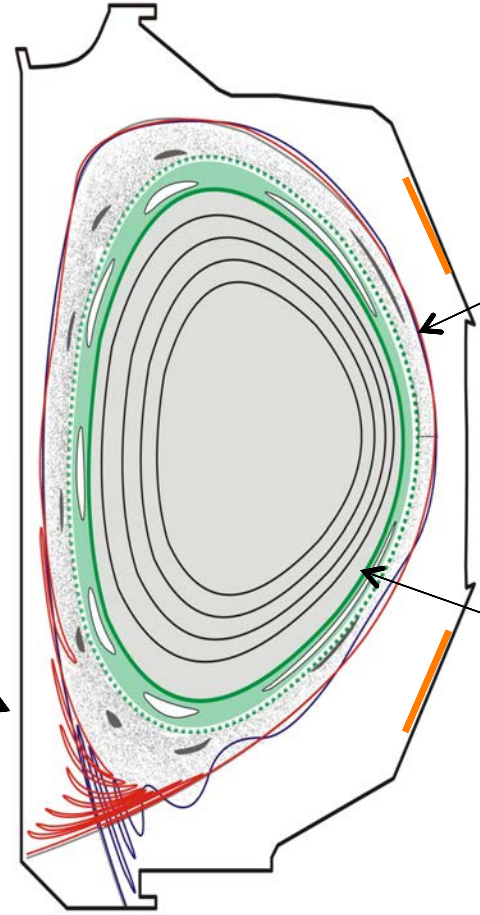


MHD Response - Edge

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Three Distinct Regions of Plasma Response are Predicted by Two-Fluid Resistive Code M3D-C1

- **High Gradient Region**
  - Screening but distortion of flux surfaces



- **Divertor: Lobe Structures Near X-point**
  - Homoclinic tangles

- **Top of Pedestal**
  - Field penetration leading to possible island formation

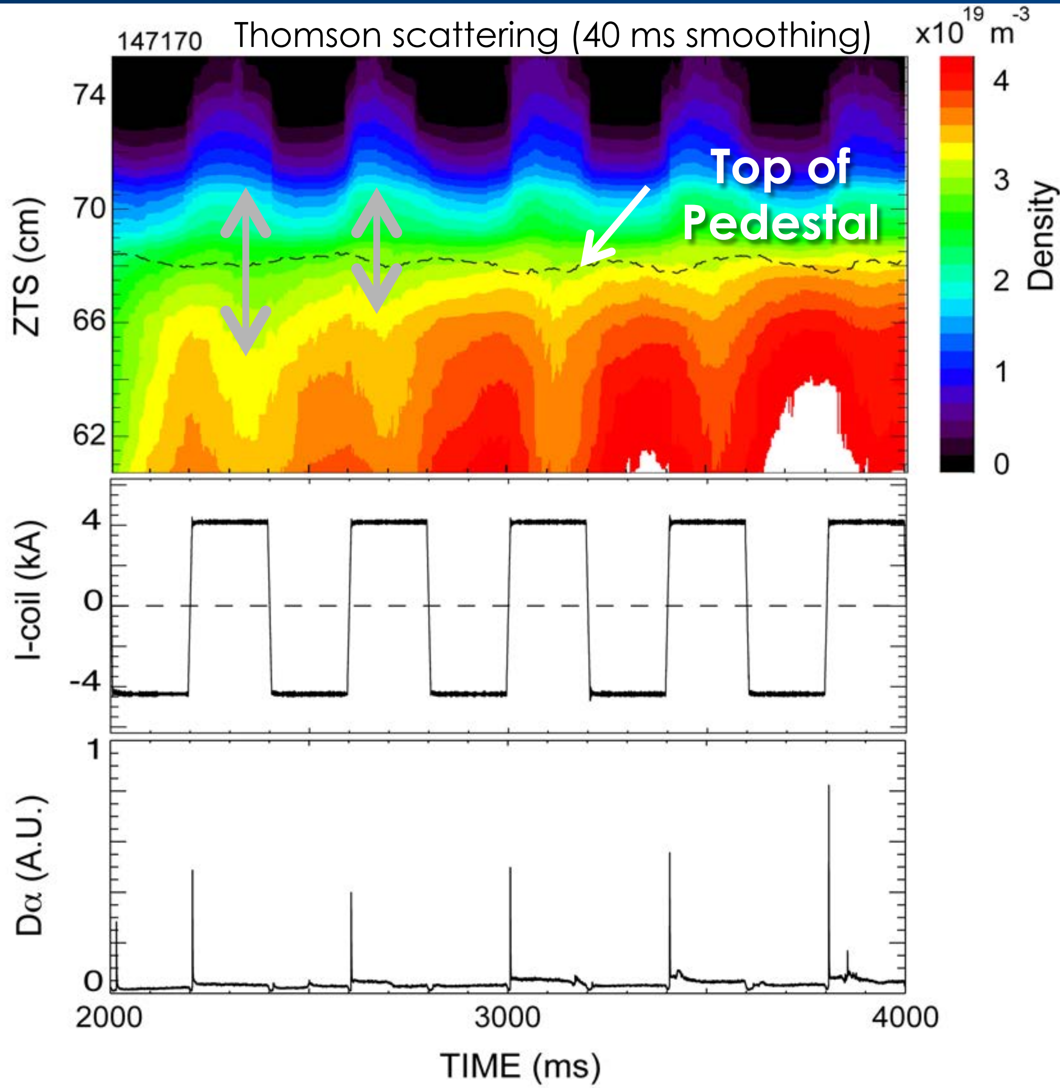
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

MR Wade/IAEA/October 2012

MHD Response - Pedestal

Edge Displacements Accompanied by Island-Like Signature at Top of Pedestal

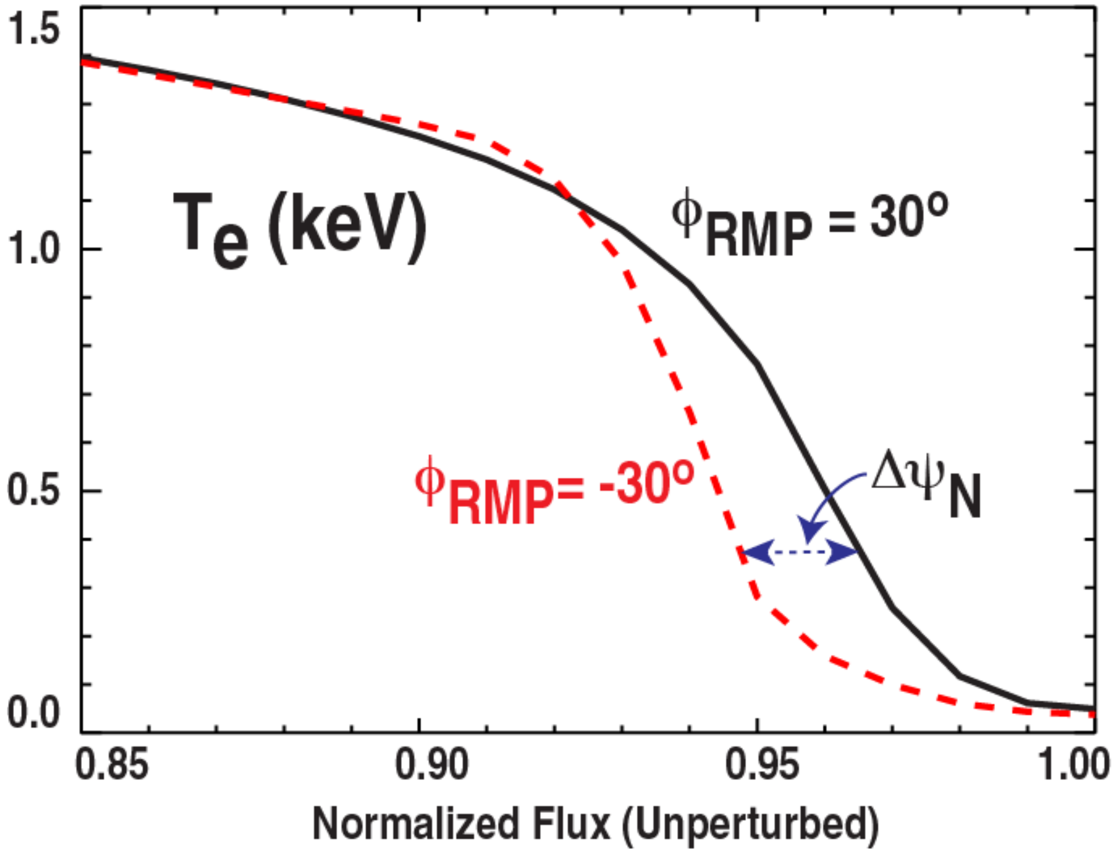
- **Toroidal phase of n=3 RMP switched by 60° every 200 ms**
- **Observe correlated displacement at very edge similar to n=2 case**
- **However, response toward top of pedestal shows phase inversion**
  - What causes this??



MHD Response - Pedestal

Technique for Estimating Flux Surface Displacement Due to Toroidal Phase Shifts

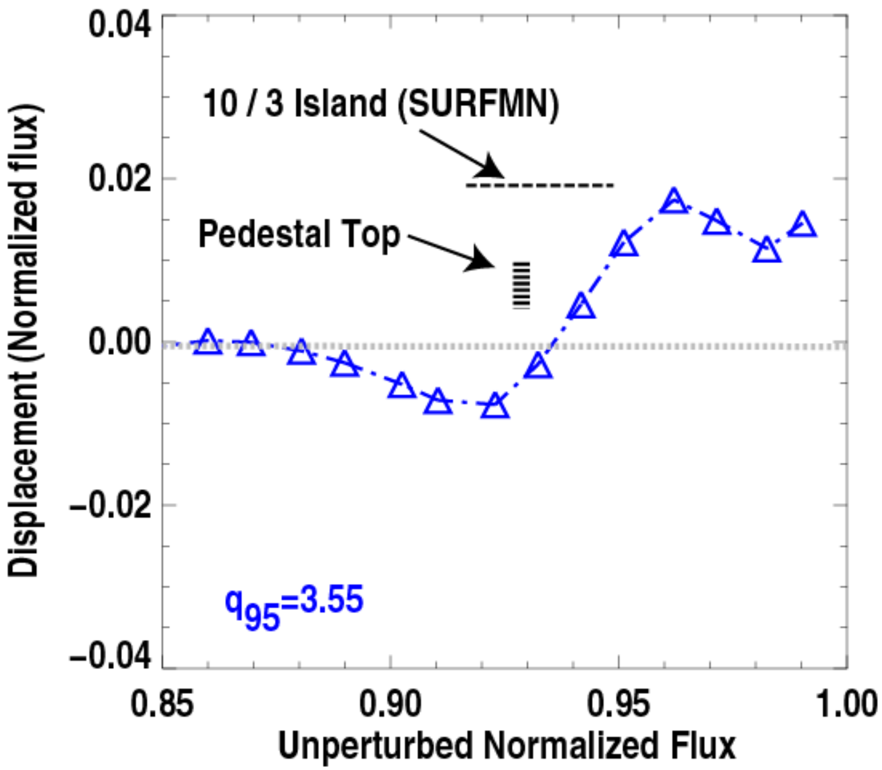
- **Displacement computed assuming change in T_e profile due entirely to flux surface displacement**



NATIONAL FUSION FACILITY SAN DIEGO

Inferred Displacement Shows Evidence of Island-Like Signature Near Top of Pedestal

- **Significant displacement observed at edge**
  - Similar to n=2 observations
- **Phase inversion layer near pedestal top**
- **Island-like signature apparent just inside pedestal top**
  - Coincident with computed location of m=10/n=3 island
- **Required compensation of n=3 error field to avoid synchronous n=0 T_e modulations**

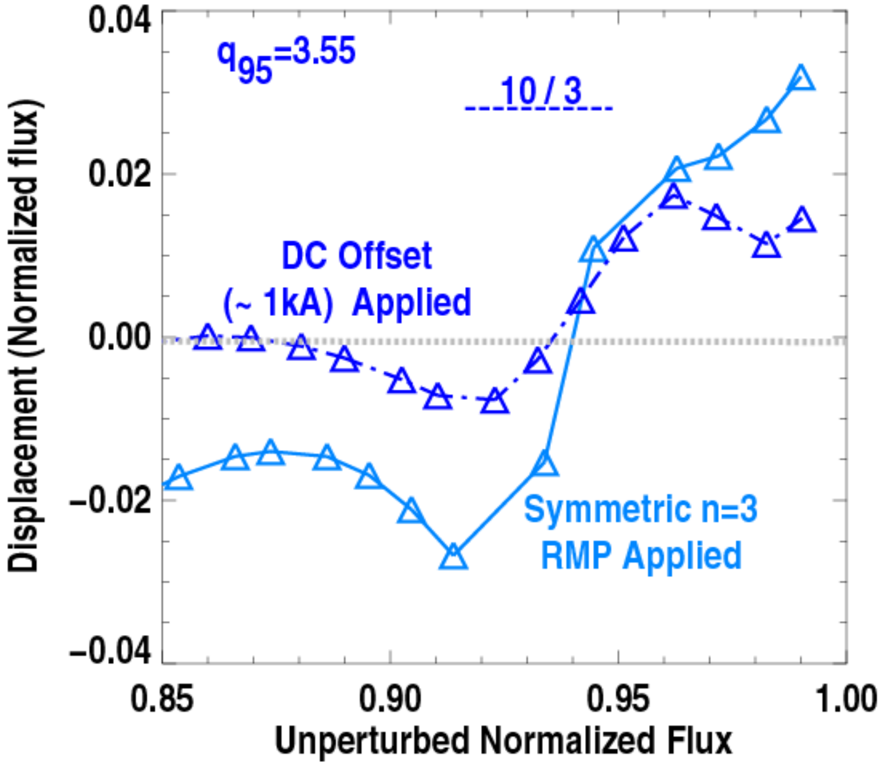


DIII-D NATIONAL FUSION FACILITY SAN DIEGO

MHD Response - Pedestal

Error Field Interaction Does Not Appear to Strongly Affect Edge Displacement Analysis ($\psi_N > 0.925$)

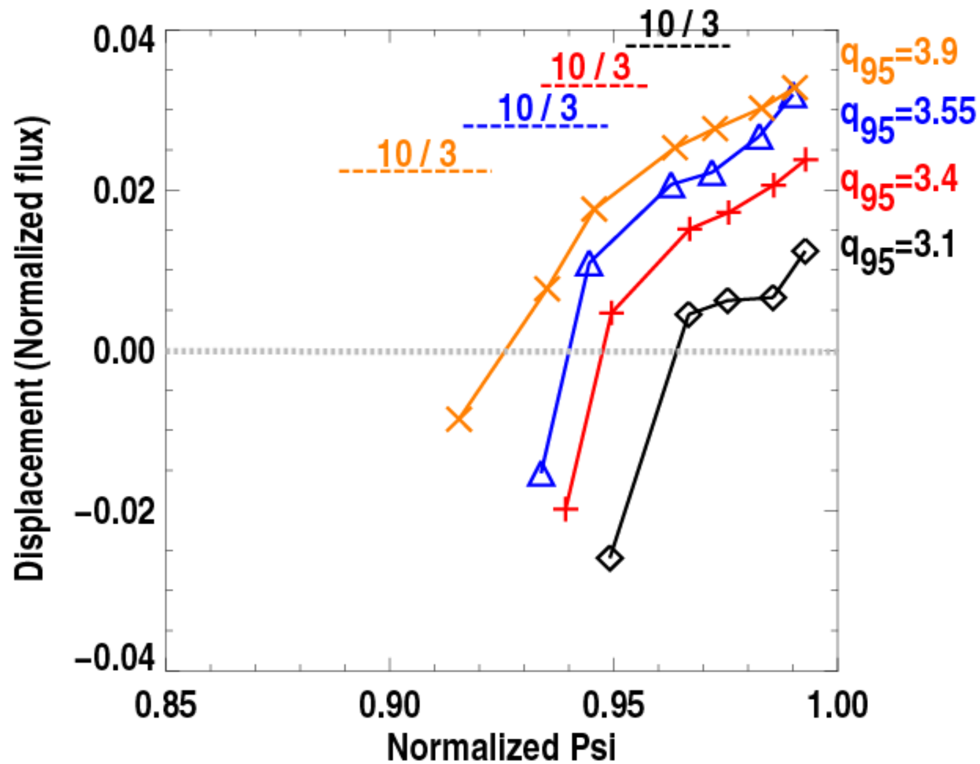
- **Inferred core displacement significantly affected by interaction with n=3 error field**
  - Due to n=0 changes in global confinement
- **However, edge displacement and phase inversion location does not change appreciably**



MHD Response - Pedestal

Edge Displacement Increases with q_{95} and Location of Phase Inversion Layer Track m=10/n=3 Island Position

- **Systematic increase in inferred displacement with q_{95}**
  - Also observed with n=2 RMP
- **Phase inversion location moves inward as q_{95} increases**
- **Tracks m=10/n=3 island position computed by SURFMN**



Evidence for island-driven transport??

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

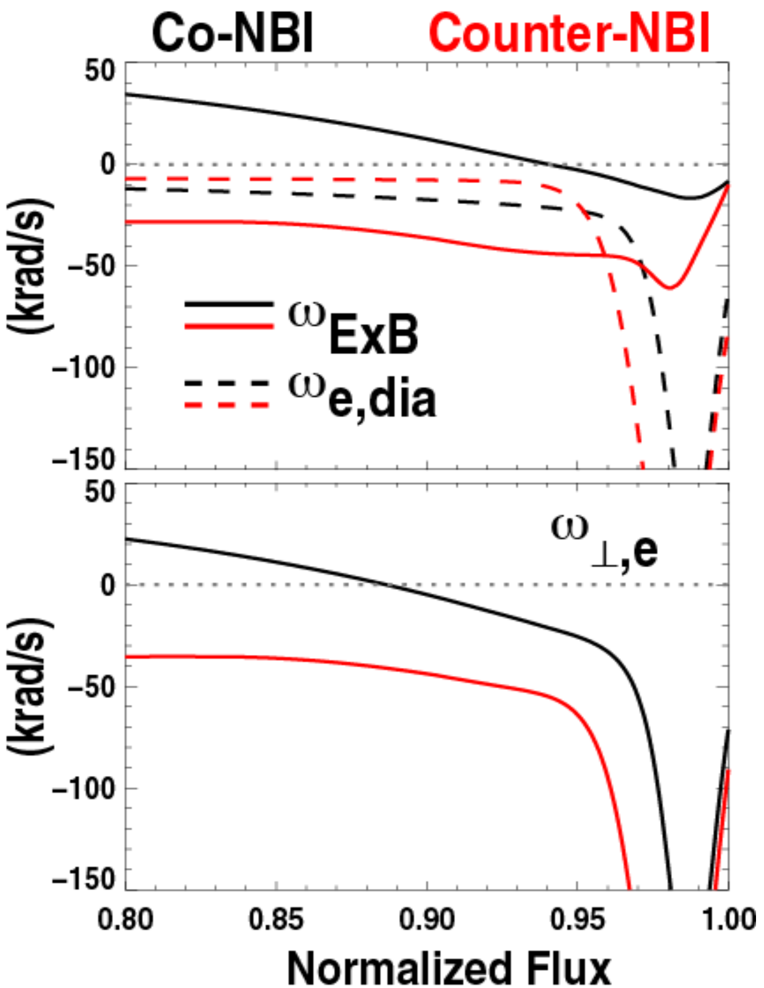
MHD Response - Pedestal

Counter-NBI Provides Compelling Test of Importance of $\omega_{\perp,e}$ at Top of Pedestal in ELM Suppression

- By switching sign of toroidal rotation, $\omega_{\perp,e} = 0$ crossing at top of pedestal is eliminated

$$\omega_{\perp,e} = \omega_{ExB} + \omega_{e,dia}$$

- If MHD response is strongly dependent on $|\omega_{\perp,e}| \approx 0$, should be difficult to obtain ELM suppression with counter NBI

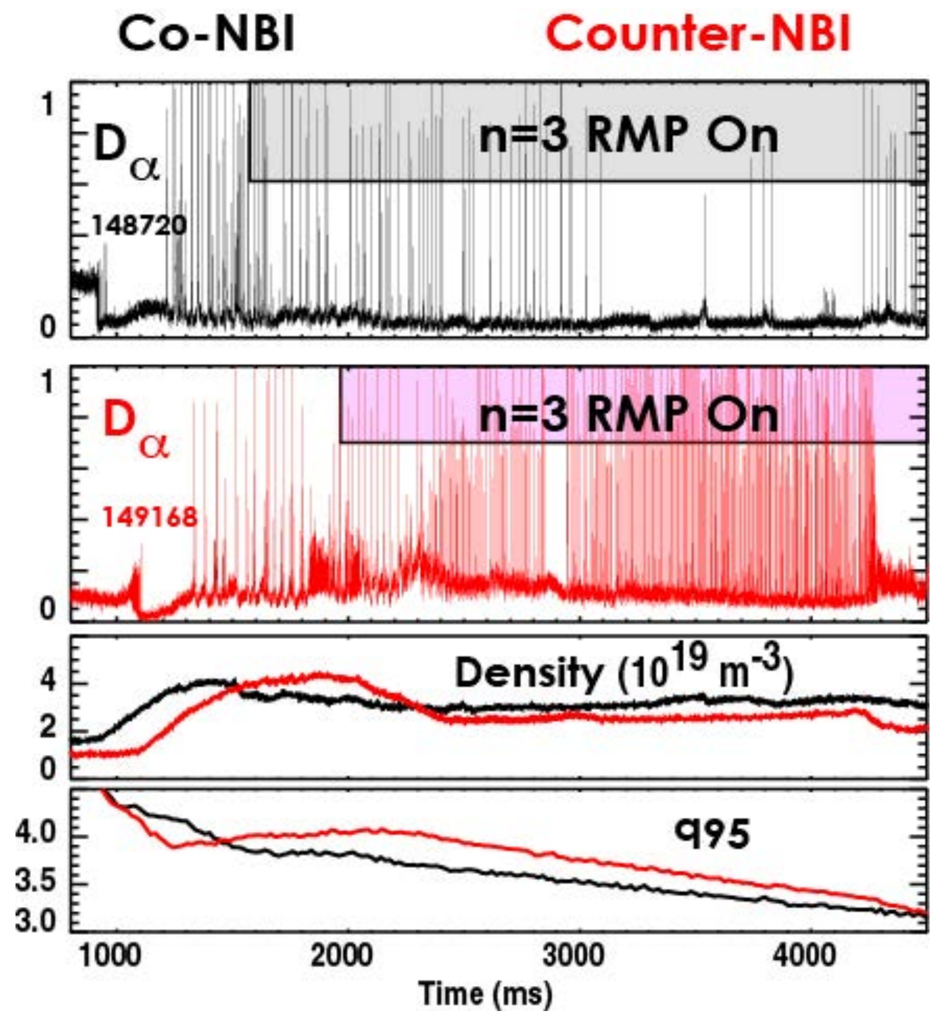


Testing Effect of $\omega_{\perp,e}$

Lack of ELM suppression with Counter-NBI Indicates Importance of $\omega_{\perp,e}$ at Top of Pedestal

- **ELMs remain in counter-NBI q_{95} ELM suppression window typically seen with co-NBI**
  - Even at comparable density

- **Small window of ELM suppression observed at q_{95} ~ 4.0**
  - EHO signature also observed → QH-mode??

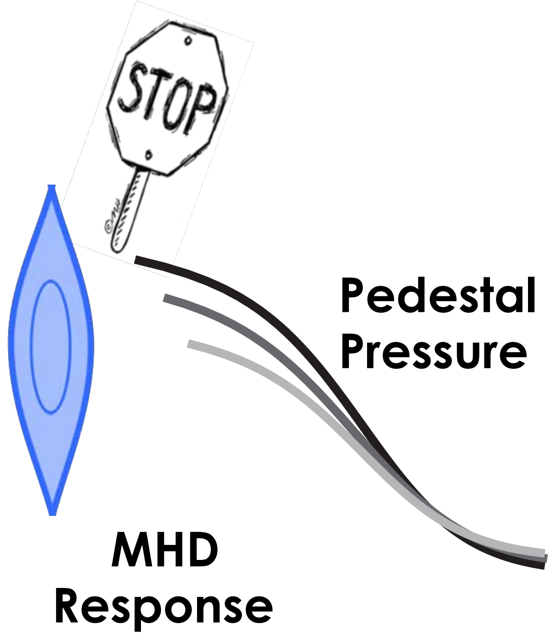


Testing Effect of $\omega_{\perp,e}$

Significant Progress Has Been Made in Improving the Physics Basis for RMP ELM Suppression in ITER

- **ELM suppression extended to ITER scenarios**
  - ITER Baseline Scenario
  - Large helium fraction
- **Measurements consistent with emerging model**
  - RMP induces MHD response at top of pedestal
  - Resulting transport impedes further widening of the pedestal

  → Peeling-ballooning stability maintained – No ELMs!!!



Significant Progress Has Been Made in Improving the Physics Basis for RMP ELM Suppression in ITER

- **ELM suppression extended to ITER scenarios**
  - ITER Baseline Scenario
  - Large helium fraction
- **Measurements consistent with emerging model**
  - RMP induces MHD response at top of pedestal
  - Resulting transport impedes further widening of the pedestal

  → Peeling-ballooning stability maintained – No ELMs!!!

Future Plans

- Compatibility with fueling
- Pure helium plasmas
- …
- Better quantify MHD response across range of conditions
- Connect MHD response to transport modifications