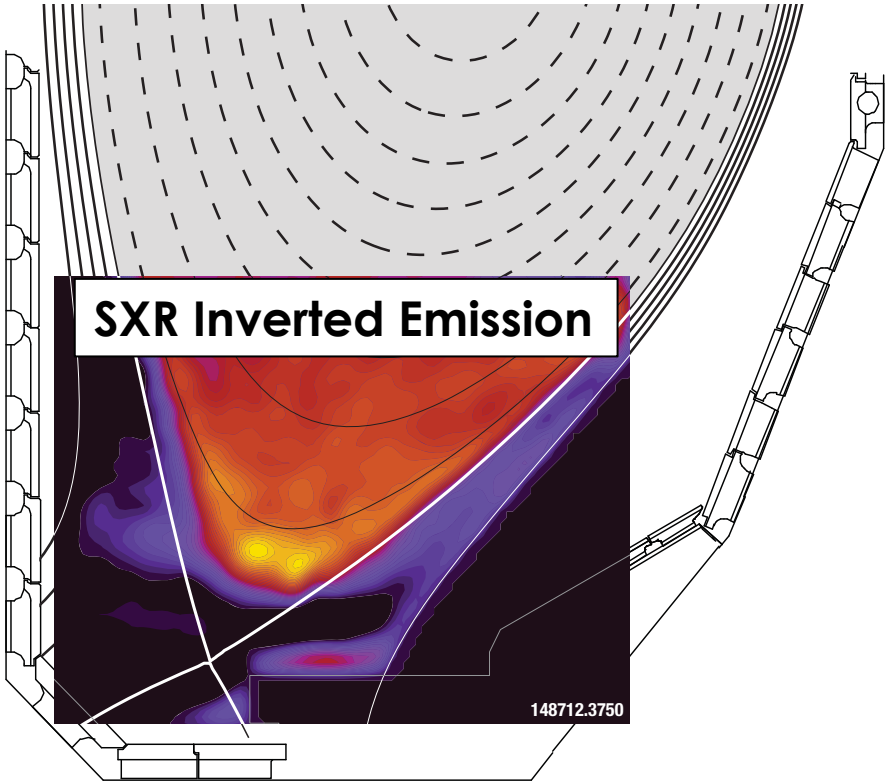
Measuring 3D Plasma Response to Resonant Magnetic Perturbations on DIII-D through SXR Imaging

By
M.W. Shafer[1,2]
with
E.A. Unterberg[1], A. Wingen[1,2], N.M. Ferraro[3], D.J. Battaglia[4], T.E. Evans[3], J.H. Harris[1], D.L. Hillis[1], S.J. Meitner[1], R. Moyer[6], R. Nazikian[4], D.M. Orlov[6]

[1]ORNL, [2]ORAU, [3]GA, [4]PPPL, [6]UCSD



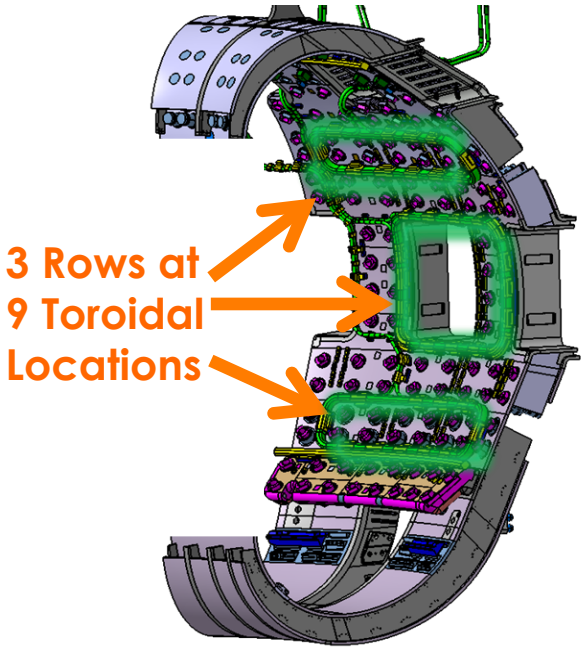
Presented at the
Fusion Energy Science & Technology Seminar
Oak Ridge National Laboratory

November 13, 2012

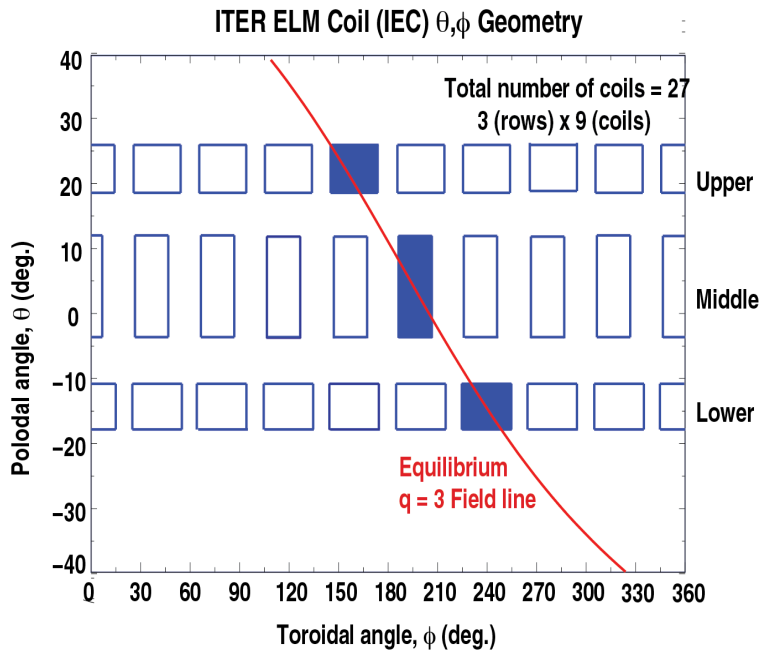
ELM Control via 3D Fields is an Important Issue for ITER

- **ELMs can be damaging to in-vessel components**
  - CFC and tungsten material limits ⇒ W_{ELM} at the divertor ≤ **1 MJ**
    - Present Scaling ⇒ ~0.15W_{ped} ⇒ **15-20x over limits** (ITER W_{ped} = 100-130 MJ)
- **Control via reducing ∇P through 3D Resonant Magnetic Perturbations**

ITER ELM Control Coils



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

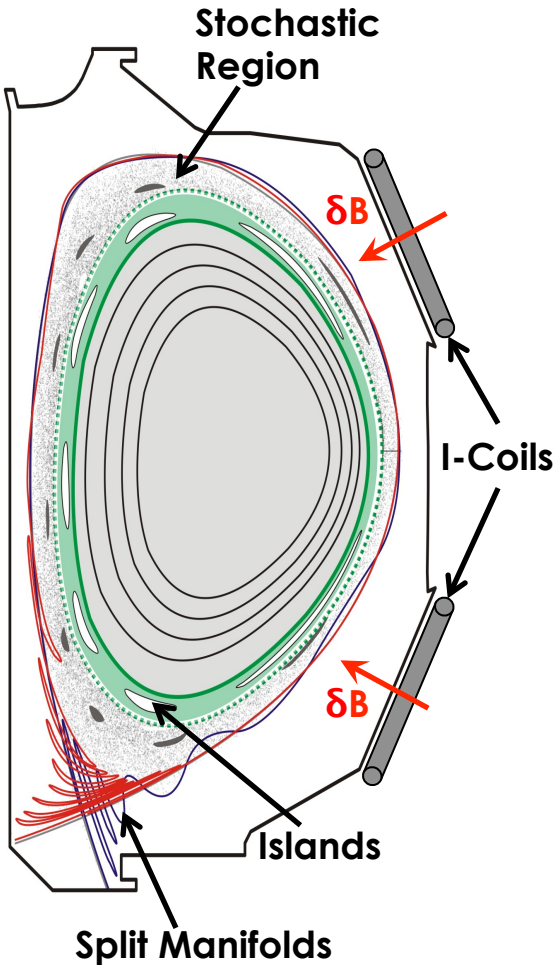


DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

Role of Plasma Response Key to Understanding 3D Fields

- **Vacuum modeling can describe aspects of 3D plasma response**
  - Islands in Limited Ohmic; Strike-point Splitting in diverted H-mode, resonance in ELM-suppression
  - What about in H-mode pedestal?

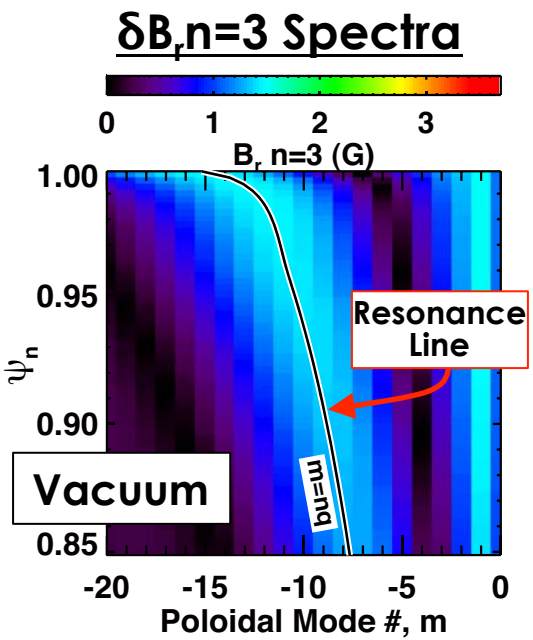


DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

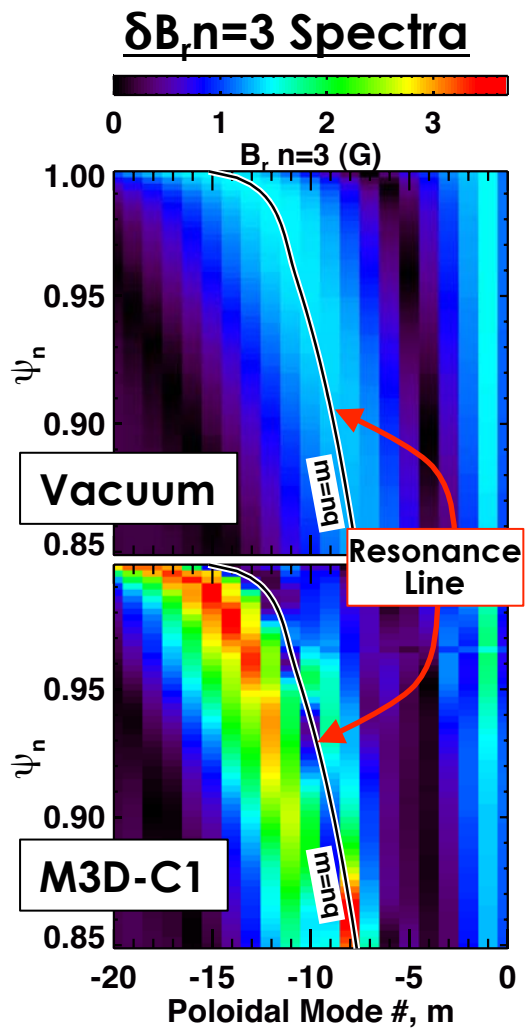
Role of Plasma Response Key to Understanding 3D Fields

- **Vacuum modeling can describe aspects of 3D plasma response**
  - Islands in Limited Ohmic; Strike-point Splitting in diverted H-mode, resonance in ELM-suppression
  - What about in H-mode pedestal?



Role of Plasma Response Key to Understanding 3D Fields

- **Vacuum modeling can describe aspects of 3D plasma response**
  - Islands in Limited Ohmic; Strike-point Splitting in diverted H-mode, resonance in ELM-suppression
- **Extended MHD offers approach to modify vacuum model**
  - Two-fluid resistive MHD (M3D-C1 code): partial resonant screening (islands) + non-resonant amplification (kinking), key: $\omega_{e,\perp}$
- **Key questions:**
  - Where can vacuum modeling be applied?
  - Which key physics govern plasma response?



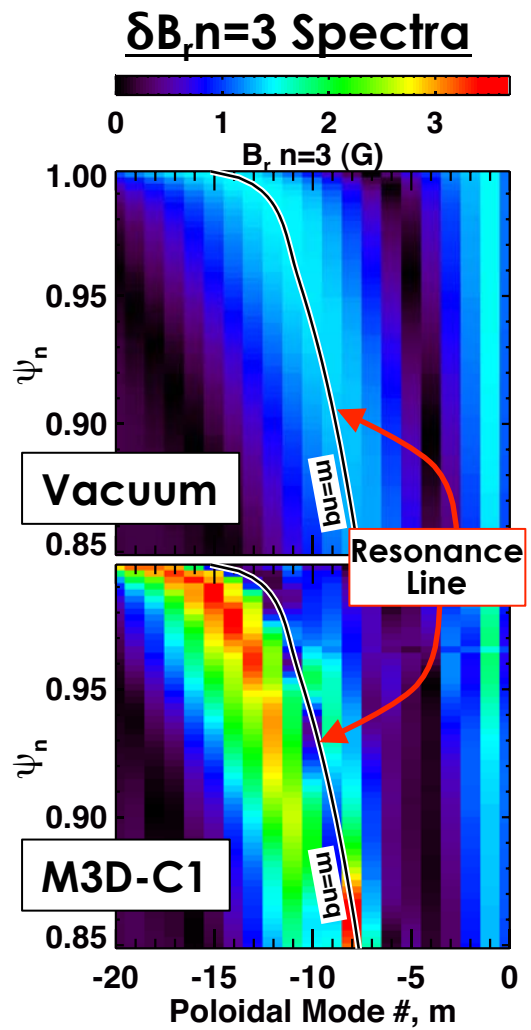
DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

Role of Plasma Response Key to Understanding 3D Fields

- **Vacuum modeling can describe aspects of 3D plasma response**
  - Islands in Limited Ohmic; Strike-point Splitting in diverted H-mode, resonance in ELM-suppression
- **Extended MHD offers approach to modify vacuum model**
  - Two-fluid resistive MHD (M3D-C1 code): partial resonant screening (islands) + non-resonant amplification (kinking), key: $\omega_{e,\perp}$
- **Key questions:**
  - Where can vacuum modeling be applied?
  - Which key physics govern plasma response?

Goal: Validate Models with new measurements – Tangential SXR Imaging in X-point Region



DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

Outline

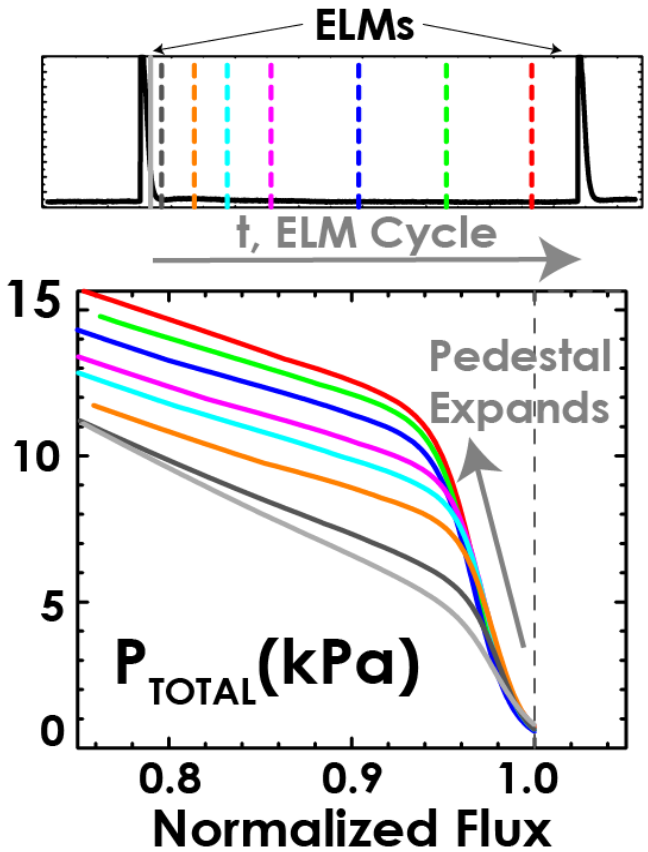
- **Potential model describes RMP ELM suppression on DIII-D invoking two-fluid resistive MHD**
  - Measurements needed to challenge/verify assumptions
- **Tangential SXR camera in X-point region exploits flux expansion to measure topological changes from RMPs**
  - Filtered emission offers effective radial discrimination
  - Differential Imaging used to isolate response
- **Radially resolved measurements of plasma response through forward modeling of SXR Imaging:**
  - Lobes extending from the unperturbed separatrix at plasma boundary agrees well with vacuum
  - Helical displacements in the steep-gradient region inside the unperturbed separatrix matching with M3D-C1 (two-fluid MHD)
- **Future & Summary**

Outline

- **Potential model describes RMP ELM suppression on DIII-D invoking two-fluid resistive MHD**
  - Measurements needed to challenge/verify assumptions
- **Tangential SXR camera in X-point region exploits flux expansion to measure topological changes from RMPs**
  - Filtered emission offers effective radial discrimination
  - Differential Imaging used to isolate response
- **Radially resolved measurements of plasma response through forward modeling of SXR Imaging:**
  - Lobes extending from the unperturbed separatrix at plasma boundary agrees well with vacuum
  - Helical displacements in the steep-gradient region inside the unperturbed separatrix matching with M3D-C1 (two-fluid MHD)
- **Future & Summary**

Emerging Model for RMP ELM Suppression

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



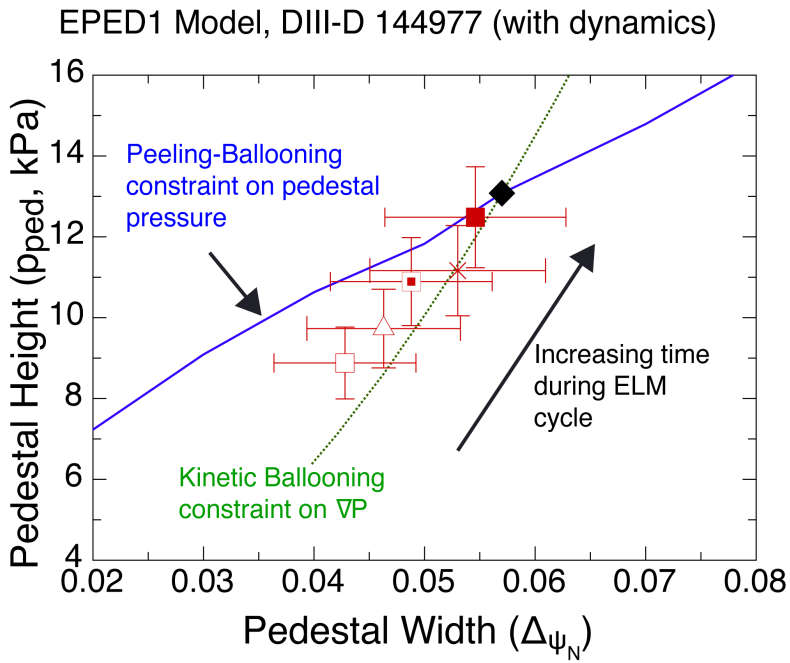
Wade, IAEA 2012

DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

Emerging Model for RMP ELM Suppression

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

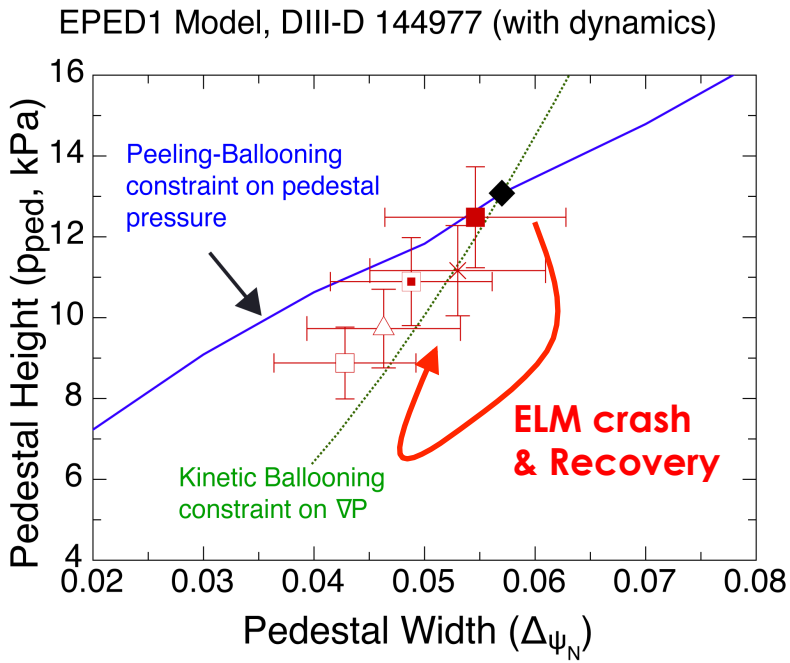


*Synder et al. POP 2012

Wade, IAEA 2012

Emerging Model for RMP ELM Suppression

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

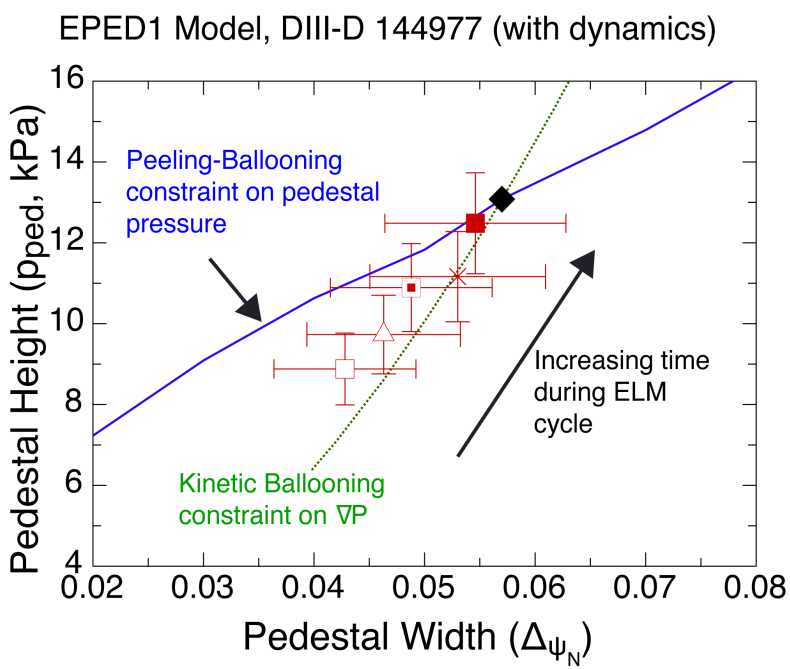


*Synder et al. POP 2012

Wade, IAEA 2012

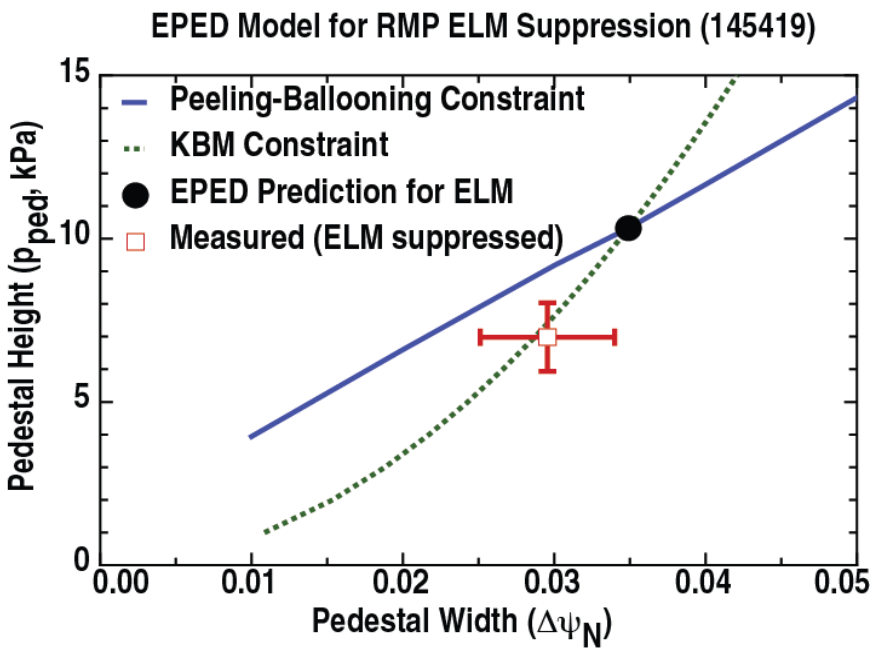
Emerging Model for RMP ELM Suppression

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



*Synder et al. POP 2012

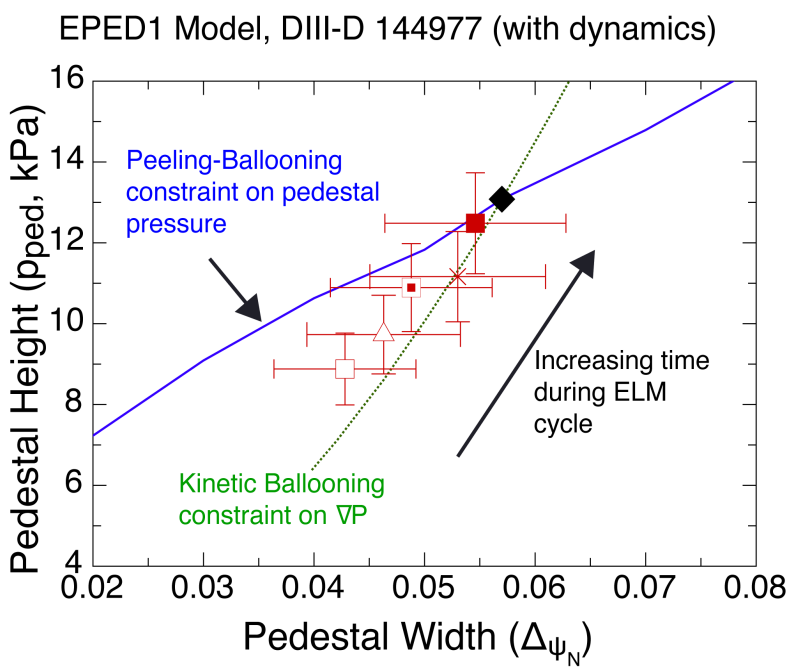
- **With RMP, P-B boundary isn't met**



Wade, IAEA 2012

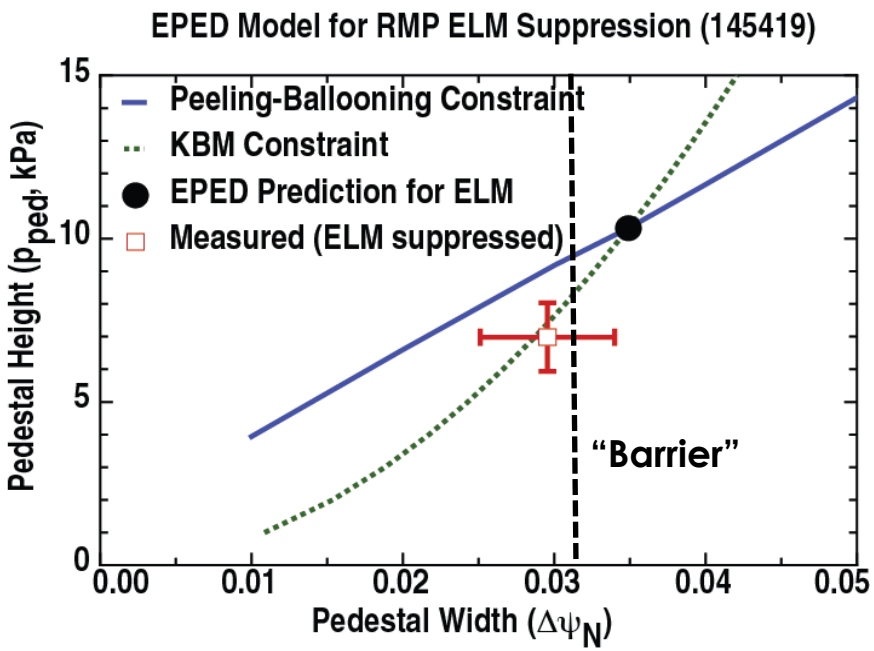
Emerging Model for RMP ELM Suppression

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



*Synder et al. POP 2012

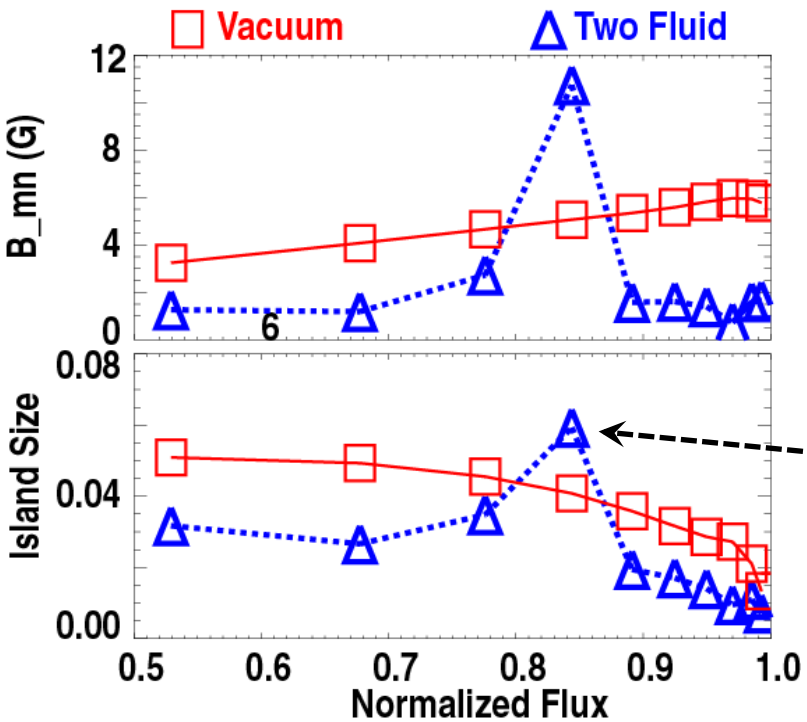
- **With RMP, P-B boundary isn't met**
  - Model: MHD response at top of pedestal enhances transport and stops pedestal expansion



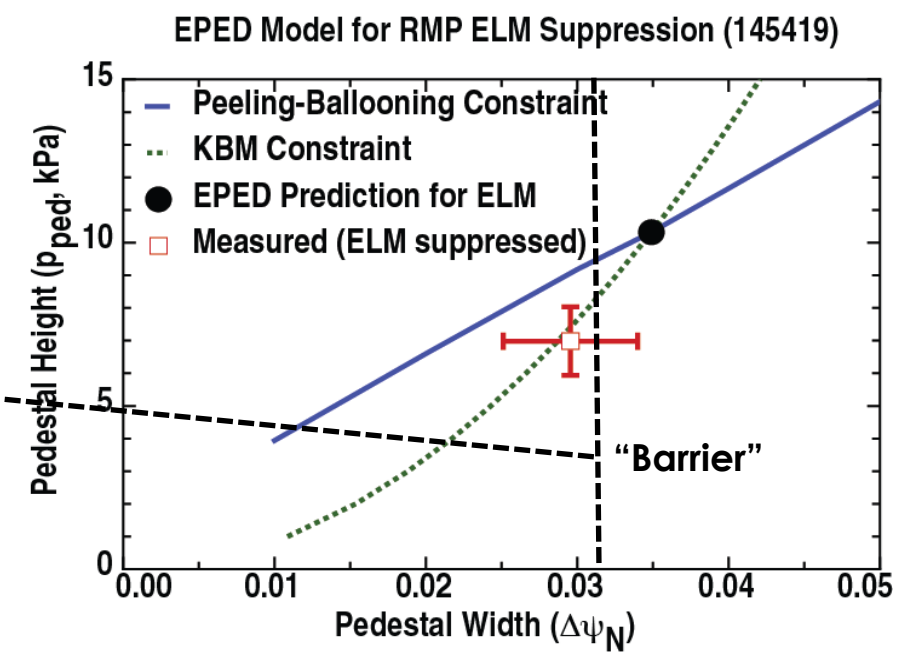
Wade, IAEA 2012

Emerging Model for RMP ELM Suppression

- **Two-Fluid MHD can indicate island formation at pedestal top**



- **With RMP, P-B boundary isn't met**
  - Model: MHD response at top of pedestal enhances transport and stops pedestal expansion

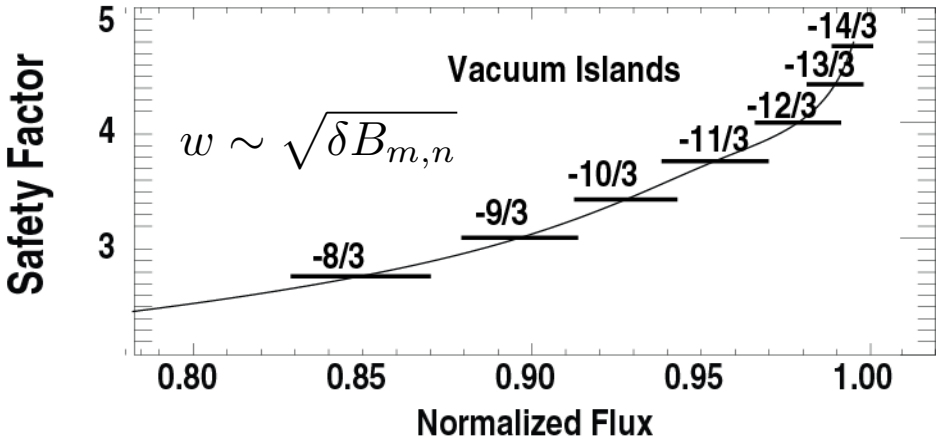


*Synder et al. POP 2012

Wade, IAEA 2012

Single Fluid Resistive MHD Predicts Shielding Currents on Rational Surfaces Depending on Rotation

- **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



Wade, IAEA 2012

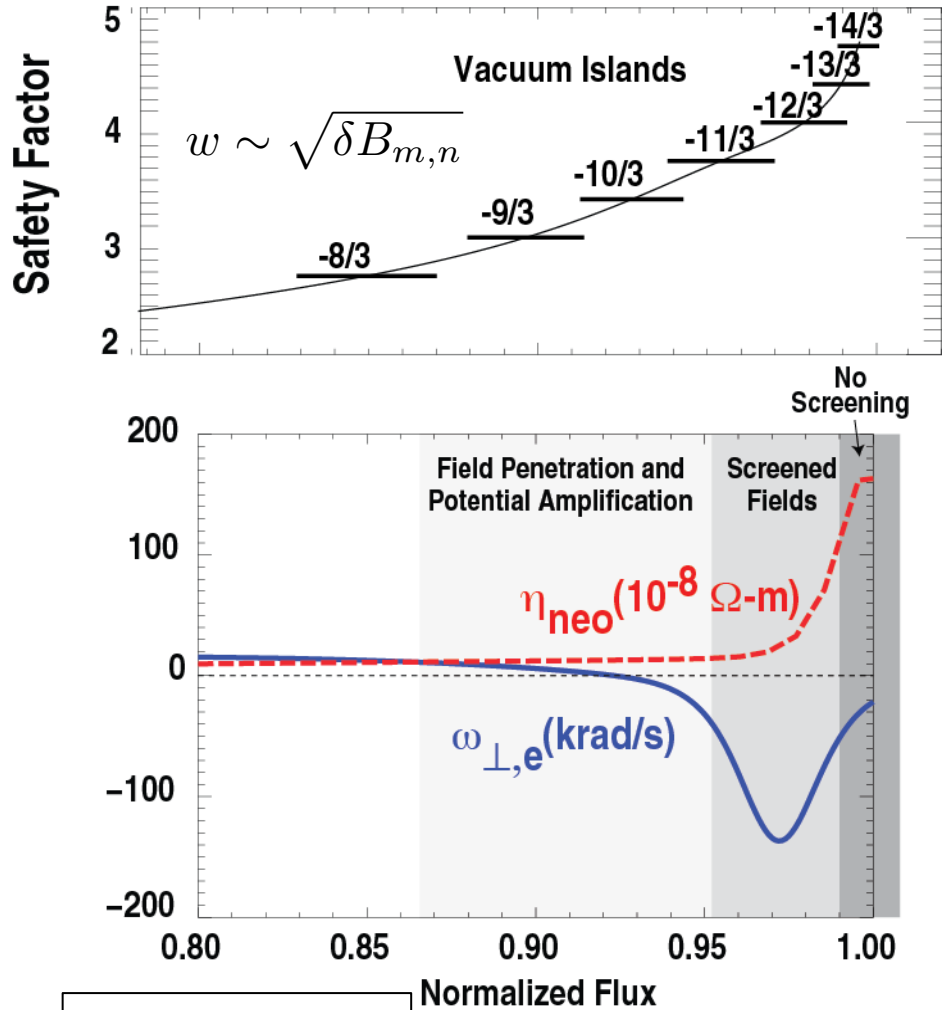
DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

Two-Fluid Resistive MHD Plasma Response Depends on $\omega_{\perp,e}$

- **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***

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



*Ferraro et al. POP 2012

Wade, IAEA 2012

DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

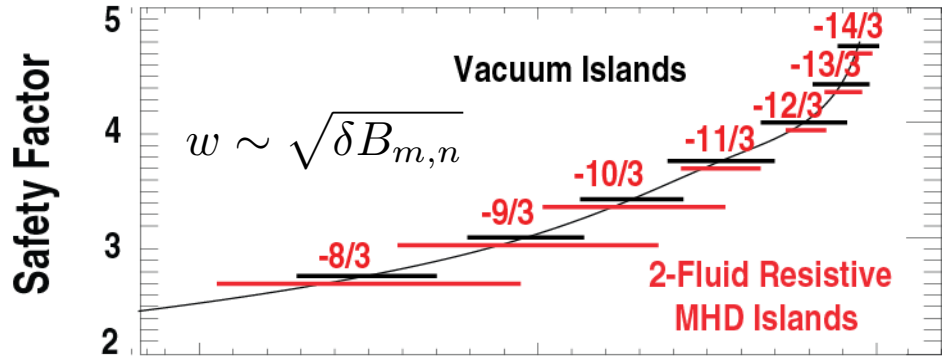
Two-Fluid Resistive MHD Plasma Response Depends on $\omega_{\perp,e}$

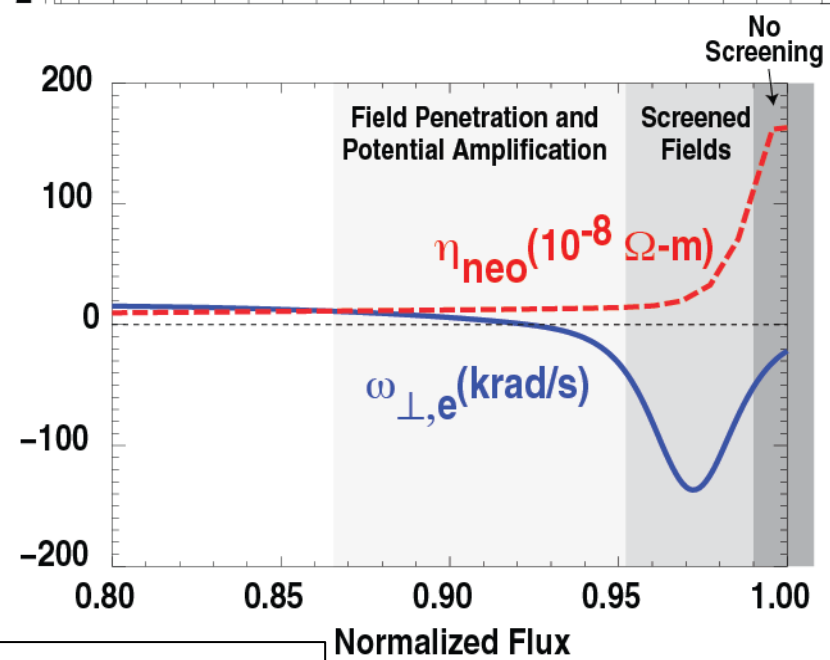
- **In vacuum model, large islands generated in edge region**
- **Applied field shielded by image currents on rational surface if:**
  - Resistivity is small (true everywhere but edge)
  - Sufficient plasma rotation
- **Fields can "penetrate" at low perpendicular electron frequency***

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

- **2-Fluid model predicts larger islands at top of pedestal**
  - Possible Mechanism?

*Ferraro et al. POP 2012

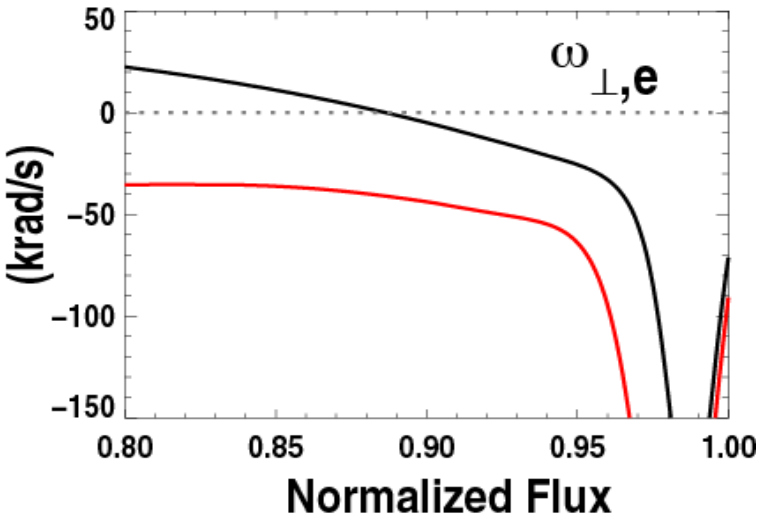


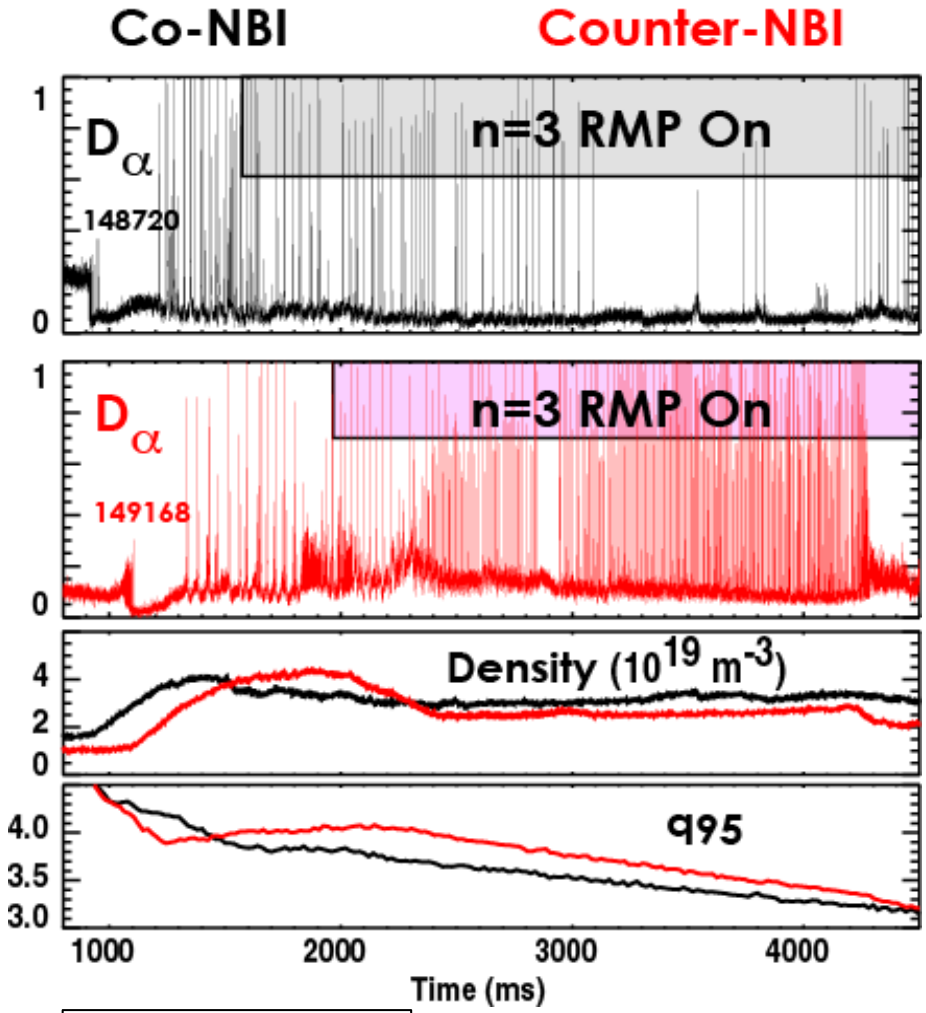


Wade, IAEA 2012

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

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

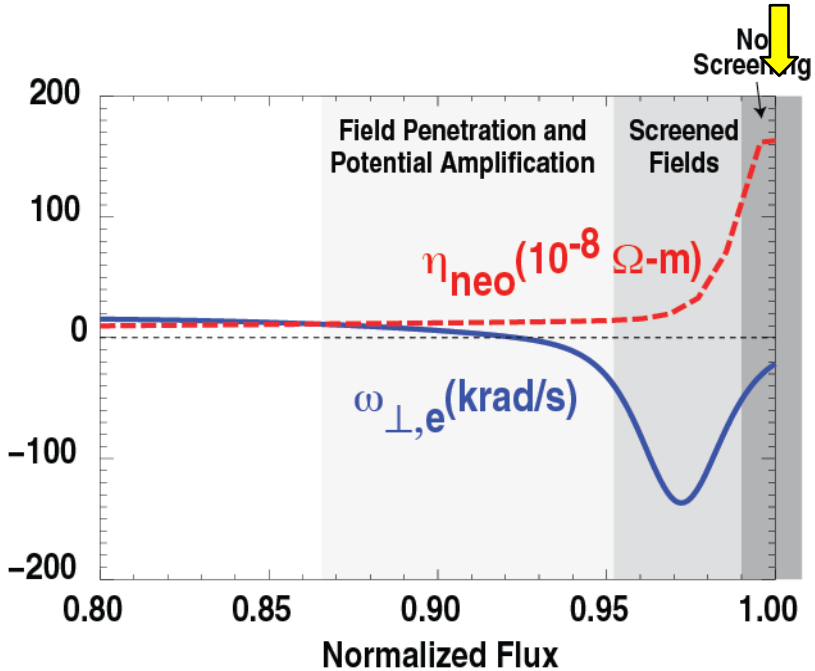


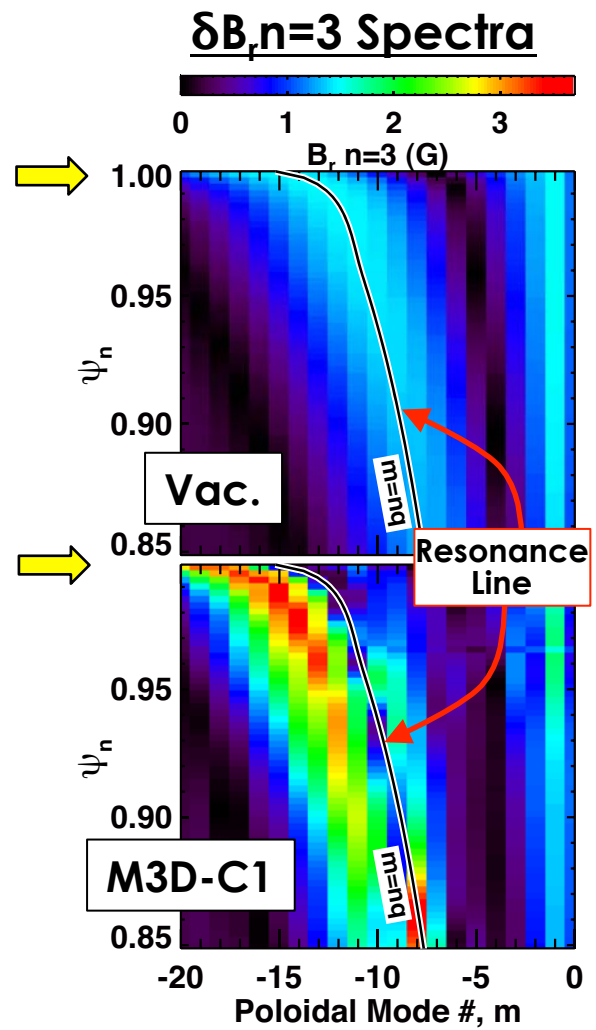


Wade, IAEA 2012

Goal of Measurements: Target Radial Regions to Test Validity of Vacuum vs. Two-Fluid

- **Edge/SOL – should be vacuum**
- **Steep gradient – vacuum vs. screening?**
  - Kinking vs islands?
- **Top of Pedestal… (not there yet)**



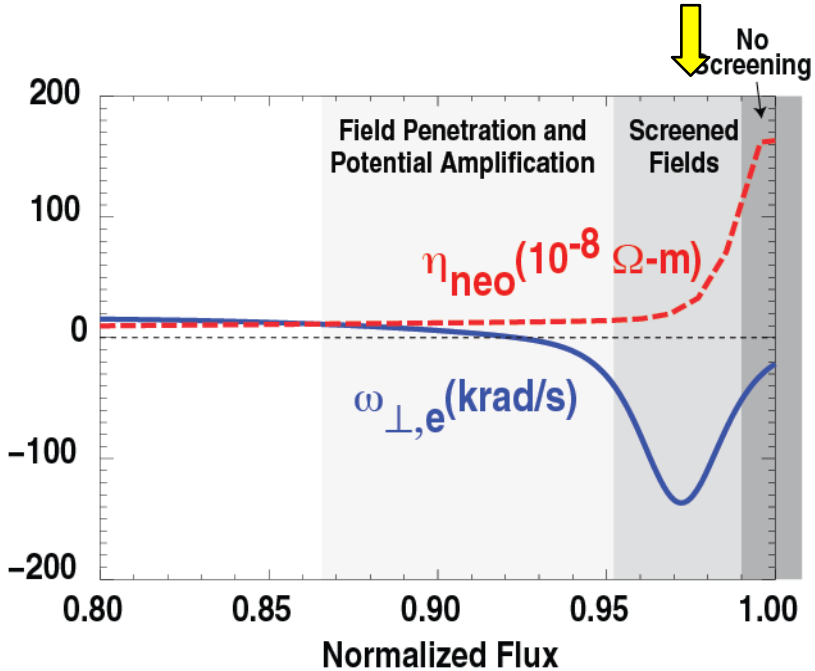


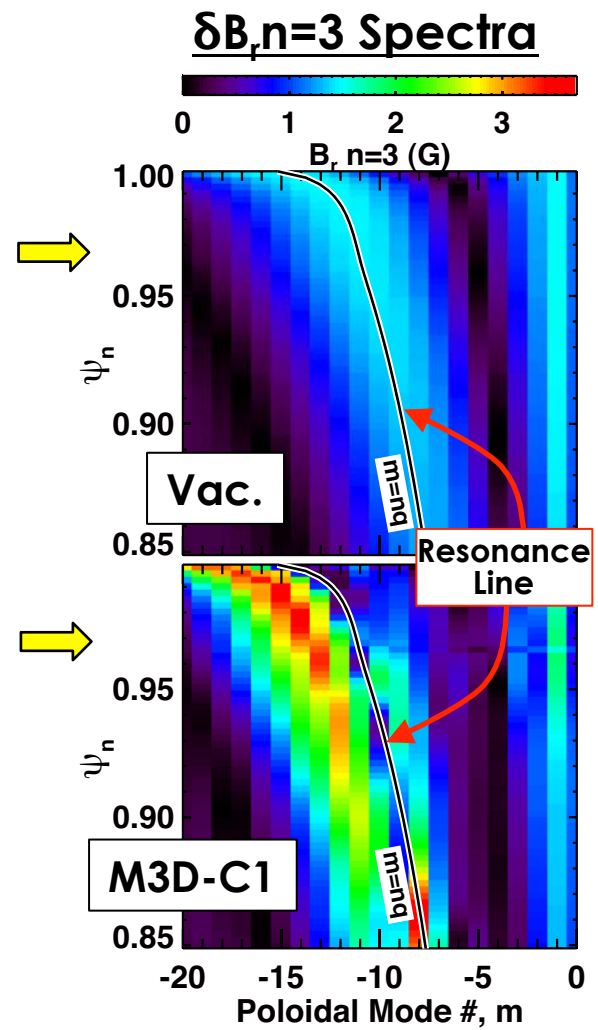
DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

Goal of Measurements: Target Radial Regions to Test Validity of Vacuum vs. Two-Fluid

- **Edge/SOL – should be vacuum**
- **Steep gradient – vacuum vs. screening?**
  - Kinking vs islands?
- **Top of Pedestal… (not there yet)**



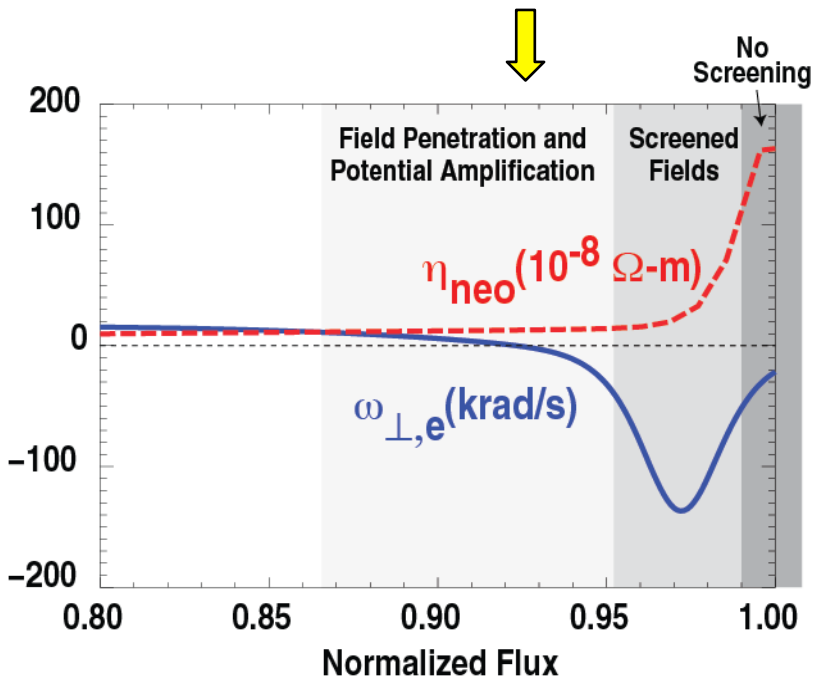


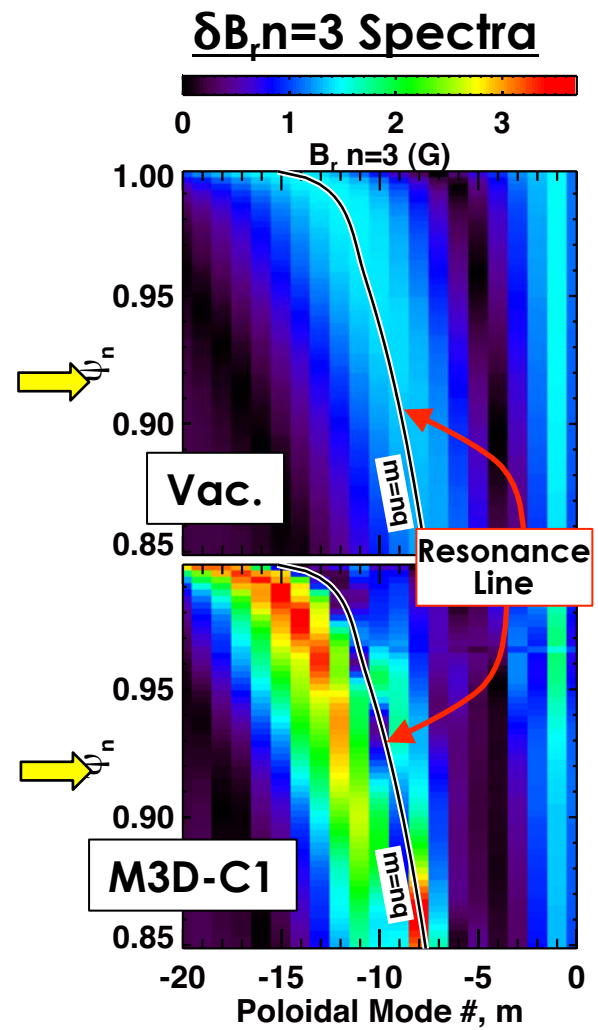
DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

Goal of Measurements: Target Radial Regions to Test Validity of Vacuum vs. Two-Fluid

- **Edge/SOL – should be vacuum**
- **Steep gradient – vacuum vs. screening?**
  - Kinking vs islands?
- **Top of Pedestal… (not there yet)**



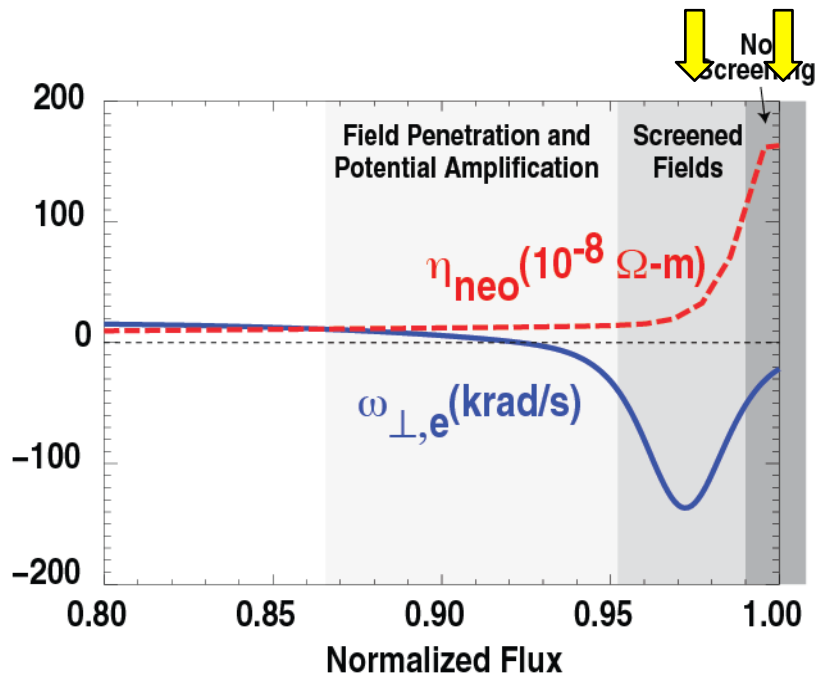


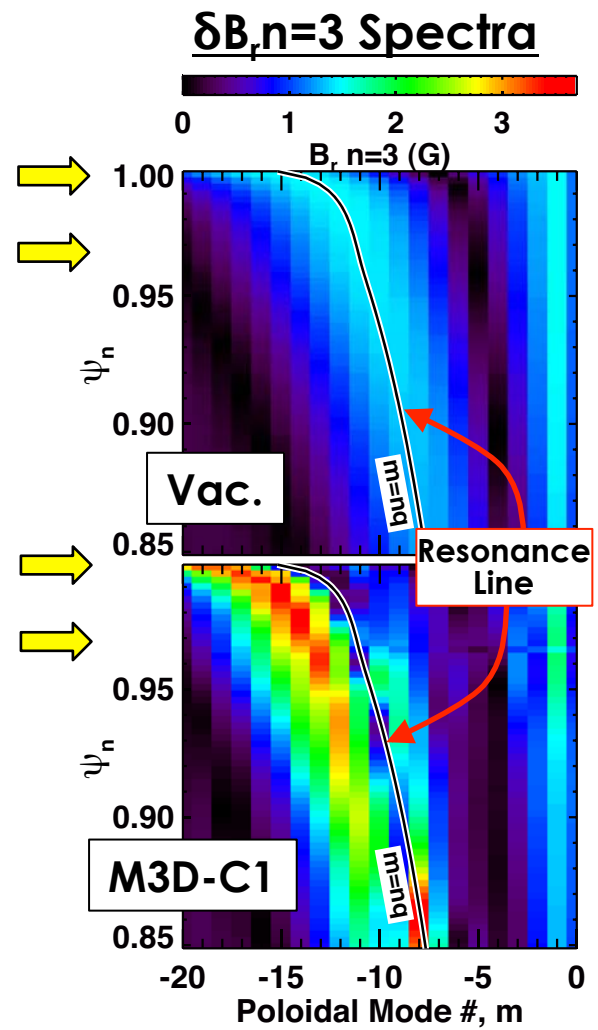
DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

Goal of Measurements: Target Radial Regions to Test Validity of Vacuum vs. Two-Fluid

- **Edge/SOL – should be vacuum**
- **Steep gradient – vacuum vs. screening?**
  - Kinking vs islands?
- **Top of Pedestal… (not there yet)**





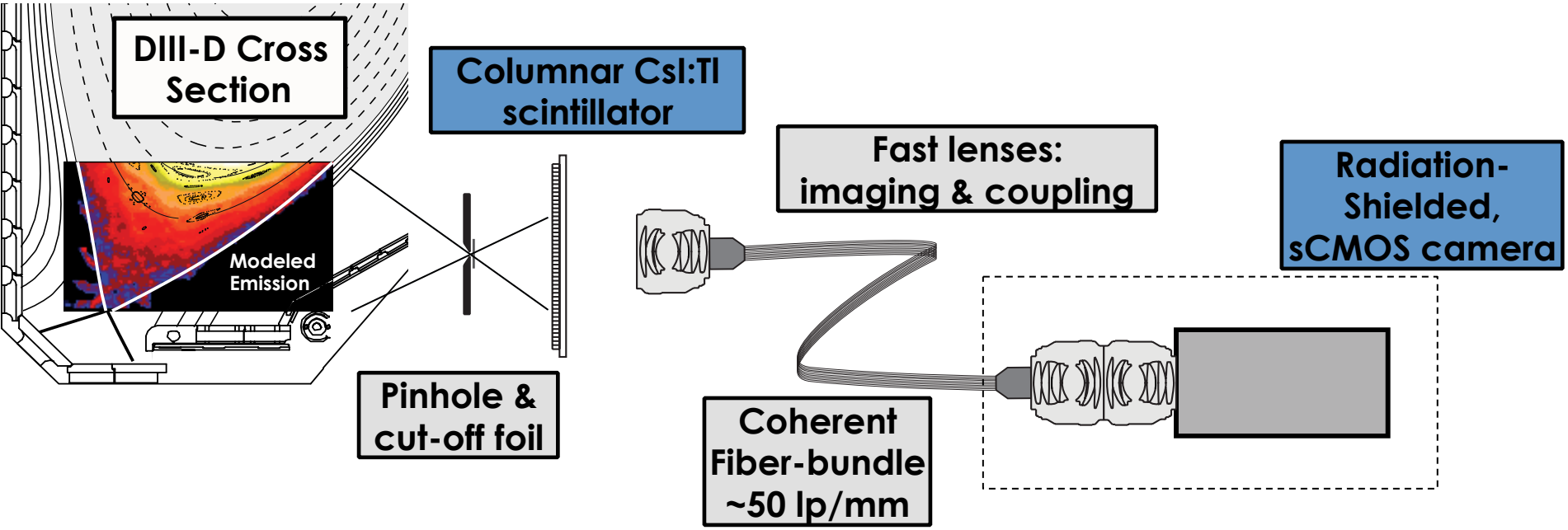
DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

Outline

- **Potential model describes RMP ELM suppression on DIII-D invoking two-fluid resistive MHD**
  - Measurements needed to challenge/verify assumptions
- **Tangential SXR camera in X-point region exploits flux expansion to measure topological changes from RMPs**
  - Filtered emission offers effective radial discrimination
  - Differential Imaging used to isolate response
- **Radially resolved measurements of plasma response through forward modeling of SXR Imaging:**
  - Lobes extending from the unperturbed separatrix at plasma boundary agrees well with vacuum
  - Helical displacements in the steep-gradient region inside the unperturbed separatrix matching with M3D-C1 (two-fluid MHD)
- **Future & Summary**

Basis of Measurement Motivated by Core Tangential SXR Systems from Many Machines: PBX-M to LHD



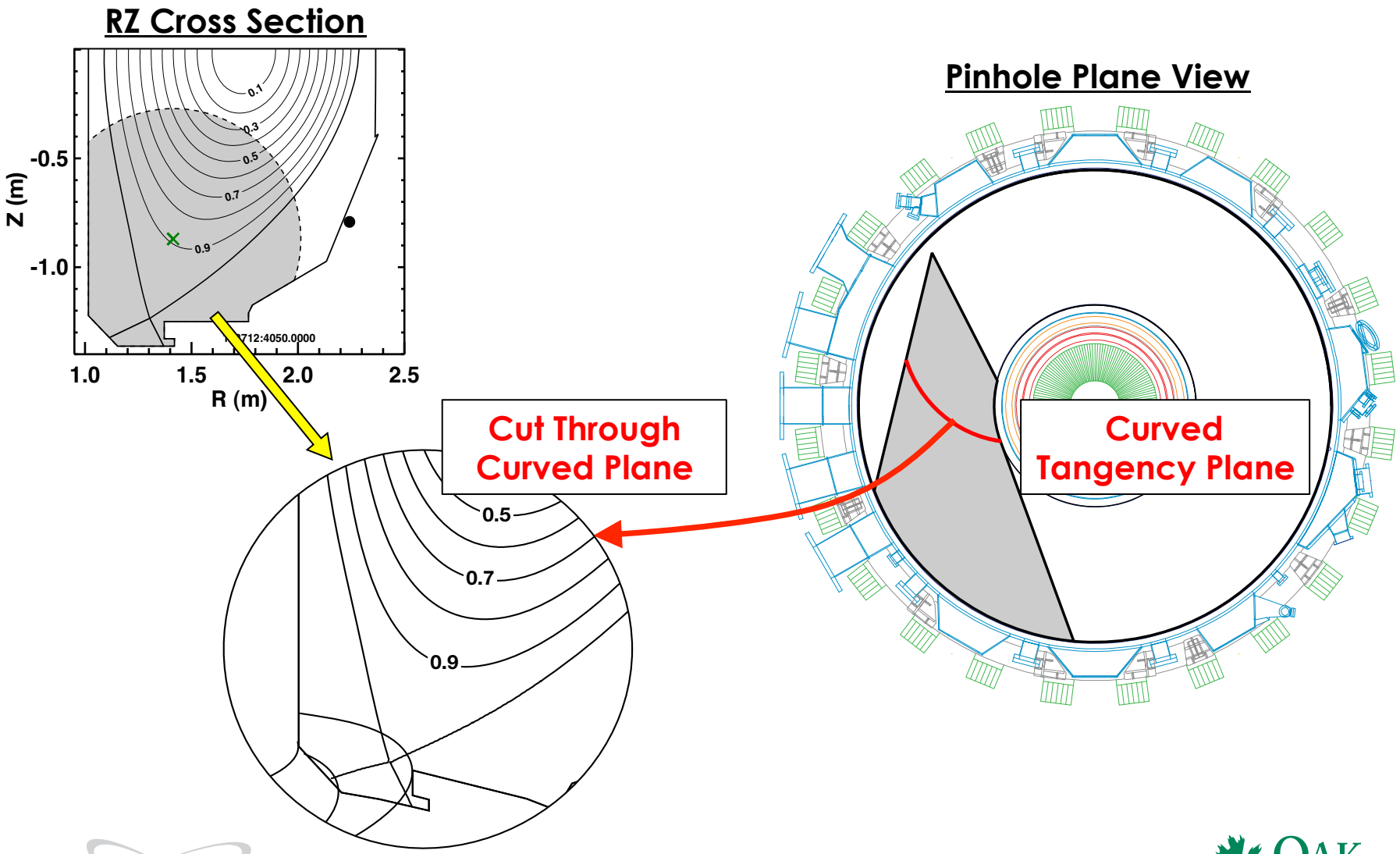
- **Systems used to image core islands***
- **Adapted to X-point region diverted H-Mode**
  - Flux expansion ~ 10:1
- **Columnar CsI:Tl ⇒ 35 ph/keV X-ray, ~15 lp/mm, linear energy resp.**
- **Camera: 16-bit sCMOS**

*Ohdachi, et al. Plasma Science Tech. (2006)

DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

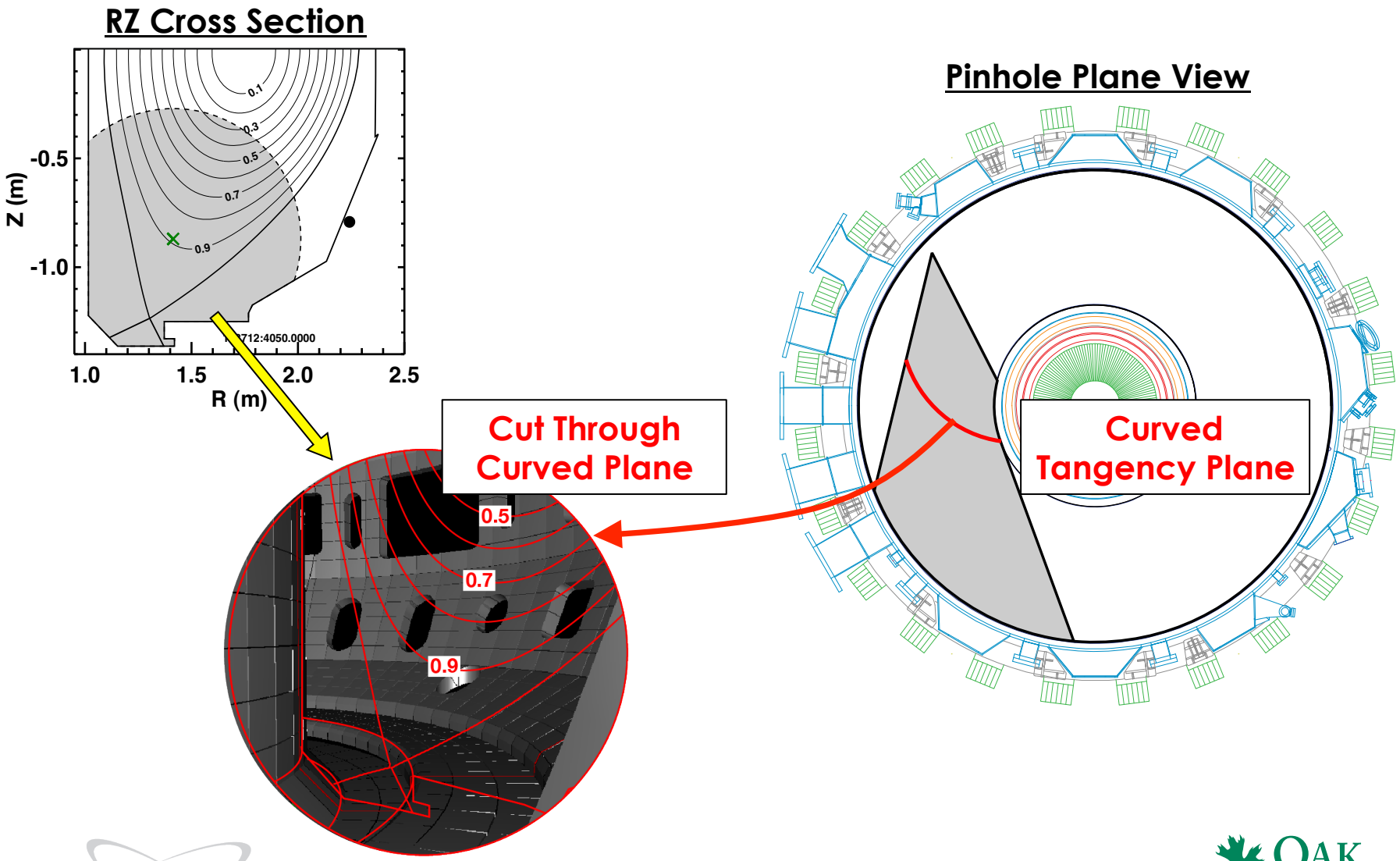
Pinhole SXR Camera Exploits Flux Expansion at X-Point



DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

Pinhole SXR Camera Exploits Flux Expansion at X-Point



DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

Different Metallic Filters Provide Radial Discrimination

1. SXR: $E_{c,10\%}$ ~ 500 eV ➔ *steep gradient region*

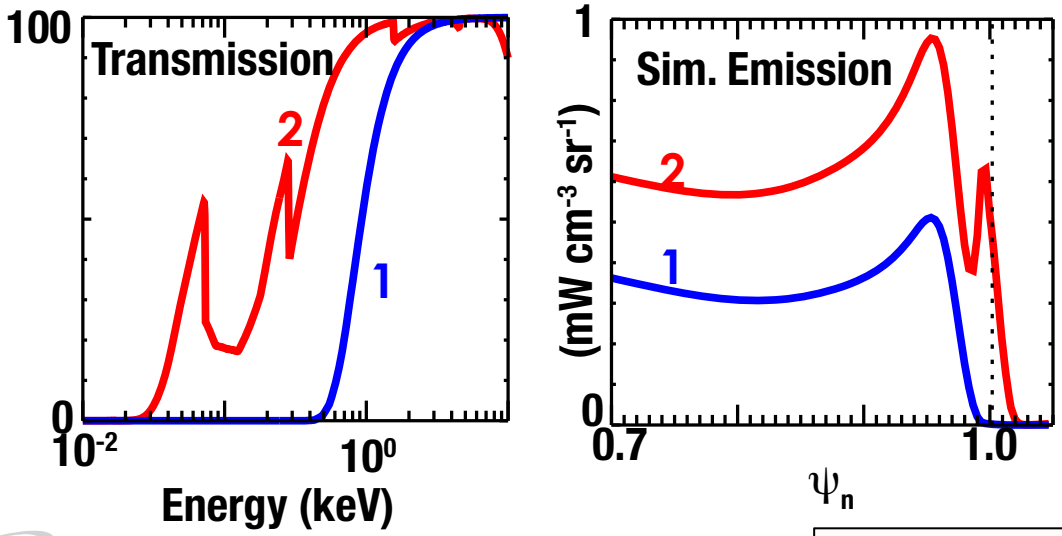
- Beryllium (5 μm)

2. USXR: $E_{c,10\%}$ ~ 40eV ➔ extended to *Edge/SOL*

- Al-coated (0.05 μm) Parylene-N (0.1 μm)

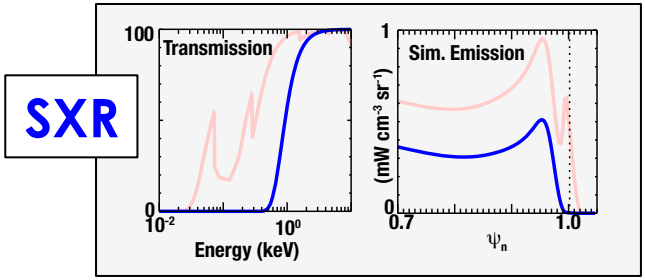
- **Simulated spectra to model SXR/USXR profile**
  - CHIANTI* astro code & measured n_e, T_e, n_z

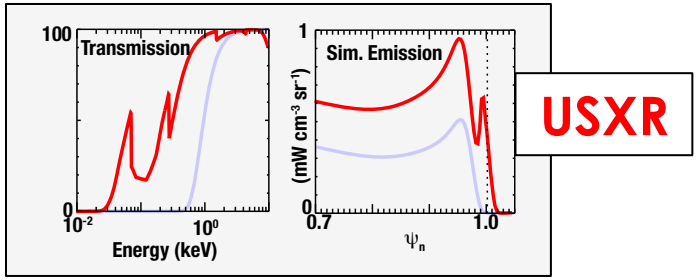
$$SXR_{cont.} \sim \frac{n_e^2}{\sqrt{T_e}} \exp\left(-\frac{h\nu}{kT_e}\right)$$

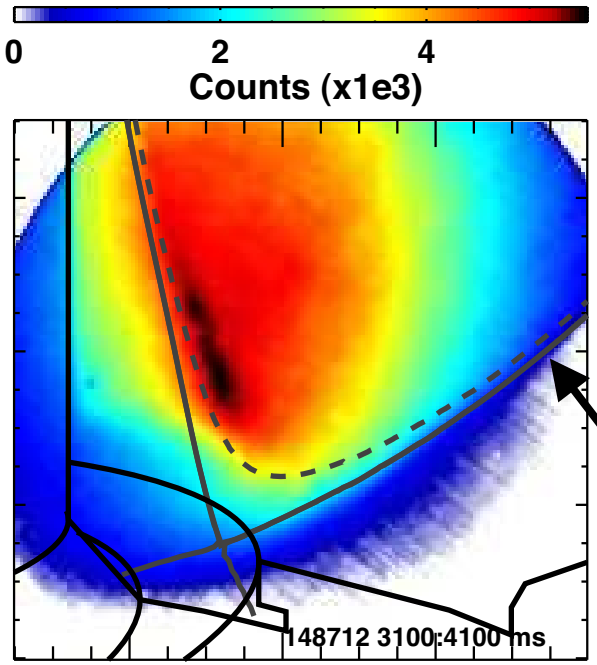


*Landi E. et al 2012 ApJ **744** 99

Views with Different Filters Access Pedestal to Divertor

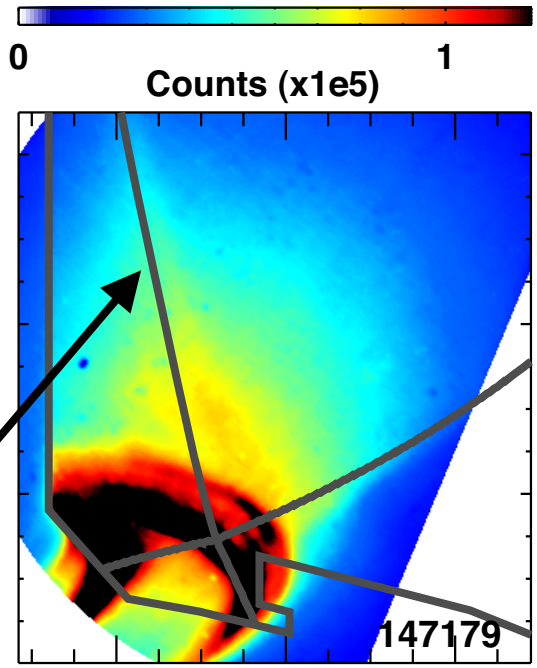






Different Scales

Boundaries from Curved Tangency Plane

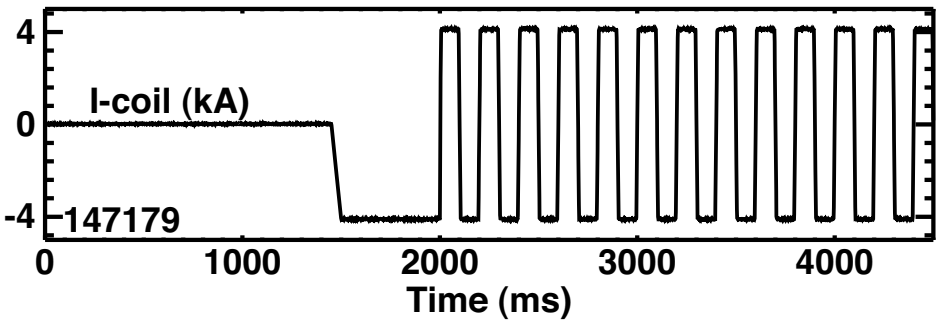


DIII-D NATIONAL FUSION FACILITY

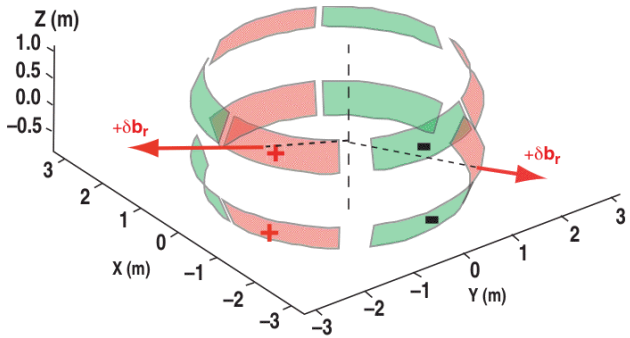
OAK RIDGE National Laboratory

n=3 RMP Phase Modulation Used to Isolate Response

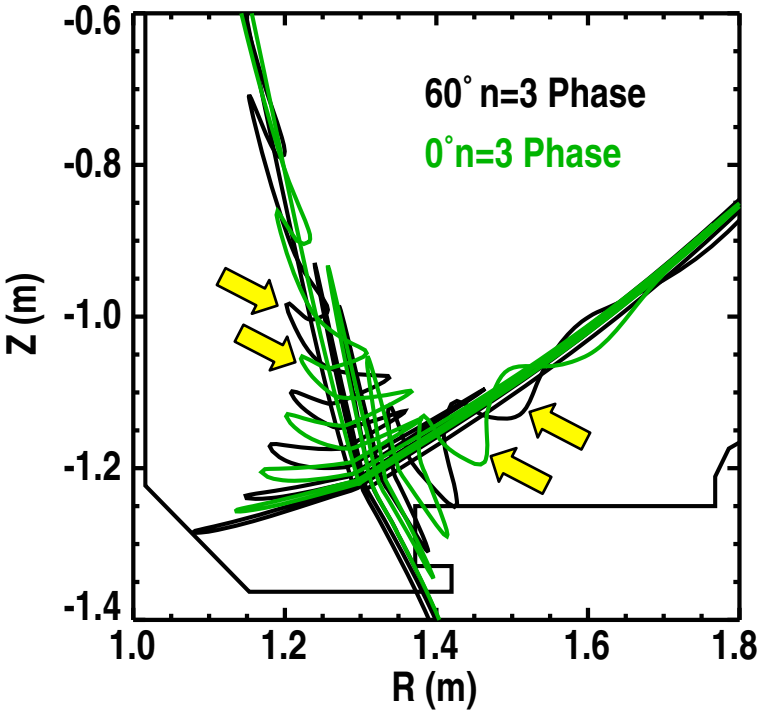
- Standard DIII-D RMP ELM-suppression plasmas with alternating n=3 phases by 60 degrees



n=3 I-Coil



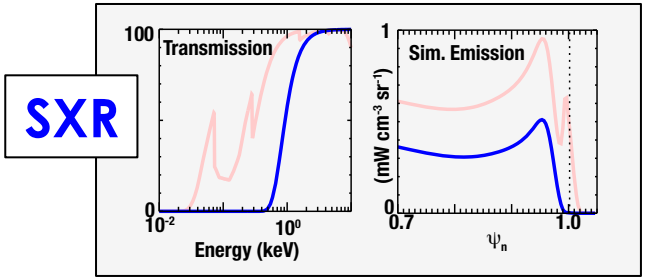
Perturbed Separatrix

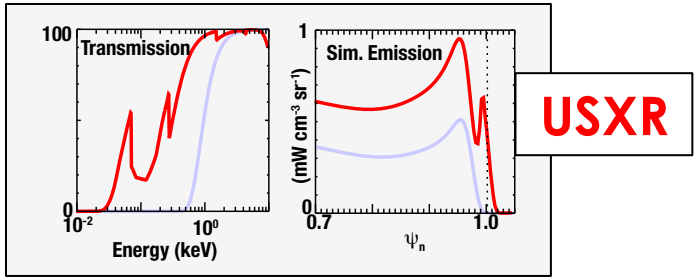


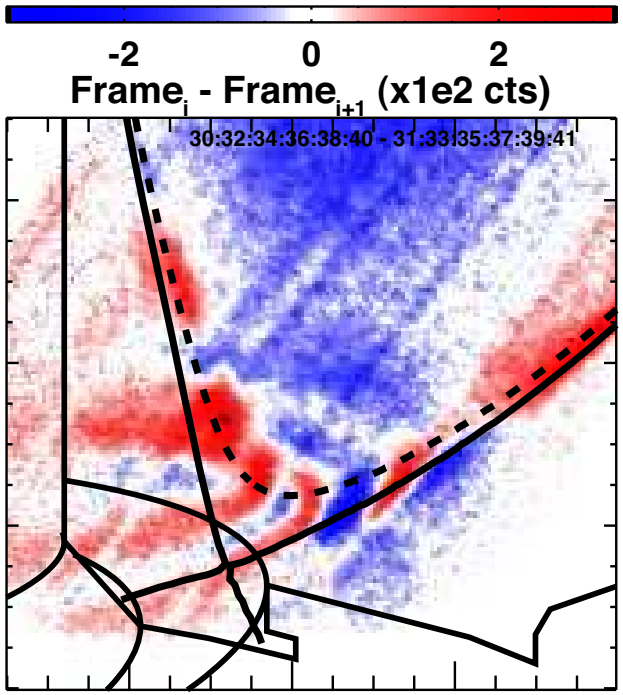
DIII-D NATIONAL FUSION FACILITY

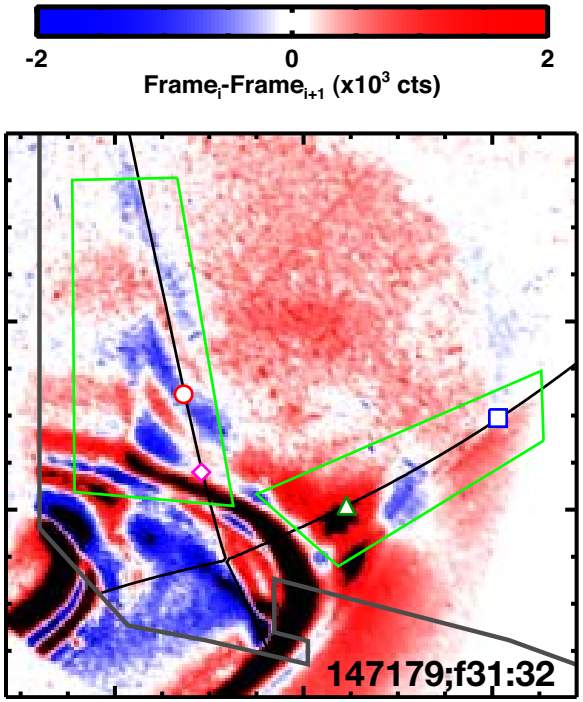
OAK RIDGE National Laboratory

Out-of-Phase Differential Images Isolate Response

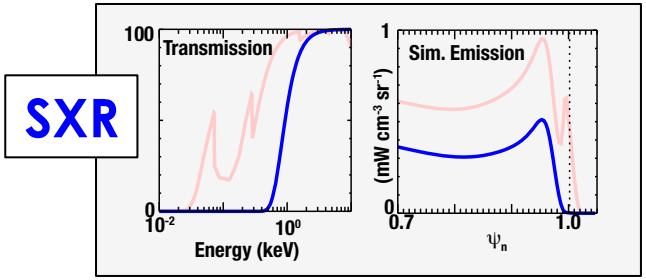


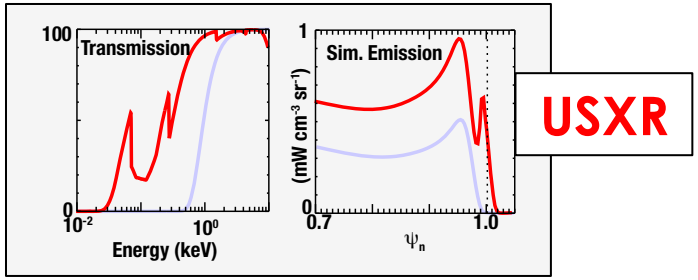


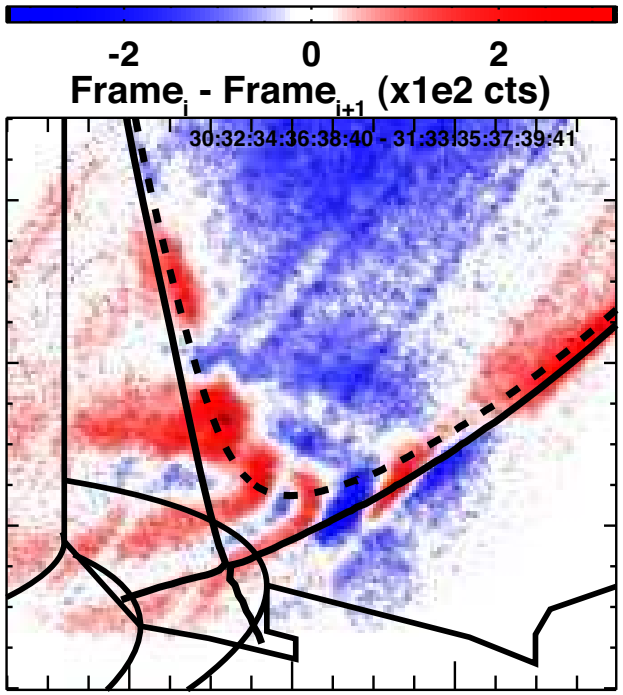


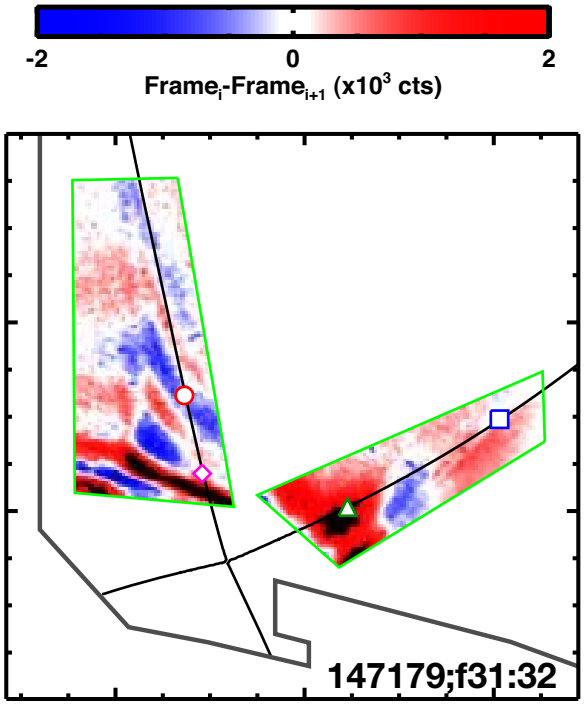


Out-of-Phase Differential Images Isolate Response

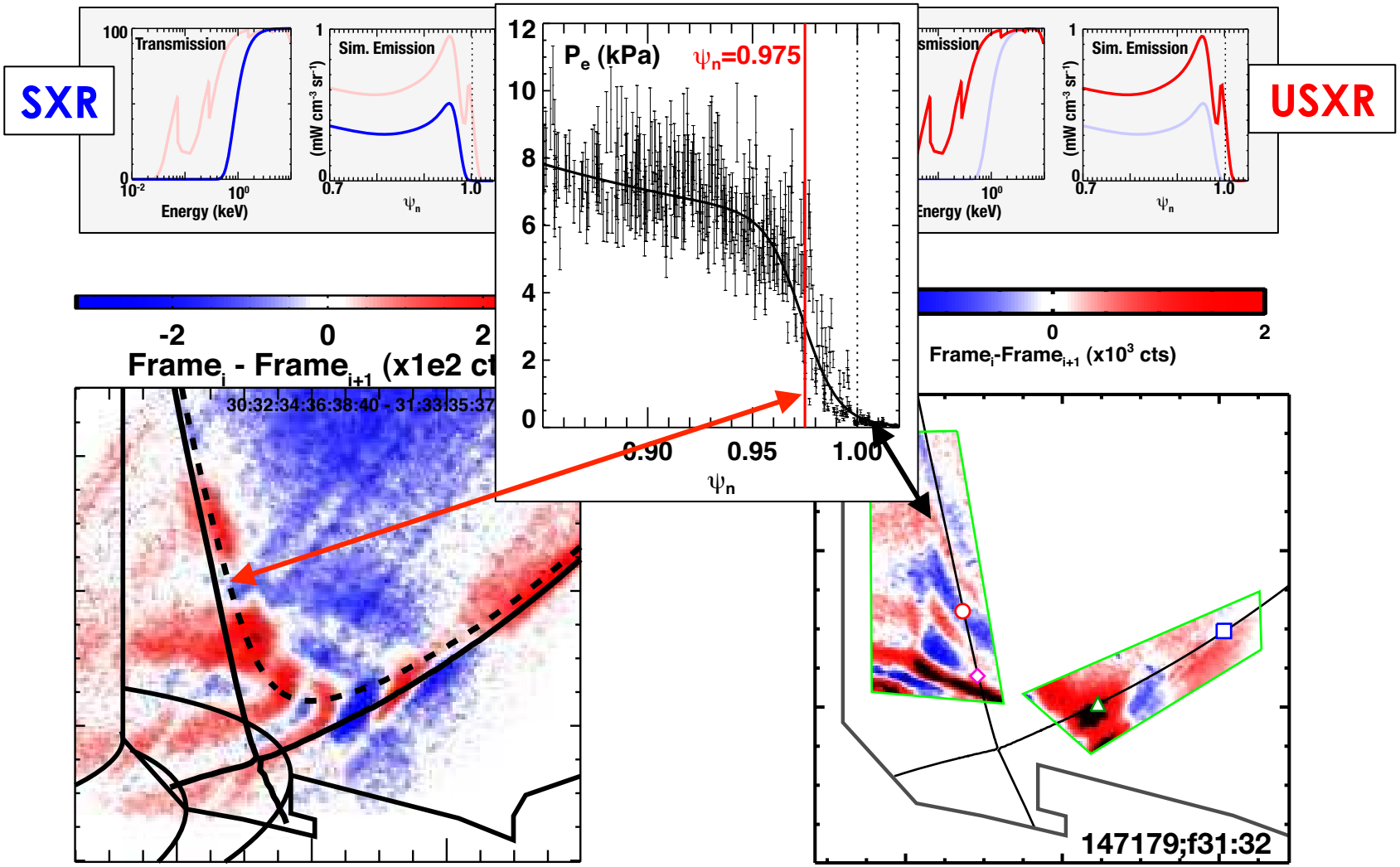








Out-of-Phase Differential Images Isolate Response



DIII-D NATIONAL FUSION FACILITY

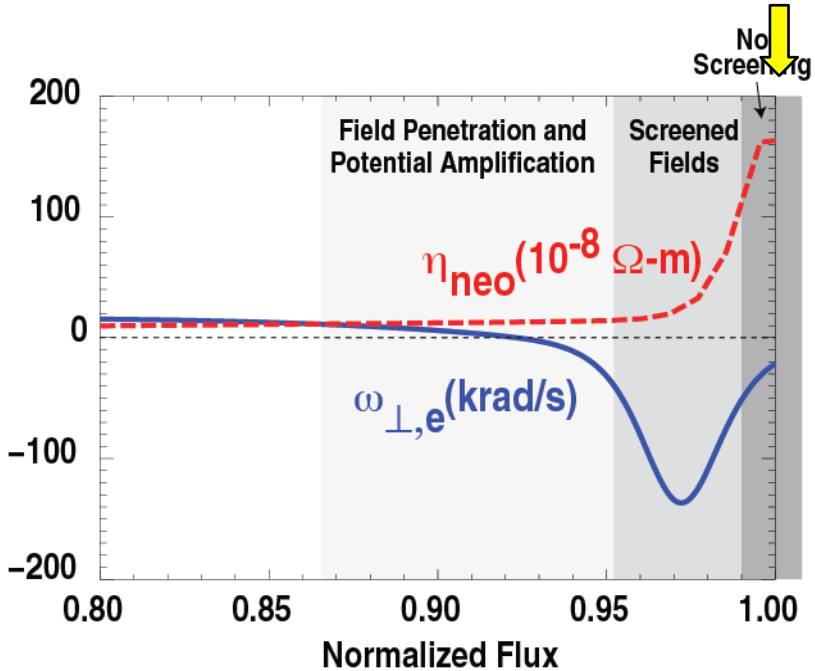
OAK RIDGE National Laboratory

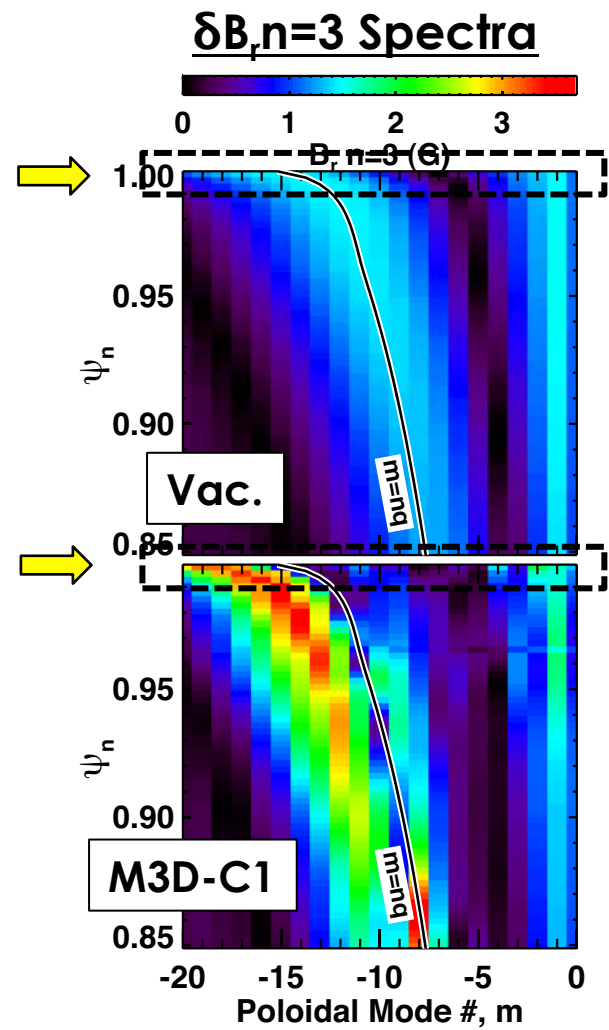
Outline

- **Potential model describes RMP ELM suppression on DIII-D invoking two-fluid resistive MHD**
  - Measurements needed to challenge/verify assumptions
- **Tangential SXR camera in X-point region exploits flux expansion to measure topological changes from RMPs**
  - Filtered emission offers effective radial discrimination
  - Differential Imaging used to isolate response
- **Radially resolved measurements of plasma response through forward modeling of SXR Imaging:**
  - Lobes extending from the unperturbed separatrix at plasma boundary agrees well with vacuum
  - Helical displacements in the steep-gradient region inside the unperturbed separatrix matching with M3D-C1 (two-fluid MHD)
- **Future & Summary**

Goal of Measurements: Target Radial Regions to Test Validity of Vacuum vs. Two-Fluid

- **Edge/SOL – should be vacuum** USXR
- **Steep gradient – vacuum vs. screening?**
  - Kinking vs islands?
- **Top of Pedestal… (not there yet)**



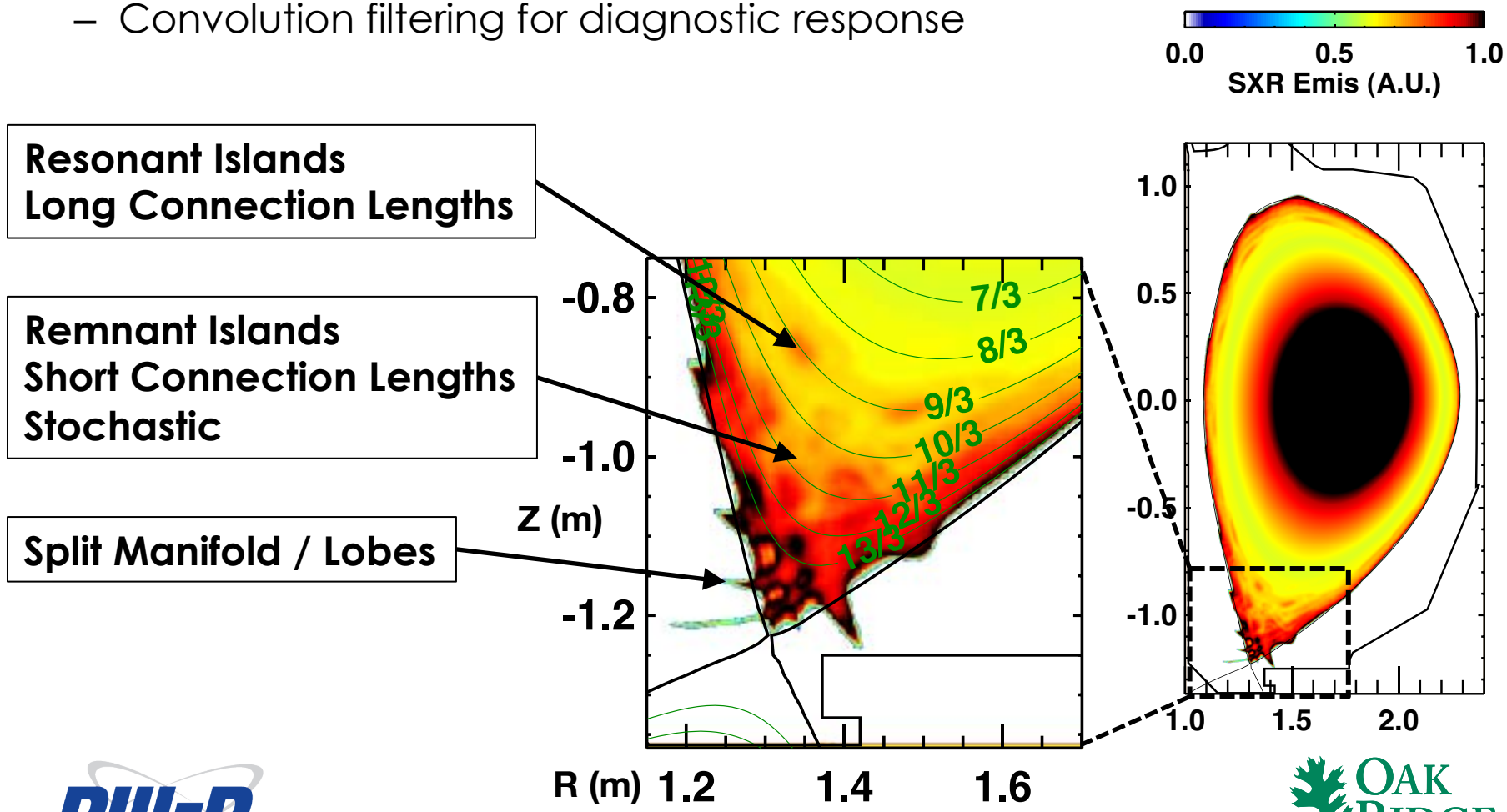


DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

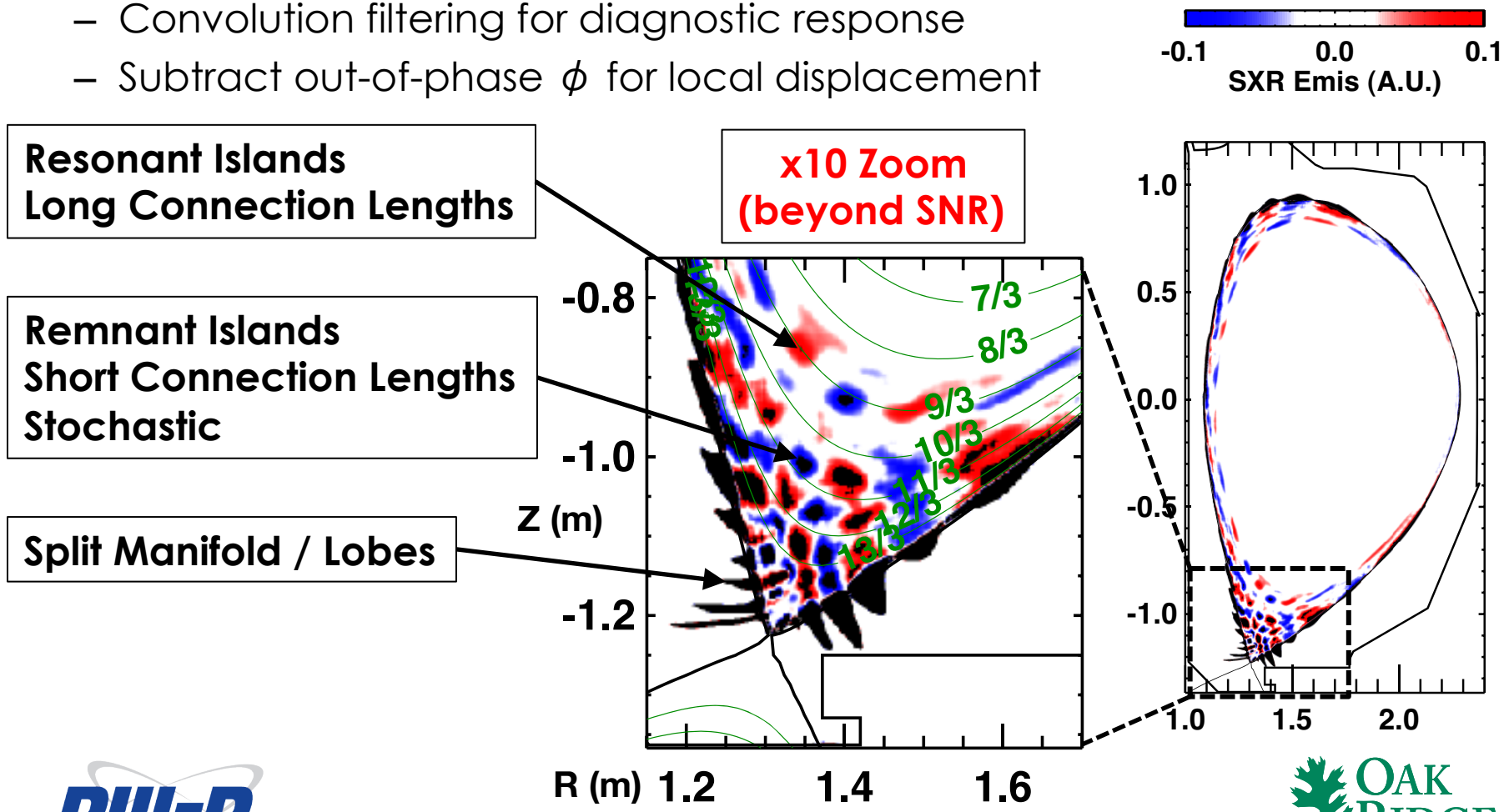
Local Vacuum Response in USXR via Forward Modeling

- **Synthetic model assumes emission constant along field lines**
  - Map 1D profile in 3D based on $\psi_{n,min}$ of FL via TRIP3D-MAFOT code
  - Convolution filtering for diagnostic response



Local Vacuum Displacement in USXR via Forward Modeling

- **Synthetic model assumes emission constant along field lines**
  - Map 1D profile in 3D based on $\psi_{n,min}$ of FL via TRIP3D-MAFOT code
  - Convolution filtering for diagnostic response
  - Subtract out-of-phase ϕ for local displacement



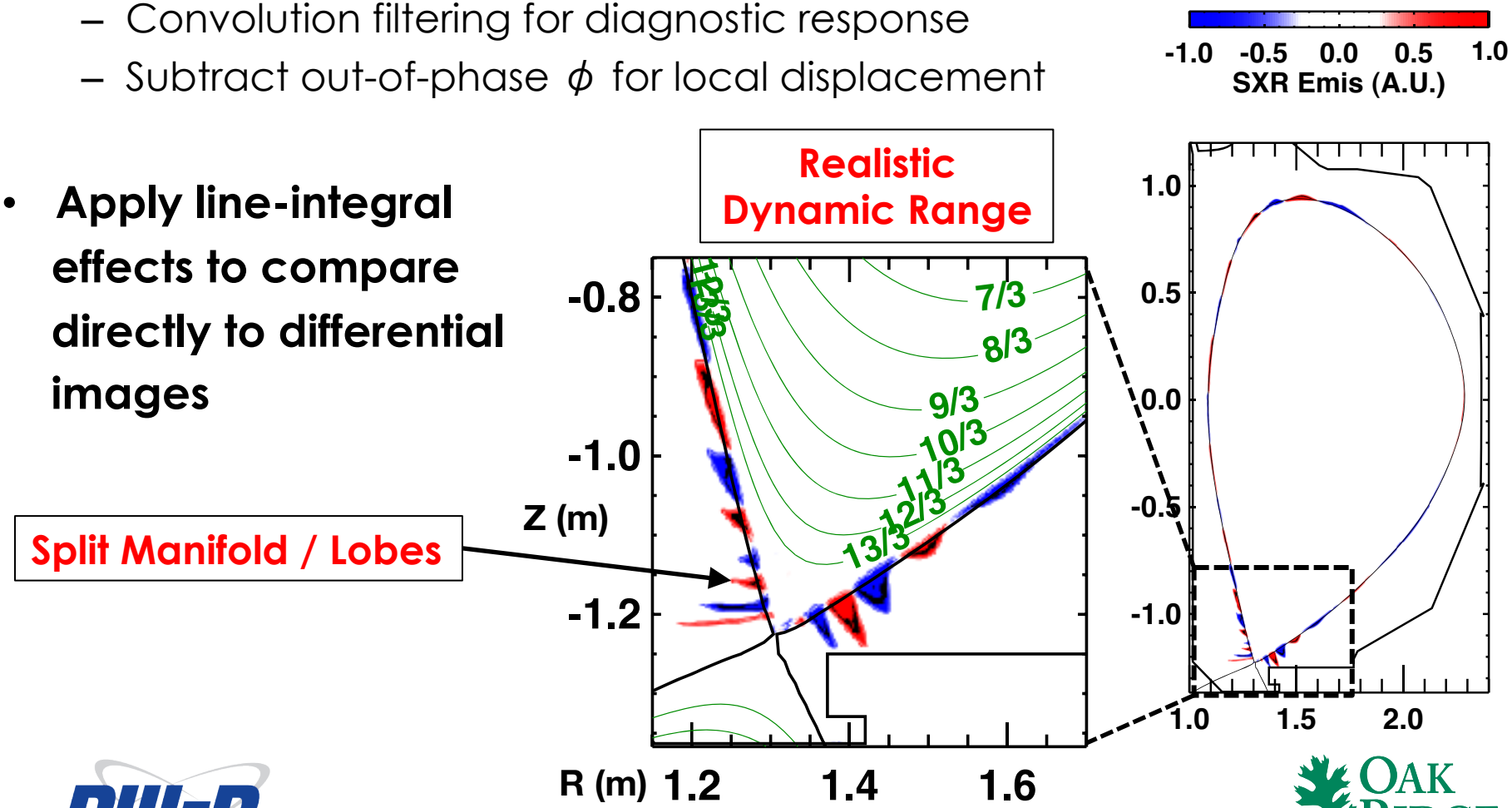
DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

Local Vacuum Displacement in USXR via Forward Modeling

- **Synthetic model assumes emission constant along field lines**
  - Map 1D profile in 3D based on $\psi_{n,min}$ of FL via TRIP3D-MAFOT code
  - Convolution filtering for diagnostic response
  - Subtract out-of-phase ϕ for local displacement

- **Apply line-integral effects to compare directly to differential images**

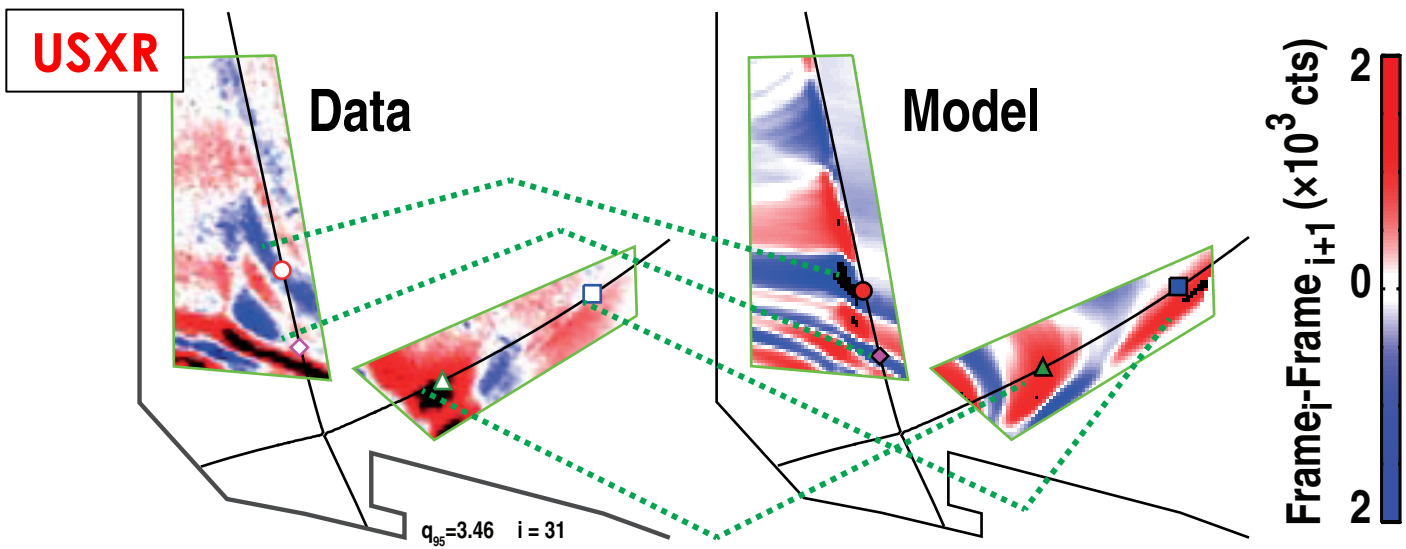


Vacuum-Predicted Lobes Observed in Data

- **Synthetic diagnostic modeling used to identify lobe structures in measurement***
  - Well matched features: gross lobe structure, line-integral effects

- **Linear M3D-C1: T_e and n_e still too low in lobes for USXR modeling**

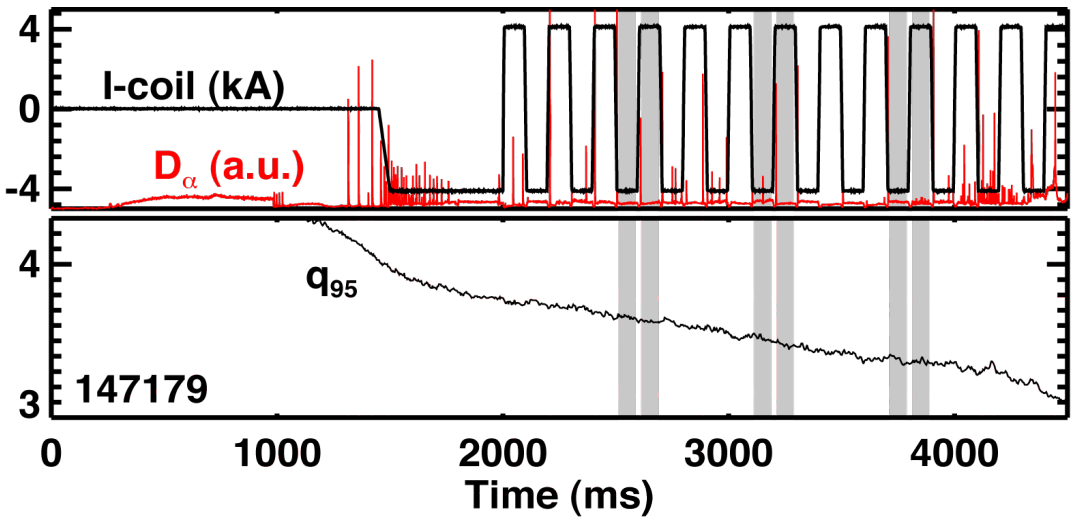
Line-Integrated Differential Images

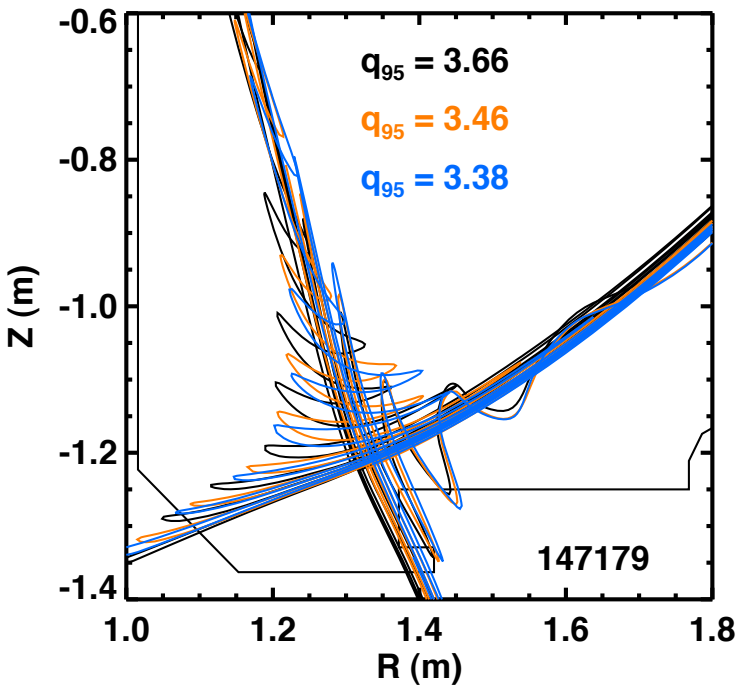


*M.W. Shafer, Nucl. Fusion 2012

q95 Ramp Applied to Change Resonance with Lobes

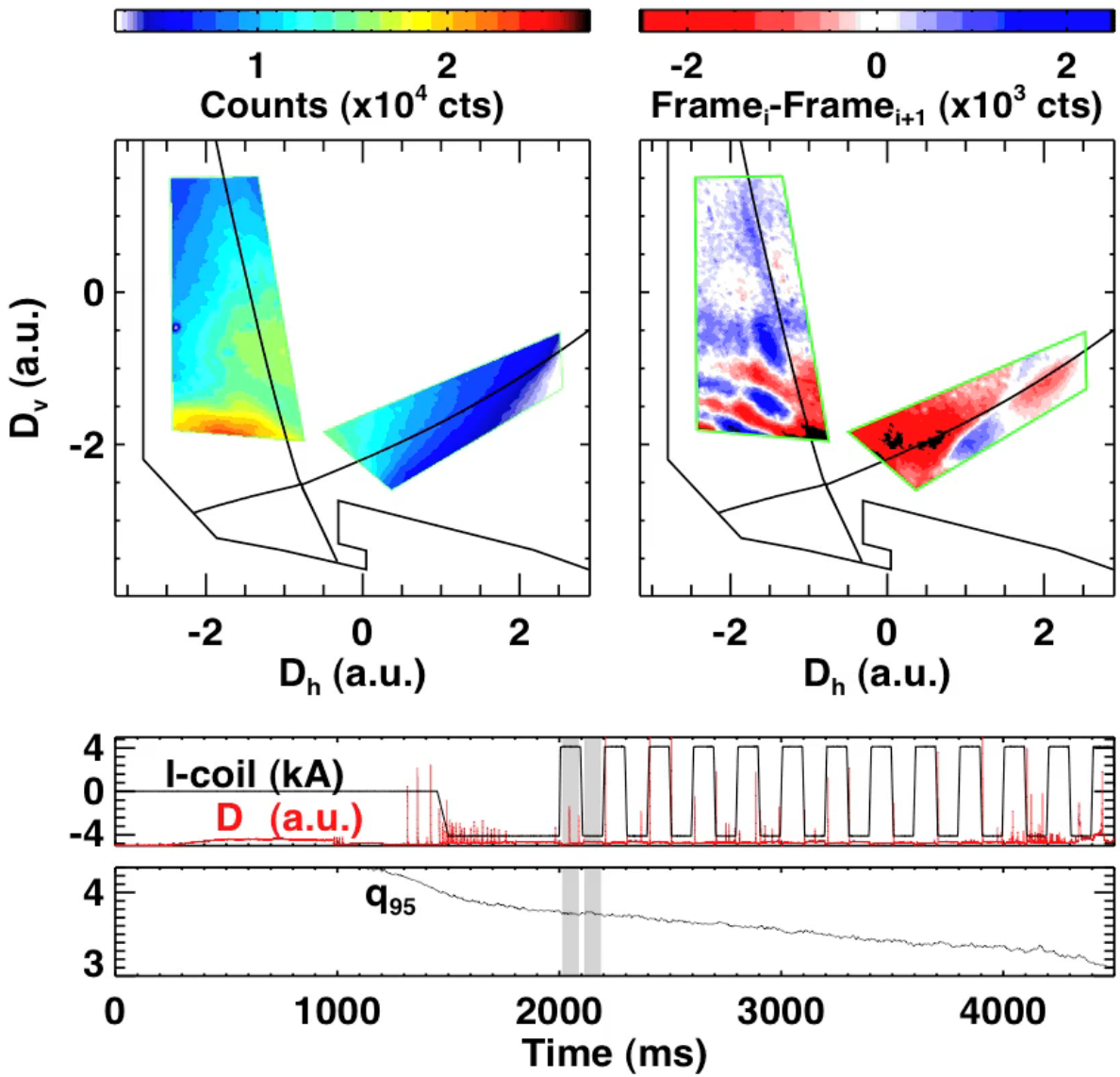
- Lobes expected to "rotate" poloidally downward on high-field side in one toroidal plane; stationary on low-field side





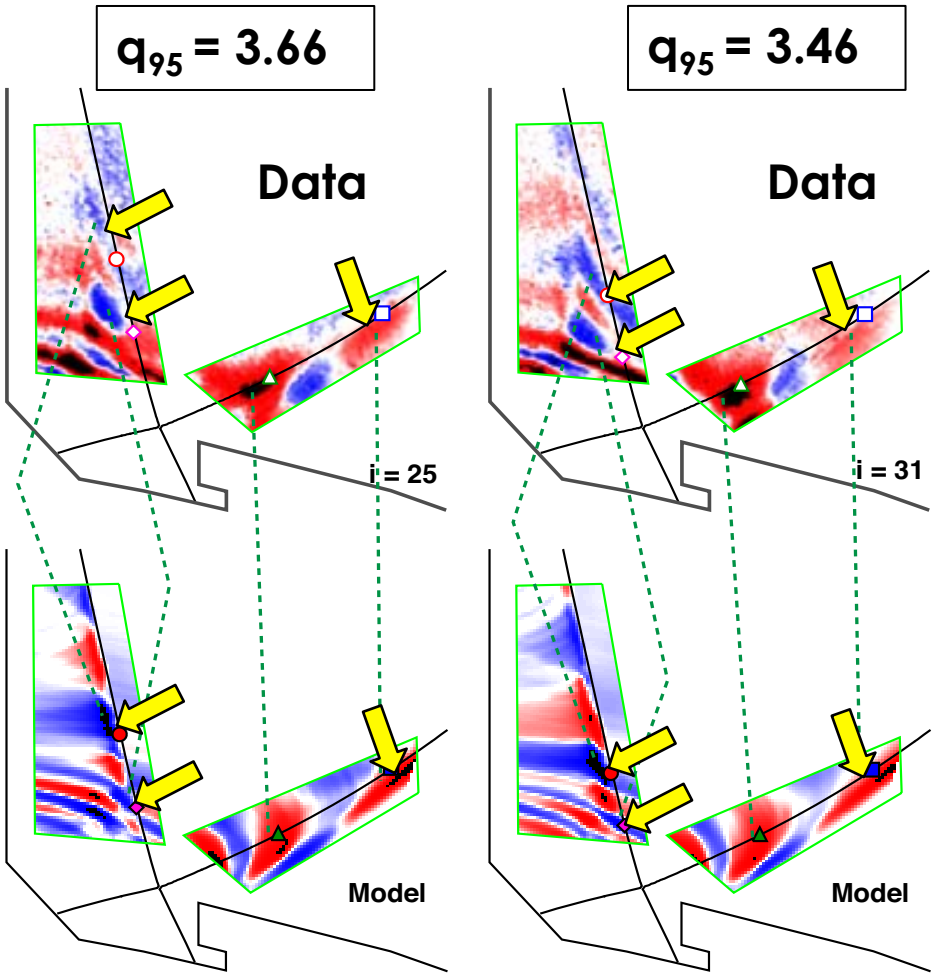
*M.W. Shafer, Nucl. Fusion 2012

Movie: Differential Images w/ q95 Ramp



Lobe Dependence on q95 Matches well to Vacuum Predictions

- **Intersection w/ unperturbed separatrix tracked**
  - Simple "pattern recognition" algorithm based on Laplacian (1st derivative) of image
- **LFS to HFS asymmetry in lobe location vs q seen**
  - Strong plasma shaping, coil feedback, q-shear contribute to observation

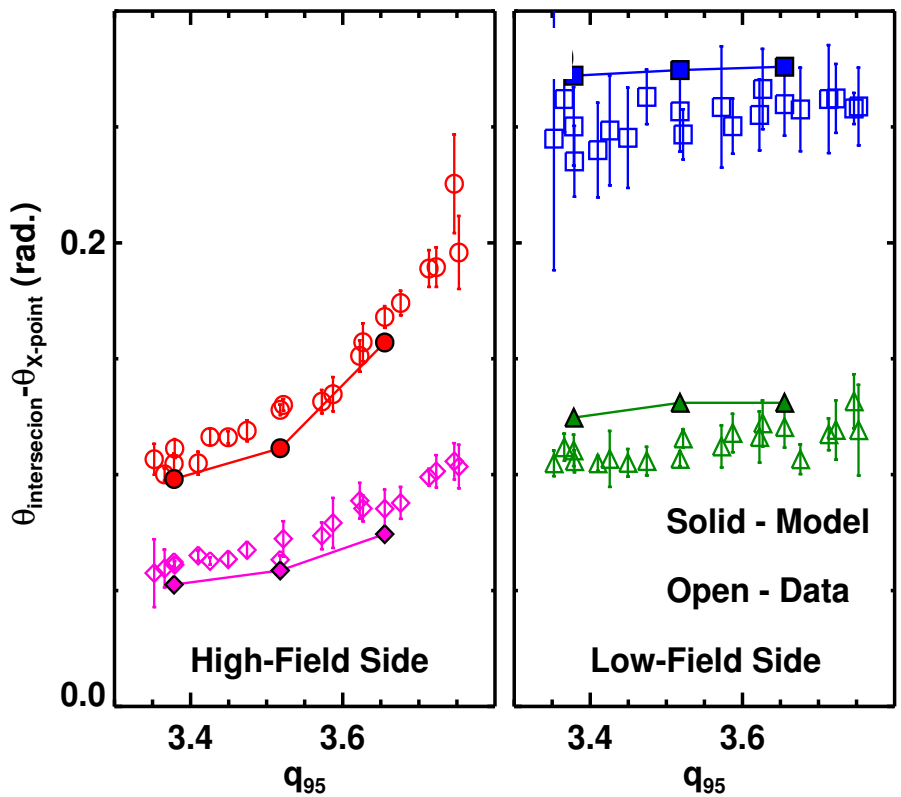


*M.W. Shafer, Nucl. Fusion 2012

Lobe Dependence on q95 Matches well to Vacuum Predictions

- **Intersection w/ unperturbed separatrix tracked**
  - Simple "pattern recognition" algorithm based on Laplacian (1st derivative) of image
- **LFS to HFS asymmetry in lobe location vs q seen**
  - Strong plasma shaping, coil feedback, q-shear contribute to observation

Polodial separation of Lobe Intersection to X-Point

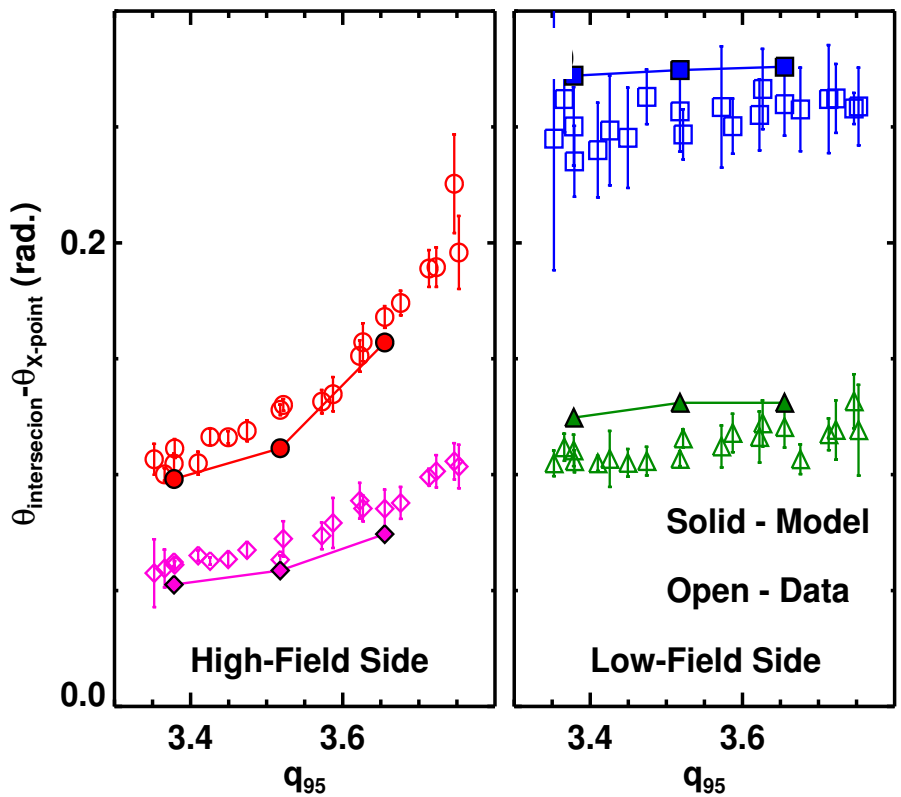


*M.W. Shafer, Nucl. Fusion 2012

Lobe Dependence on q95 Matches well to Vacuum Predictions

- **Intersection w/ unperturbed separatrix tracked**
  - Simple "pattern recognition" algorithm based on Laplacian (1st derivative) of image
- **LFS to HFS asymmetry in lobe location vs q seen**
  - Strong plasma shaping, coil feedback, q-shear contribute to observation
- **Yet to determine effects of screening/plasma response on lobe structure**

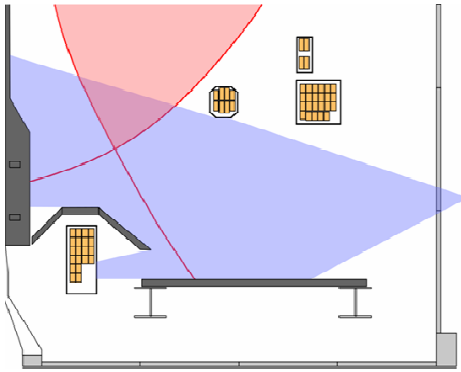
Polodial separation of Lobe Intersection to X-Point

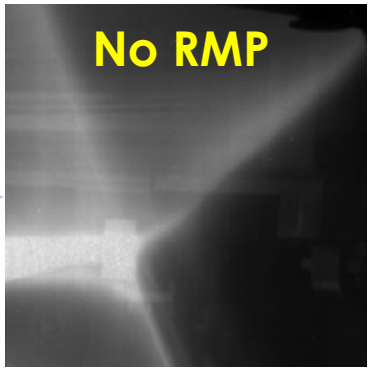


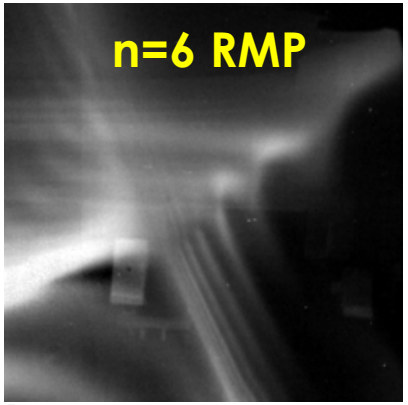
*M.W. Shafer, Nucl. Fusion 2012

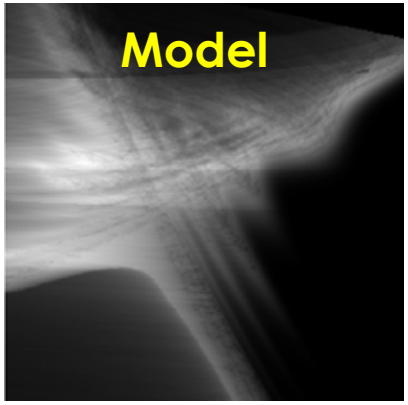
Modeling of MAST X-Point Imaging Suggests Partial RMP Screening

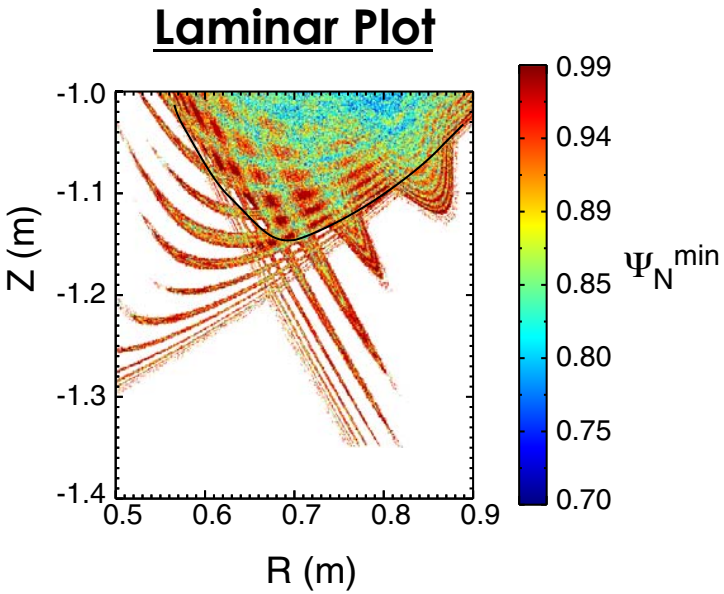
- **Forward modeling of X-point images (He II emission) required x3 reduction in applied RMP current to match data**
  - Lobe length relates to level of stochasticity inside unperturbed separatrix











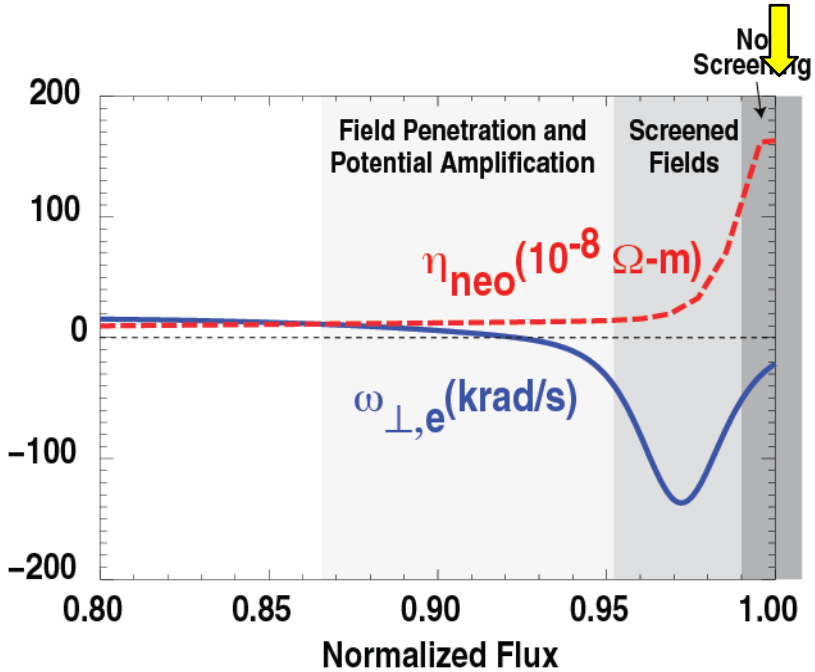
Kirk PRL 2012
Chapman PPCF 2012
Harrison EPS 2012

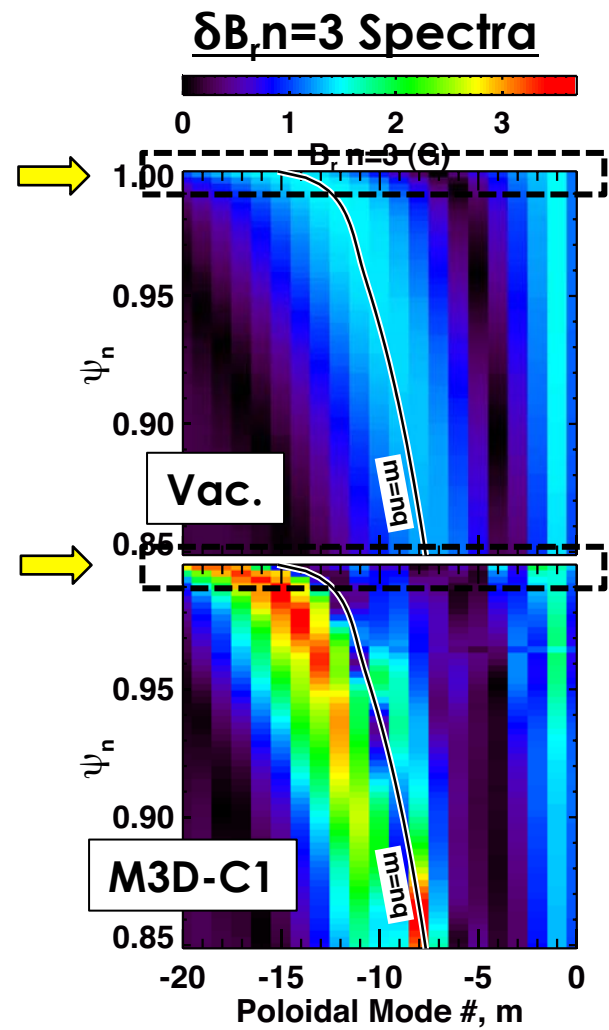
DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

Goal of Measurements: Target Radial Regions to Test Validity of Vacuum vs. Two-Fluid

- **Edge/SOL – matches well to vacuum**
- **Steep gradient – vacuum vs. screening?**
  - Kinking vs islands?
- **Top of Pedestal… (not there yet)**





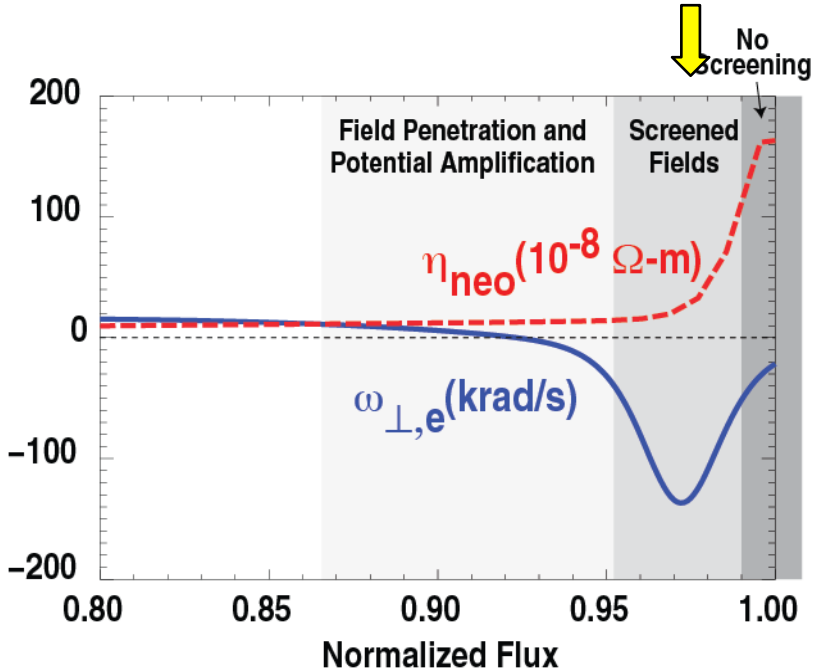
DIII-D NATIONAL FUSION FACILITY

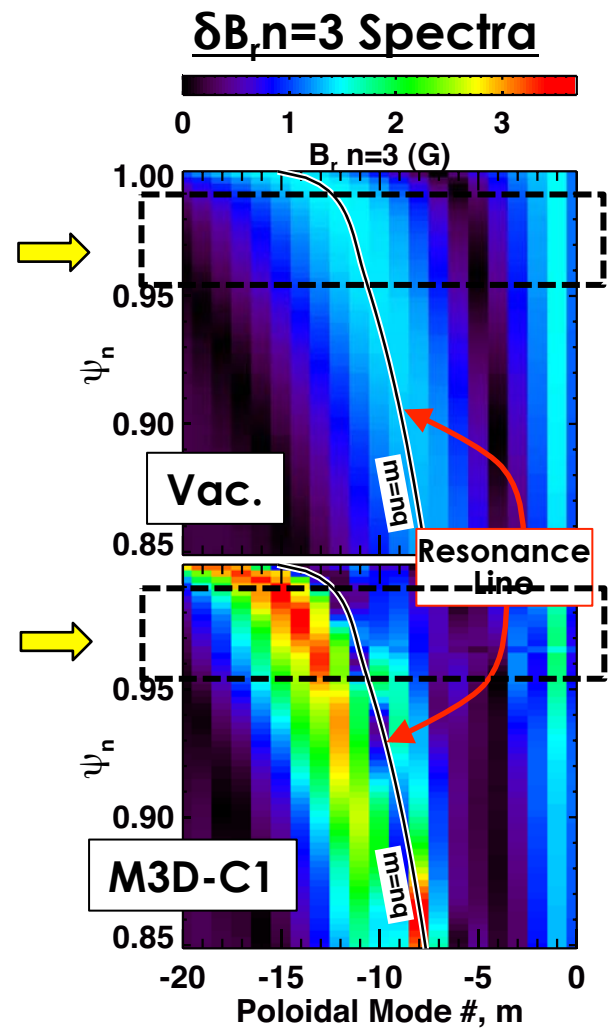
OAK RIDGE National Laboratory

Goal of Measurements: Target Radial Regions to Test Validity of Vacuum vs. Two-Fluid

- Edge/SOL – should be vacuum
- **Steep gradient – vacuum vs. screening?**
  - Kinking vs islands?
- Top of Pedestal… (not there yet)

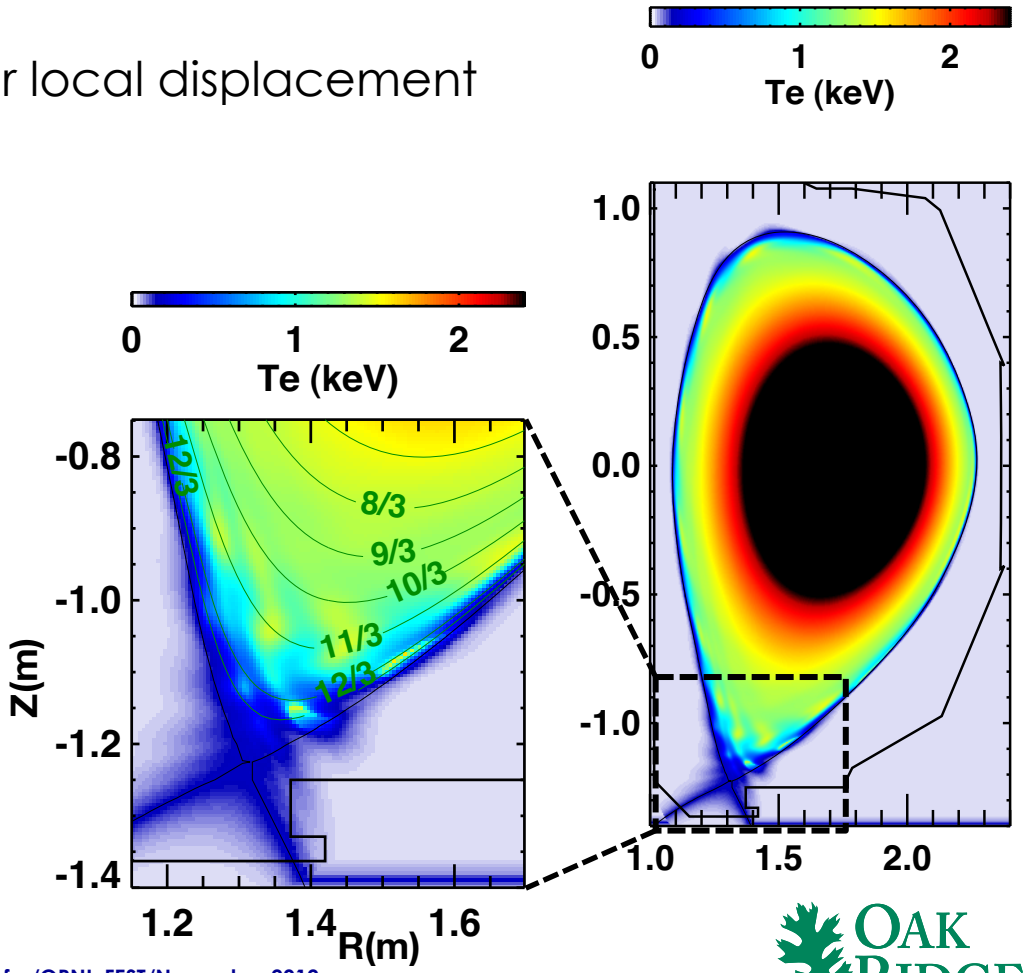
SXR





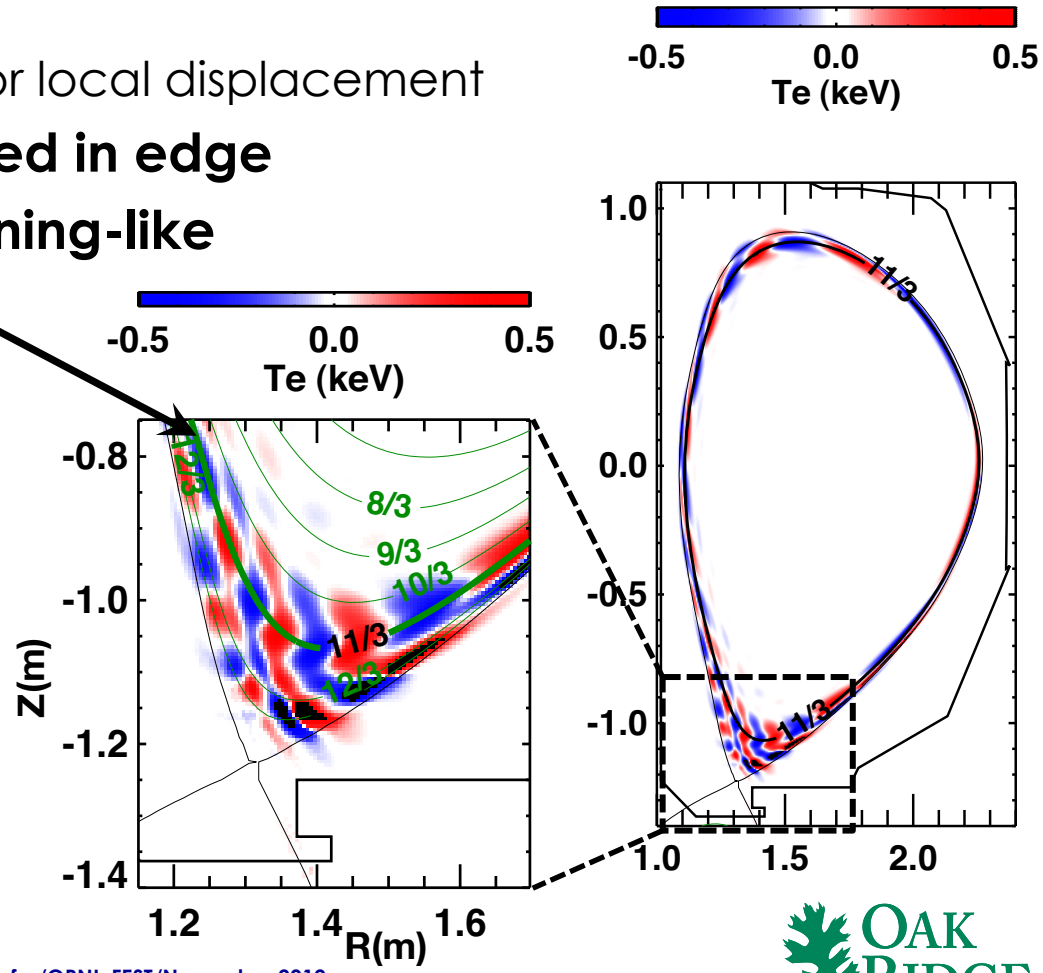
Two-Fluid MHD Response via M3D-C1 Code

- **Resistive, Two-fluid Effects, but *linear* time-independent calculations**
  - Perturbed T_e & n_e direct output
  - Subtract out-of-phase ϕ for local displacement



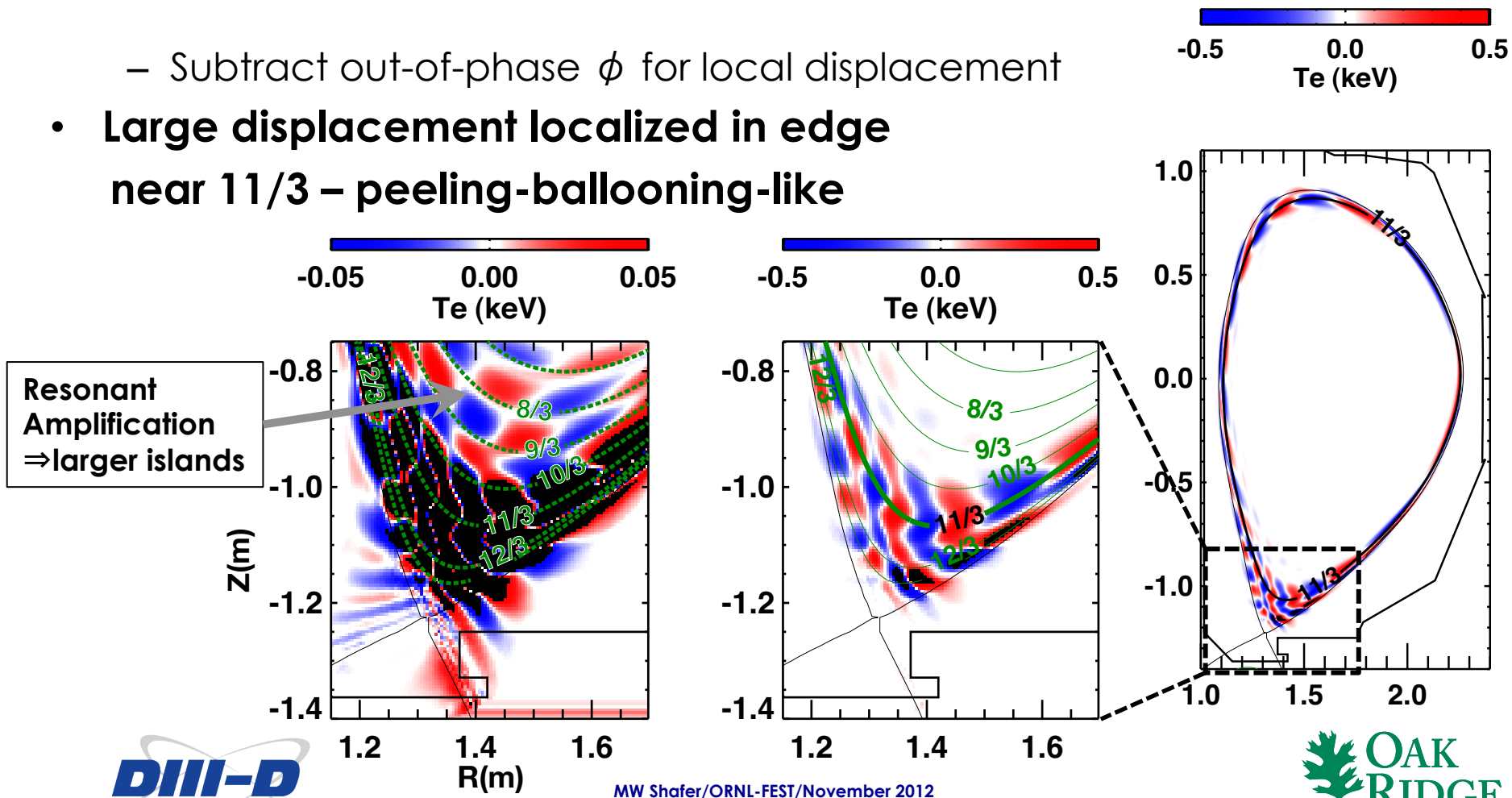
Two-Fluid MHD Response via M3D-C1 Code

- **Resistive, Two-fluid Effects, but *linear* time-independent calculations**
  - Perturbed T_e & n_e direct output
  - Subtract out-of-phase ϕ for local displacement
- **Large displacement localized in edge near 11/3 – peeling-ballooning-like**



Two-Fluid MHD Response via M3D-C1 Code

- **Resistive, Two-fluid Effects, but *linear* time-independent calculations**
  - Perturbed T_e & n_e direct output
  - Subtract out-of-phase ϕ for local displacement
- **Large displacement localized in edge near 11/3 – peeling-ballooning-like**

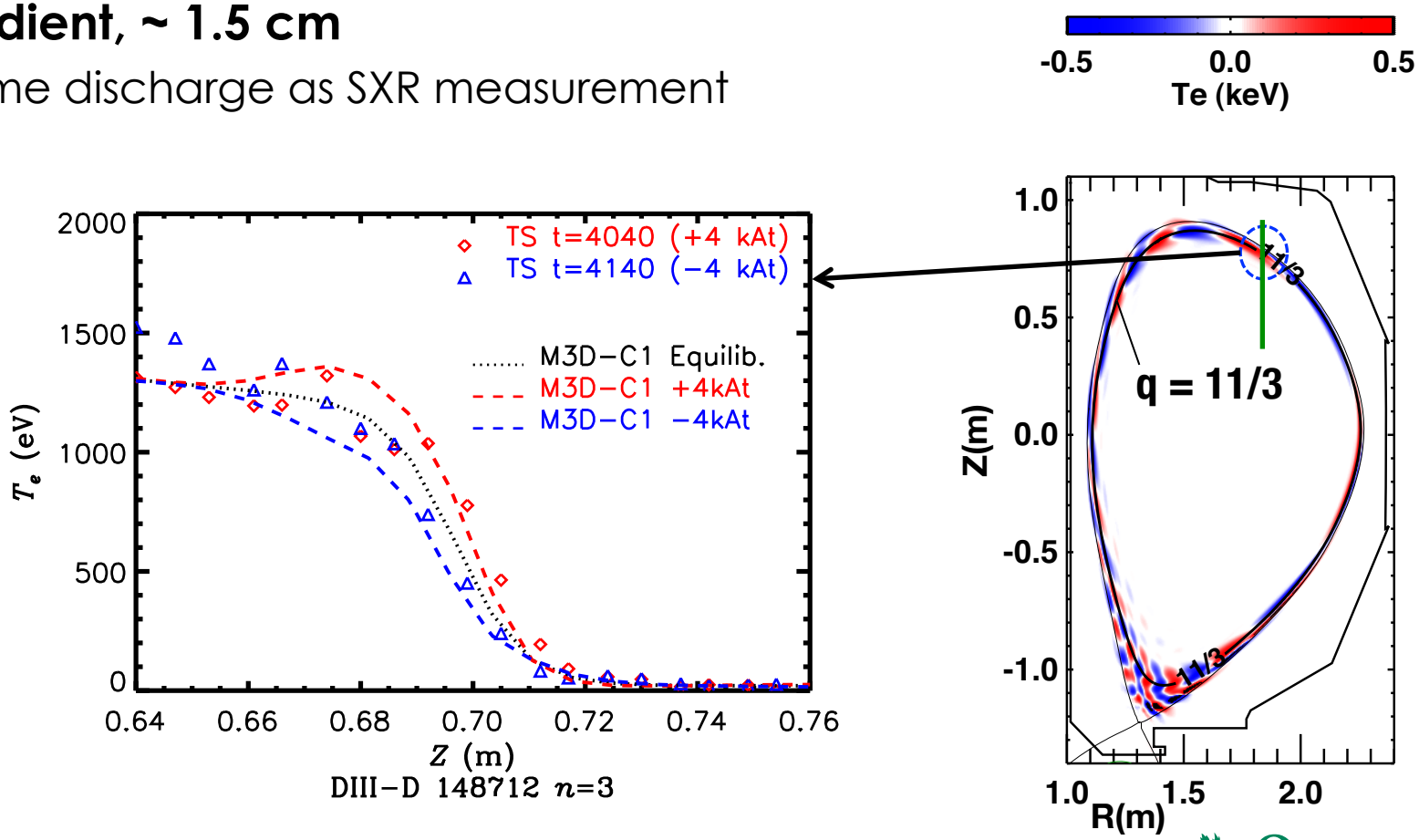


DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

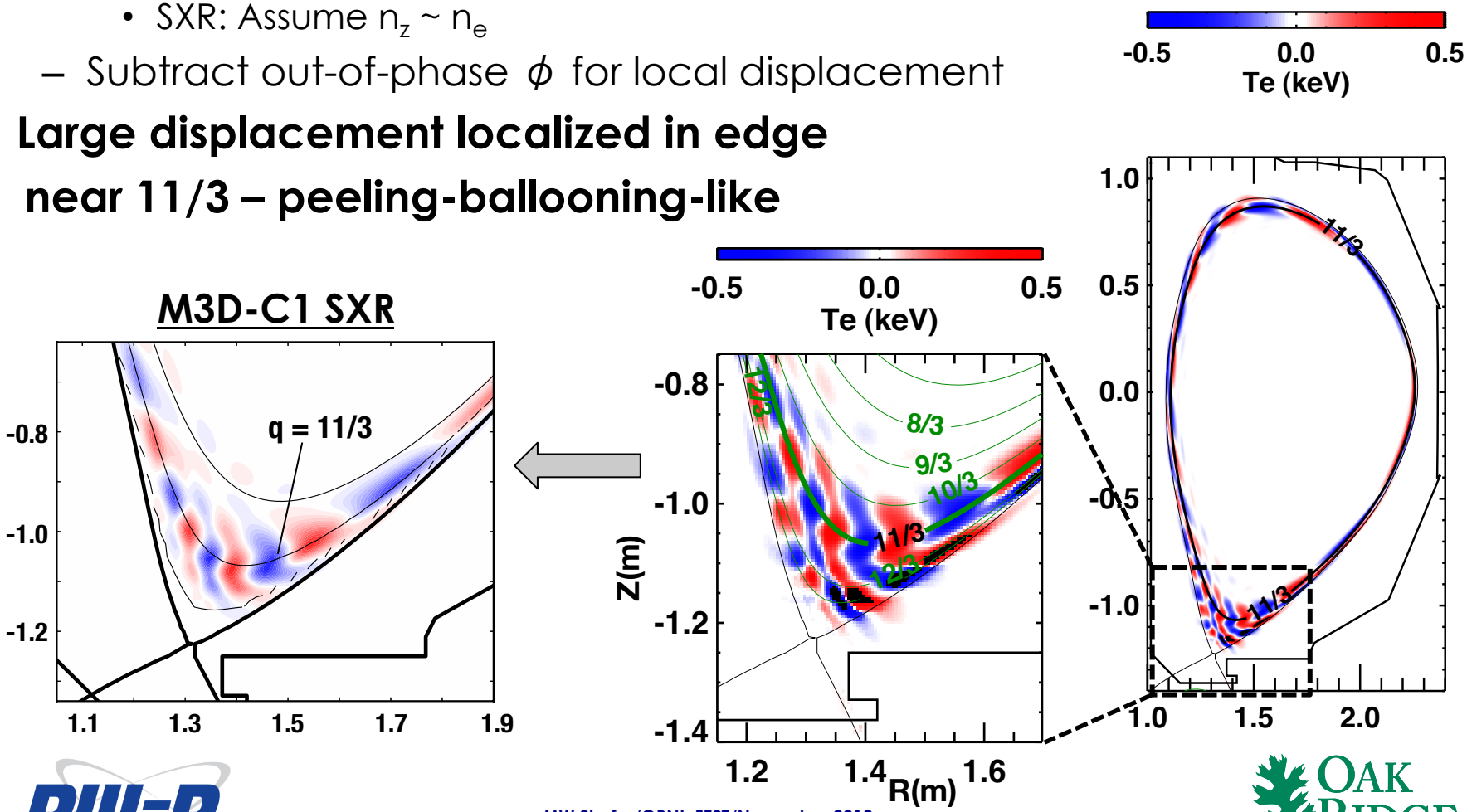
Predicted Displacement Matches Well with Thomson T_e

- **Perturbation calculated along vertical path of Edge Thomson has good agreement with shift in T_e gradient, ~ 1.5 cm**
  - Same discharge as SXR measurement



Two-Fluid MHD Response via M3D-C1 Code: Filtered SXR

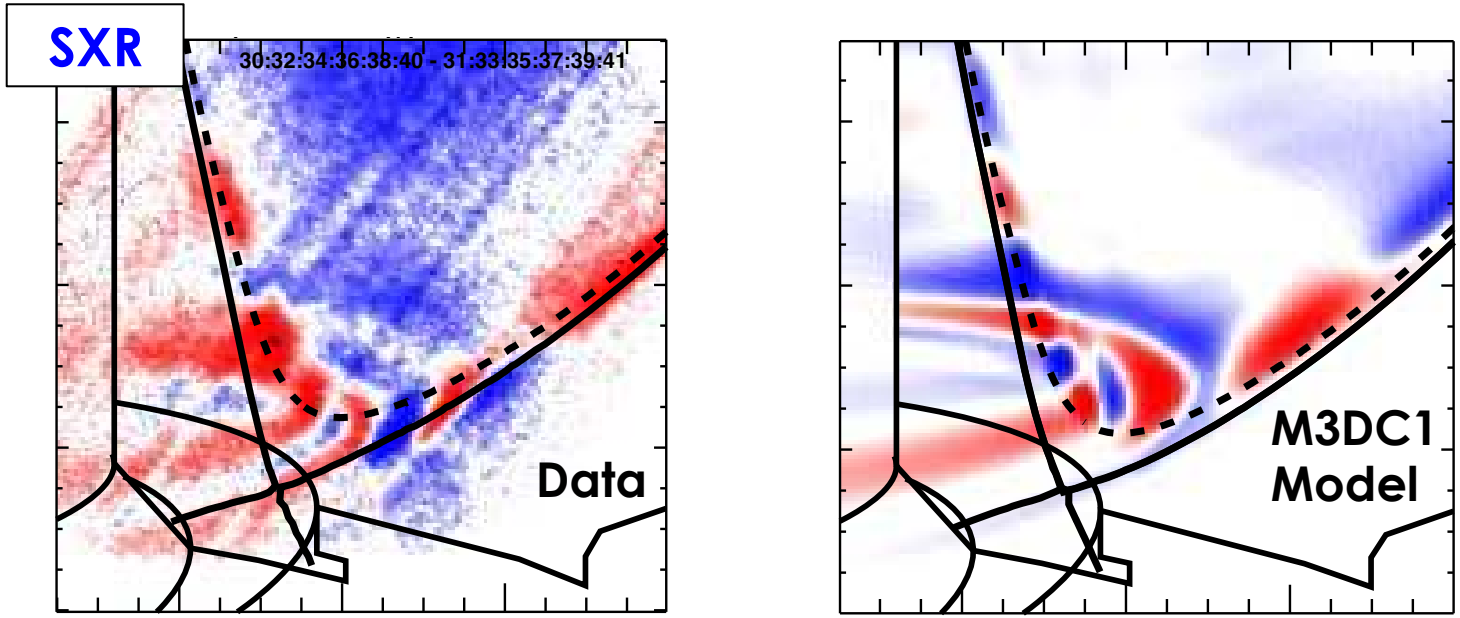
- **Resistive, Two-fluid Effects, but *linear* time-independent calculations**
  - Perturbed T_e & n_e direct output
    - SXR: Assume $n_z \sim n_e$
  - Subtract out-of-phase ϕ for local displacement
- **Large displacement localized in edge near 11/3 – peeling-ballooning-like**



Measured Internal Helical Structure Shows Reasonable Agreement with M3D-C1 Calculations

- **3D internal helical response measured**
  - Poloidally varying field aligned structure
  - High contrast results from displacement of steep gradient in emission, also near steep gradient in pedestal

Line-Integrated Differential Images

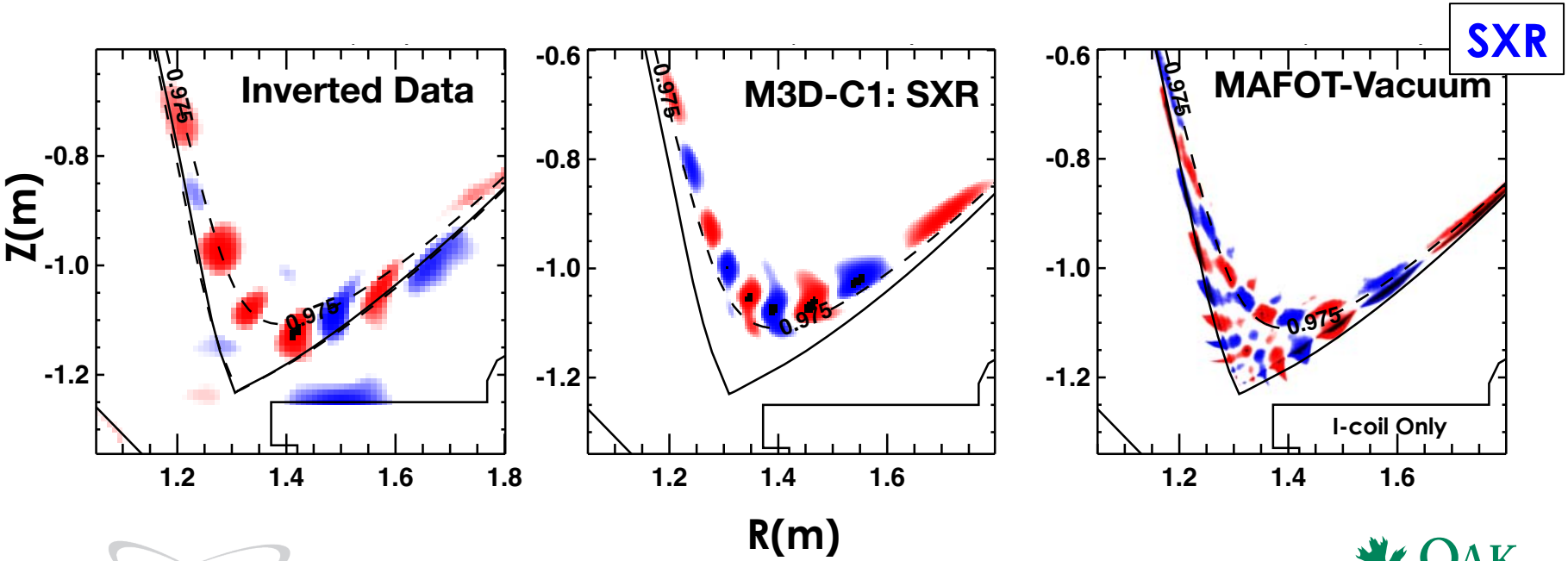


DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

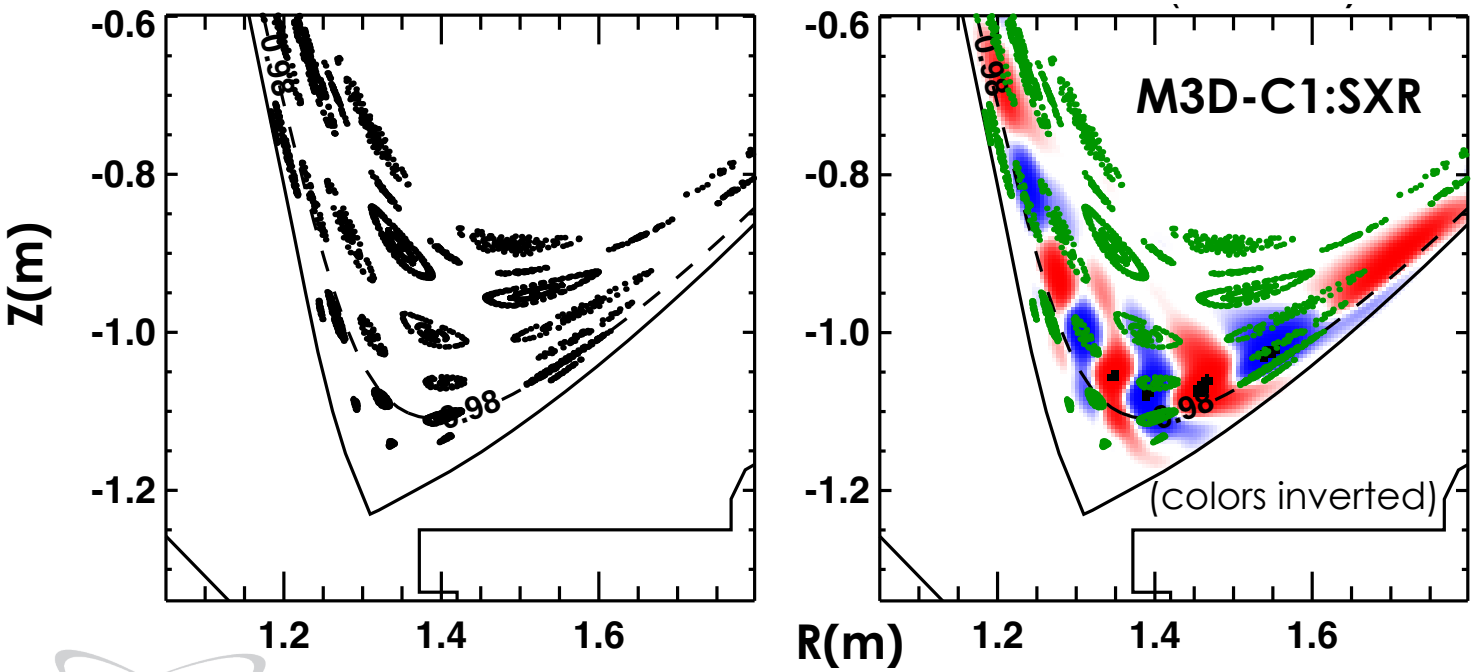
Image Inversion Gives Reasonable Agreement with M3D-C1 Predicted Displacements

- **Inversion provides direct measure of ~5-10cm displacements**
  - Philips-Tikhonov regularization, helical symmetry
  - On-going testing, relatively new capability
- **Plasma response effects needed to provide better agreement**
  - Vacuum shows smaller internal structure, remnants of lobes



But… Linear M3D-C1 Displacement Also Align with Scaled Down Island Poincaré Map

- **Poincaré FL tracing of M3D-C1 with ¼ RMP**
  - FL tracing essentially non-linear ⇒ ¼ RMP shows remnant islands, otherwise looks stochastic.
  - Fluid perturbation is linear ⇒ structure remains the same.
- **Maximum in emission aligns with Island structure**
  - Is this just resulting from field-aligned structures or islands?



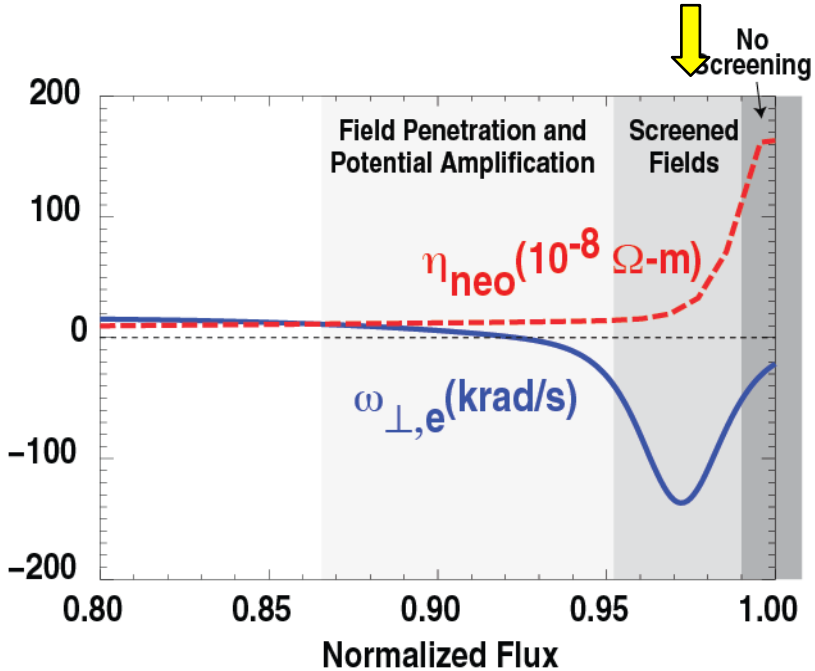
DIII-D NATIONAL FUSION FACILITY

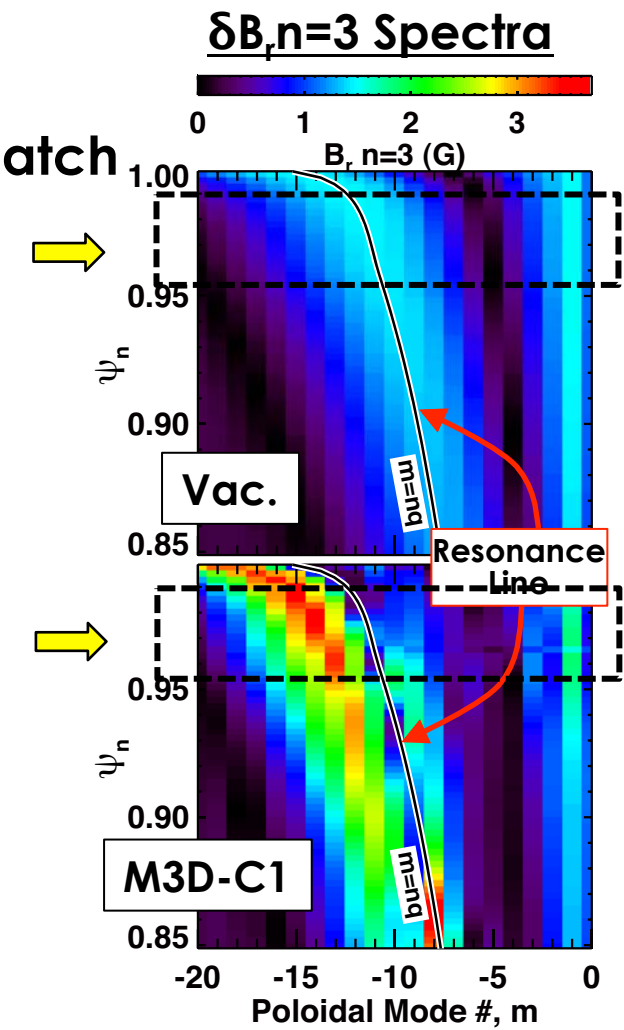
OAK RIDGE National Laboratory

Goal of Measurements: Target Radial Regions to Test Validity of Vacuum vs. Two-Fluid

- Edge/SOL – should be vacuum
- **Steep gradient – M3D-C1 provides closer match**
  - Kink-like structure most likely
- Top of Pedestal… (not there yet)

SXR





DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

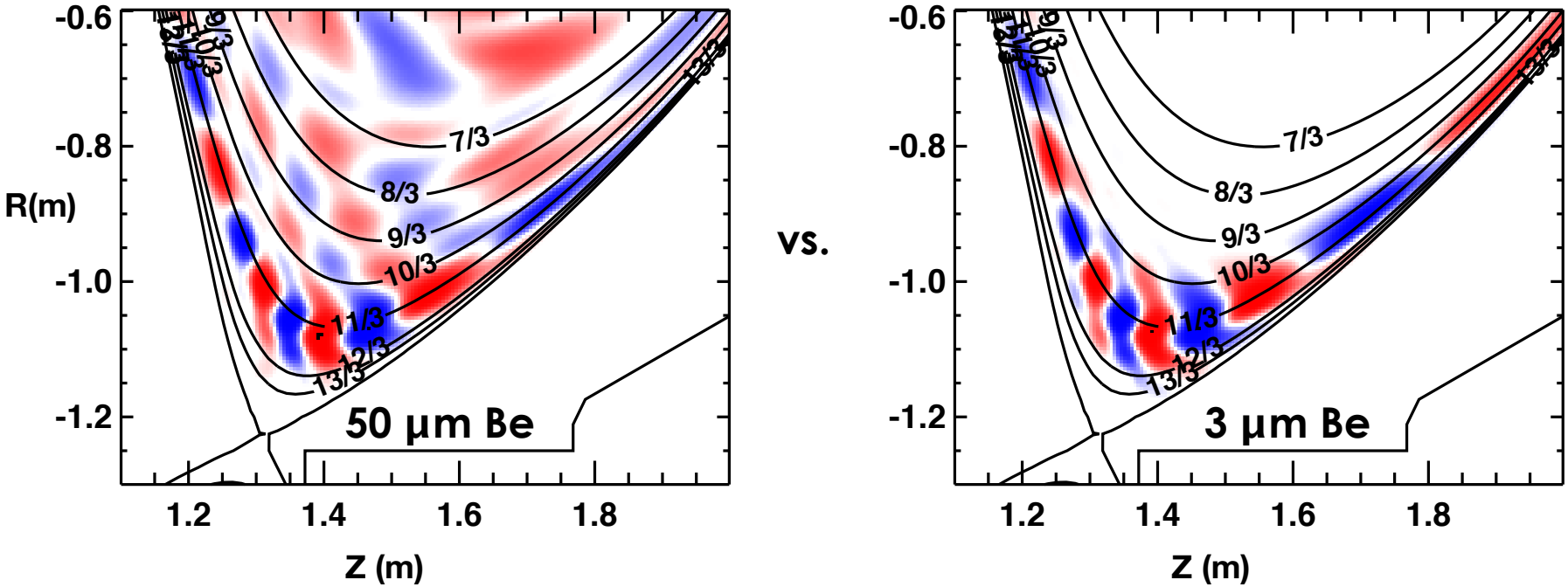
Outline

- **Potential model describes RMP ELM suppression on DIII-D invoking two-fluid resistive MHD**
  - Measurements needed to challenge/verify assumptions
- **Tangential SXR camera in X-point region exploits flux expansion to measure topological changes from RMPs**
  - Filtered emission offers effective radial discrimination
  - Differential Imaging used to isolate response
- **Radially resolved measurements of plasma response through forward modeling of SXR Imaging:**
  - Lobes extending from the unperturbed separatrix at plasma boundary agrees well with vacuum
  - Helical displacements in the steep-gradient region inside the unperturbed separatrix matching with M3D-C1 (two-fluid MHD)
- **Future & Summary**

Future: Higher Energy Filter for Response Near Pedestal Top

- **Better challenge to RMP ELM suppression model**
  - Higher Energy filter: 1-2 keV allows relative contrast inside pedestal
  - requires longer integration (x3-10)

M3D-C1 Filtered SXR Displacements



DIII-D NATIONAL FUSION FACILITY

OAK RIDGE National Laboratory

Summary: Unique New Measurements of Plasma Response

- **Tangential Imaging of USXR and SXR provide radial discrimination of plasma response in RMP ELM-suppressed plasmas**
  - Lobes measured boundary region
  - Helical displacements measured in steep-gradient region

- **Plasma response models implications**
  - Vacuum predictions work well in boundary region
    - Further tests with FL modeling/Inversion to test inward stochasticity
    - Nonlinear M3D-C1 calculations needed to evaluate response in SOL
  - Steep gradient measurement requires some plasma response (partial screening and kinking) to better match measurement
    - Self-consistent M3D-C1 solution best match
    - But Vacuum isn't too far off: higher-k structure

- **Emerging RMP ELM suppression model implications**
  - Future experiments targeting pedestal top