ABSTRACT

Flux surface shape information is imaged with an X-ray pinhole camera and used as a constraint for reconstruction of the plasma current and q profiles for shaped, low-aspect ratio toroidal plasmas. The camera system is comprised of a 30cm Gd2O2S:Pr scintillator plate whose X-ray incident side is lens coupled to an MCP image intensifier. A slow-scan CCD camera is then lens coupled to the MCP for a time resolution of ~1ms. Installation of a 0.2μm nickel X-ray filter provides necessary contrast between the hot interior and cooler plasma edge region. Equilibrium reconstructions demonstrate sensitivity of profile reconstruction to tangential image constraints. The scintillator system is compared to direct X-ray illumination of a CCD sensor. Direct illumination uses a custom chip mask and frame transfer for exposure control and sampling at multiple time points. Increased sensitivity of direct illumination imaging system will raise the SNR allowing for shorter integration times.

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The SXR PHC Imaging system on PEGASUS provides an internal measurement constraint for equilibrium and current profile reconstruction.

Outline

- Flux surface shape constraints: motivation and theory
- 2-D camera forward projection modeling technique
- Modeling of reconstruction using SXR image constraint
- Imaging system schematic
- Equilibrium reconstructions using SXR PHC data
- Monte Carlo sensitivity analysis and comparison
- Next generation imaging hardware
- Future work

Internal Measurements are Needed for Accurate Profile Reconstruction on Pegasus

- Knowledge of the profiles is crucial for the physics mission of PEGASUS
  - Local internal pressure measurements will provide added constraints for equilibrium calculations
  - The resulting current, pressure, and q profiles from the equilibrium can be used to better understand the equilibrium and stability properties of PEGASUS plasmas

- Many conventional j(r) diagnostics are problematic for ST's and spheromaks
  - Low toroidal field challenges techniques such as MSE and Faraday rotation

- For any internal diagnostics, j(r) is only determined through equilibrium analysis including all other available diagnostics (e.g. magnetics)
  - Pinhole camera image data constrains equilibrium reconstruction similar to all other j(r) diagnostics (e.g. MSE)

- SXR image gives operational information in real time

Knowledge of the Flux Surface Geometry will Specify the Current Profile in the Plasma

- Plasma equilibrium in a toroidal geometry is specified by the Grad-Shafranov equation *:

$$\Delta^* \psi = -\mu_0 R J_\phi = -\mu_0 R^2 \frac{dp}{d\psi} - g\frac{dg}{d\psi}$$

  p $\Rightarrow$ pressure

  g $\Rightarrow$ RB_T (toroidal field)

- If the flux surfaces are defined as F(R,Z) = *constant*, then $\psi=\psi(F)$ and the G-S equation can be rewritten:

$$\frac{d^2\psi}{dF^2}|\nabla F|^2 + \frac{d\psi}{dF}\Delta^* F = -\mu_0 R^2 \frac{dp}{d\psi} - g\frac{dg}{d\psi}$$

- All of the unknowns (ψ'', ψ', p', gg') are constant on a flux surface, and Δ^*F and $|\nabla F|^2$ vary over a flux surface

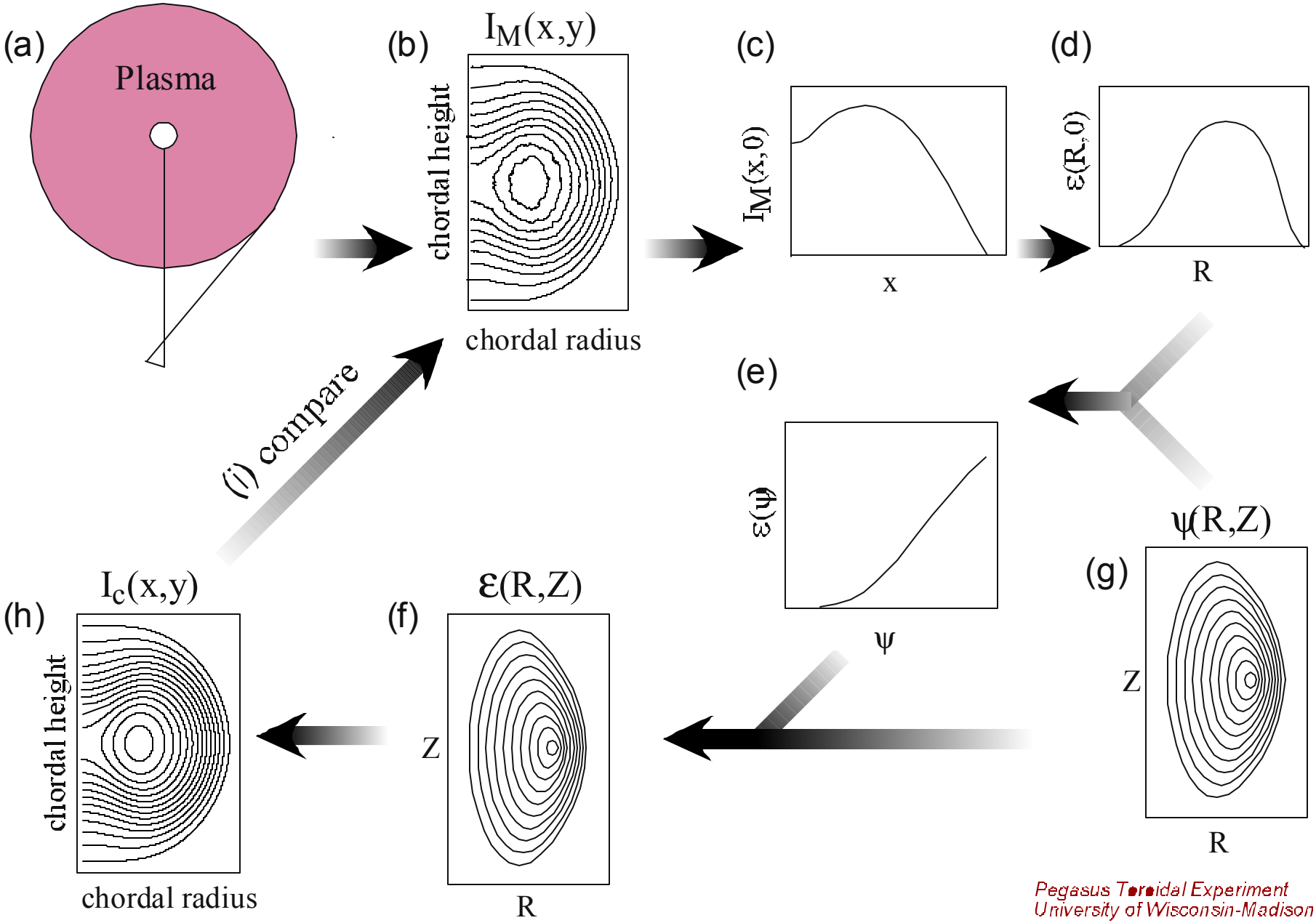
- By convolving this equation with a known function whose flux surface average is zero, one defines $\psi(F)$ in terms of known quantities:

$$-\frac{d^2\psi}{dF^2}\left(\frac{d\psi}{dF}\right)^{-1} = \lambda(F)$$

- $\lambda(F)$ depends on the flux surface variation of ∇F, which vanishes in the large aspect-ratio, circular flux surface limit
  - Solution for ψ determines j(r) through G-S eq.
  - p(r) can also be determined, especially at high β

*Christiansen, J.P., Taylor, J.B., Nucl. Fusion 22 (1982) 111

The SXR Pinhole Camera Provides Contours to Fit to Flux Surfaces



The SXR Pinhole Camera Provides Contours to Fit to Flux Surfaces (cont)

- Fit is performed through iterated equilibrium reconstruction

  (a) SXR Camera has a tangential view of the plasma

  (b) Measure SXR intensity with camera

  (c) Extract midplane intensity profile

  (d) Abel invert intensity profile to obtain emissivity profile at Z=0

  (e) Use equilibrium flux from code (g) to map emissivity to the local value of ψ

  (f) Use emissivity-flux mapping to obtain the plasma emissivity cross section

  (h) Project emissivity to a calculated camera intensity image

  (i) Compare calculated image to measured intensity

- Equilibrium code minimizes the residual difference between the measured image and the calculated image

Image Comparison Techniques were Evaluated for Constraint Sensitivity

- Image Residual compares measured image to projected image on a pixel-by-pixel basis

$$I_{res}(x,y) = \frac{\text{abs}(I_{meas}(x,y) - I_{proj}(x,y))}{\sigma(x,y)} \text{ (pixel weighting)}$$

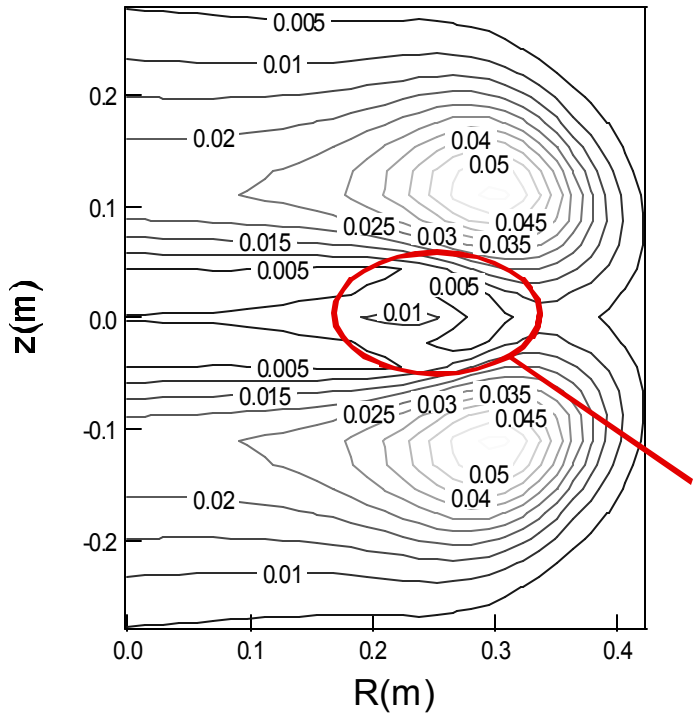
  - Global constraint based off sum of residual

$$\chi^2 = \Sigma I_{res}$$

- Image Contour constraint attempts to match the intensity contour paths of the projected image to the contours of the measured image

Image Residual Constraint Relatively Insensitive to q_0

- Residual constraint minimizes difference between measured image and tangentially projected reconstruction

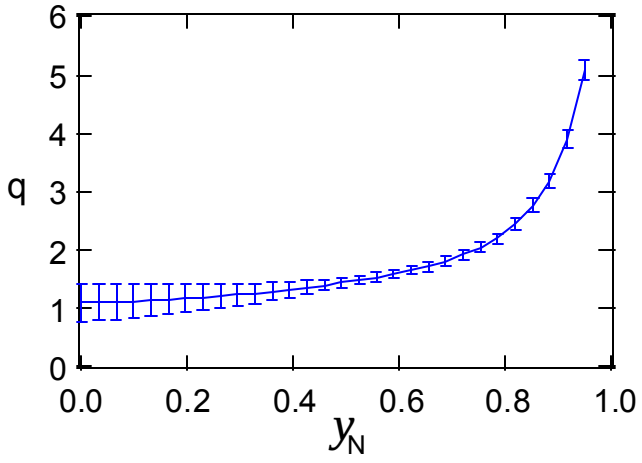


Tangential projection image residual between plasma with q_0 =1.1 and q_0 = 2.2

Central q related to central ellipticity

Residual at image center lower than typically specified noise values

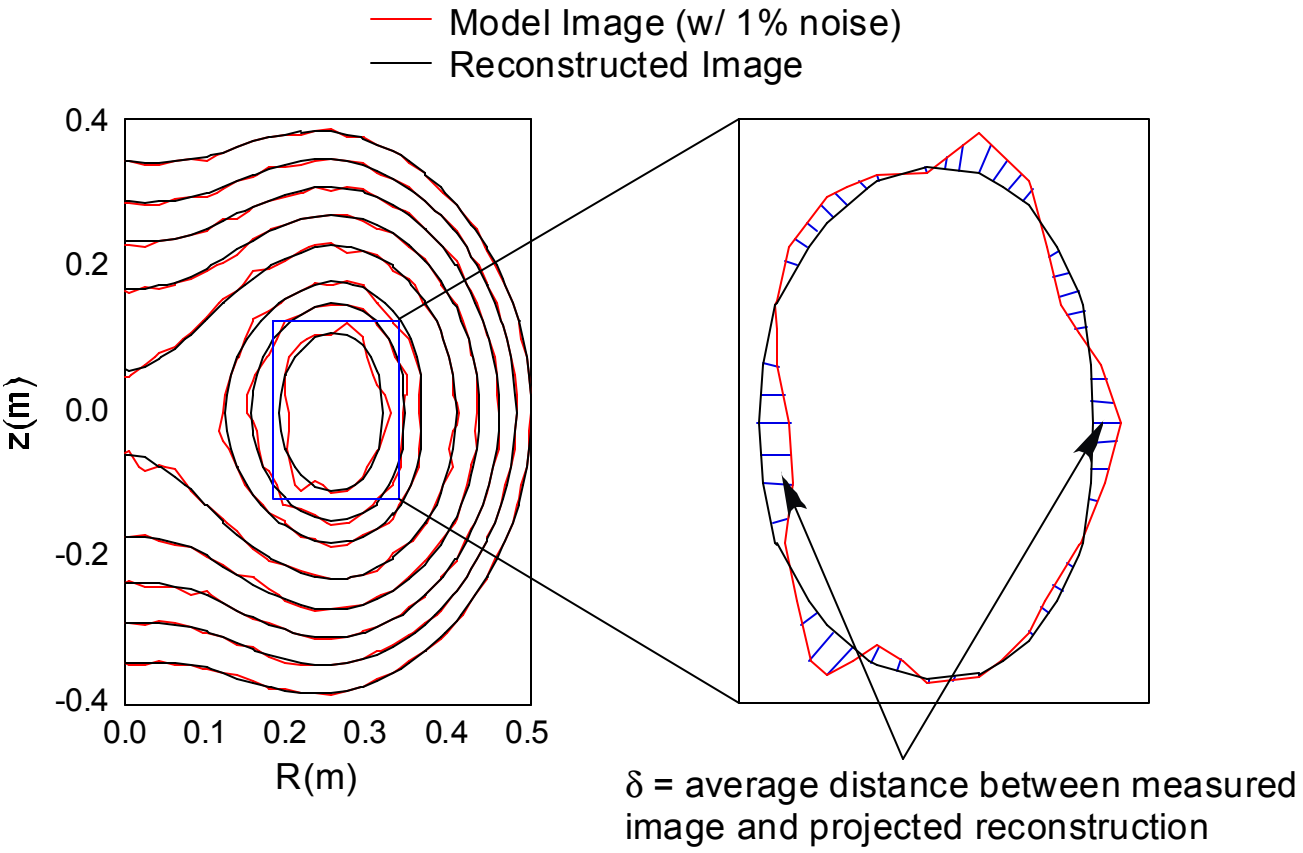
- Image residual has poor sensitivity at central peak
  - χ^2 sum of residual dominated by off-axis difference



Average q profile with error bars from Monte Carlo reconstructions with 1% image noise

Standard deviation of q_0 ~ 30%

Image Contour Constraint Minimizes Contour Distance from Measured Image

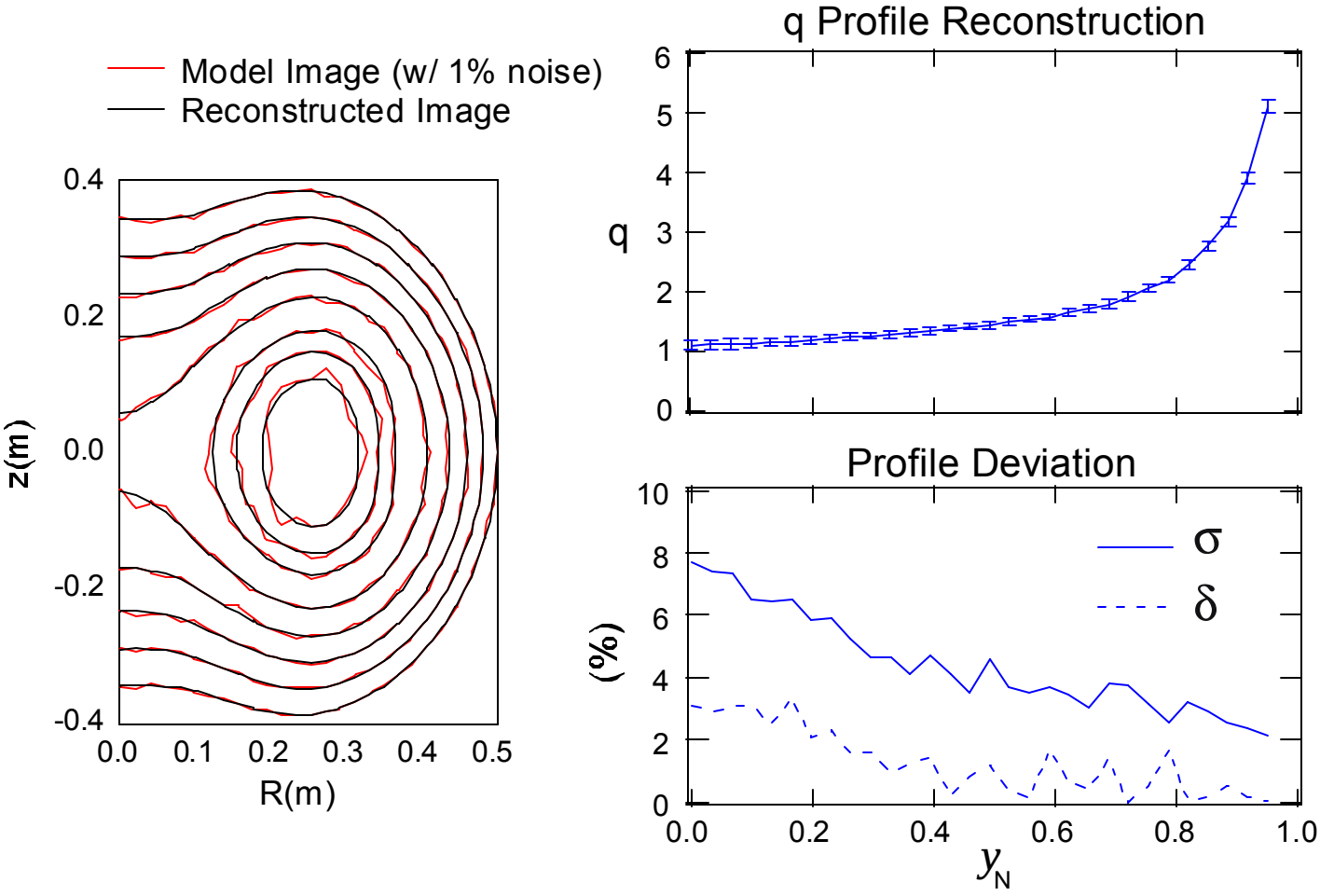


- Individual constraints for each contour level

$$\chi^2_{cont} = \frac{\delta_{cont}}{\sigma_{cont}}$$ (weighting factor)

- Constraints used for contour levels from 50-95% of image intensity
  - Outer contours have higher photon noise and less q_0 sensitivity

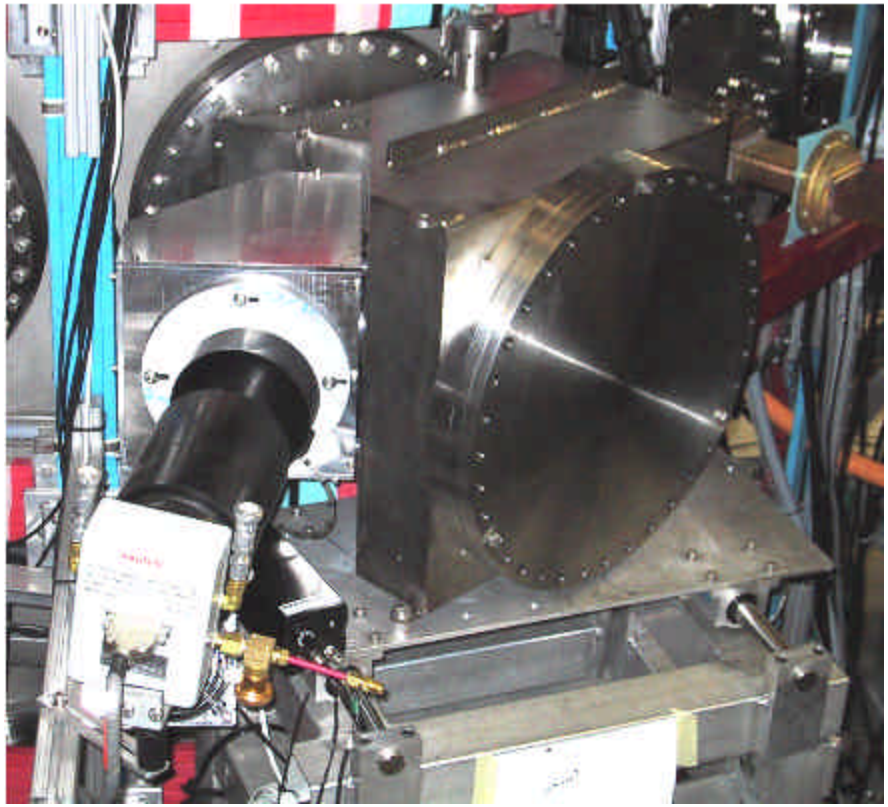
Image Contours Constrain q Profile Reconstruction



- Model equilibrium used to study image constraint
  - Image with 1% noise used with external magnetics
- Monte Carlo reconstructions show sensitivity of constraint
  - Random starting points fit to different q profiles
  - Standard deviation of reconstructed profiles, $\sigma < 8\%$
  - Average deviation from model profile, $\delta < 4\%$.
- Typical fits will initiate with parameters close to expected PEGASUS profiles

Present SXR System Operates Routinely with Single Time Point Capability

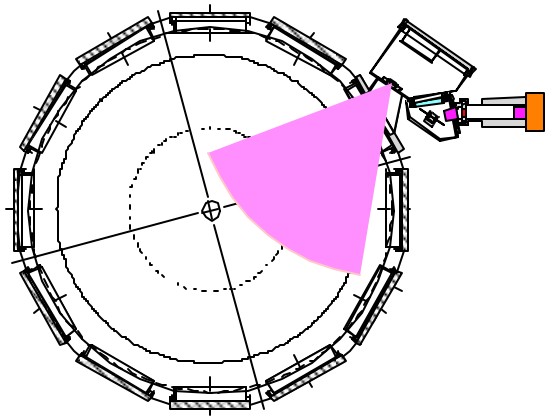
- Pinhole Camera Specifications
  - 4mm dia. pinhole
  - 2000Å Be or Ni filter
  - 300x200mm imaging phosphor (P43:Pr)



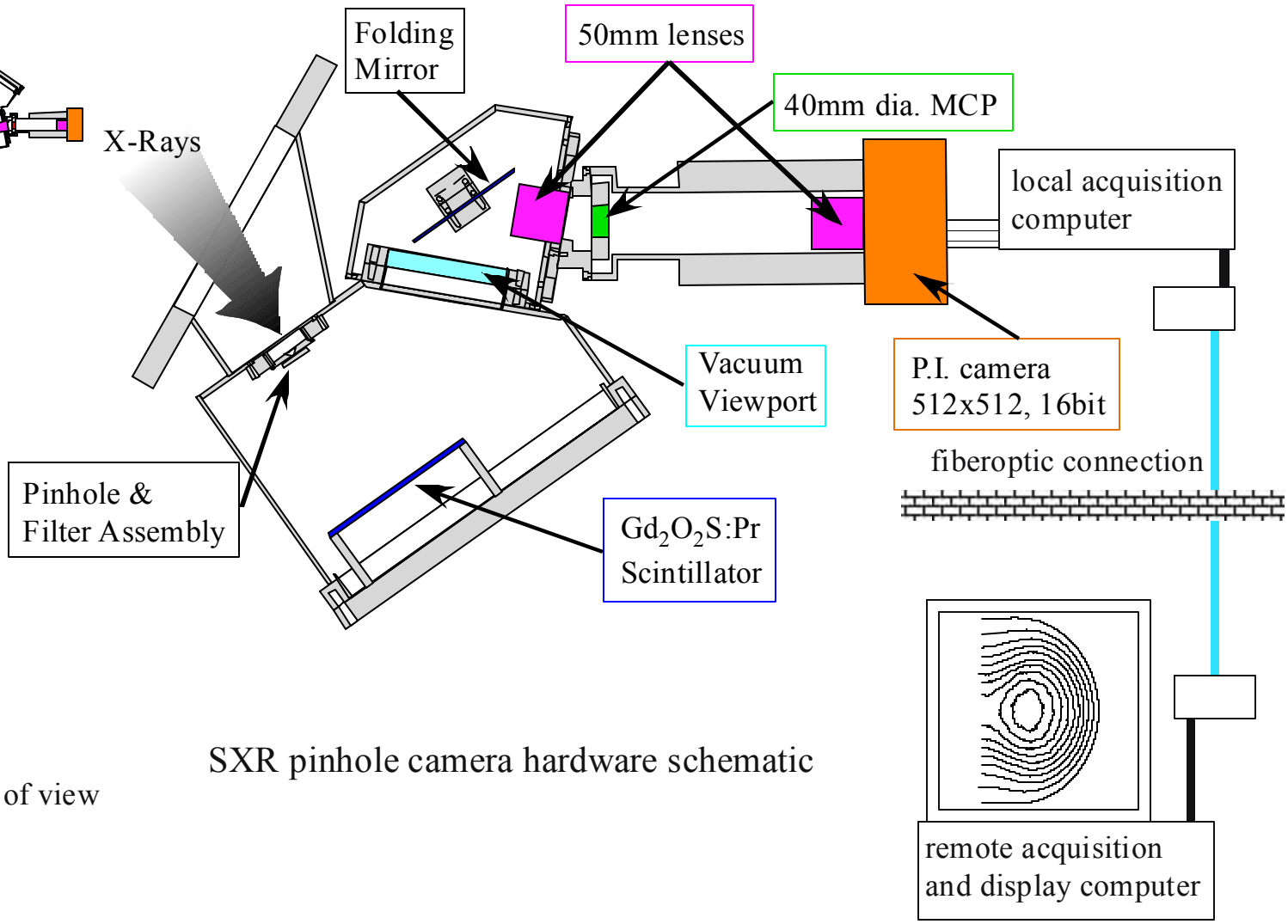
PI camera and PHC assembly

- PI Camera Specifications
  - Coupled via. f/0.95 lens to 40mm MCP
  - Resolution 512x512, 16bit
  - Capable of exposure times <1μs (typ. exposure times 1-3ms)
  - Only 1 image acquired per shot

Imaging System Includes a Pinhole Camera, Lens Coupled MCP, and High Sensitivity CCD Camera



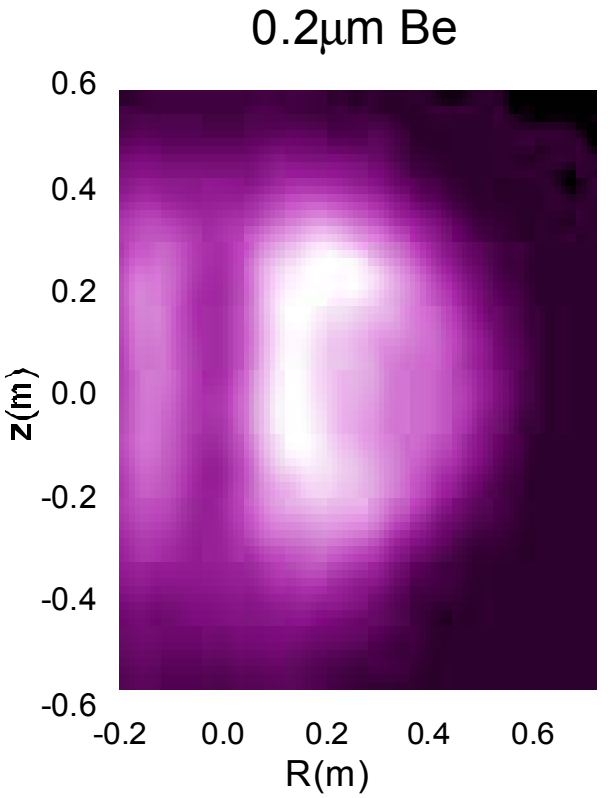
Horizontal and vertical fields of view for the SXR pinhole camera

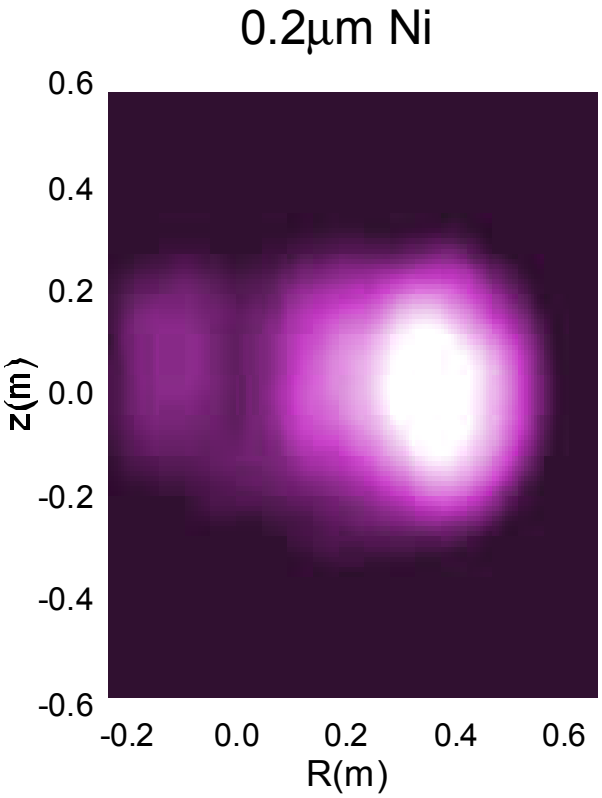


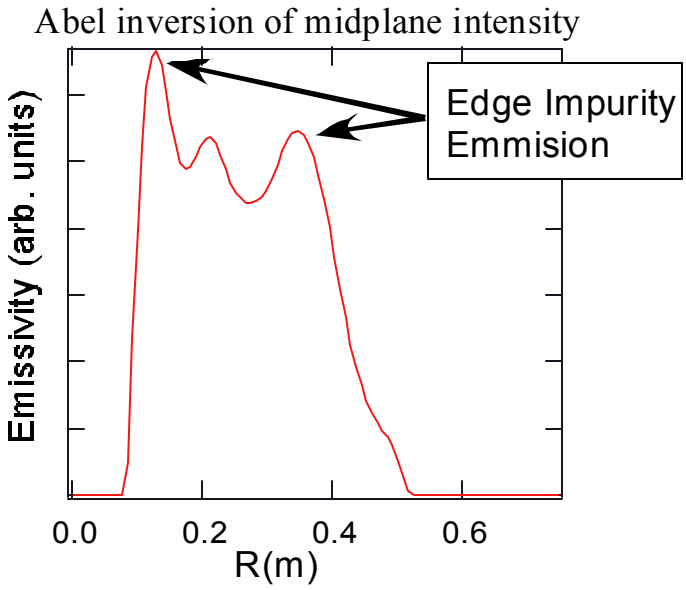
SXR pinhole camera hardware schematic

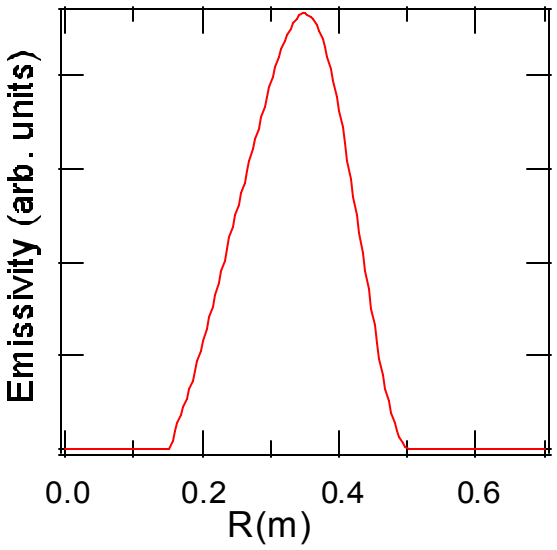
- Diagnostic is optically isolated from control room for high voltage protection

X-Ray Emission from Edge Impurity Influx Blocked with Ni Foil



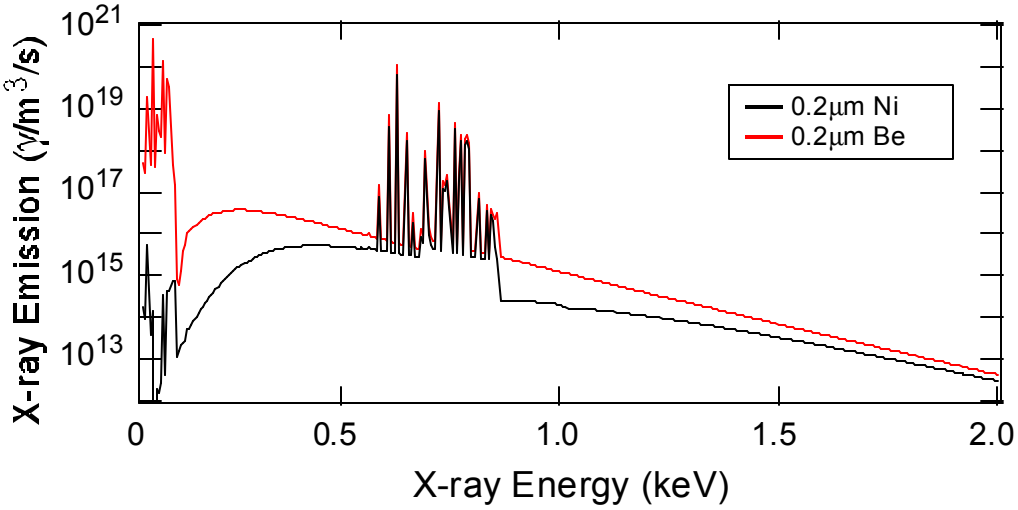




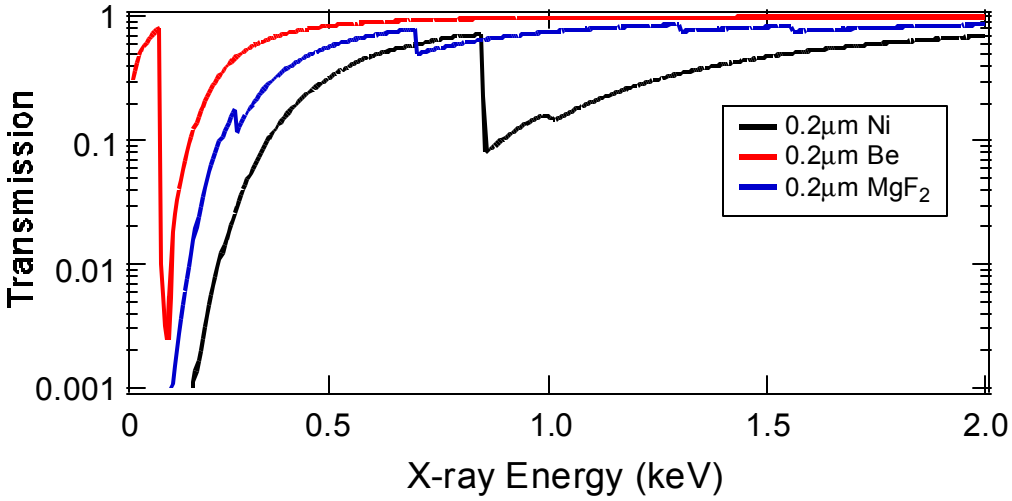


- Fitting code developed to optimize rejection ratio of low energy edge and maximize signal
- 0.2μm MgF_2/Al/Parylene foils will maintain edge rejection and improve signal

Be Filter has Transmission Window for Low Energy X-rays

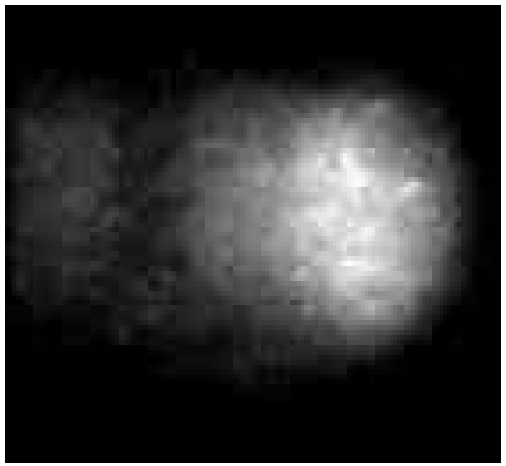


- X-ray emission spectrum for plasma parameters: $n_{e0} = 3x10^{19}\ m^{-3}$, $T_{e0} = 0.2$ keV, O = 1%



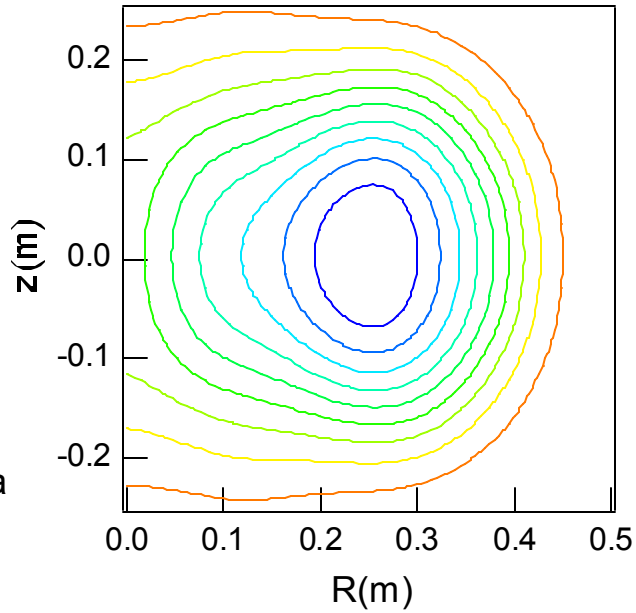
- MgF_2 avoids Ni transmission drop (~0.8-1.5 keV) and still maintains blockage of low energy emission

Image Data from SXR PHC Demonstrates Constraint on Reconstruction

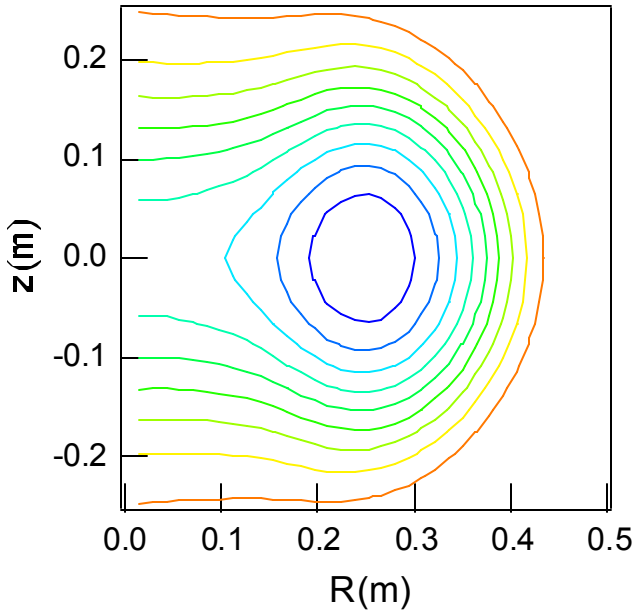


SXR image taken with PI camera lens coupled to MCP (step a)

Visible image from Dalsa
Shot 12920 (t = 19 ms)



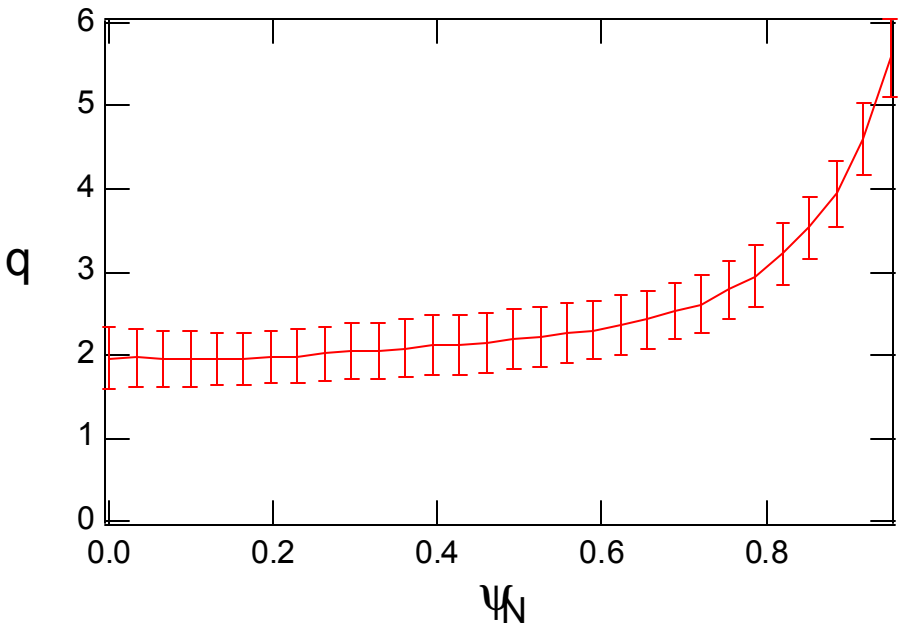
Intensity contours from SXR PHC after processing (step b)



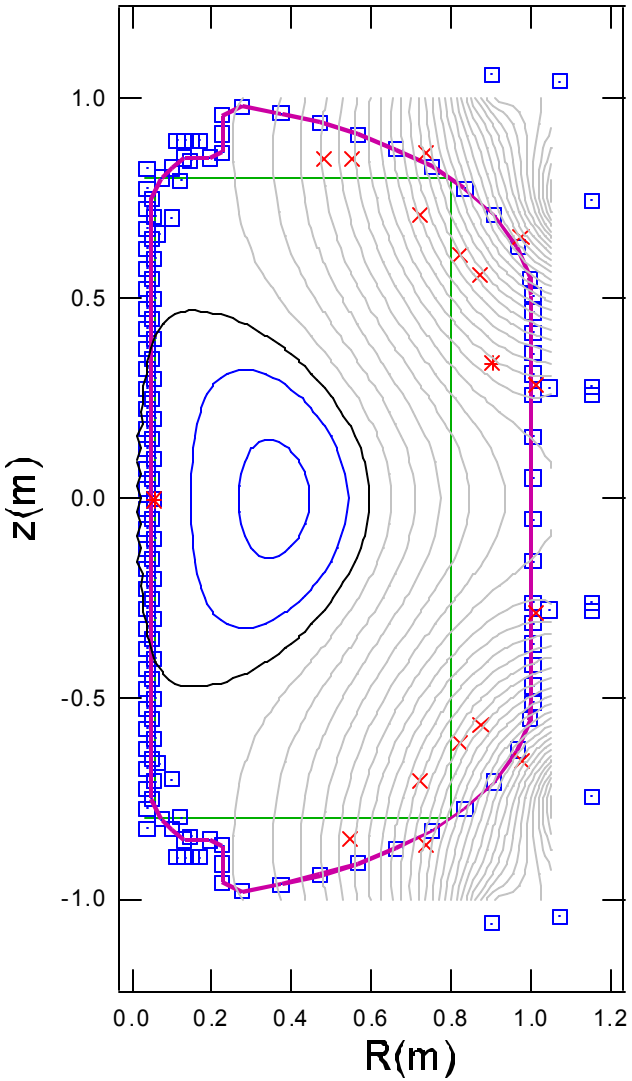
Projection from reconstructed cross-section (step h)

- SXR image obtained with multi-shot averaging and 2ms exposure time
  - Image centered to accommodate positional instability
- Image smoothed using a multipass 7x7 Gaussian filter
- Result used to constrain equilibrium reconstruction of shot 14729

SXR Image Data Provides Internal Constraint for Determination of q_0



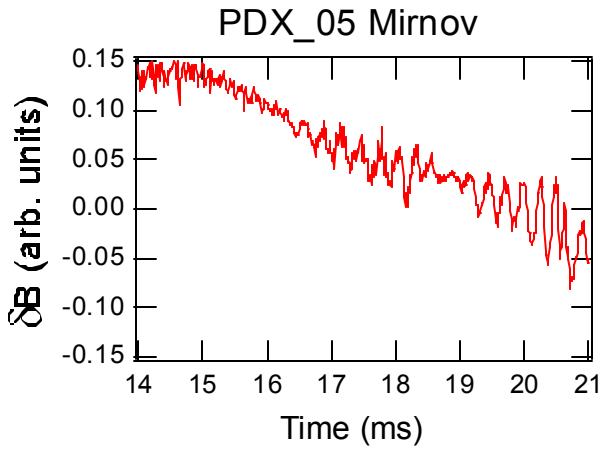
- External magnetics constrain plasma boundary, SXR image provides internal constraint
- Reconstruction matches visible image from Dalsa CA-D6
- Reconstructed $q_0 \sim 2 \pm 0.4$
  - Error bars function of low signal, noisy data
  - Improved SNR will provide tighter constraint

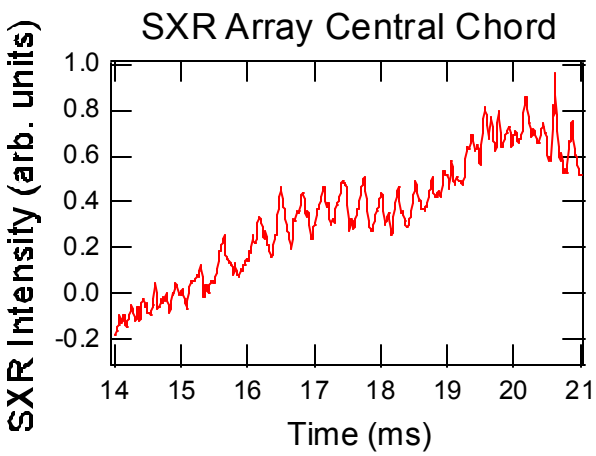


Reconstructed flux map
shot 14729 (step g)

Reconstructed q > 2 Consistent with Absence of Coherent MHD Activity

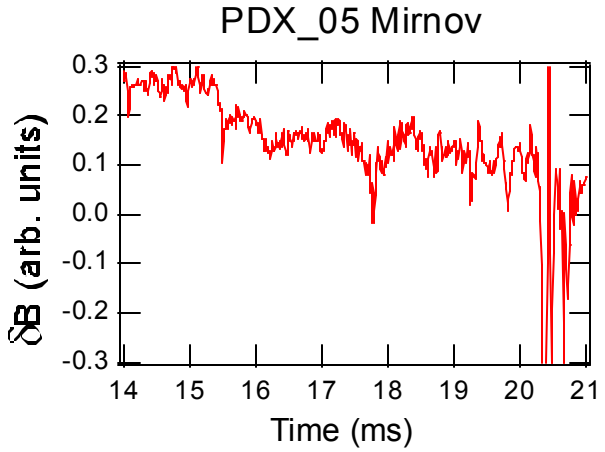
MHD Active Shot

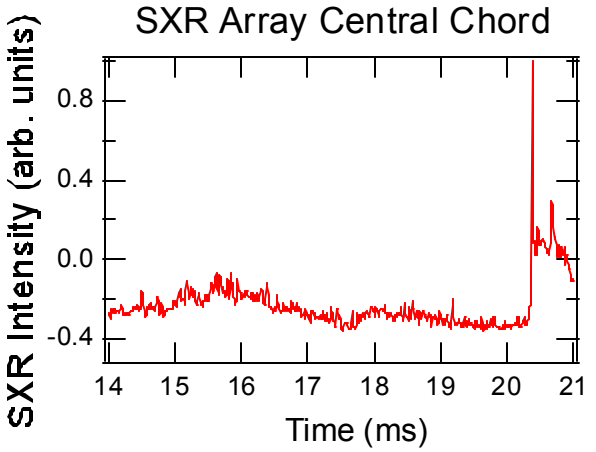




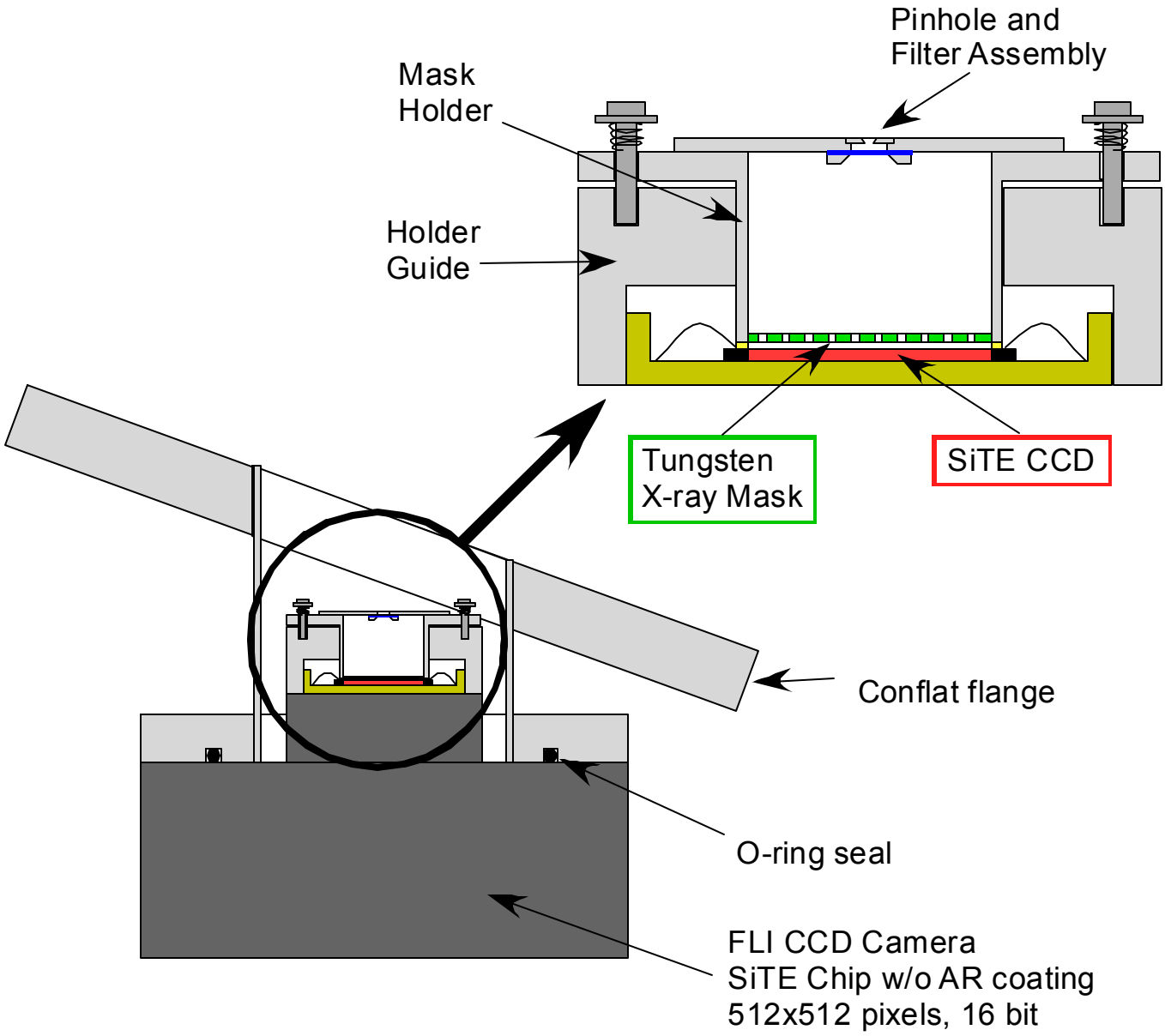
- MHD active shots contain coherent 2/1 and/or 3/2 mode activity with large region of q < 2

Reconstructed Shot 14729
No Coherent MHD Activity



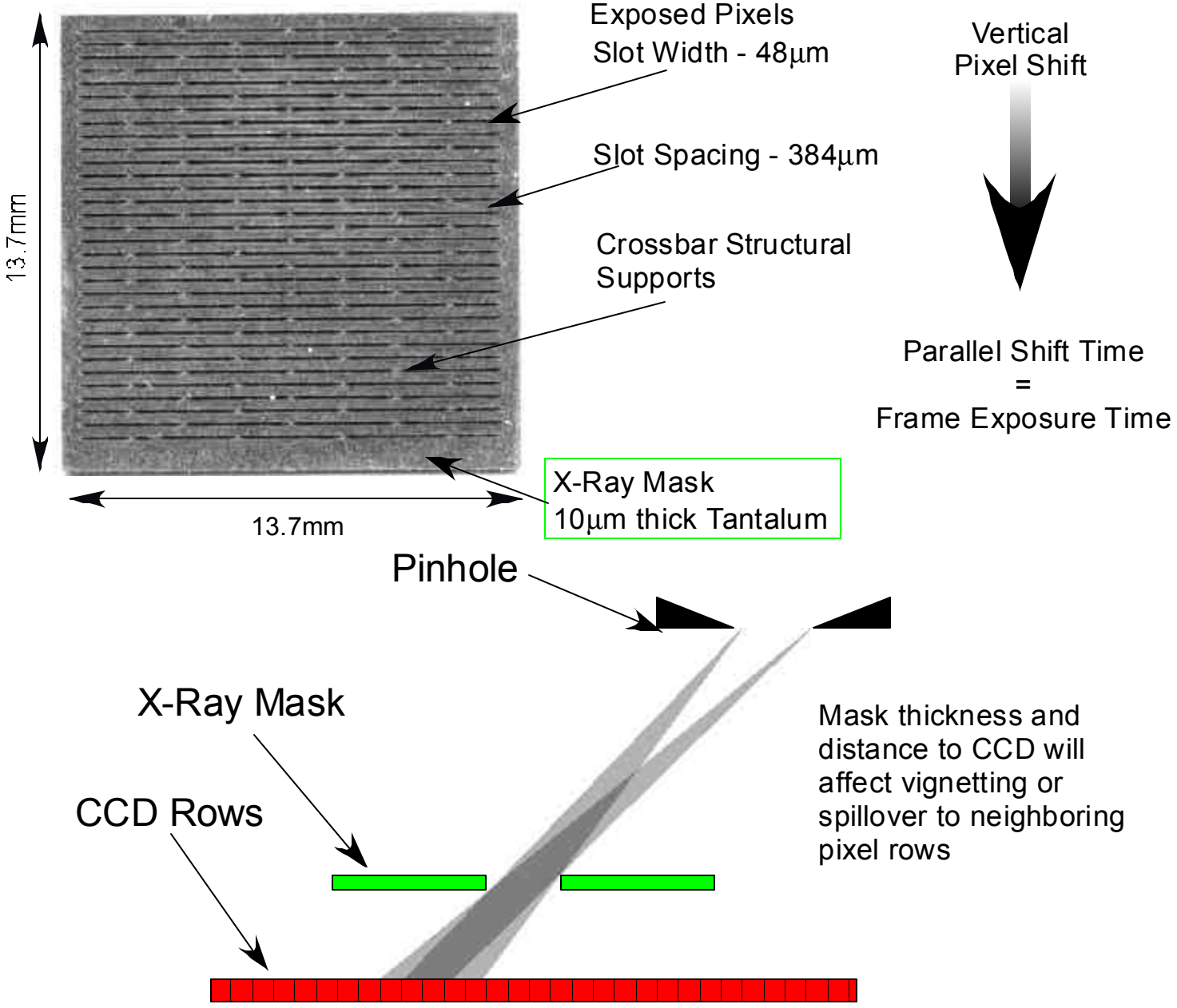


Next Generation PHC Features Direct X-ray Illumination and Pixel Masking of CCD



- Direct illumination design will decrease photon noise x10
- Increased SNR will allow better time resolution and tighter constraint on q(r),j(r)
- Pixel masking provides multiple frames for time reconstruction of shot evolution

Pixel Masking Allows Multiple Frames Using High Sensitivity Camera



- Single frame exposure time >100μs (typ. ~1ms)
- Mask must be near CCD (~100-500μm) to reduce shadowing
- For a given chip, tradeoff # frames vs. spatial resolution

Future Plans Include Software Improvements and Masked Direct Illumination CCD

- Additional profile parameterizations will be added for increased reconstruction flexibility
  - Movable spline knot points
- Next generation imaging system will be built and installed
  - SXR signal will be increased through direct illumination
- X-ray pixel mask will allow multiple frames for time evolving equilibrium reconstructions
- Direct Illumination will increase SNR and provide a tighter constraint on q(r), j(r)

Summary

- Internal measurements crucial for full equilibrium reconstruction on PEGASUS
- Flux surface shape provides information about current profile
  - Integrated analysis including SXR imaging and external magnetics (p(R) when available)
- Modeling indicates sensitivity of SXR measurement constraints to internal profiles
- First results from PHC system demonstrate sensitivity of q_0 to the SXR imaging diagnostic constraint
  - Improved SNR and reduction of edge impurities will tighten constraint
- Fabrication of next generation imaging system is in progress
  - Direct illumination currently under testing

Reprints