Edge Soft X-Ray Imaging for 3D Topology on DIII-D: A First Look

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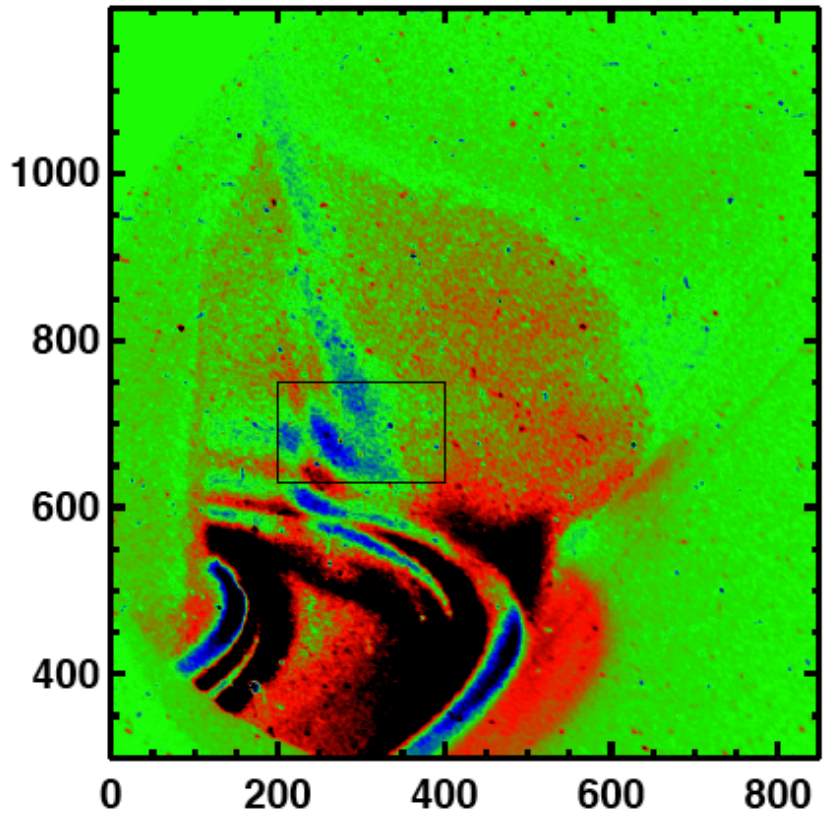

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Primary Motivation: Understand ELM Control via Applied 3D Fields

- **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} **= 15-20 MJ** (ITER W_{ped} = 100-130 MJ)
- **Addition of 3D Resonant Magnetic Perturbation ⇒ ELM control**
  - How does transport change? Imposed Islands?
- **3D RMPs (δ B/B~10^{-3}) found to both suppress and destabilize ELMs in tokamaks**
  - DIII-D, ASDEX-U ⇒ Suppression
  - NSTX, MAST, COMPASS-D ⇒ On-demand triggering
- **Magnetic topology measurements desired to understand plasma response to 3D magnetic perturbations**
  - Needed for extrapolation of ELM control to future machines

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

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Outline: Overview of Camera Results (not just 3D)

- **Diagnostic Overview:**
  - New System, final part of installation in August
    - ARRA Milestone completed
  - Modeling Approach, Views & Alignment

- **Early results show range of diagnostic:**
  - ELM evolution
  - QH-mode evolution
  - 3D field effects
  - Comparison to modeling & inversion progress

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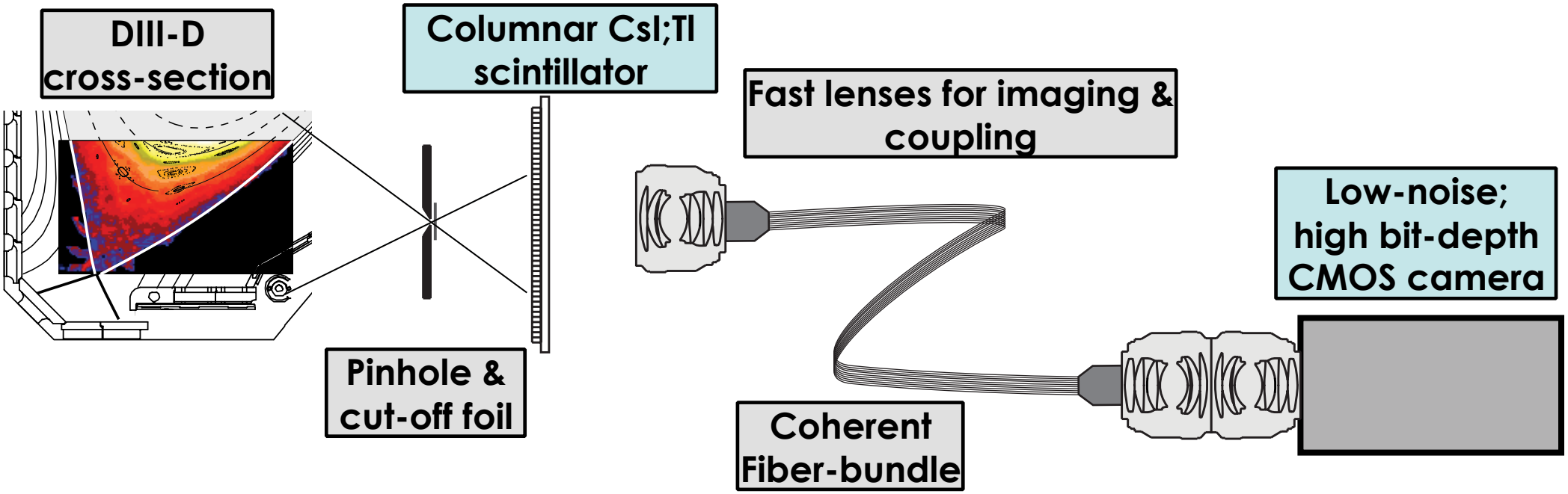
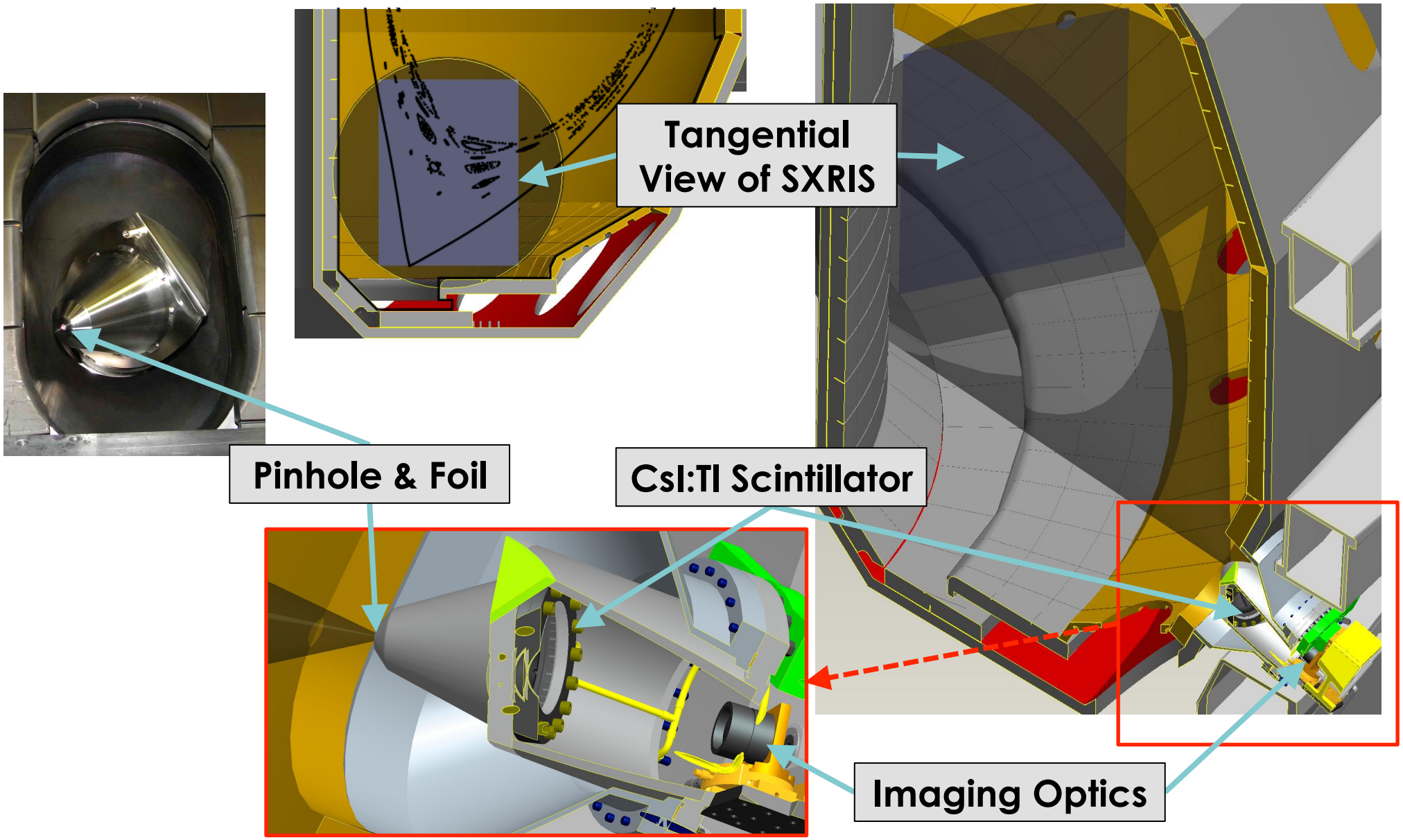
Principle of Measurement Motivated by Core Tangential SXR Systems on LHD, NSTX, TEXTOR



- **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

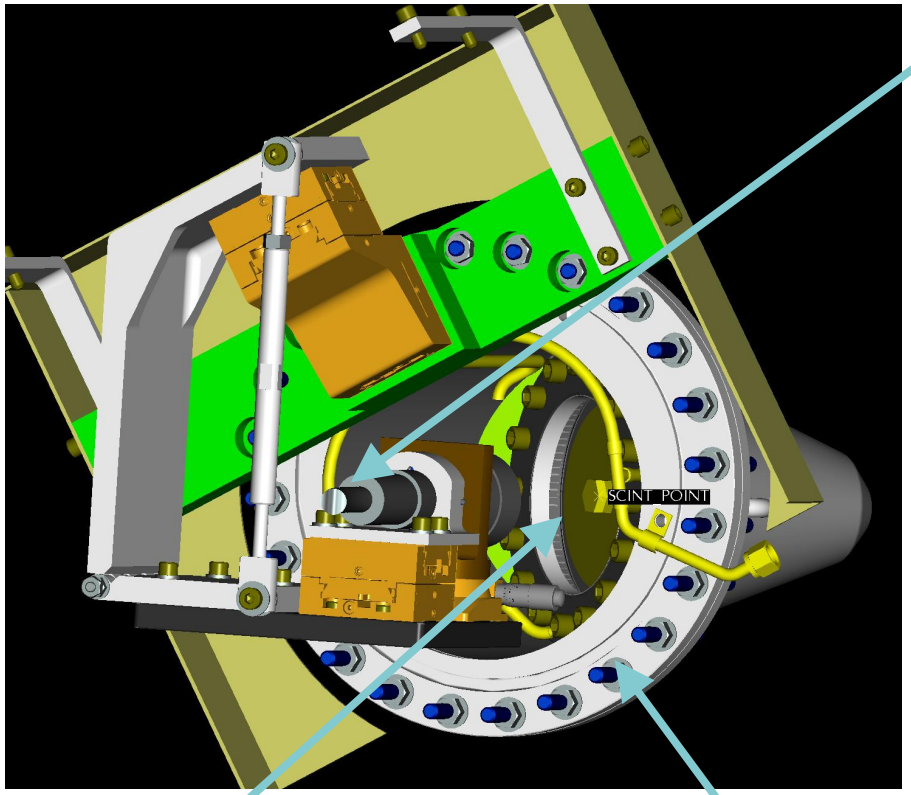
** Ohdachi, et al. Plasma Science Tech. (2006)*
Shafer, et al., Rev. Sci. Instrum.* ***81*, 10E534 (2010)*

DIII-D Edge SXRI System Implemented During 2011 Run Campaign



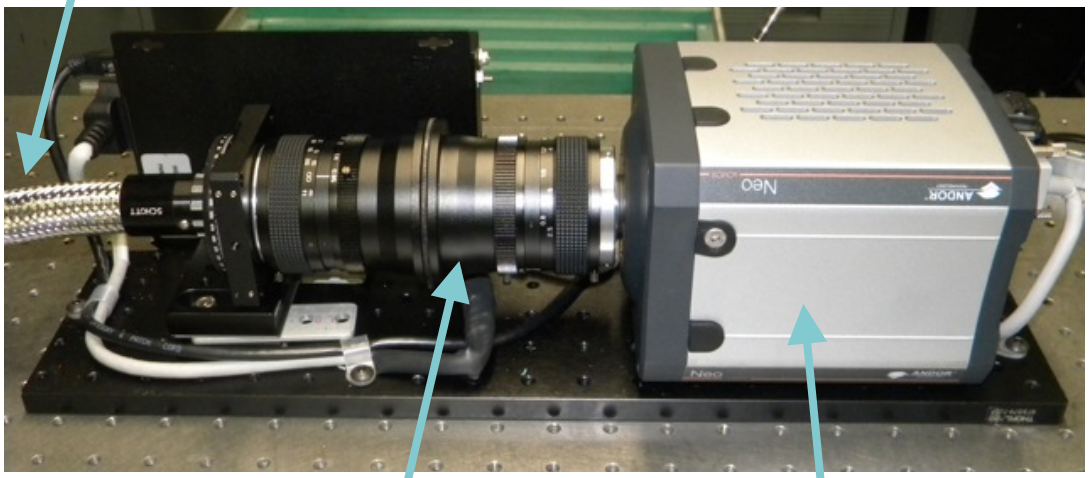
Visible Optics Used to Couple to sCMOS Detector

Machine-side Optics



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

Detector Assembly



Scintillator Window

Vaccum Port

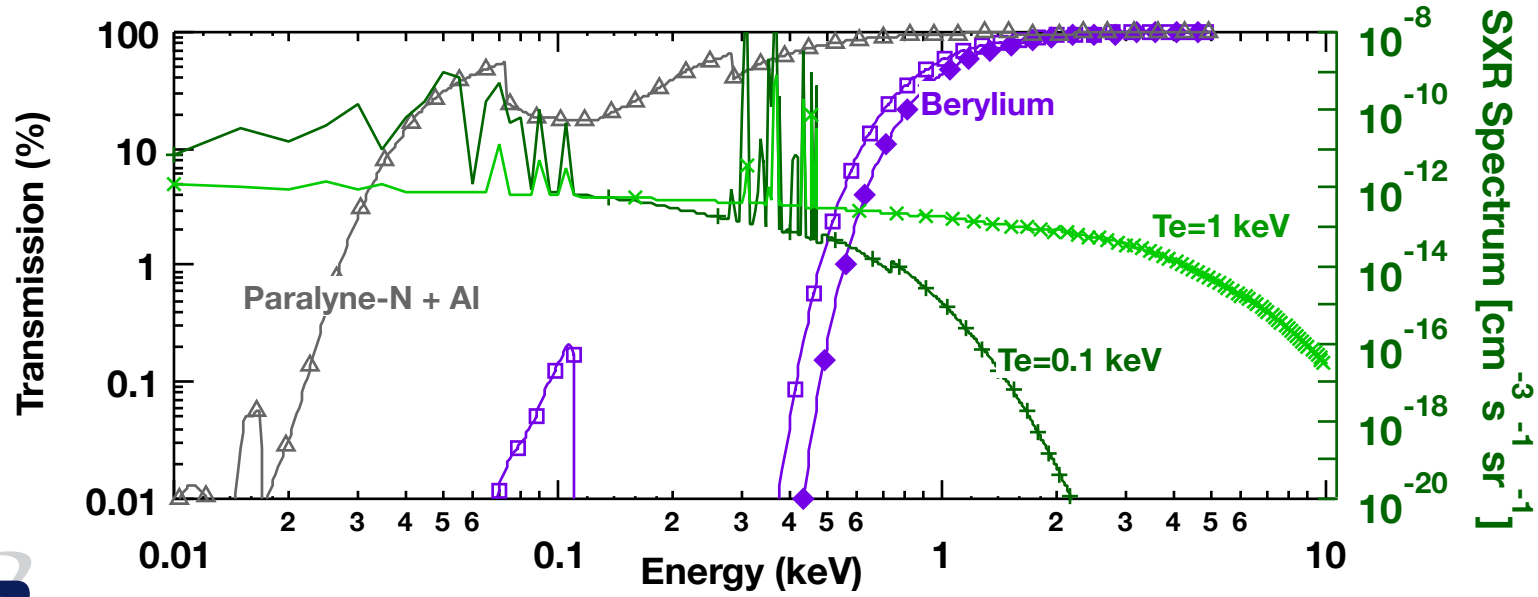
f/0.95 Coupling Optics

16-bit Andor Neo sCMOS Camera

Variety of Filter Thickness Used: SXR to UV

- **Data with 3 different energy filters, changeable w/ 'clean vent'**
  - "Thick" Filters: 5 μm Be, 7um Be
    - Inside $\psi_n \sim 0.95$, Continuum + Some Line radiation
  - "Thin" Filter: 0.1 μm Parylene-N + 0.05 μm of Al
    - Bright Edge/SOL: CIII, CIV, (Lyman-alpha, not included)
  - Chronology: Thick filter ➔ Thin filter

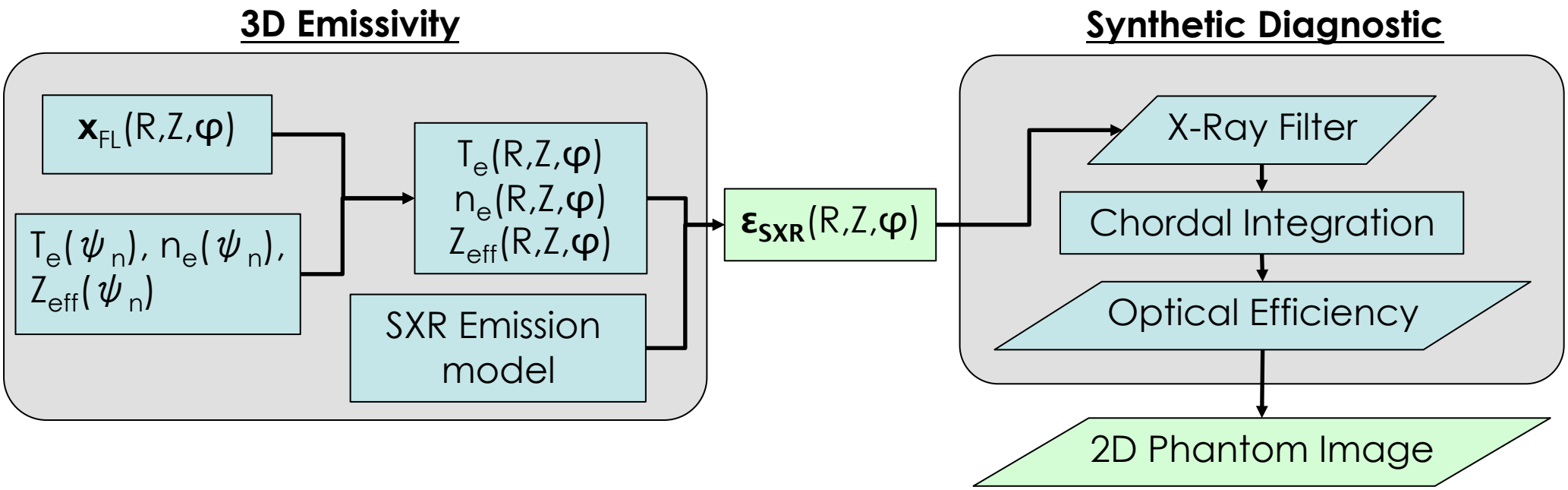
Filter Transmission + CHIANTI SXR Emission Model



Data in 2011 Campaign: Highlighted Topics

Date	Experiment	Filter
Aug 2011	Opaque SOL (High Density)	7.5 um
Sep 2011	Multiple 3D Fields (n=3 vs n=2, n=2 rotation, q-ramps, torque scans)	5 um
Oct 2011	3D Fields: Phase-flipping + q ramp	Parylene
Oct 2011	(Reverse B_T) QH-mode	Parylene
Nov 2011 (Next Week)	Pellet Pacing ELM studies	Parylene

Modeled 3D Emissivity + Synthetic Diagnostic Used for Design, Comparison to Data



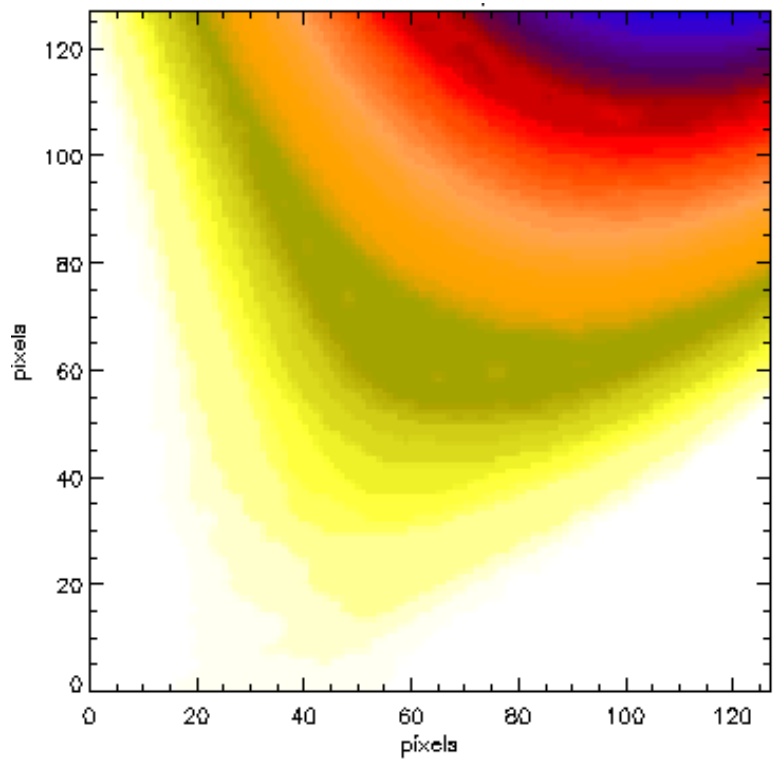
- **3D emissivity model:**
  - Perturbed 3D B-field via field line tracing & simple models
  - 1D profiles via diagnostics (e.g. Thomson Scattering, CER, etc.)
  - CHIANTI astro X-ray model (continuum + line radiation)
- **Axis-symmetric SXR estimate + synthetic diagnostic matches NSTX L-mode data****

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

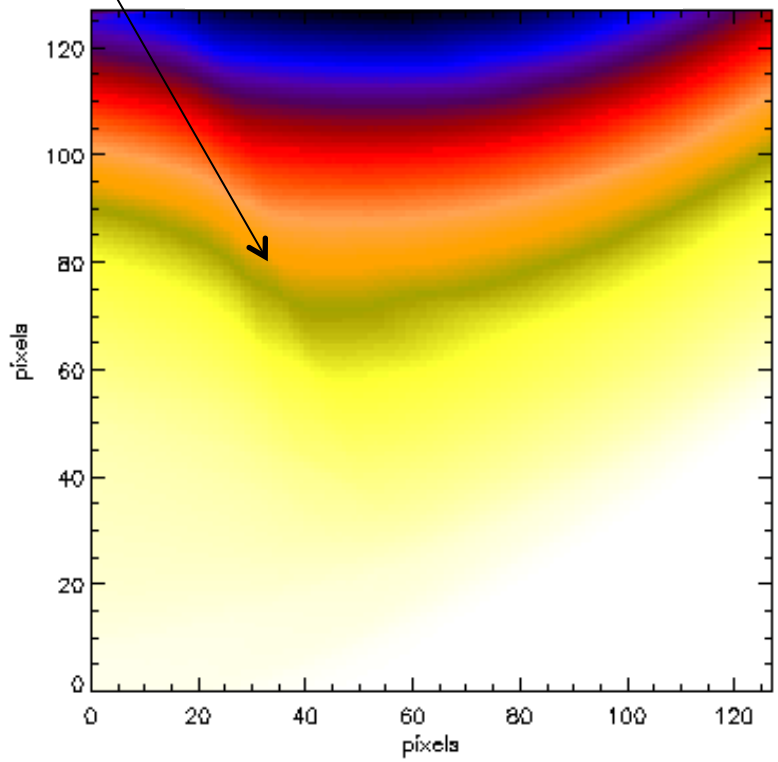
Image Primer: Construction of Line Integrated Image Helps Describe Gross Features

- **Simplified Axis-symmetric SXR emission example**
  - 7.5 um Be filter
  - Inner Separatrix has sharpest definition

SXR Emission @ Tangency



Integrated Image



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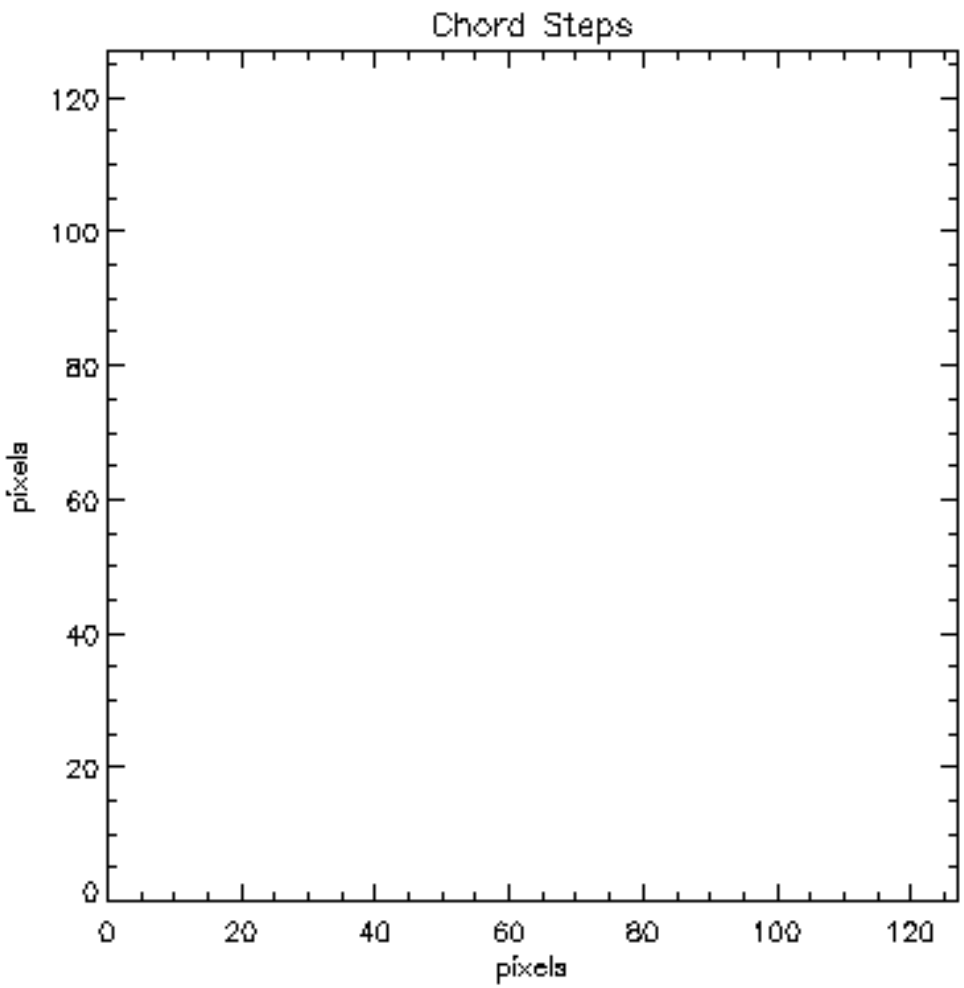
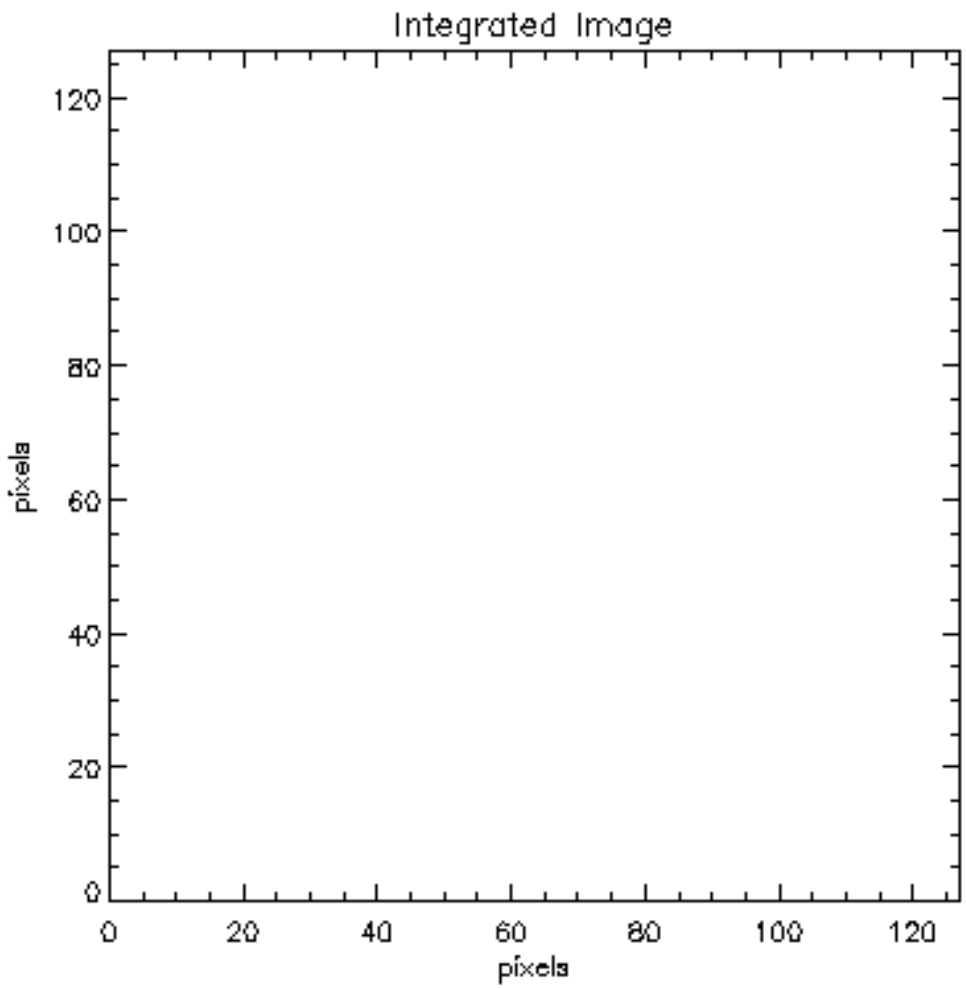
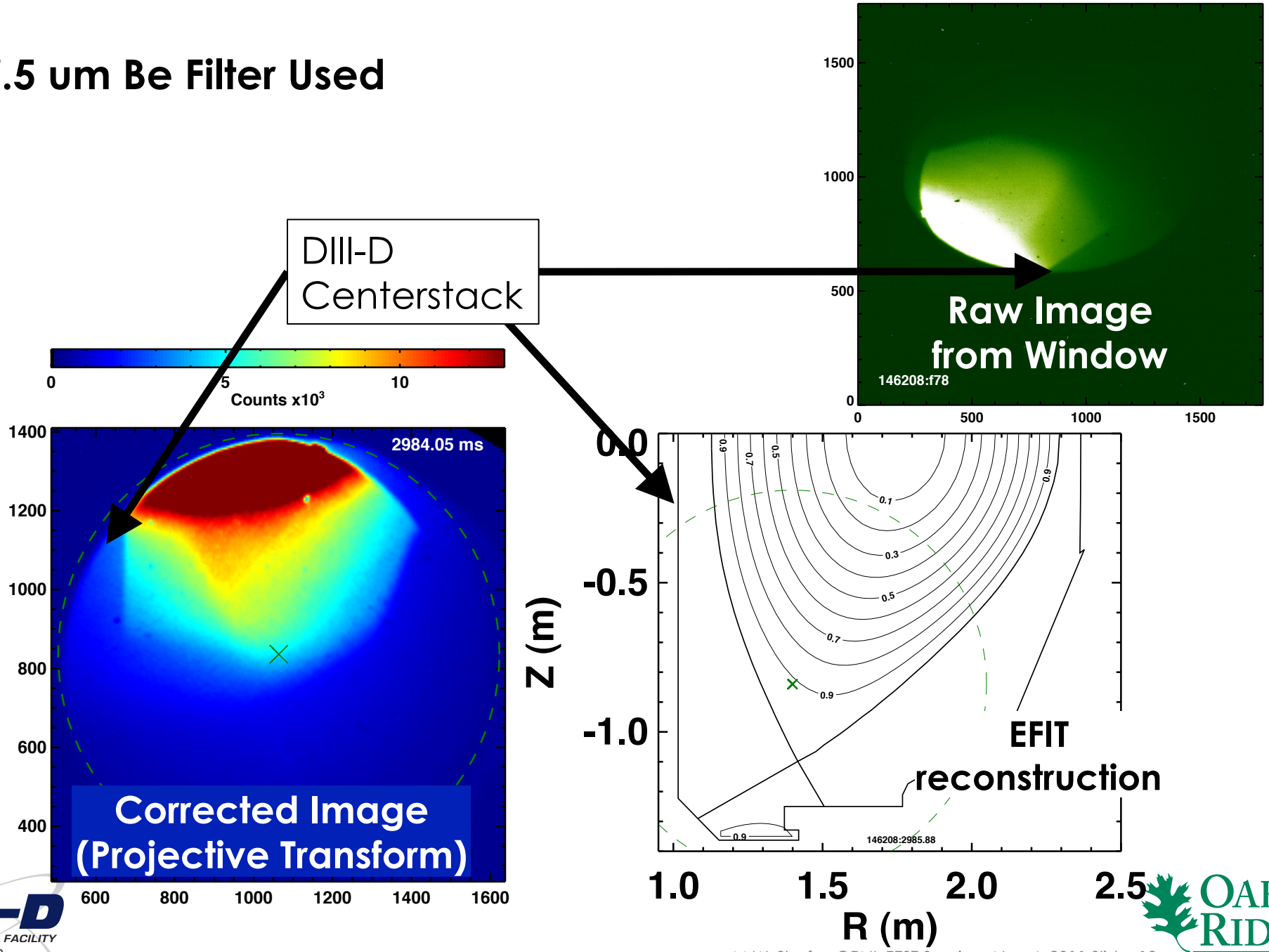




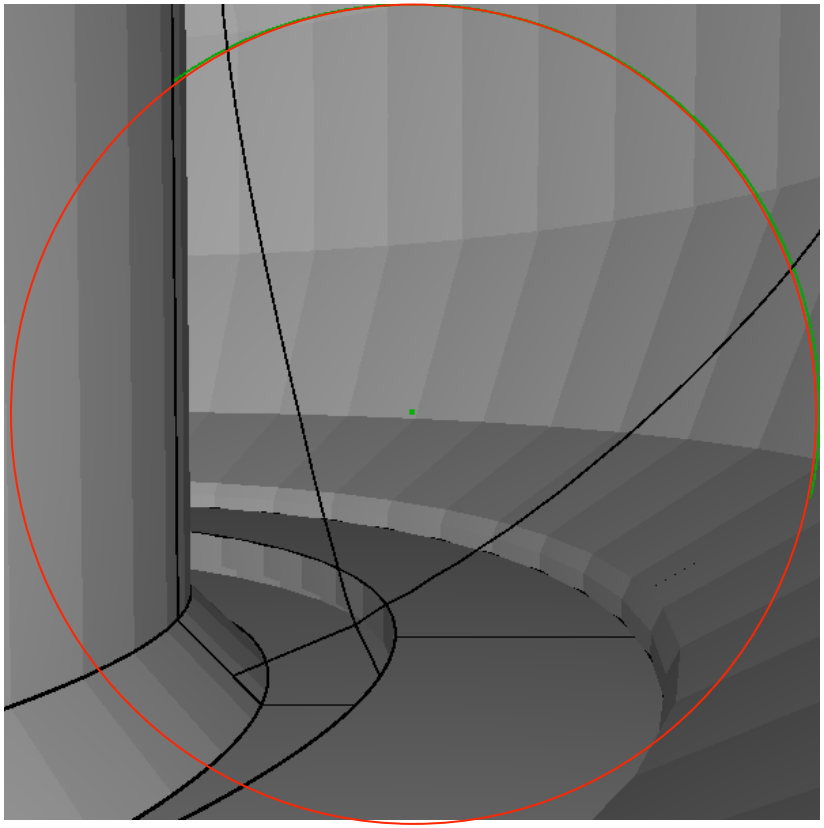
DIII-D First Data Shows Hot Core & Plasma Boundary

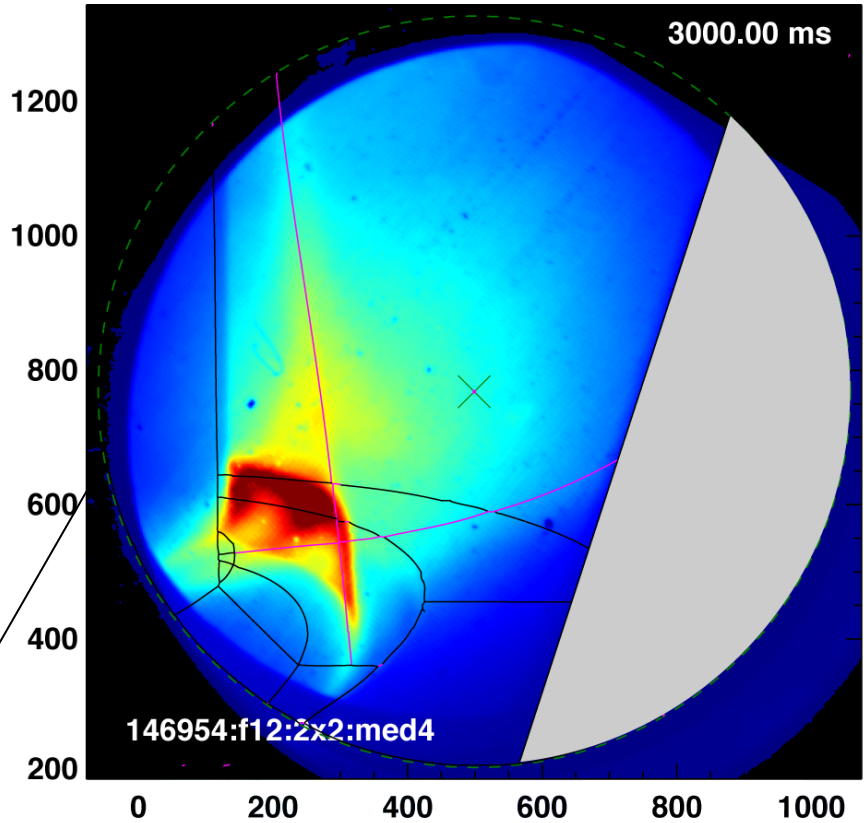
- **7.5 um Be Filter Used**



Alignment Key to Analysis, Inversion Algorithms

- **Ray Tracing used for first cut alignment**
  - Example compared to thin filter edge emission
    - Higher light flux, Edges more visible
  - Iterations on camera geometry to better match image





Center Post

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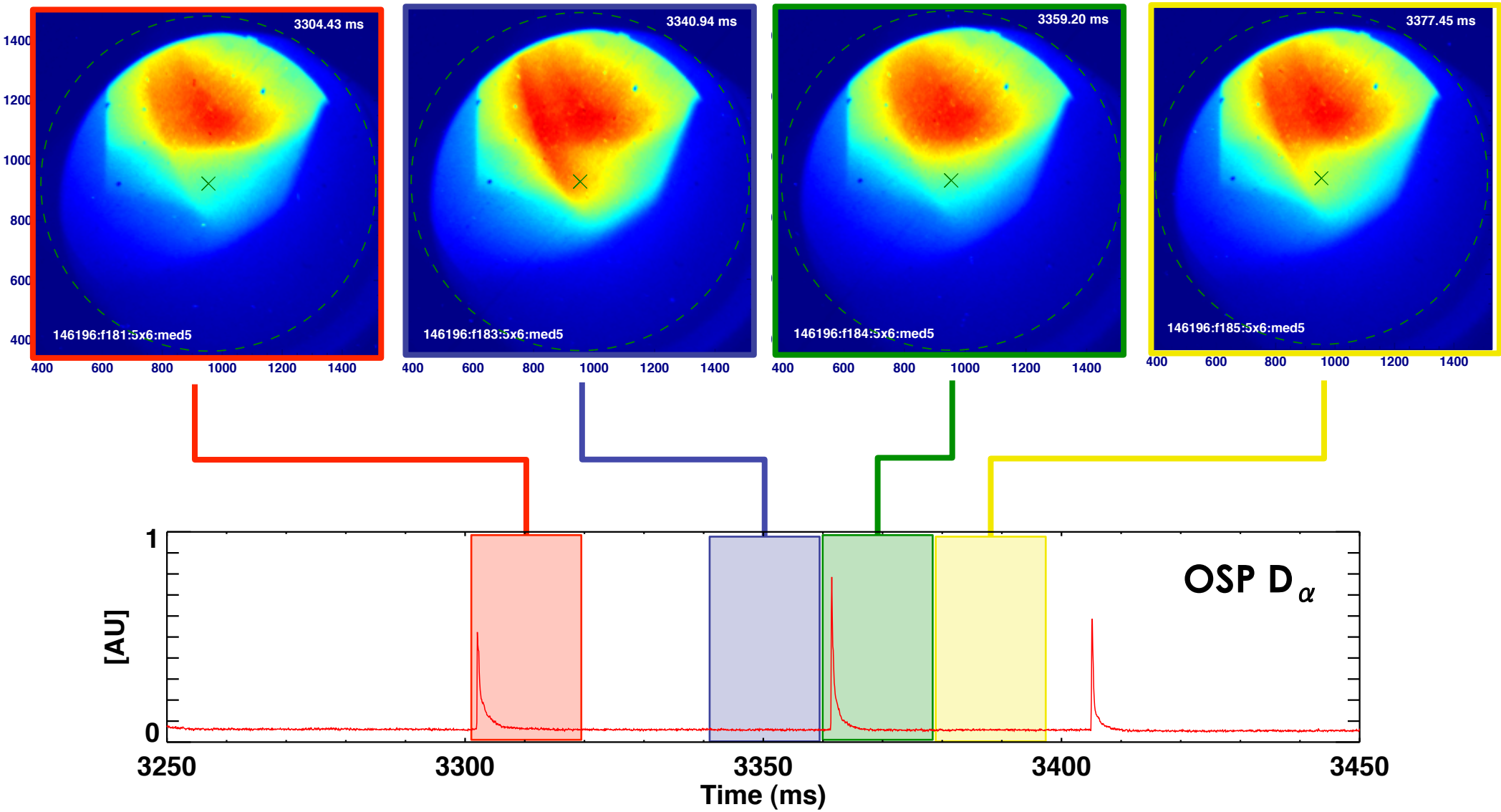
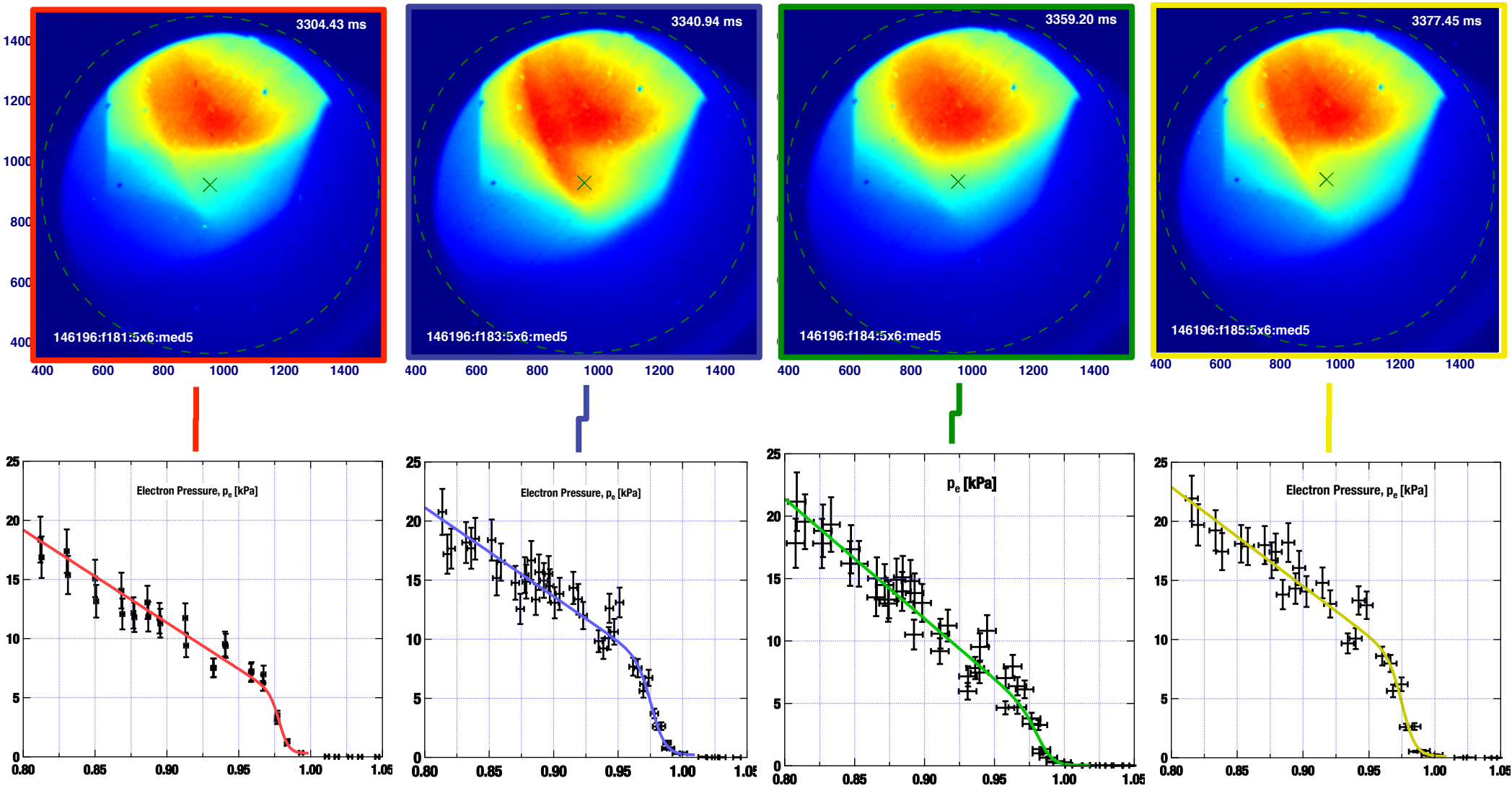
ELM Events Correlate with Localize Changes in eSXR Emissivity Signal

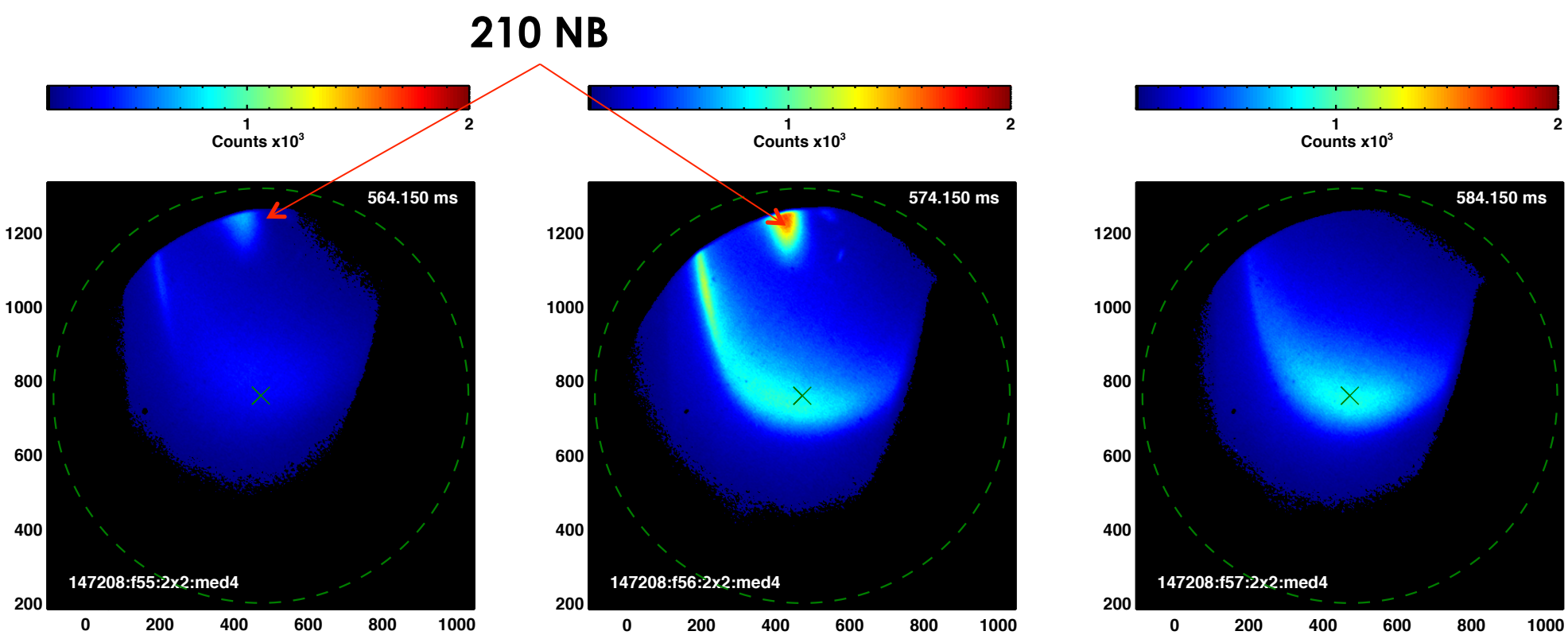


Variation in 2D eSXR Emissivity Signal Attributed to Edge Pressure Gradient Changes



Interesting Feature Observed in QH-mode (Reverse B_T)

- **Synced with NBI, rotating emission source seen.**
  - Speculation: shine-thru, entrained neutrals (Lyman-α), ?
  - Rotates in ExB direction
  - Viewing Crown: double-null, biased up



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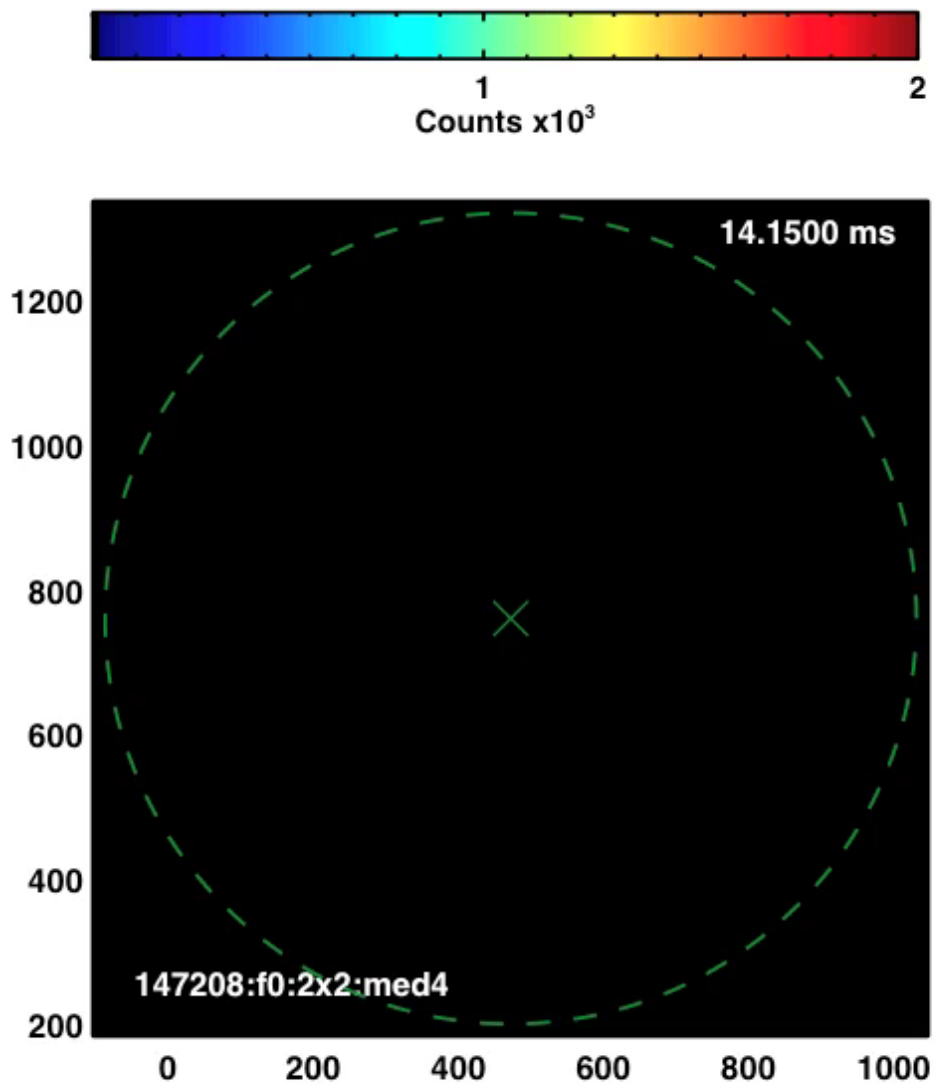
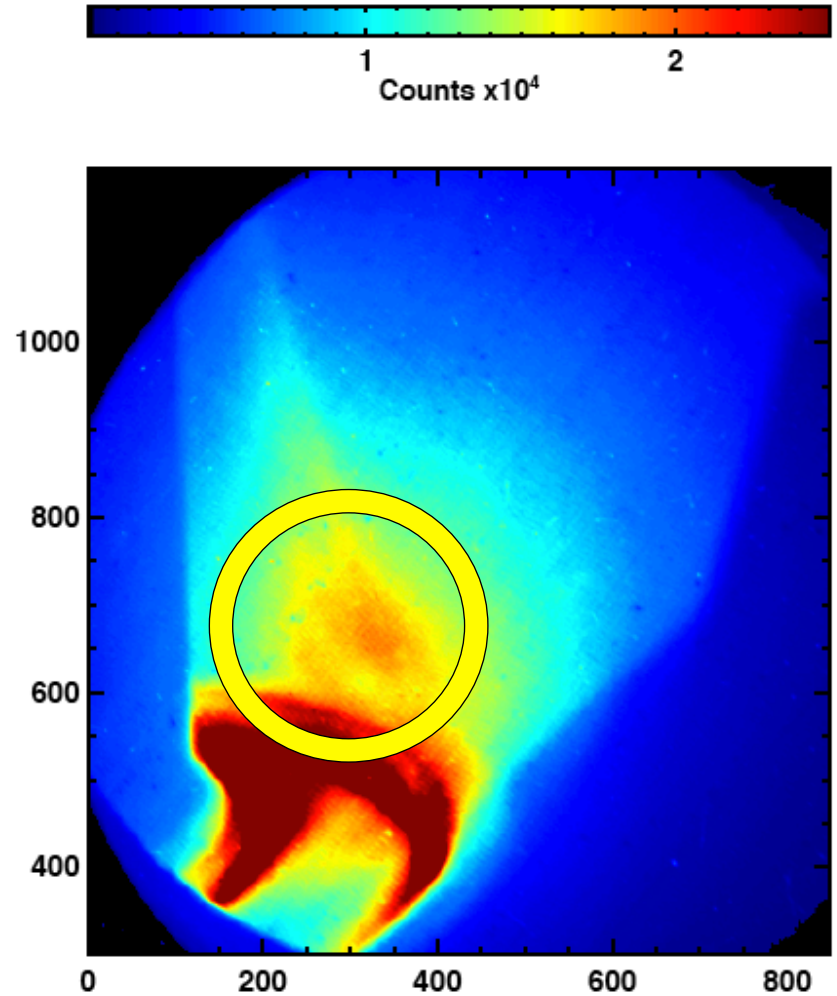


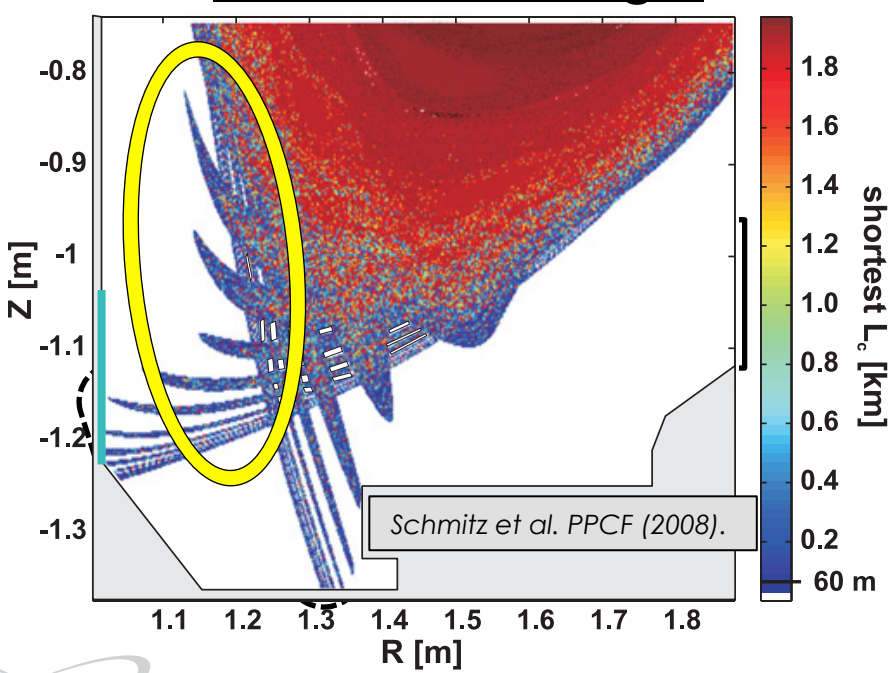
3D Fields: Separatrix Lobes with n=3 RMP ELM Suppression

- **Measurements suggest features seen in FL tracing analysis**
  - Previously, PWI / strike point splitting
  - Now, more structure

Image w/ Thin Edge Filter

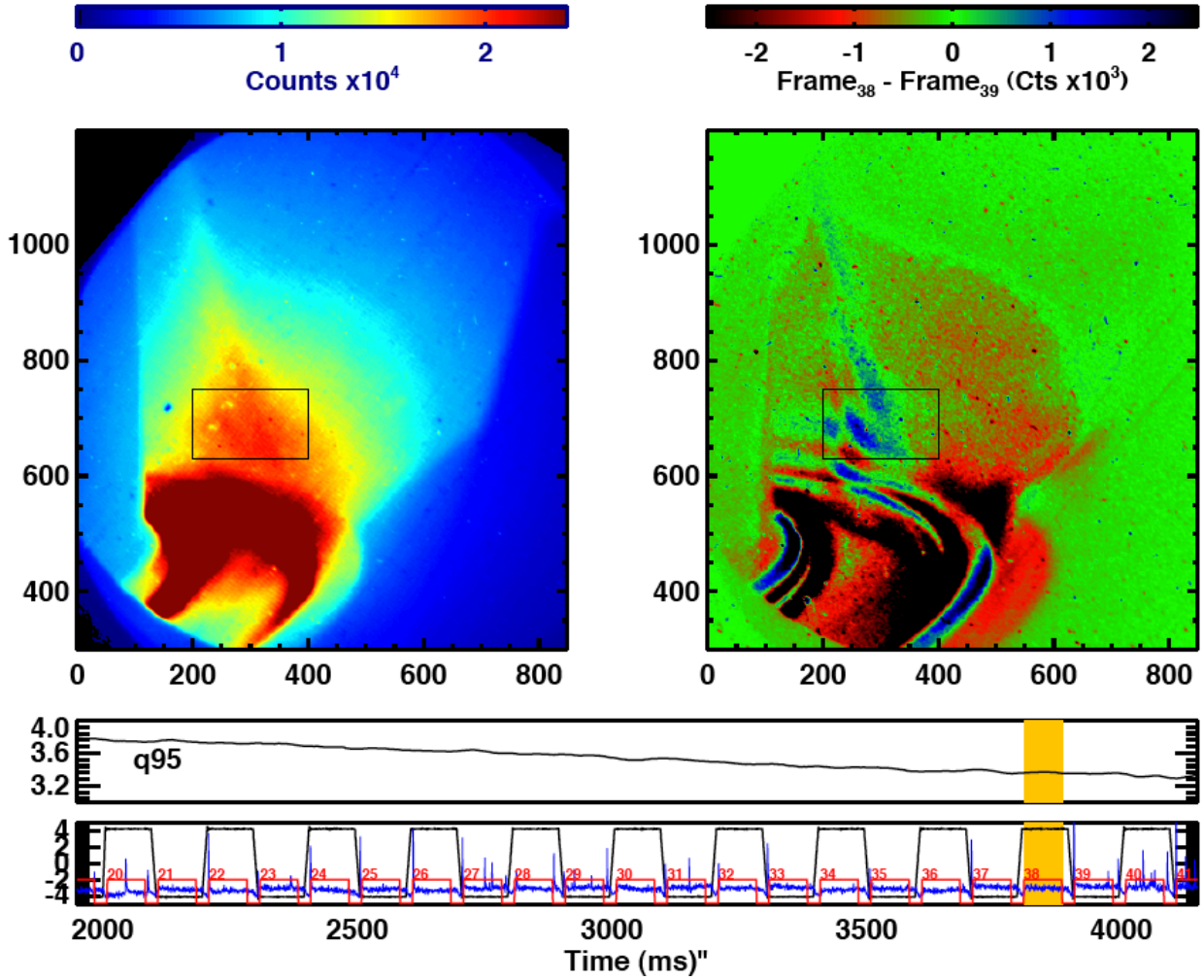


TRIP3D (Vacuum) FL Connection Length

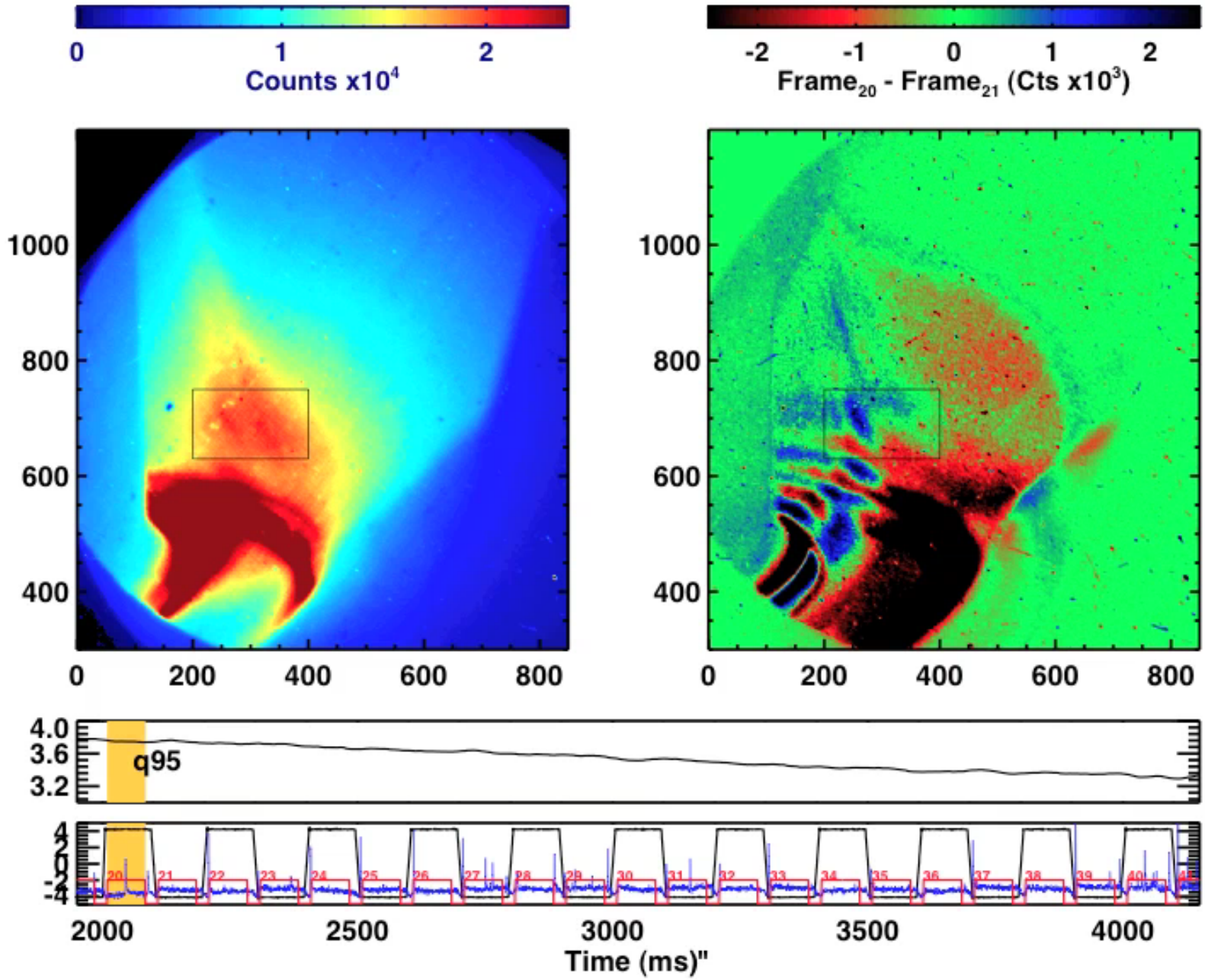


3D Fields: Subtracting Phase-Flipped n=3 field Enhances Lobe Structure

- **Frame integration synced with I-coil waveform**
  - n=3 field has phase rotated by 60 degrees in the machine (180 degrees out of phase in the perturbation) via flipping coil currents.
- **q95 ramp changes edge field pitch, linked to lobe movement**



3D Fields: Subtracting Phase-Flipped n=3 field Enhances Lobe Structure (Movie)

- 

Phillips-Tikhonov Regularization Targeted for Image Inversion

- **Image modeled with:**

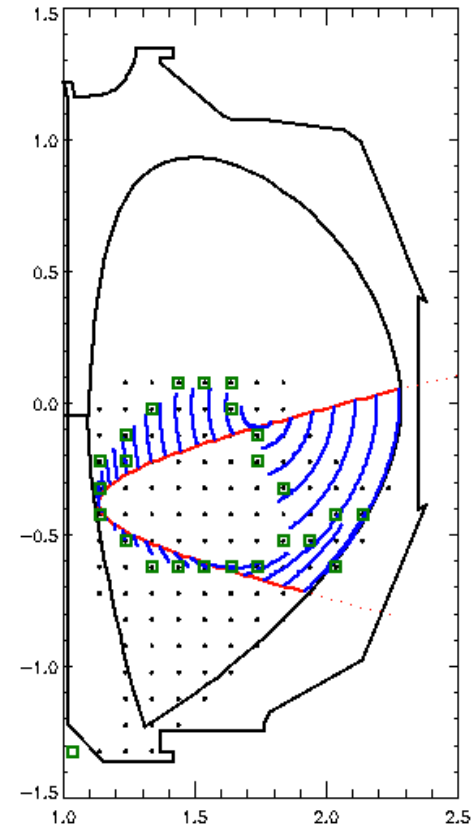
$$\mathbf{S} = \mathbf{L} \cdot \mathbf{E} + \mathbf{e}$$

  - **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
    - Apply minimization to weighting factor

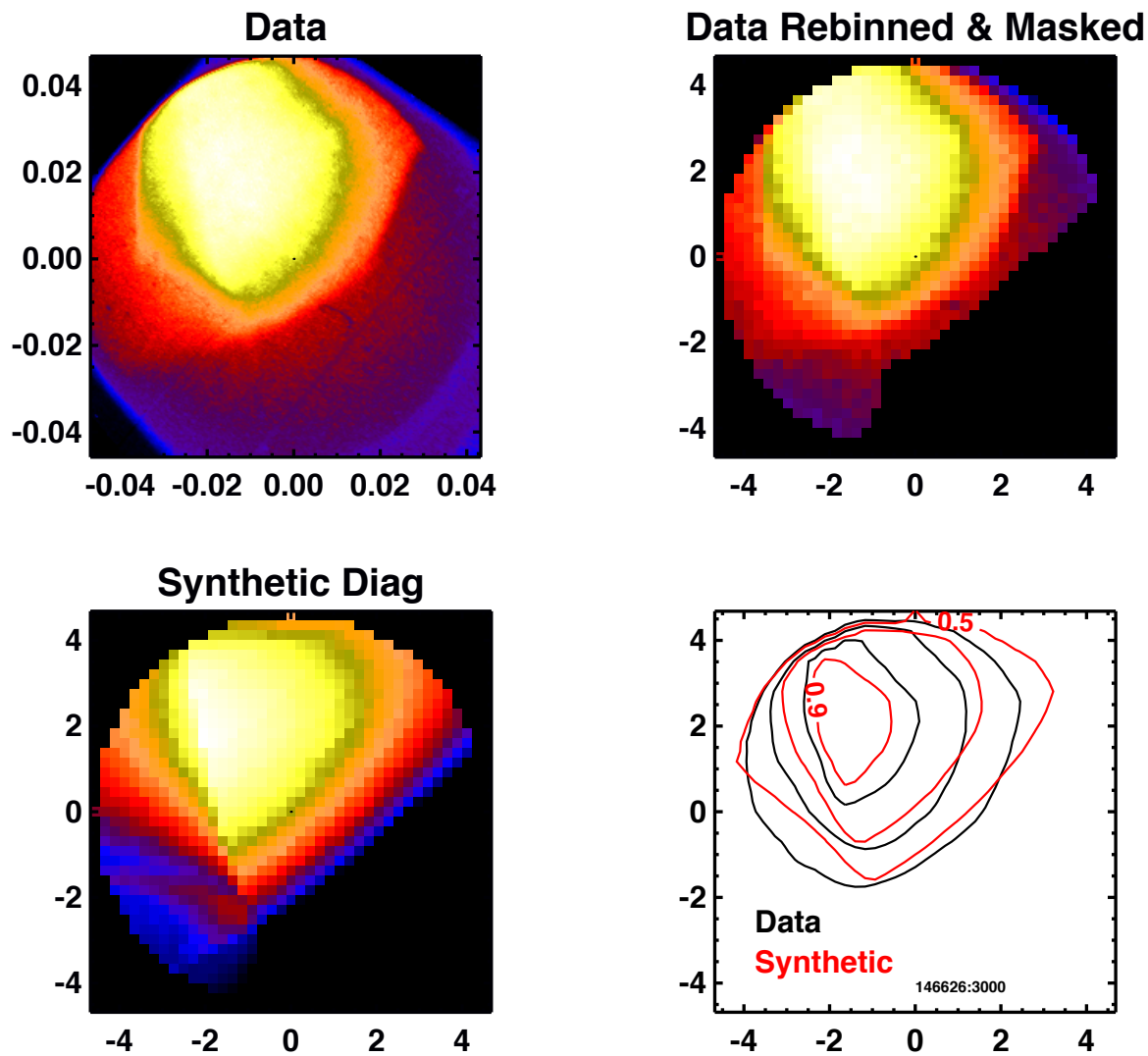
L Construction



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

Line-Integrated Modeling Compares Well to Measurements

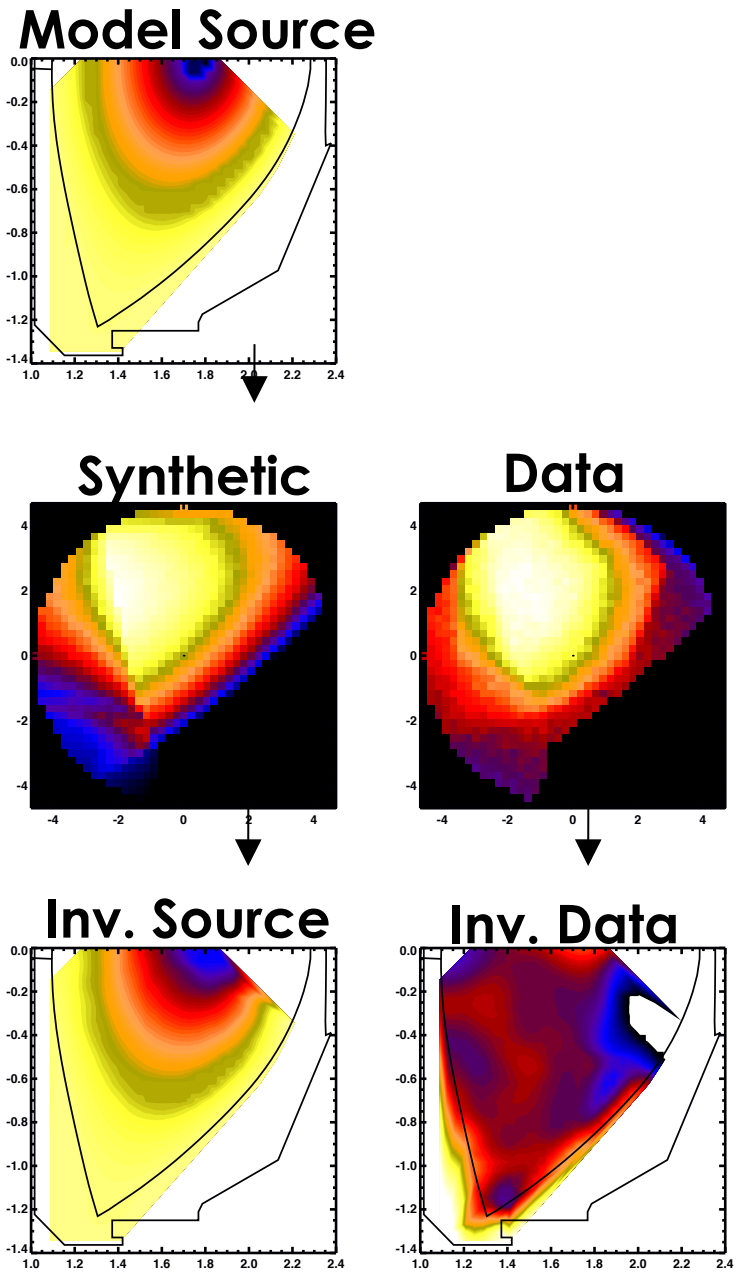
- **Modeling uses:**
  - EFIT, profiles, rough estimate of impurity density via CVI (CER).
  - Coarse grid for speed
- **Discharge:**
  - RMP ELM suppression
  - 7.5 um filter
- **Further Improvements:**
  - Impurities
  - Better masking
    - Center post
    - Tile obstruction
  - Absolute scale



Inversion is a Work in Progress

- **Modeling works fine, inversion not yet**
  - Same images as previous slide used
  - Previously modeling showed robustness to noise
    - M.W. Shafer, et al. PFR 2011

- **Next Steps:**
  - Simplify scheme (flux surface vs FL)
  - Alignment (Tilt, pan, roll)
  - Modifying source
  - SVD Filtering
  - New inversion methods



Summary: SXR Camera Successfully Installed, Data Obtained, 3D Fields Exploration Begun

- **First data taken with newly installed X-Point SXR camera.**
  - ARRA Milestone
- **Feature Highlights:**
  - ELM cycle imaged shows profile collapse, possible 3D structure.
  - Good initial match to line-integrated data.
  - Clear Evidence of n=3 RMP effects on plasma boundary.
    - Edge q-ramp shown to shift lobe positions.
  - Neutral Beam / Edge Interaction – yet to be explained
- **Future Work:**
  - Inversions:
    - scale problem back, try toroidal symmetry
    - Develop alignment algorithm
  - Experiments:
    - Pellet Pacing ELMs Next Week, image ELM cycle
    - Develop Proposal for next campaign, likely Argon puffing + n=1 fields

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