ABSTRACT

Flux surface shape information is imaged with a 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 with pixel masking for a time resolution of <1ms and multiple frames. This system will give provide photon noise <1% with a 1 ms integration time for intensities typical of Pegasus plasmas. This scintillator system, will then be compared to direct illumination of the CCD sensor. Equilibrium reconstructions using this image data illustrate the evolution of q(R,t) and j(R,t) and help elucidate operational limits caused by MHD instabilities. A Monte Carlo analysis gives an estimate of the uncertainties in the reconstruction and the sensitivity of the profiles to the 2-D SXR image constraint.

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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 are 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 *:

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

p ⇒ pressure

g ⇒ RB_T (toroidal field)

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

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

- All of the unknowns (ψ'', ψ', p', gg') are constant on a flux surface, and ∆ F and ∇F ^{2} vary over a flux surface

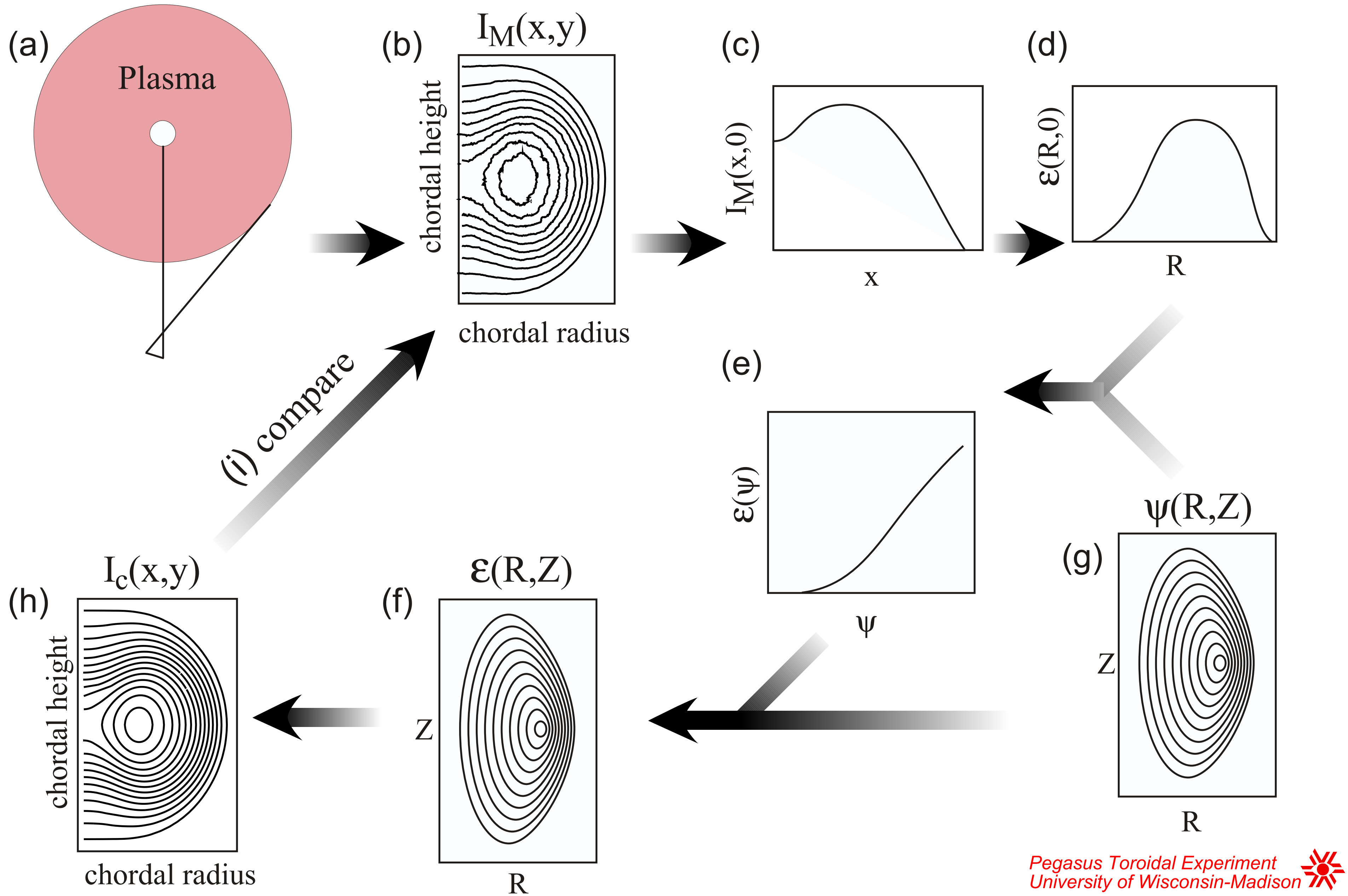
- By convolving this equation with a known function whose flux surface average is zero, one defines ψ(F) in terms of known quantities:

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

- λ(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

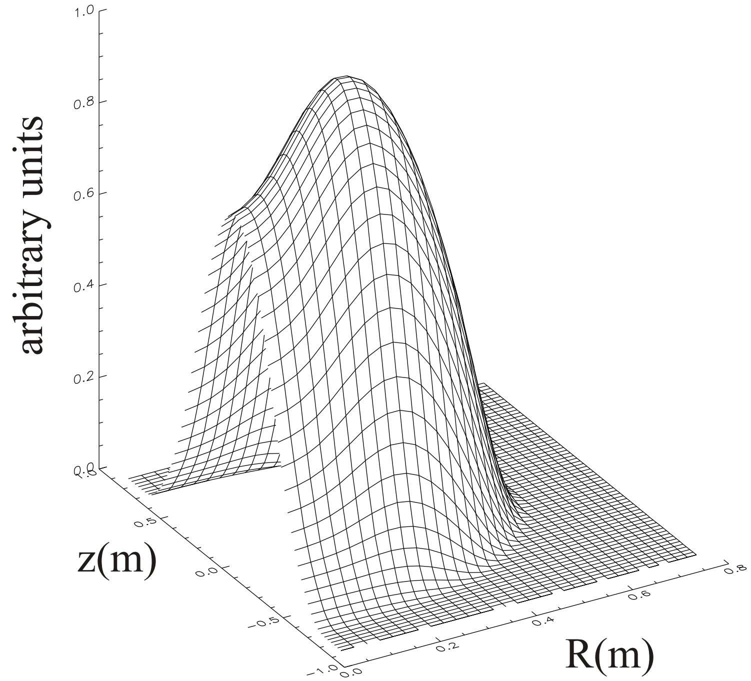
(f) Use emissivity-flux mapping to obtain the plasma emissivity cross section

(h) Project emissivity to a calculated camera intensity image

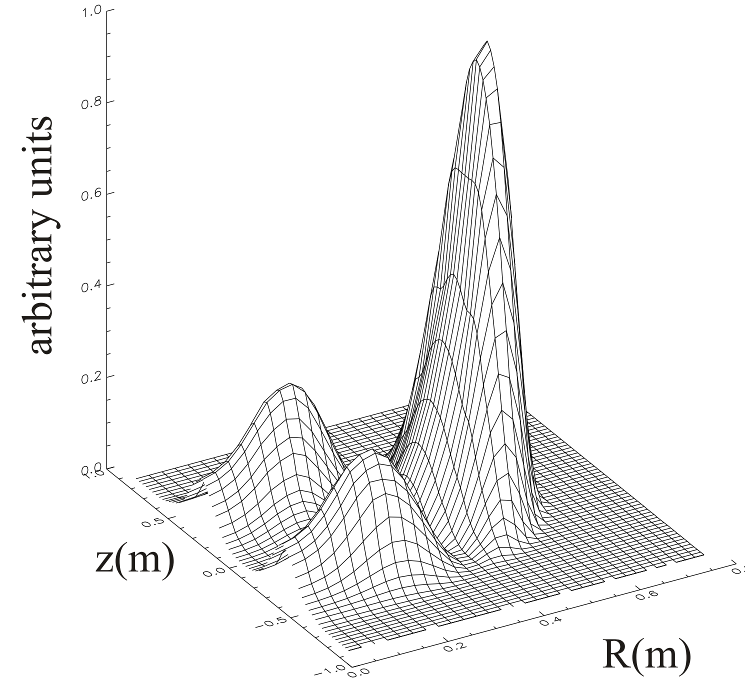
(i) Compare calculated image to measured intensity

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

SXR Emissivity Constraint Minimizes Residual from Image Comparison



Projected image from baseline equilibrium model α=1.4, β=0.7

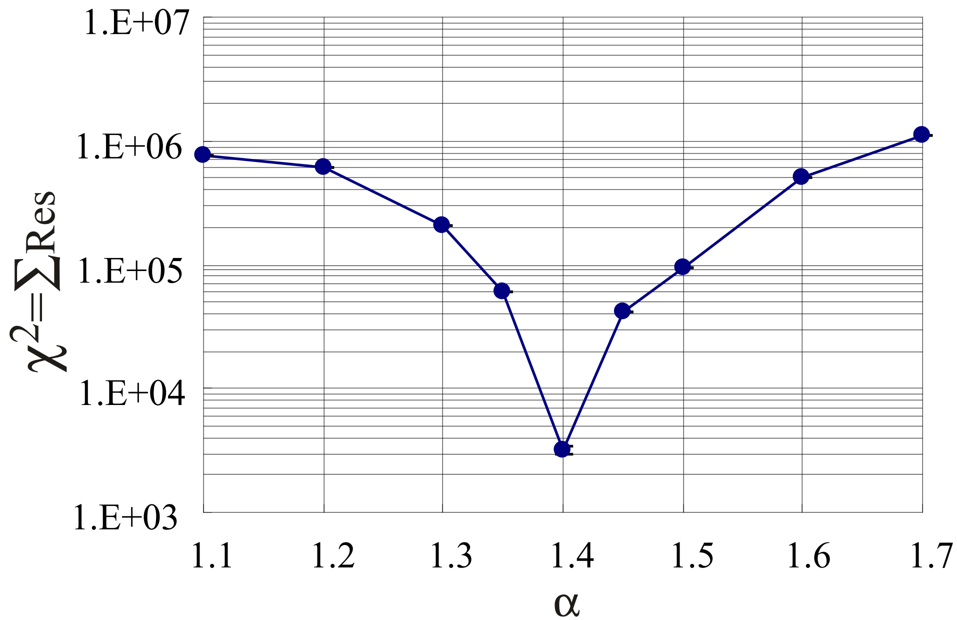


Residual of squared difference of baseline equilibrium and model equilibrium with α=1.6, β=0.8

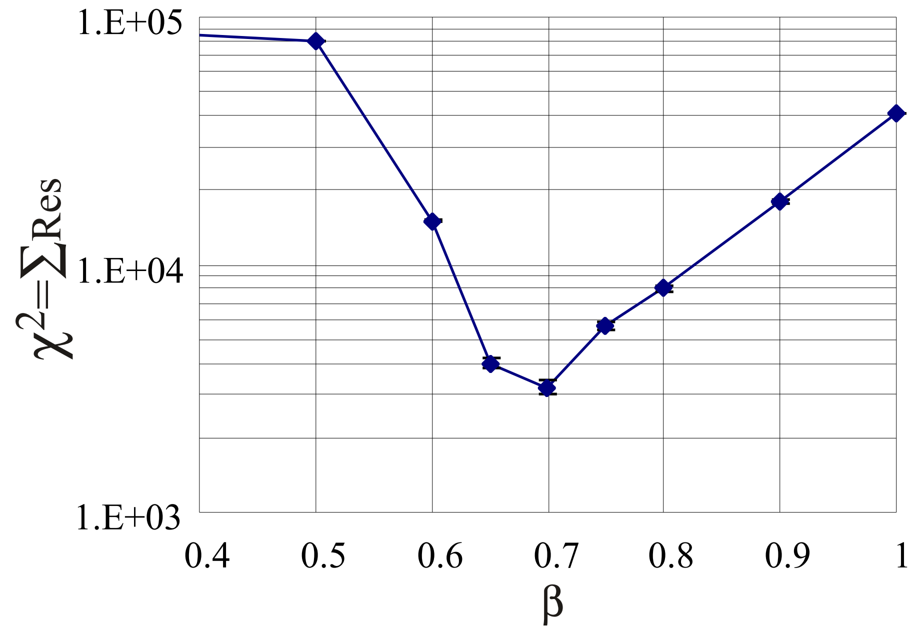
- Equilibrium specified with current and pressure profiles:
  $GG' \propto (1-\psi)^{\alpha-1}$ $P' \propto (1-\psi)^{\beta-1}$

- Residual minimization has been directly incorporated into equilibrium reconstruction code as opposed to manual, post-reconstruction comparison performed on PBX-M
- Incorporation allows both automation of residual minimization and combination of external and internal constraints for reconstruction

Image Residual Minimization Shows High Sensitivity to Current and Pressure Profiles



Current Profile Scan: $GG' \propto (1-\psi)^{\alpha-1}$

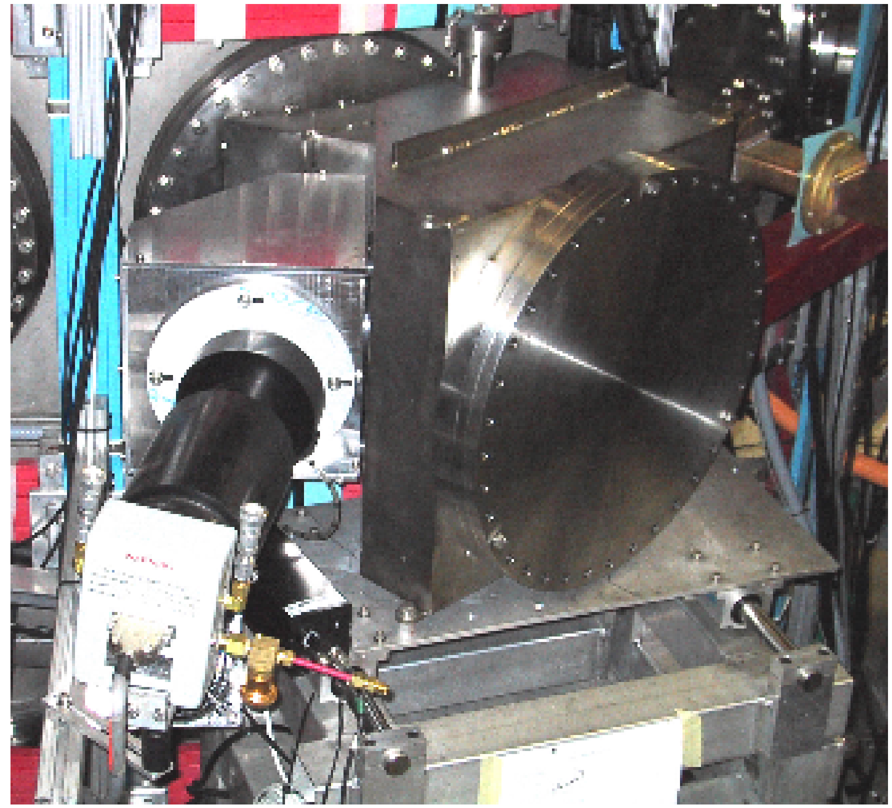


Pressure Profile Scan: $P' \propto (1-\psi)^{\beta-1}$

- Model images with 2% noise were generated for varying α and β
- Generated images were then subtracted from the baseline image (α=1.4, β=0.7)
- χ^2 calculated by summing the square of the residual from the image subtraction
- A strong dependence on current profile is shown, and a significant dependence on pressure profile is also apparent

Present SXR System Operates Routinely with Single Time Point Capability

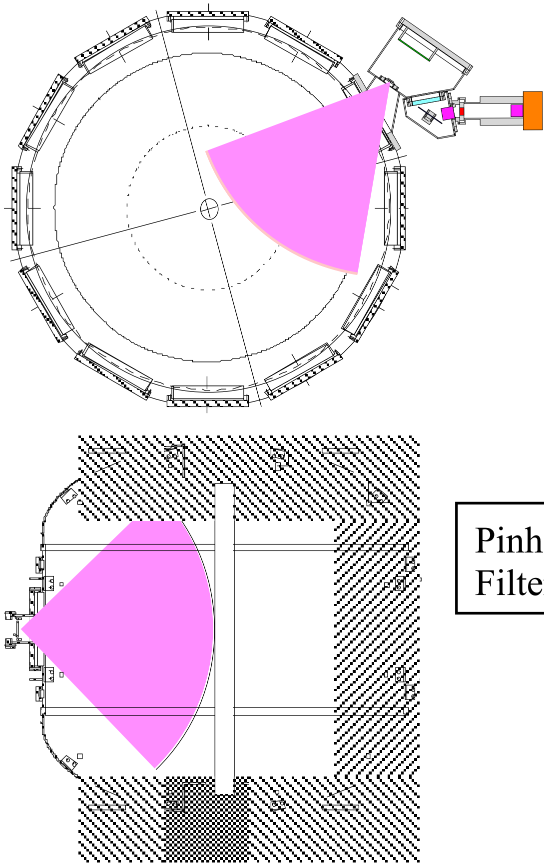
- Pinhole Camera Specifications
  - 4mm dia. pinhole
  - 2000Å Be filter
  - 300x200mm imaging phosphor (P43:Pr)



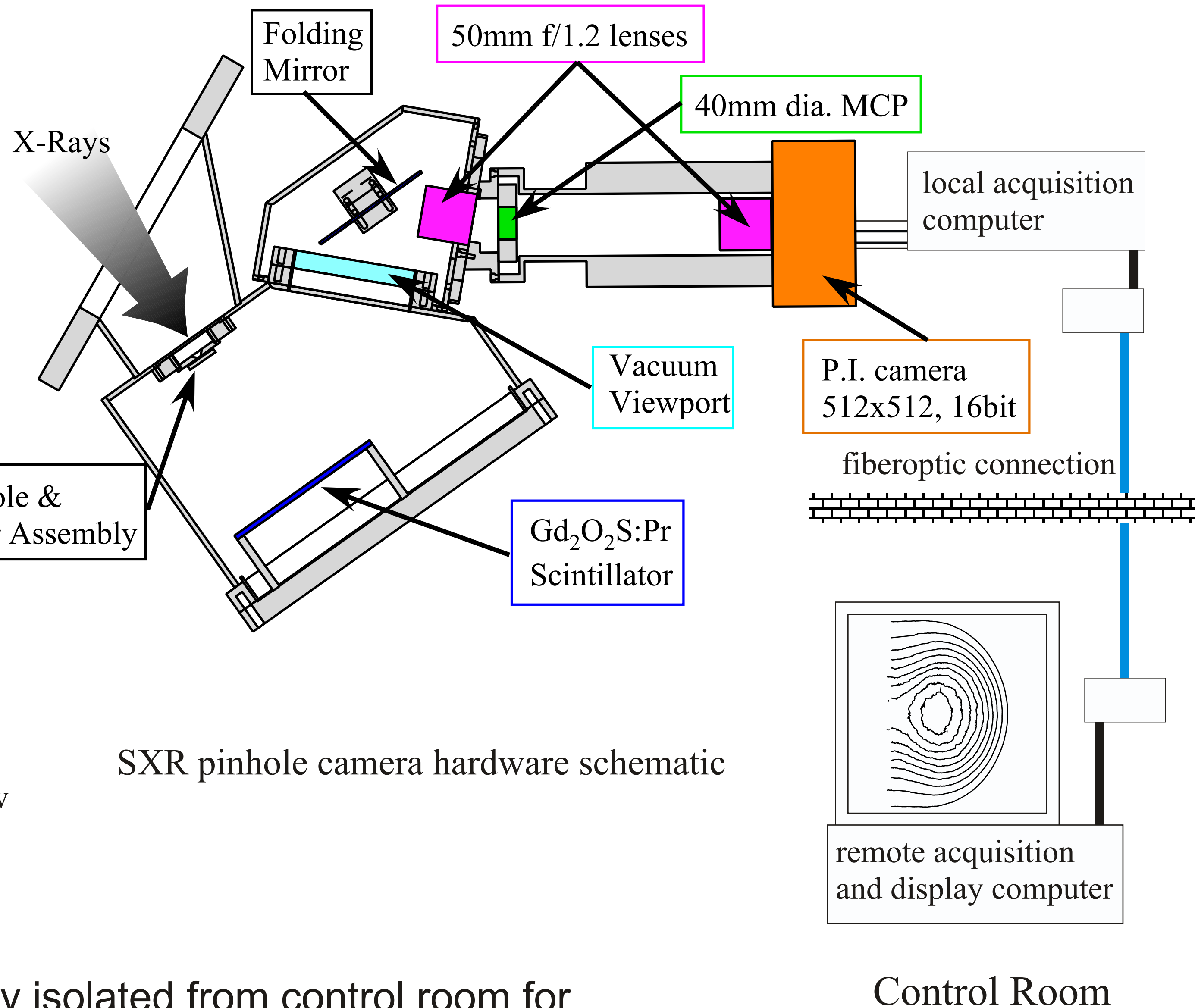
PI camera and PHC assembly

- PI Camera Specifications
  - Coupled via. f/1.2 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

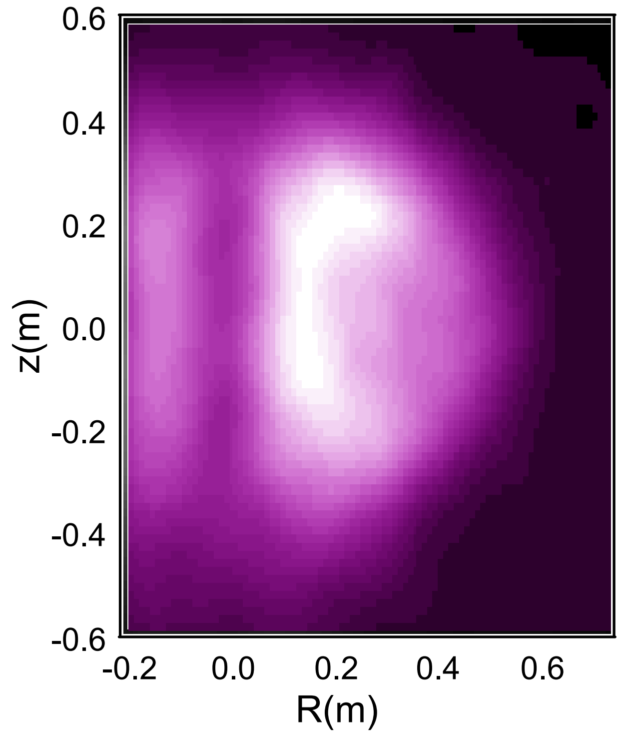


SXR pinhole camera hardware schematic

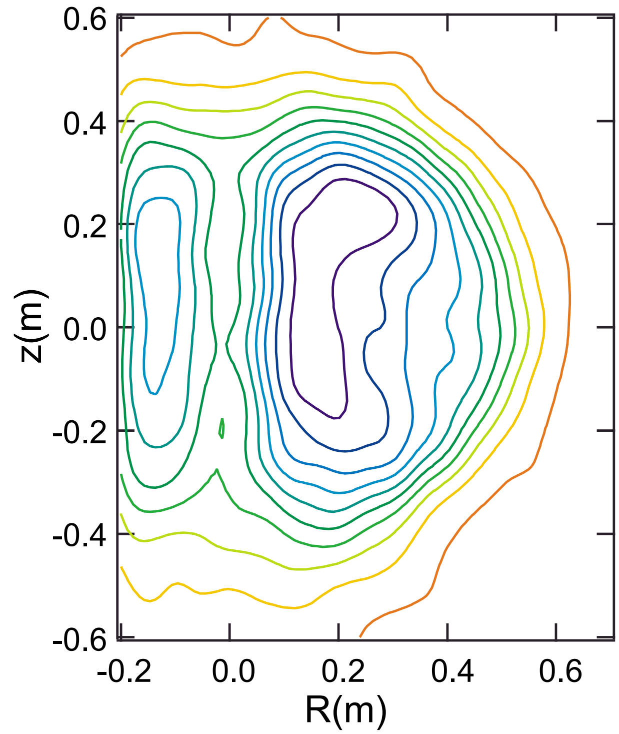
- Diagnostic is optically isolated from control room for high voltage protection

X-Ray Emission from Edge Impurity Influx will be Blocked with Thicker Filter

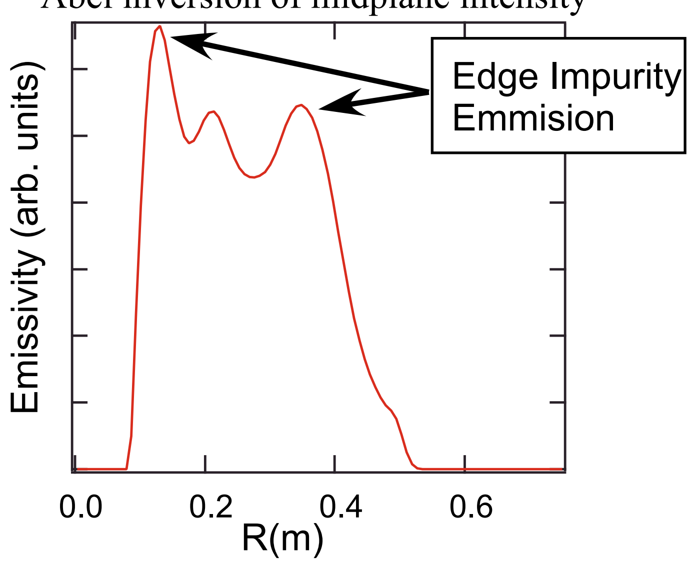
SXR PHC image



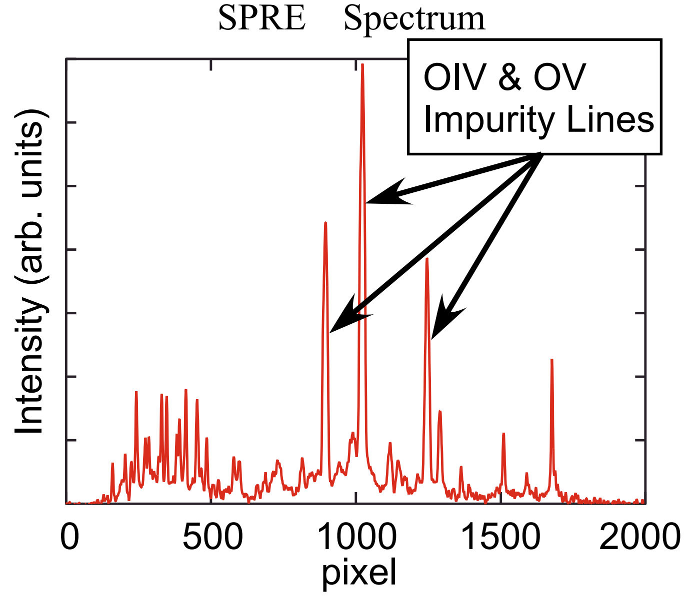
Intensity contours of X-ray image



Abel inversion of midplane intensity

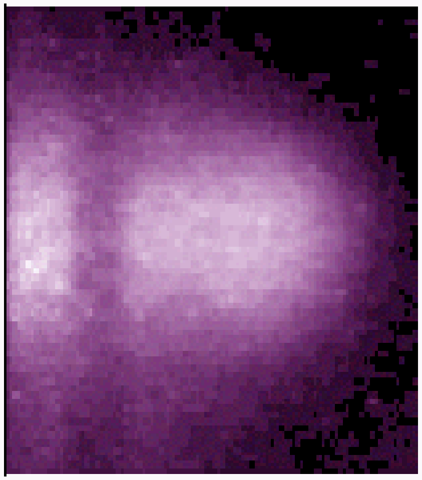


SPRE Spectrum

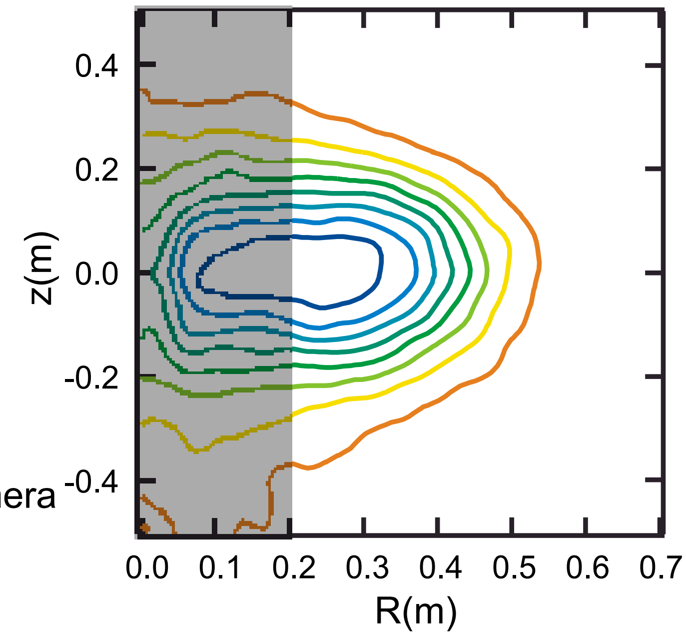


- Thin filter used to maximize signal for lower performance PEGASUS plasmas
- Variable filter assembly now installed
  - can select between 5, 1, and 0.2 μm be filters

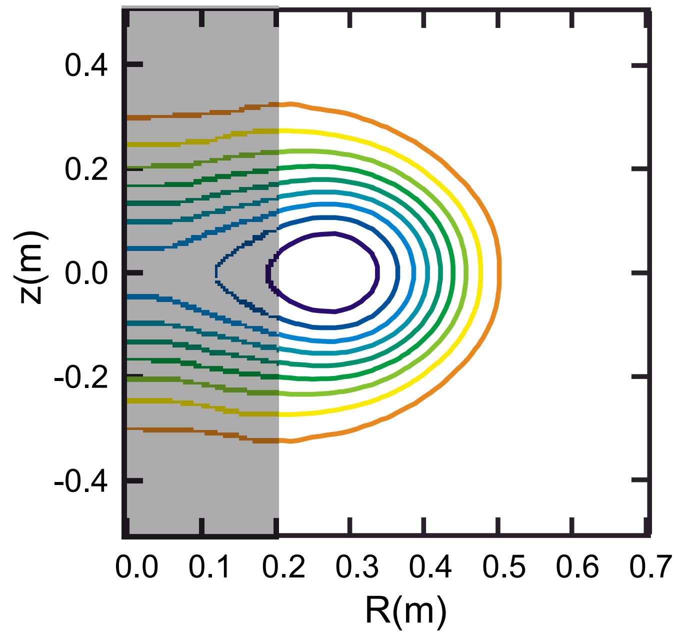
Image Data from SXR PHC Demonstrates Constraint on Reconstruction



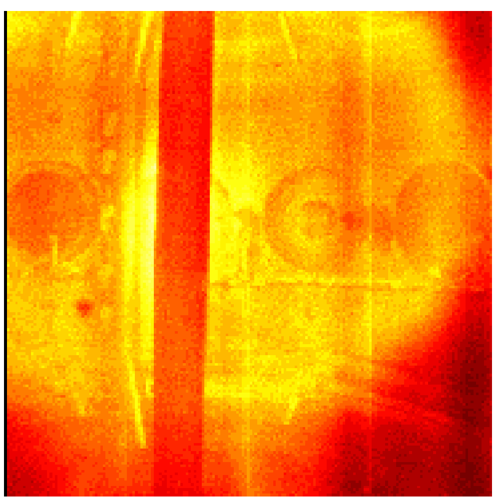
SXR image taken with PI camera lens coupled to MCP (step a)



Intensity contours from SXR PHC after processing (step b)



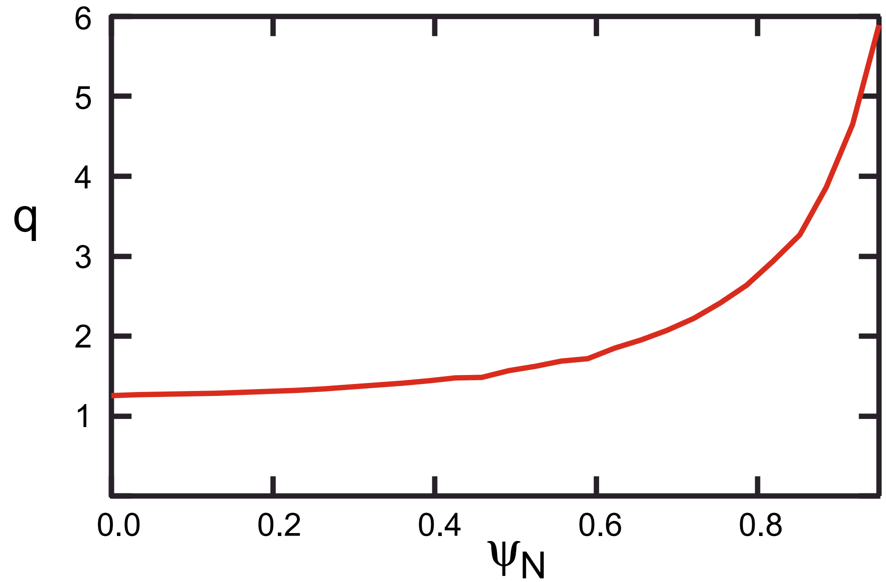
Projection from reconstructed cross-section (step h)



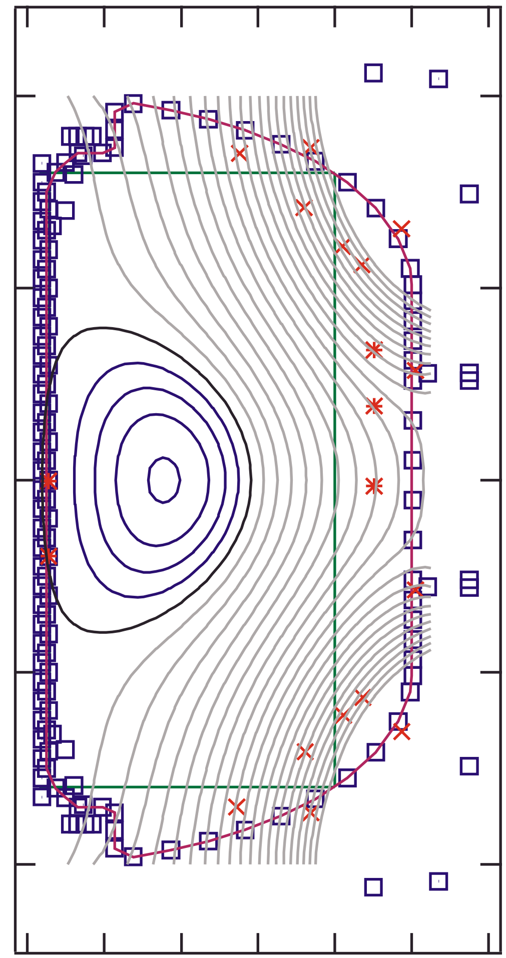
Visible image from Dalsa Shot 12920 (t = 19 ms)

- SXR image obtained with 3ms exposure time
- Image smoothed using a multipass 5x5 Gaussian filter
- Result used to constrain equilibrium reconstruction of shot 12920
- Contour differences < 0.2m due to inner core impurity radiation effects

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



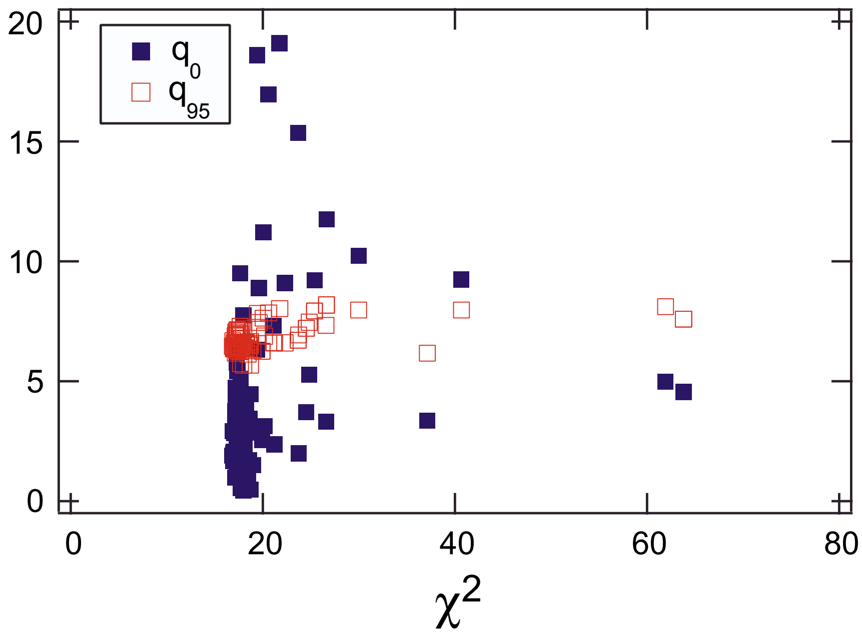
Reconstructed flux map
shot 12920 (step g)

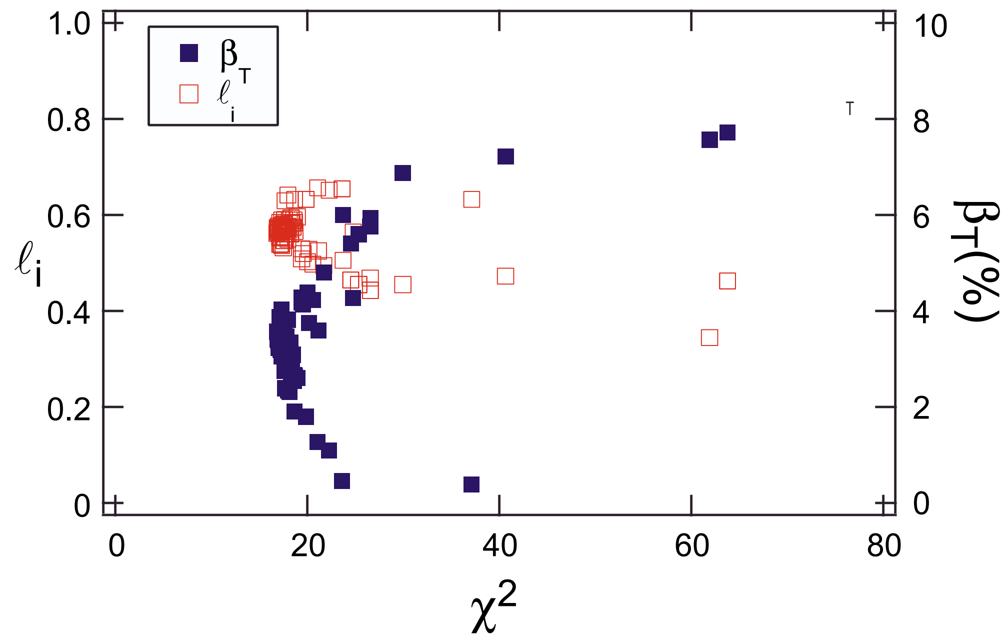
Using Spline Profiles for Reconstruction Requires Accurate Spatial Measurements

- Due to noise and X-rays from edge impurities, SXR image does not provide adequate spatial resolution
  - Aggregate residual is used for a single measurement constraint
  - Sensitivity of q_0 to image data is demonstrated
  - Present image quality not sufficient for tight constraint of spline model

- Polynomial model allows less profile freedom
  - Monte Carlo using external magnetics shows smaller deviation in reconstruction
  - Incorporation of image data into polynomial Monte Carlo in progress

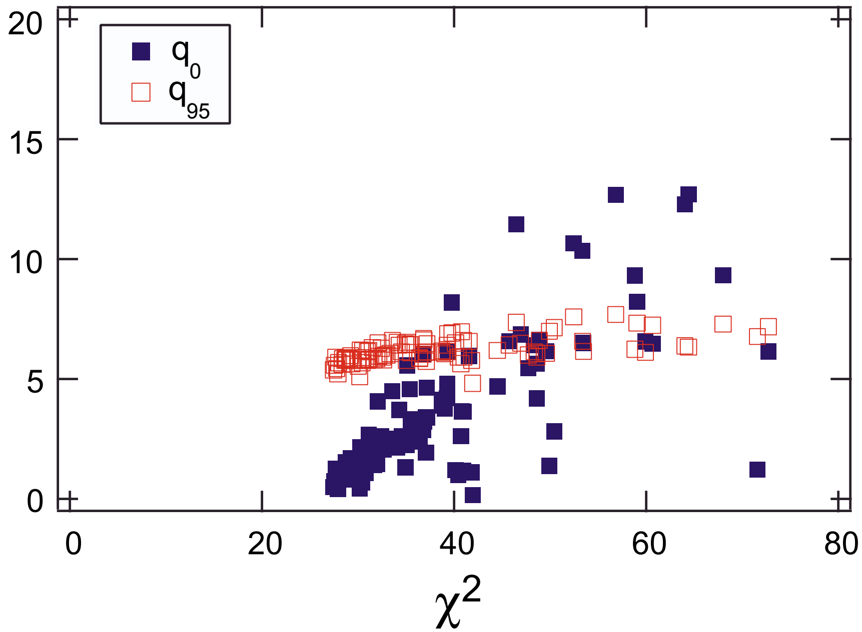
Monte Carlo Analysis Shows Insensitivity of Internal Profile Reconstruction to External Measurements

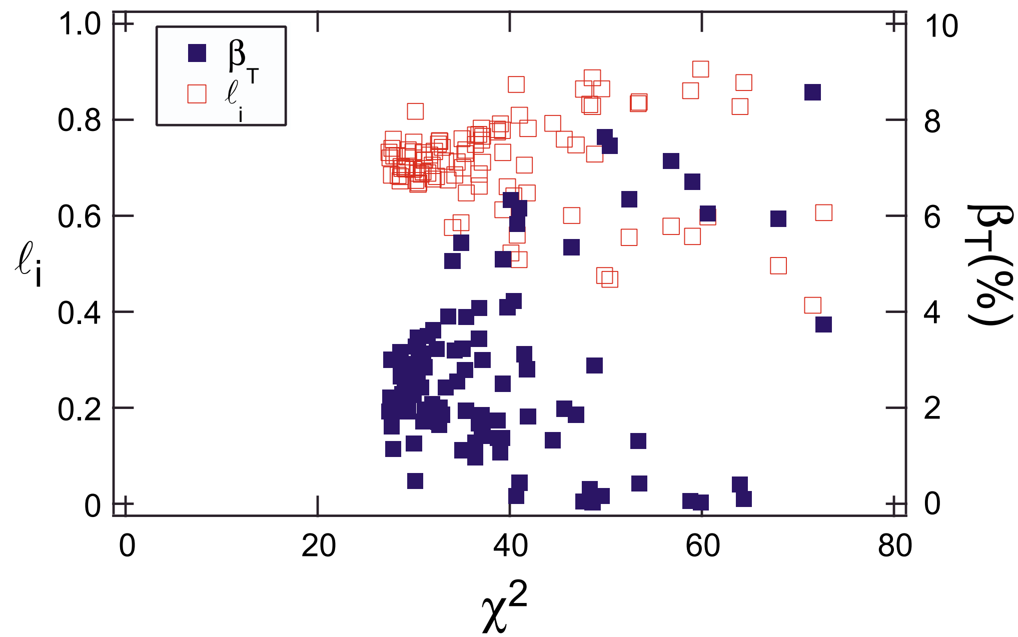




- Initial GG' and P' profiles randomly chosen for nonlinear least squares fit
- Global reconstruction results demonstrate relative insensitivity to initial guess
- Plasma position and boundary well determined (R_0 = 0.291 ± 0.007 m)
- q_0 and profile effects have minmal impact on final χ^2 of external measurement fit
  - as expected, q_0 not well constrained by external measurements

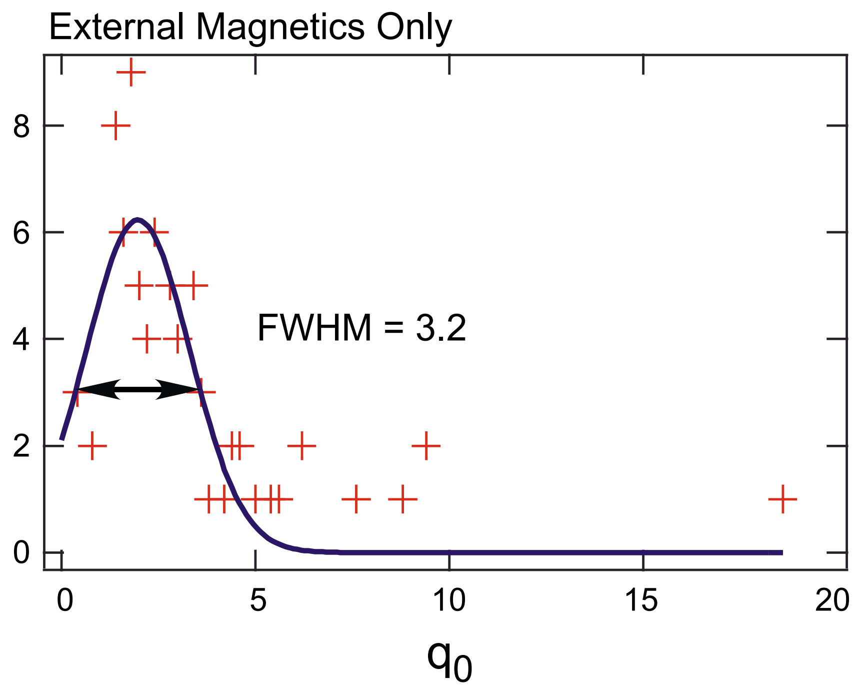
SXR Image Data Provides Tighter Constraint on q_0



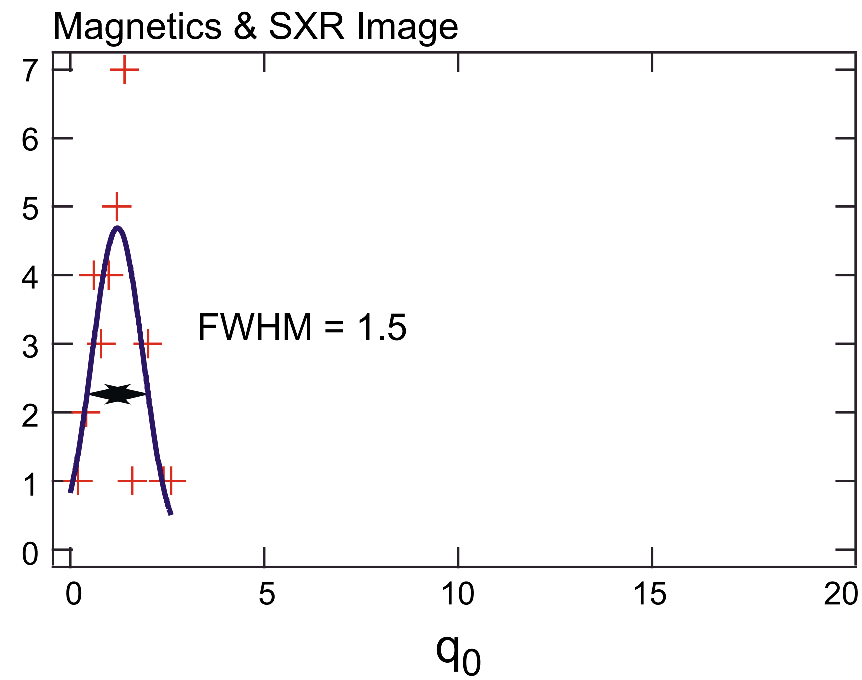


- Flexibility of spline parameterization produces many local minima
- Image data helps distinguish local minima in parameter space
- q_0 from reconstruction with X-ray image ~ 1.2 ± 0.7
- Reduction of noise and edge impurity effects will better constrain q_0

Monte Carlo Histograms Illustrate Impact of SXR Image Data on q_0 Reconsutrction



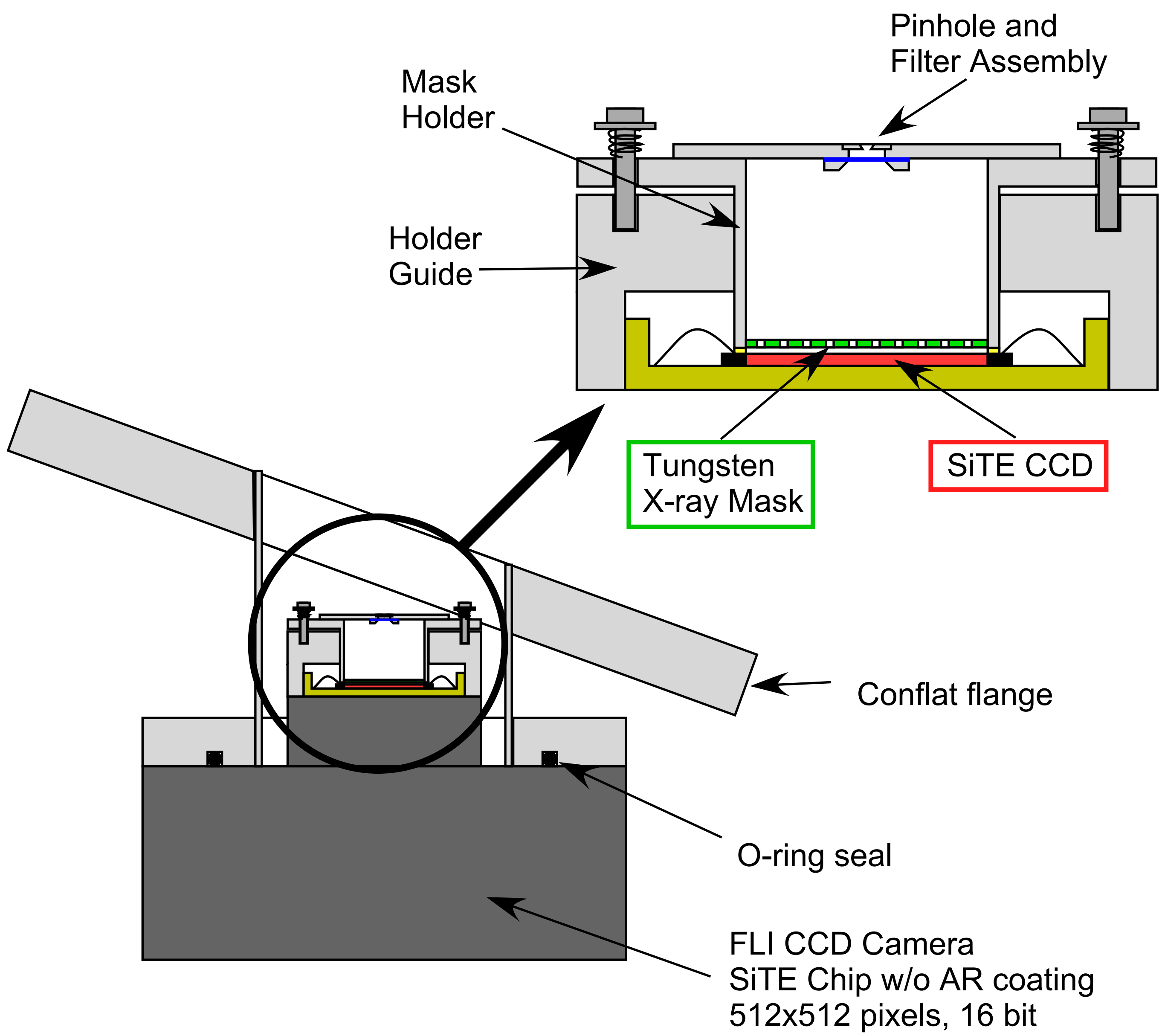
q_0 histogram without SXR image constraint from χ^2 of 16.6 to 20



q_0 histogram with SXR image constraint from χ^2 of 27.4 to 32

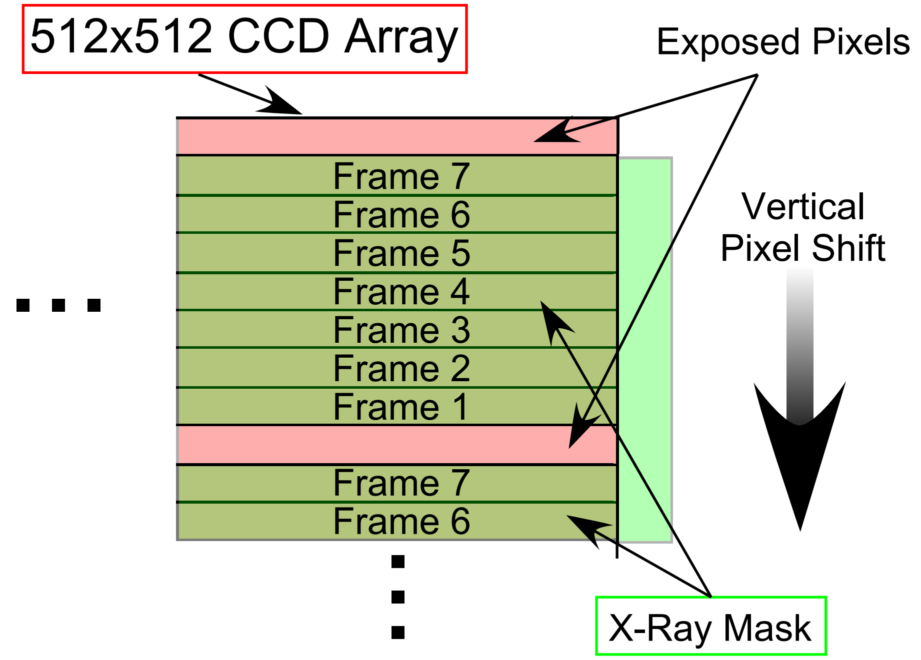
- Reconstruction chosen which have χ^2 within 20% of lowest χ^2 value
- Estimated q_0 uncertainty without SXR image is optimistic
  - poor fit to Gaussian
  - many outliers at higher values

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

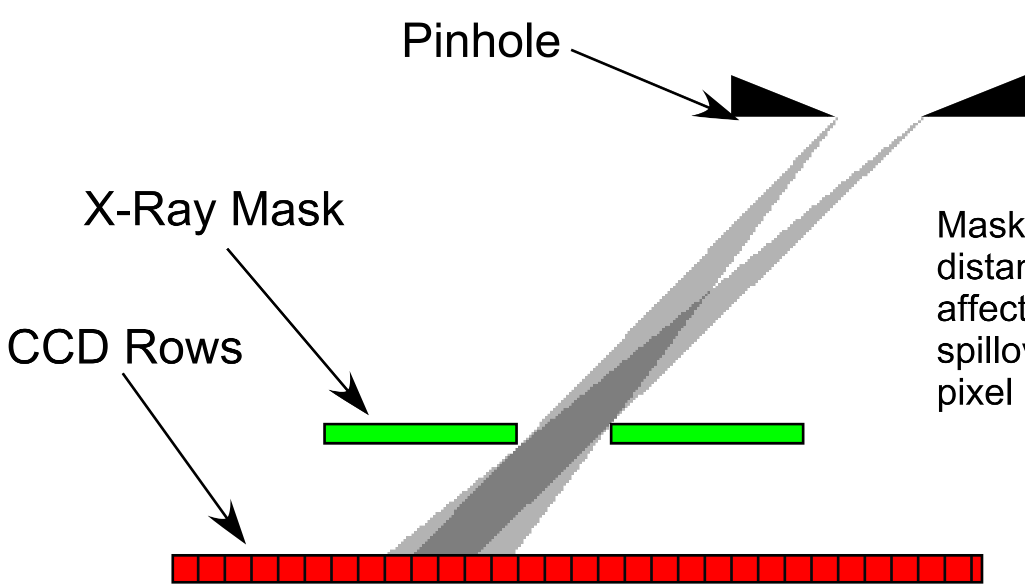


- Direct illumination design will decrease photon noise x10
- Increased SNR will allow better time resolution and tighter constraint on q(r),j(r)
- Pixel masking provides multiple frames for time reconstruction of shot evolution

Pixel Masking Allows Multiple Frames Using High Sensitivity Camera



Parallel Shift Time
=
Frame Exposure Time



Mask thickness and distance to CCD will affect vignetting or spillover to neighboring pixel rows

- 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
  - Imroved SnR and reduction of edge impurities will tighten constraint

- Fabrication of next generation imaging system is in progress
  - direct illumination currently under testing