Edge Soft X-ray Imaging for Measurements of Magnetic Topology During 3D External Perturbations in DIII-D

E.A. Unterberg, M.W. Shafer, S.J. Meitner, T.E. Evans[1], J.H. Harris, S. Ohdachi[2]

[1]GA

[2]NIFS

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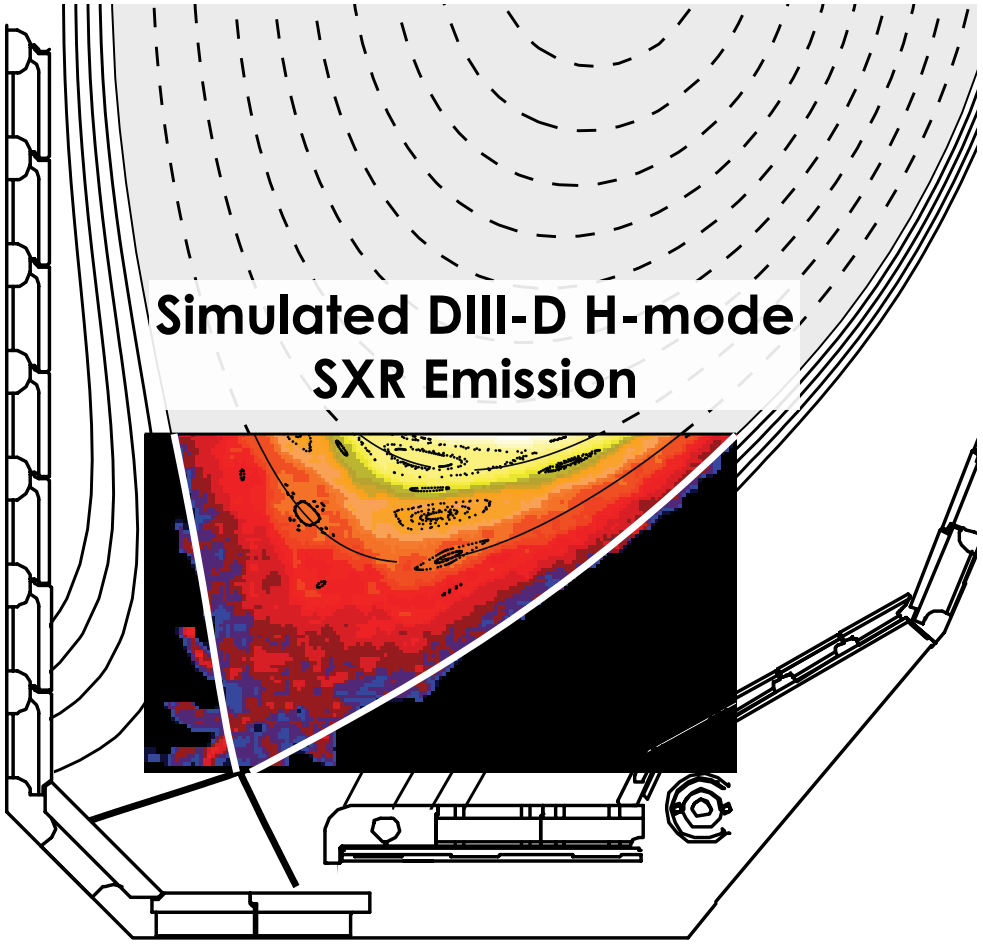
Oak Ridge, TN August 2011



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ELMs Have Been Shown to be Controlled by RMPs

- **ELMs are dangerous to in-vessel components**
  - CFC and tungsten material limits ⇒ W_{ELM} at the divertor ≤**1 MJ**
    - Present Scaling ⇒ ~$0.15W_{ped}$ = **15-20 MJ** (ITER W_{ped} = 100-130 MJ)
- **Tokamak ELMs: thought to be ballooning-peeling instability**
  - Bootstrap current kink + ballooning mode
- **Addition of 3D Resonant Magnetic Perturbation ⇒ ELM control**
  - Islands change pressure profile?
  - Penetration depth of RMP into rotating plasma?
- **3D RMPs ($\delta B/B \sim 10^{-3}$) found to both suppress and destabilize ELMs in tokamaks**
  - DIII-D, ASDEX-U ⇒ Suppression
  - NSTX, MAST, COMPASS-D ⇒ On-demand triggering
- **Understanding missing between ELM control & plasma response**

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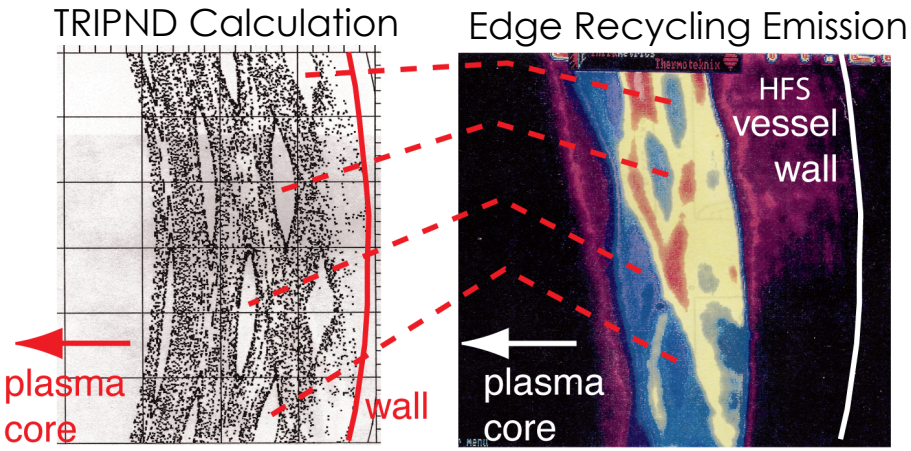
Plasma Response to RMP not Well Understood ⇒ Need to Determine the Internal Magnetic Topology

- **How does the plasma respond to 3D Resonant Magnetic Perturbations (RMPs)?**
  - Field screening and/or island formation?

SOL islands in Tore Supra**



- **Past measurements agree with vacuum modeling**
  - Islands imaged in Ohmic discharges
  - Strike-point splitting in H-mode
  - How does interior H-mode respond?

- **Magnetic topology measurements desired to understand plasma response to 3D magnetic perturbations**
  - Needed for extrapolation of ELM control to future machines

T. E. Evans et al., *Phys. Plasmas* **9 (2002) 4957

Outline: Internal 3D Magnetic Topology Measurements on DIII-D

Approach: Pin-hole based tangential soft X-ray imaging system in the X-point region of a diverted tokamak

- **Diagnostic concept & implementation**
  - Straightforward approach + new technologies
  - 2011 run campaign ⇒ First data
- **Diagnostic simulations & assessments – data interpretation is critical**
  - 3D SXR synthetic diagnostic model developed
  - Inversion analysis developed & tested

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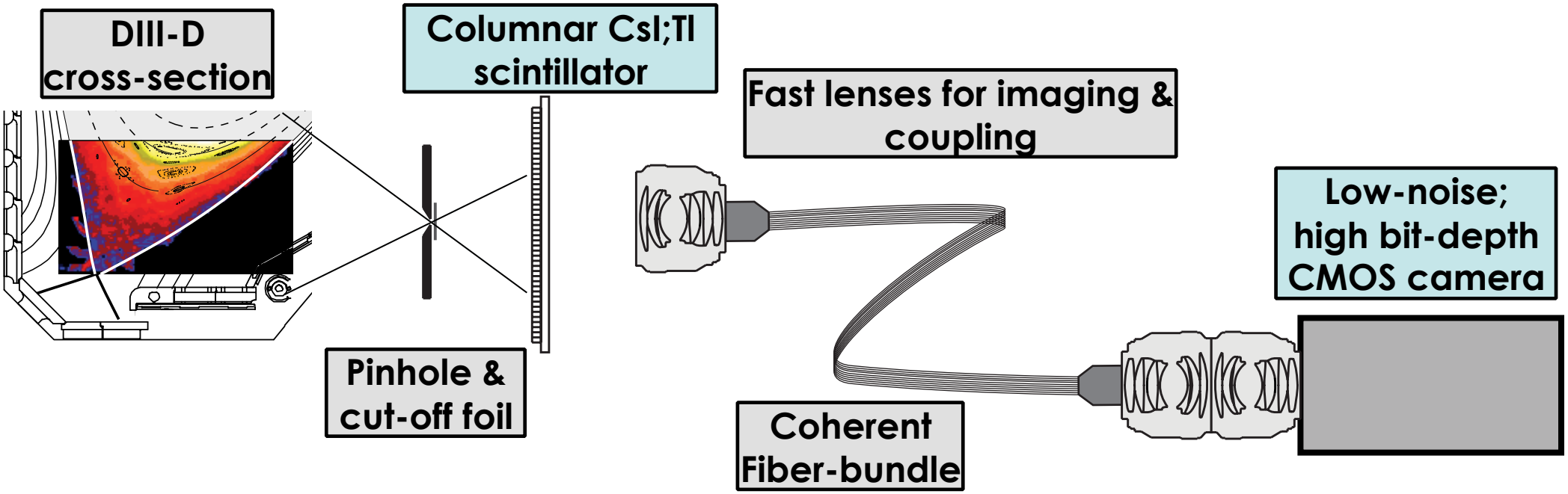
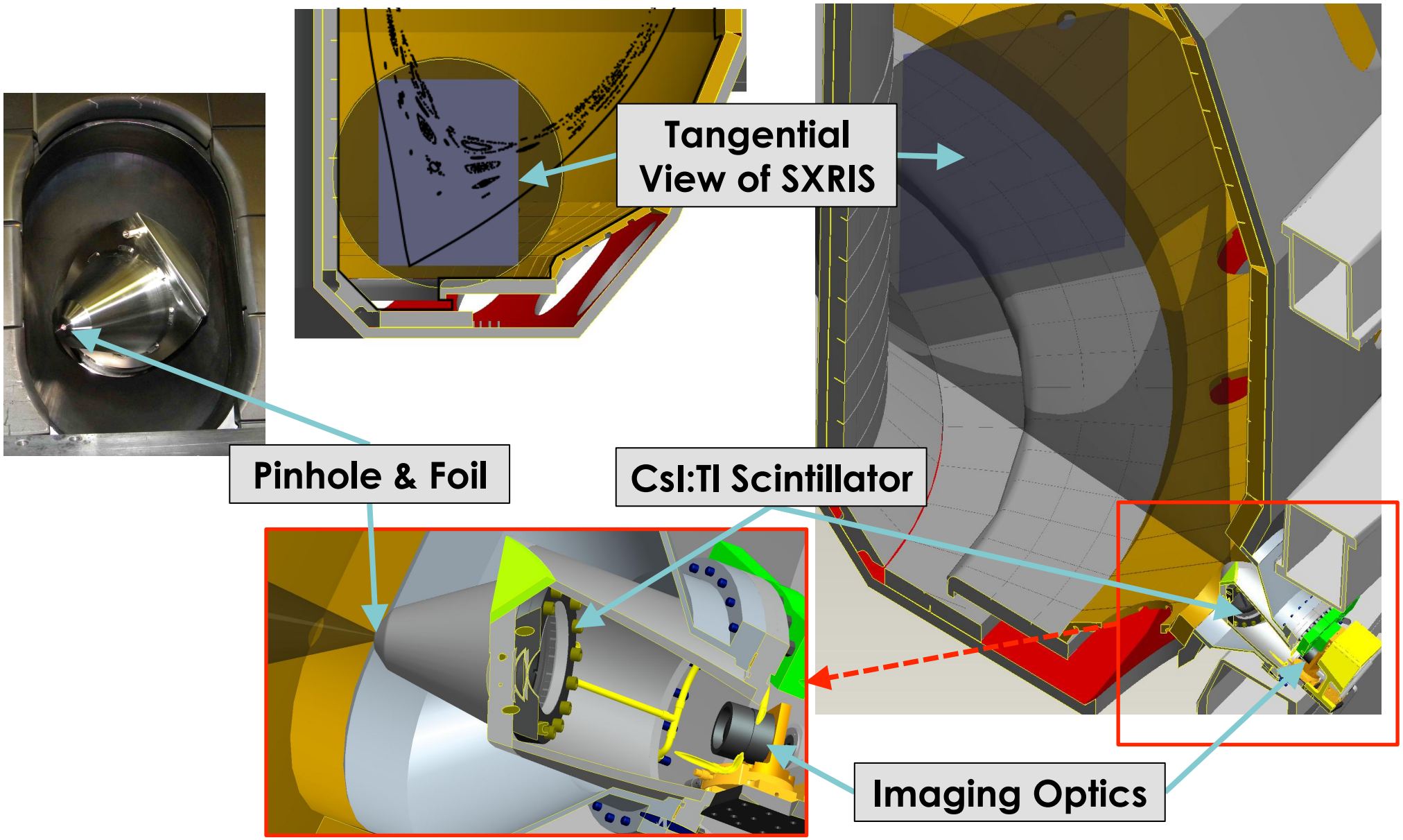
Principle of Measurement Motivated by Core Tangential SXR Systems on LHD, NSTX, TEXTOR



- **Successfully used to image core islands using inversion methods***
- **Adapted to diverted H-mode islands**
  - Higher T_e (> 1keV); Filtered for edge emission; Flux expansion ~ 10:1
- **Edge SXR imaging realized through new technologies****
  - Scintillator ⇒ columnar CsI:Tl ⇒ high efficiency & resolution
  - Camera ⇒ 16-bit sCMOS w/ 4GB on-board memory; up to 100 fps

** Ohdachi, et al. Plasma Science Tech. (2006)*
Shafer, et al., Rev. Sci. Instrum.* ***81*, 10E534 (2010)*

DIII-D Edge SXRI System Implemented During 2011 Run Campaign



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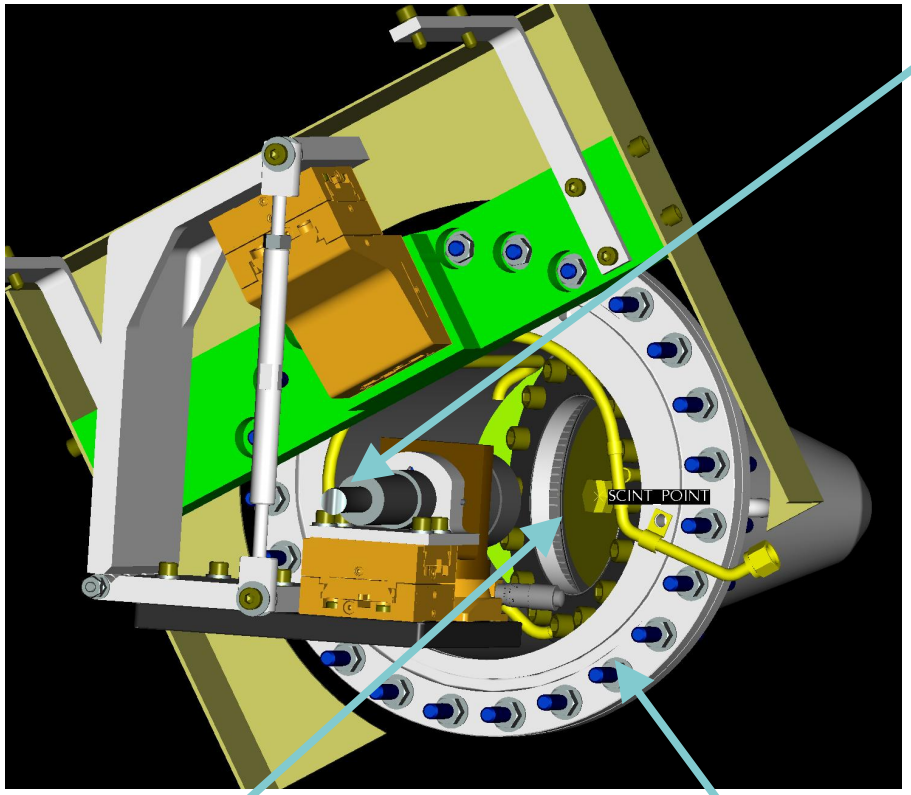
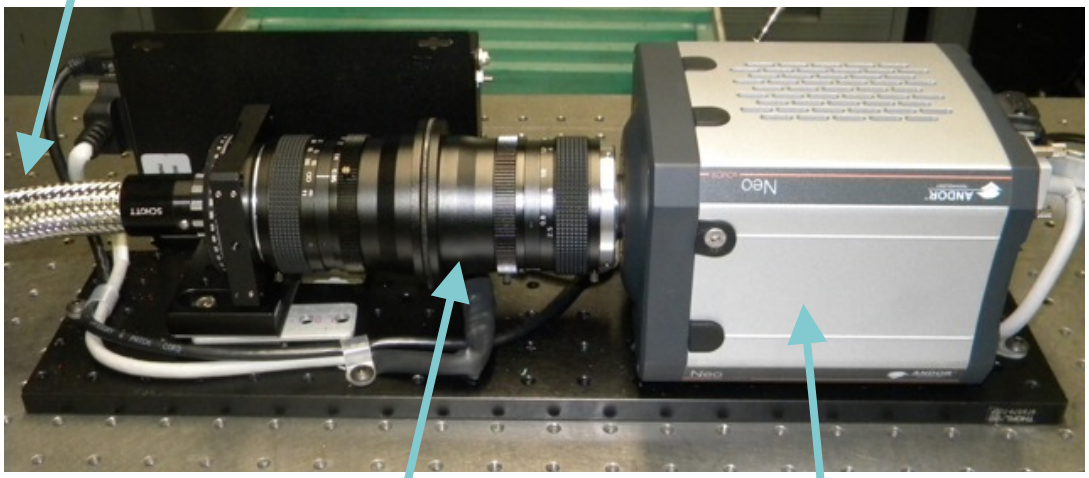
Visible Optics Used to Couple to sCMOS Detector

Machine-side Optics



8mm x 10mm Coherent Fiber Bundle ~ 50 LP/mm res.

Detector Assembly



Scintillator Window

Vaccum Port

f/0.95 Coupling Optics

16-bit Andor Neo sCMOS Camera

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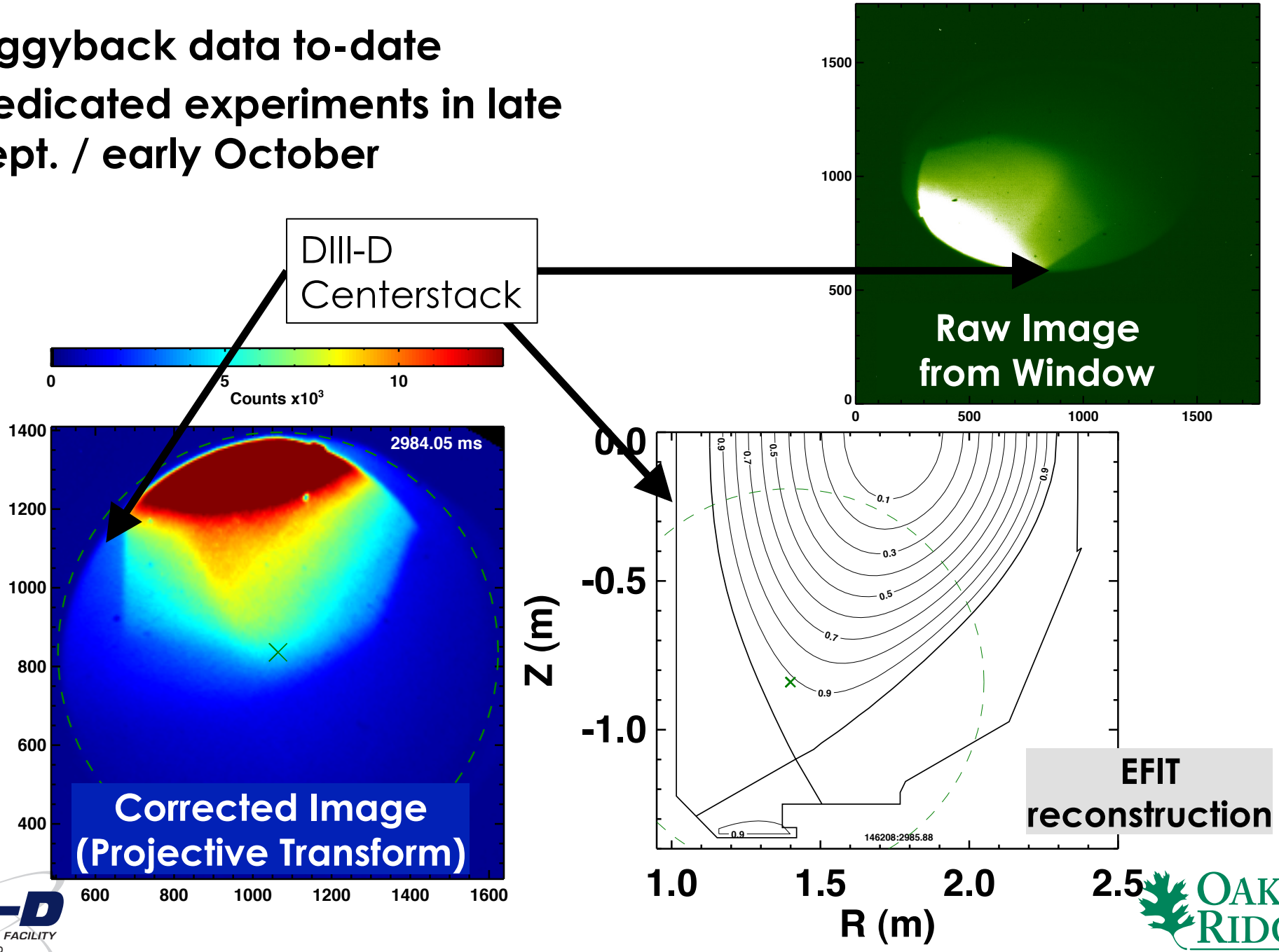
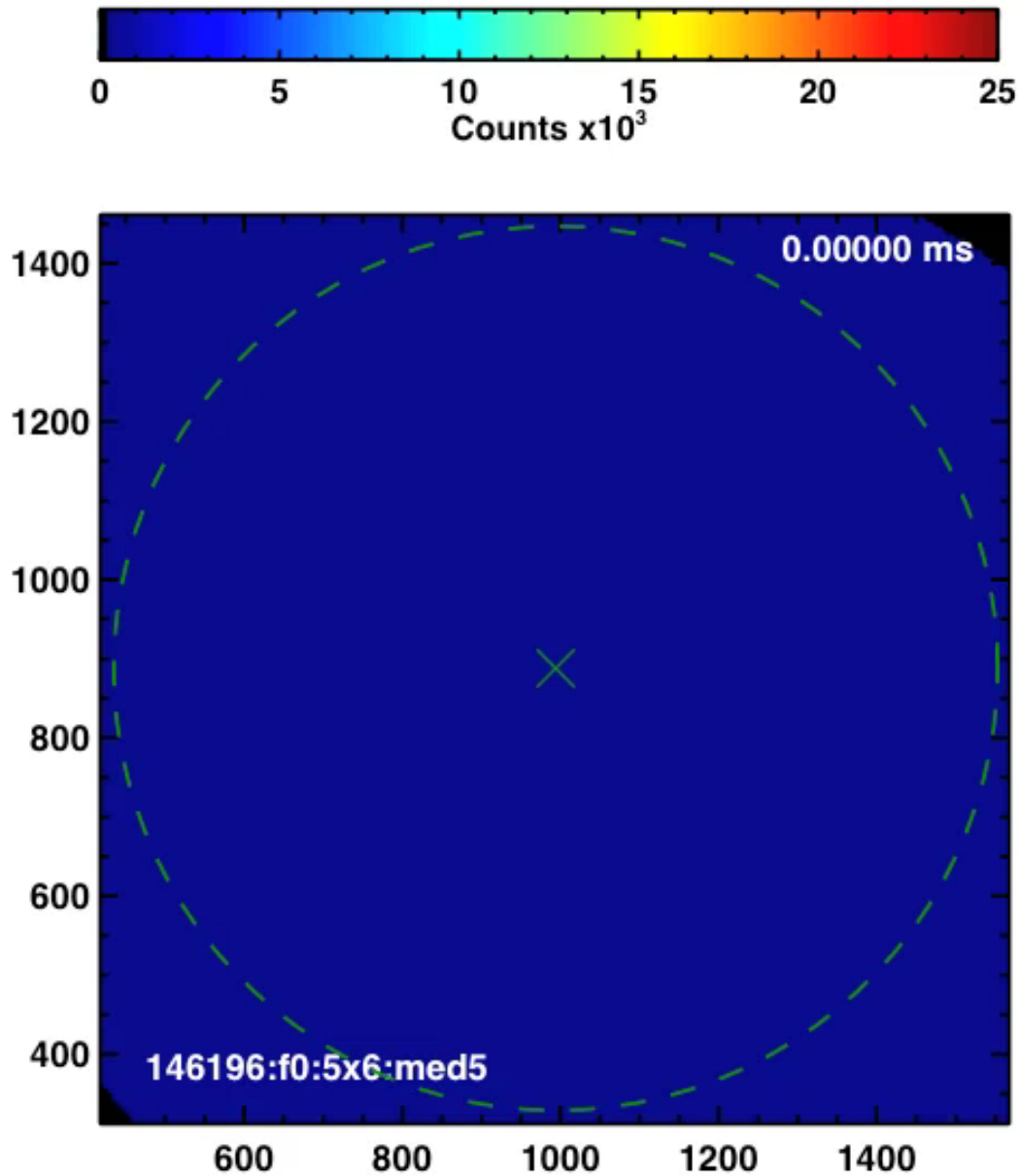
DIII-D First Data Shows Hot Core & Plasma Boundary

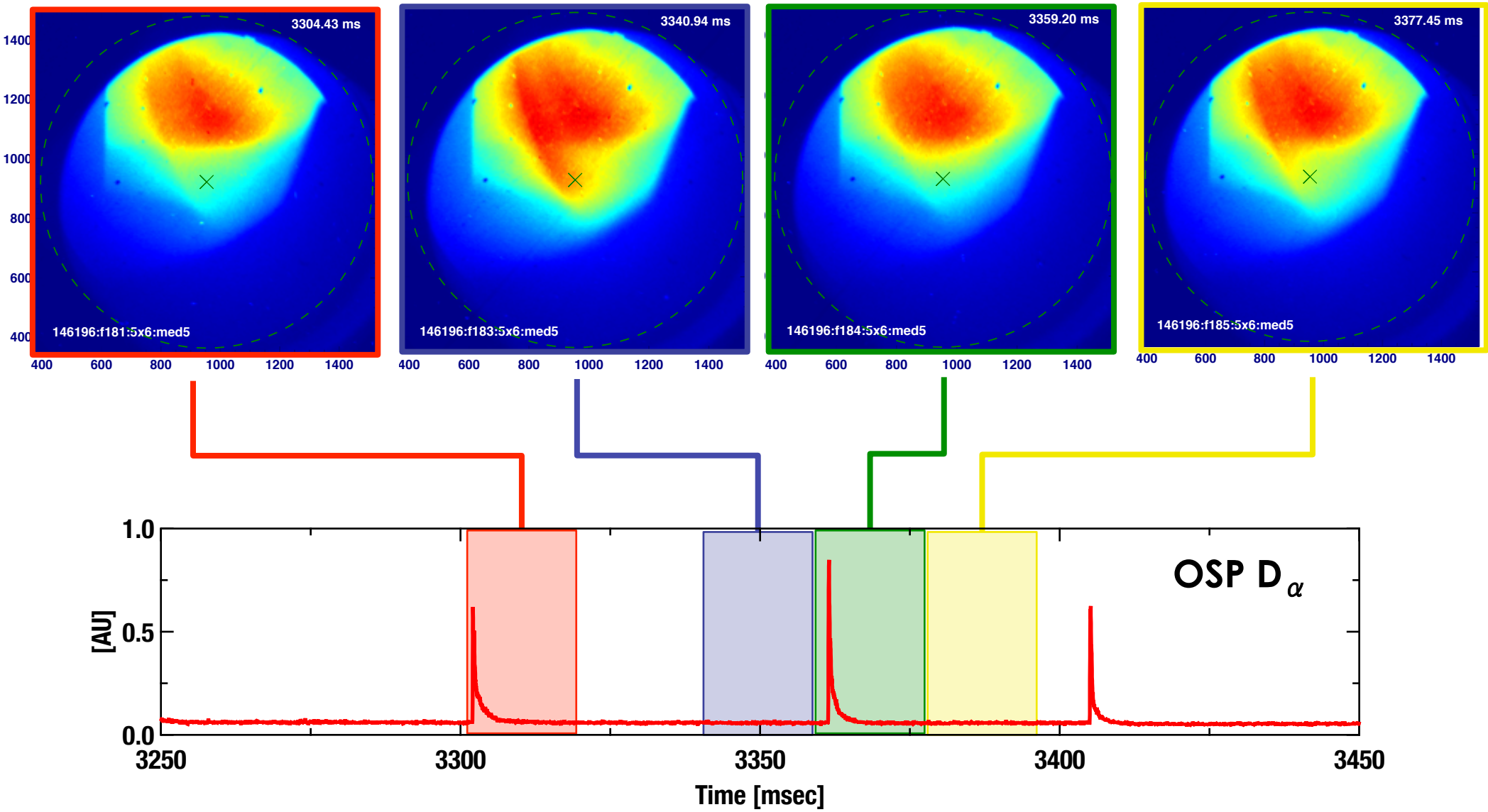
- Piggyback data to-date
- Dedicated experiments in late Sept. / early October



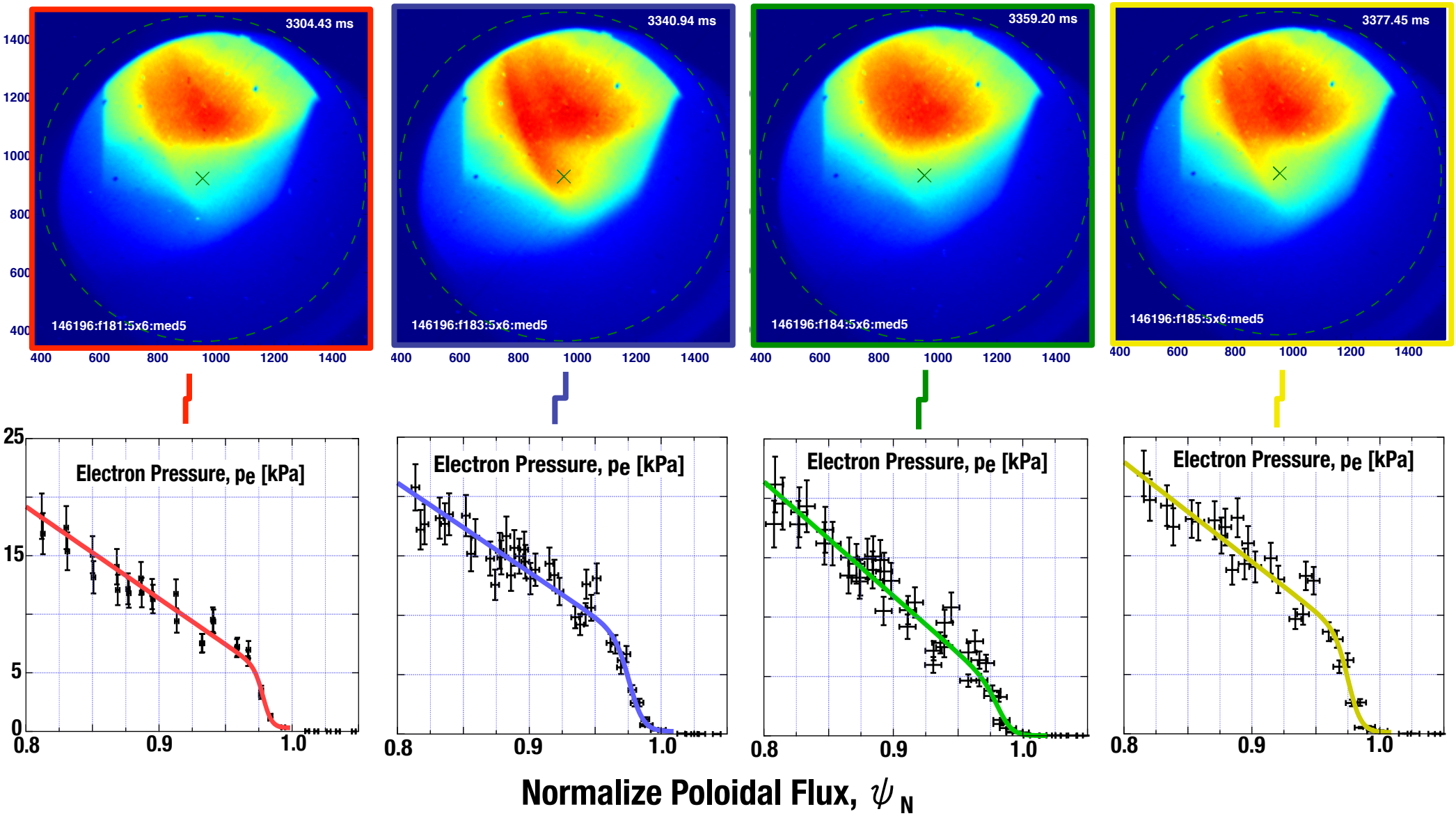
DIII-D First Data: A Movie



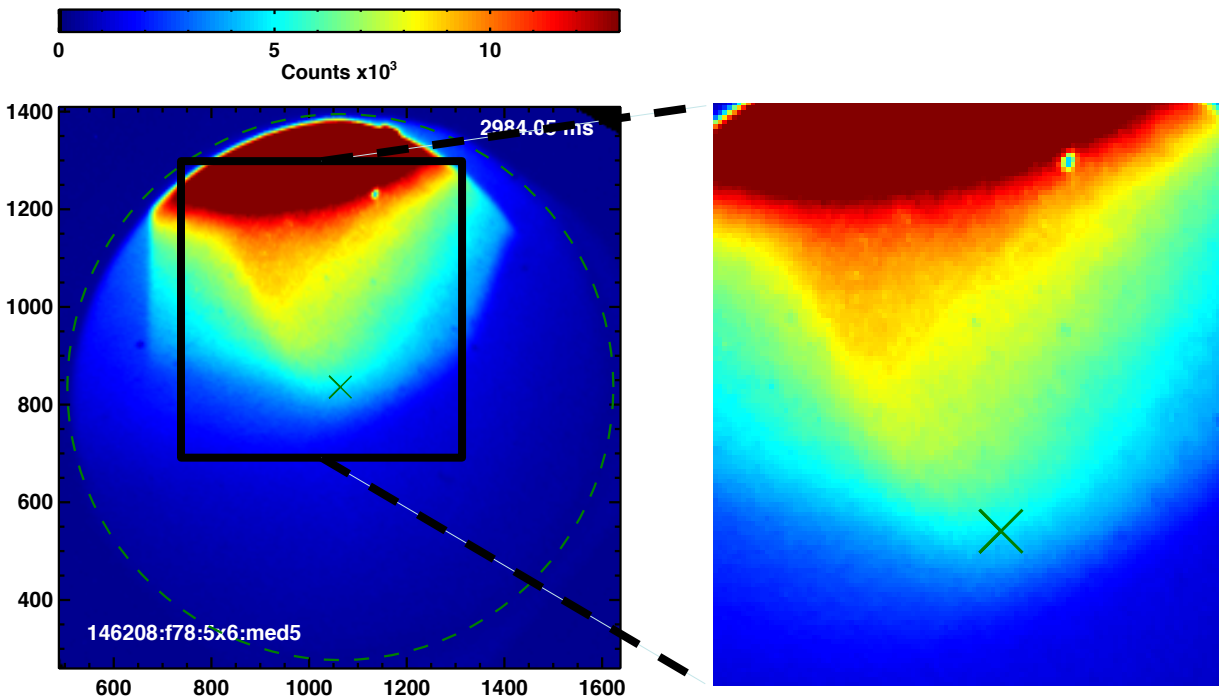
ELM Events Correlate with Localize Changes in eSXR Emissivity Signal

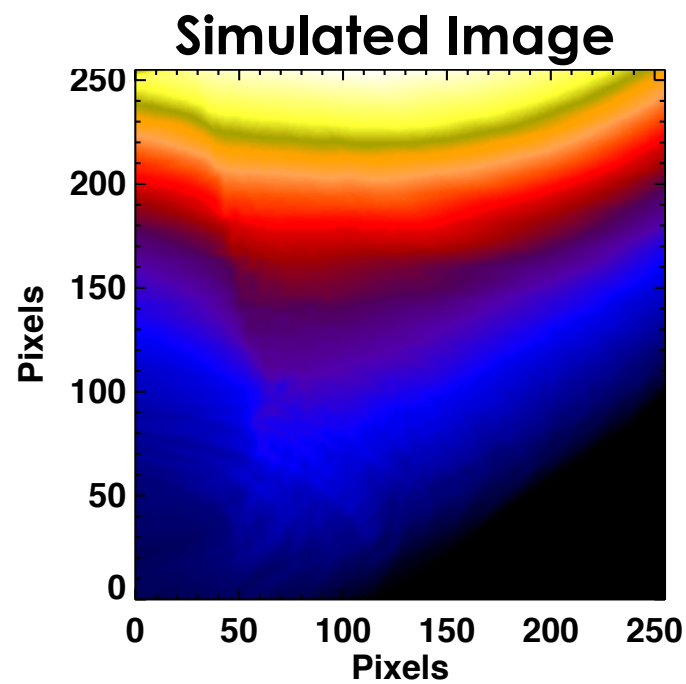


Variation in 2D eSXR Emissivity Signal Attributed to Edge Pressure Gradient Changes



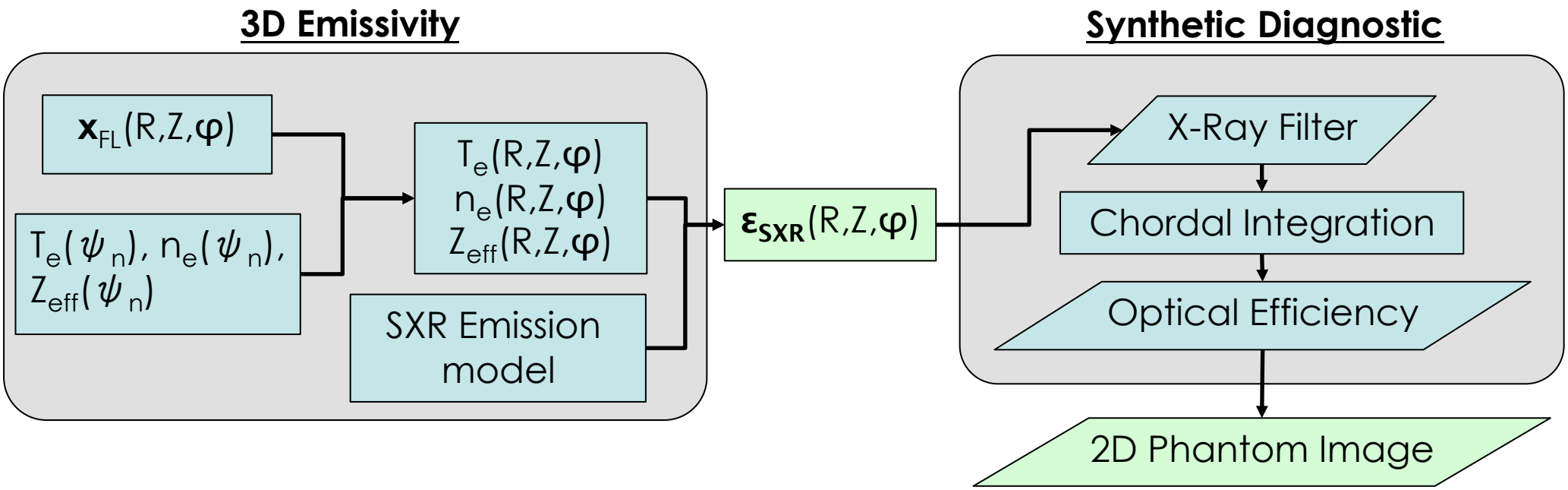
Modeled Phantom Images (Chordal-Integrated) & First Data Loosely Correlate





- **Images do not corrected for optical distortions (eg, flat-field, pin-cushioning); except Scheimpflug**
  - Need hardware in-house + break from experiments
- **Image inversion for 3D structure characterization on the way**
  - Need optical corrections & good plasma targets

Phantom Image Constructed via Synthetic Diagnostic Coupled to 3D Emissivity Estimates



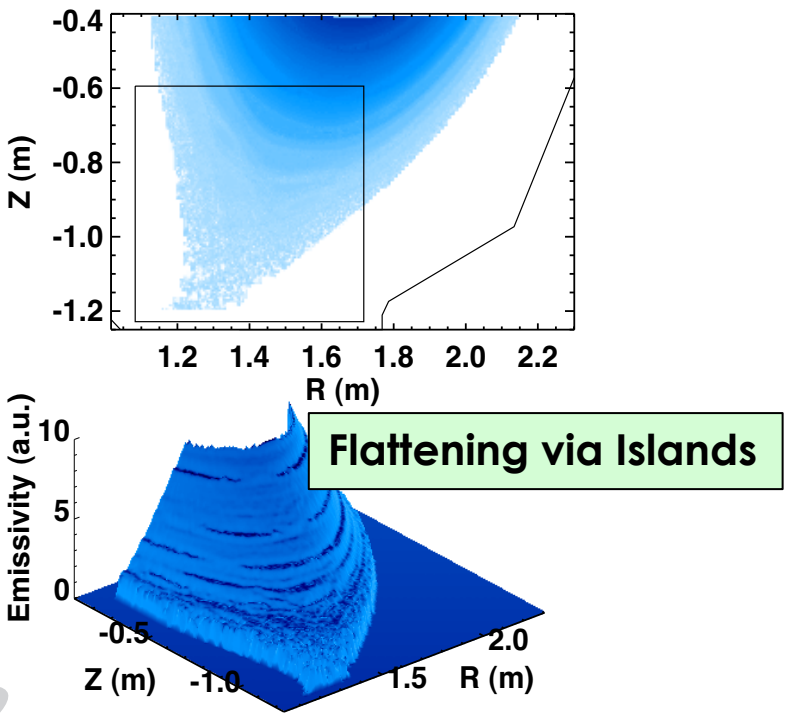
- **3D emissivity model:**
  - Perturbed 3D B-field via field line tracing & simple models
  - 1D profiles via diagnostics (e.g. Thomson Scattering, CER, etc.)
  - CHIANTI astro X-ray model (continuum + line radiation)
- **Axis-symmetric SXR estimate + synthetic diagnostic matches NSTX L-mode data****

***Battaglia, et al., Rev. Sci. Instrum. **81**, 10E533 (2010)*

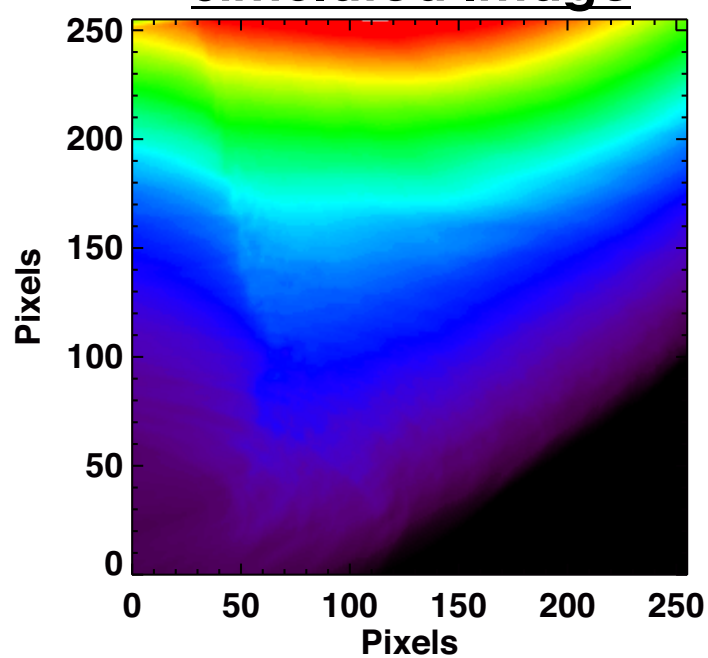
Image Inversion Needed to Interpret Island Structures in Measurement

- **Line integration masks structure in local SXR emissivity.**
- **To begin: Inversion methods investigated for stationary structures**
  - Most difficult for data interpretation
  - Frequency locking / phase subtraction more robust, not examined

Local SXR Emissivity

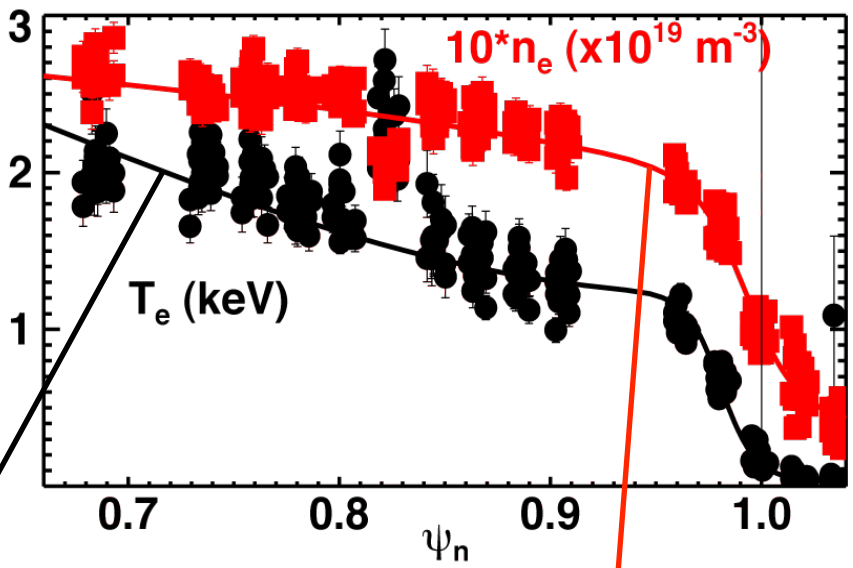


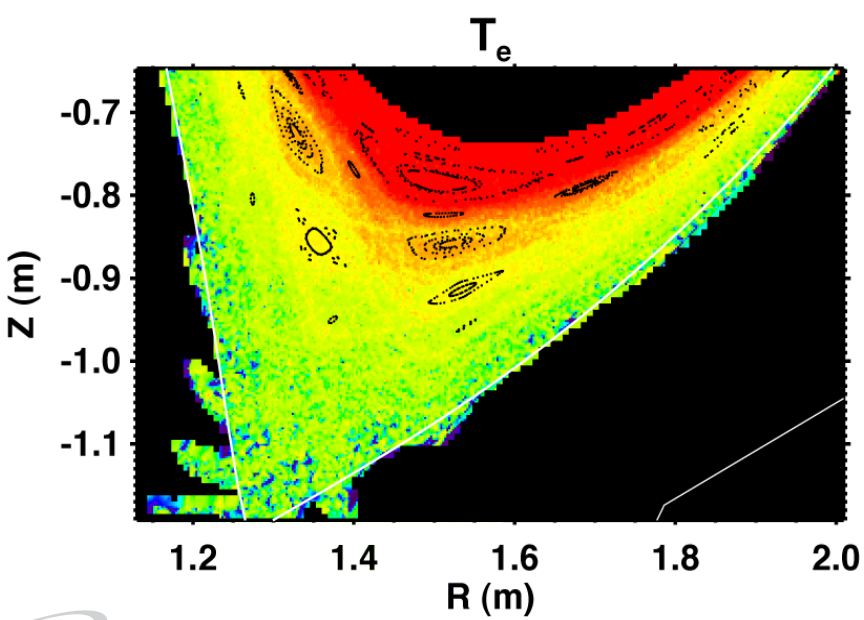
Line Integrated Simulated Image

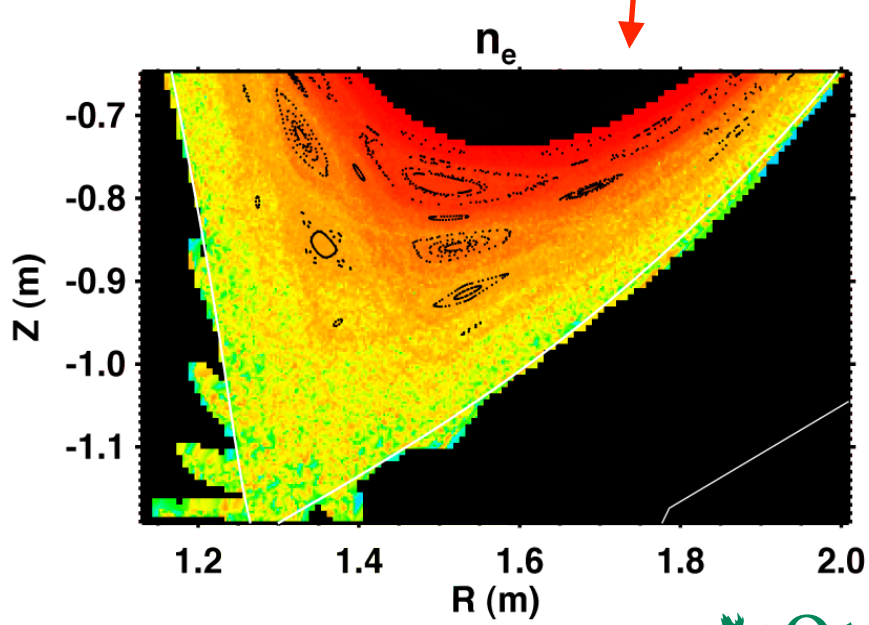


Simple Model Used to Generate 3D SXR Emission for Synthetic Diagnostic

- **Turns 1D flux functions, f(ψ) to 3D based on perturbed 3D ψ**
  - 3D ψ estimated via FL tracing or simple models
- **Assumptions: $\chi_{||} >> \chi_{\perp}$**
  - Radial transport coefficients implicit in profiles







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Phillips-Tikhonov Regularization & Geometry Assumptions Used to Invert Images

- **Image modeled with:**

$$\mathbf{S} = \mathbf{L} \cdot \mathbf{E} + \mathbf{e}$$

  - **S** = line-integrated image measurement
  - **L** = Geometric transform matrix
    - *Here, emission assumed constant along field lines*
  - **E** = Local SXR intensity; **e** is measurement noise.

- **Inversion is ill-posed; regularization needed**

- **Phillips-Tikhonov (PT) regularization** incorporates diffusive smoothing via Laplacian cost function, C**
  - Minimizes: $\gamma \left|\mathbf{C} \cdot \mathbf{E}\right|^2 + \left|\mathbf{S} - \mathbf{L} \cdot \mathbf{E}\right|^2 / M$
  - Linearized Operator: $\hat{\mathbf{E}}(\gamma) = \left(\mathbf{L}^{\mathbf{T}}\mathbf{L} + \gamma M \mathbf{C}^{\mathbf{T}}\mathbf{C}\right)^{-1} \mathbf{L}^{\mathbf{T}}\mathbf{S}$
    - γ ~ weighting factor

**Iwama et al., Appl. Phys. Lett (1989), Ohdachi et al., Plasma Sci. & Tech. (2006).*

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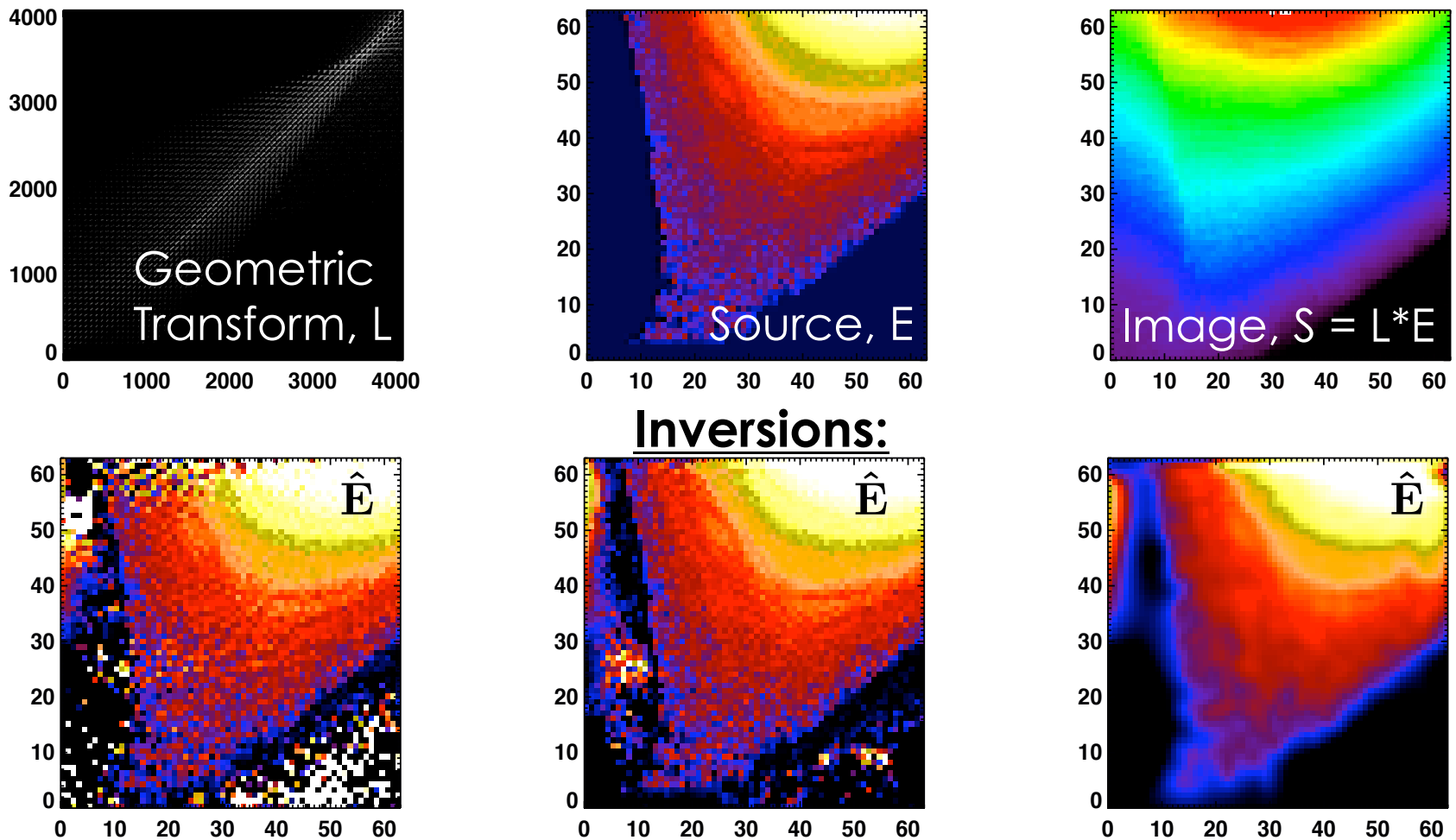
Phillips-Tikhonov Method Allows Control of Noise via Smoothing Operator

- **Smoothness controlled with weighting factor, γ, in linear operator:**

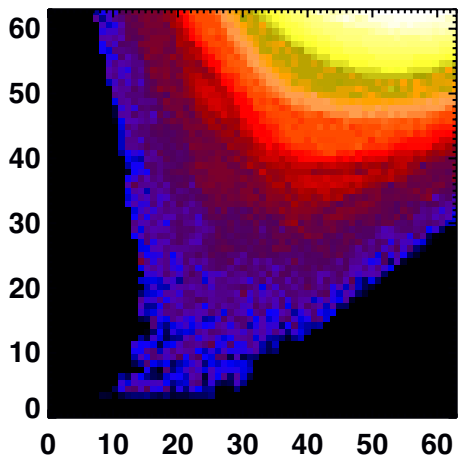
$$\hat{\mathbf{E}}(\gamma) = \left(\mathbf{L}^{\mathbf{T}}\mathbf{L} + \gamma M \mathbf{C}^{\mathbf{T}}\mathbf{C}\right)^{-1}\mathbf{L}^{\mathbf{T}}\mathbf{S}$$



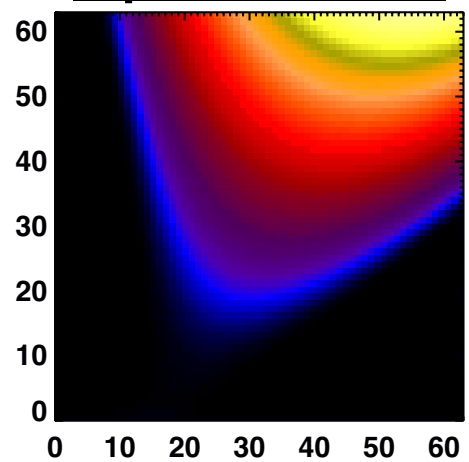
Results Found to be Insensitive to Small Changes in Inversion Operator

- **Inversion operator depends largely on geometric transform, L**
  - Test different operators using perturbed FL (L_{RMP}) vs equilibrium FL(L_{EQ})

Source, E_{RMP}

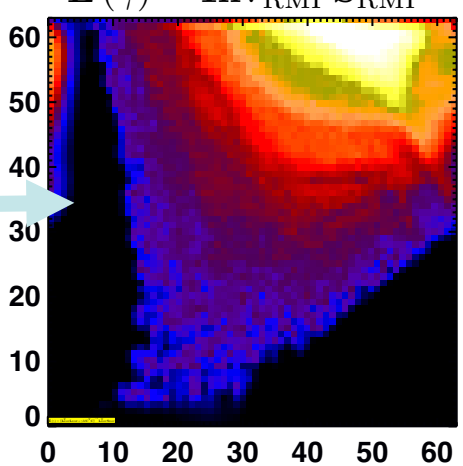


Equilibrium, E_{EQ}



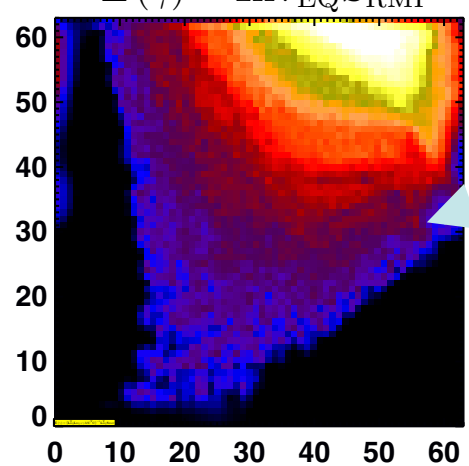
S_{RMP} Inverse w/ L_{RMP}

$$\hat{\mathbf{E}}(\gamma) = \mathbf{Inv}_{\mathrm{RMP}}\mathbf{S}_{\mathrm{RMP}}$$



S_{RMP} Inverse, w/ L_{EQ}

$$\hat{\mathbf{E}}(\gamma) = \mathbf{Inv}_{\mathrm{EQ}}\mathbf{S}_{\mathrm{RMP}}$$



Inversion Operator uses RMP Perturbed Field Lines

Inversion Operator uses Equilibrium Field Lines

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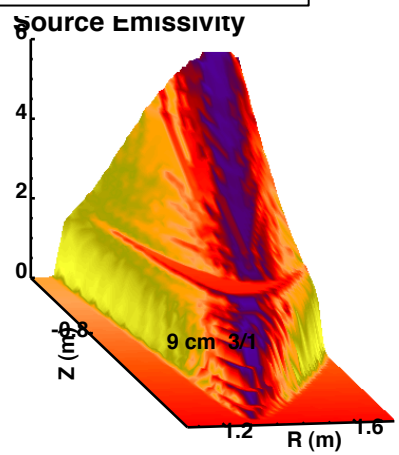
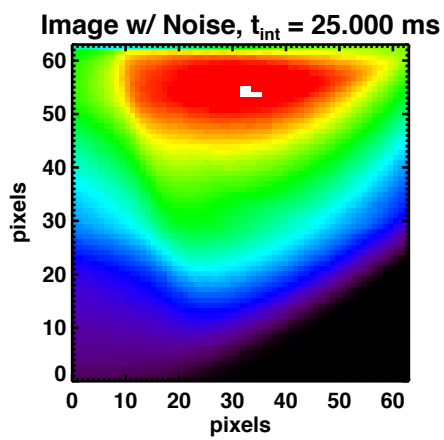
Modeling of Variable Island Widths Used to Test Noise and Size Sensitivity of Inversion

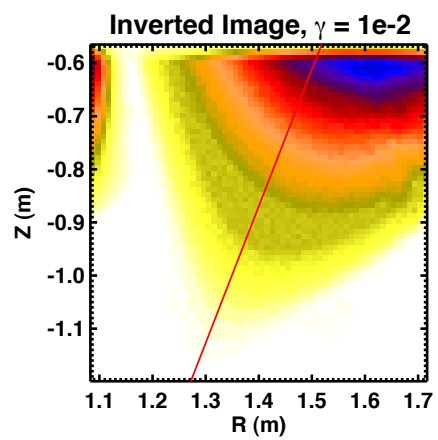
- **Single helicity island model used to generate 3/1 island near X-point with widths varying 1-11 cm**
  - J.E. Menard et al 2005 Nucl. Fusion 45 539
- **Radial cut through X-point illustrates width (W_{xpt} ~ 10 * $w_{midplane}$)**
- **Integration time, t_{int}, is controls noise**
  - Models realistic dark, read and photon noise sources

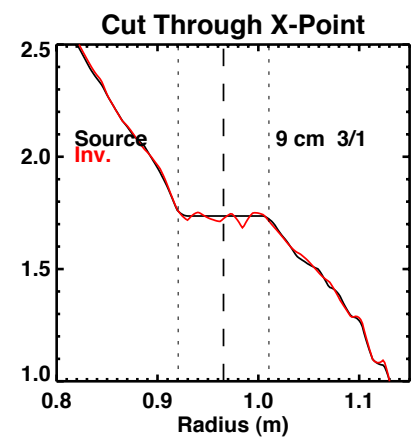
Inversion Flow Chart

Generate 3D Emissivity w/ Island Width → **Apply Synth. Diagnostic, Add Noise** → **Invert Image** → **Compare Radial Profiles Through X-pt.**









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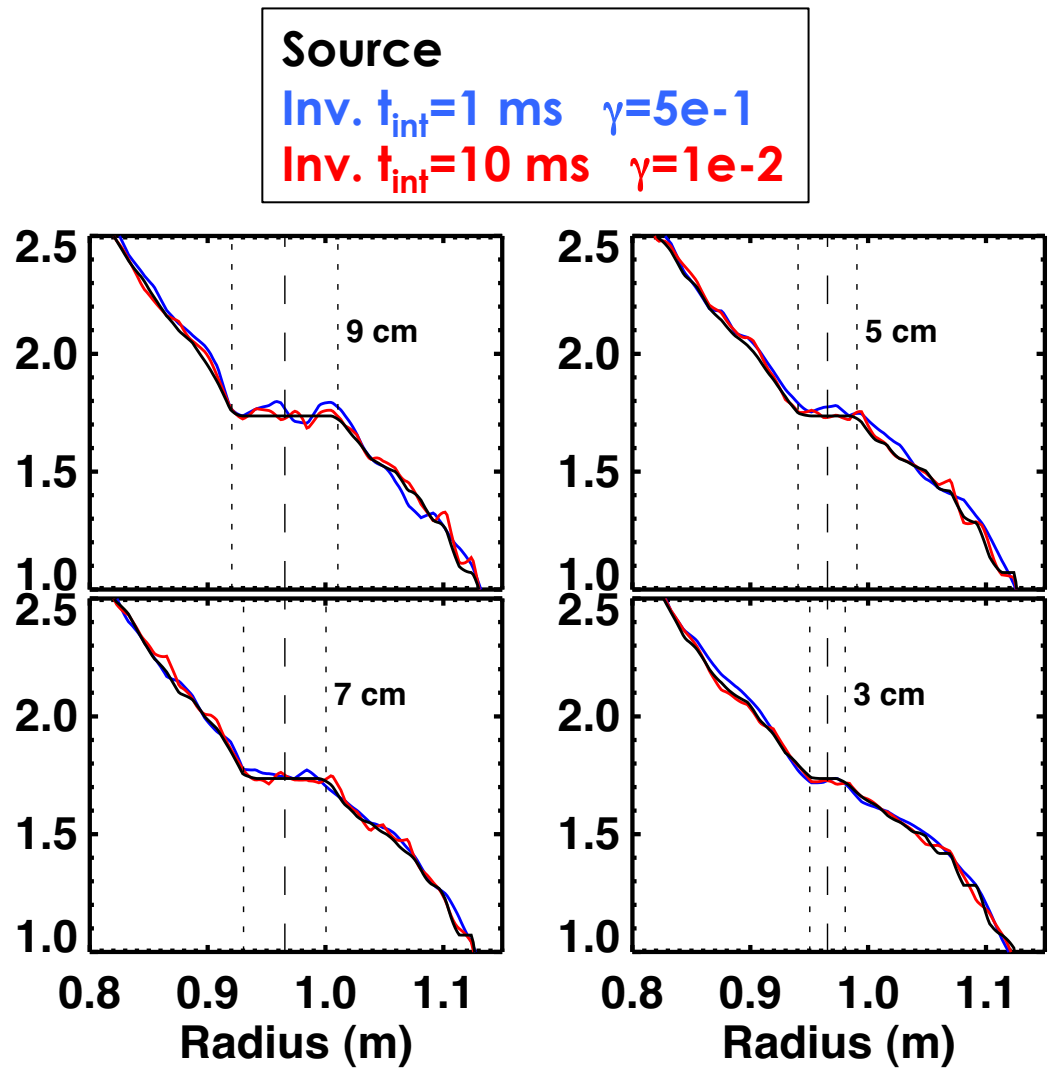
Small Islands (~ 3 cm) Can Be Measured with Only a "Coarsely Gridded" Phantom Image

- **Algorithm optimized to 64x64 grid based on convergence time**
  - Plans to double grid size under development
- **Comprehensive scan includes size, smoothing, and noise effects**
- **Smaller island detection needs longer integration for better SNR**
  - 3 cm island near X-point is ~3 mm at midplane
- **Inversion is robust for large island sizes (> 5 cm)**

SXR Inverted Emissivity (A.U.)



Inversion Methods Suited to Investigate Local Emissivity due to Topology Changes

- **Philips-Tikhonov method well-suited for image inversion**
  - Accurately reproduces source
  - Effect of realistic noise countered by integration time (or smoothing)
  - Perturbed field line structure not needed for Inversion
  - Island width reproduced down to ~3 cm with 64x64 grid

- **Allows interpretation of imaging measurements for island structures**
  - Can discriminate between islands and closed flux surfaces
    - Can distinguish small islands, given flattening is sufficient
  - Covers region wide range $0.7 < \psi_n < 0.98$
    - If screening expected, $0.95 < \psi_n$ is target region
    - If strong penetration, $0.7 < \psi_n < 0.85$ is target for intact islands

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Summary: Methods to Improve Understanding of 3D Field Effects in Tokamaks is Ready for Exploitation

- **Measurement of island structure will be a key factor for understanding RMPs ELM suppression**

- **New pinhole-based SXR camera implemented in X-point region**
  - Exploit flux expansion for island measurements.
  - Efficient, high-resolution CsI:Tl, high sensitivity sCMOS camera

- **First data obtained in DIII-D 2011 run campaign**
  - Initial images are similar to past modeling (phantom images)
  - Local changes in eSXR emissivity ⇒ Edge gradient changes

- **Development of analysis methods is a key aspect for qualitative understanding of data**
  - Course-gridded PT regularization suited for image analysis and access to island flattening ~ 3 cm near the X-point

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