

An Upgraded Soft X-ray Pinhole Camera for Current Profile Measurements on the Pegasus Toroidal Experiment

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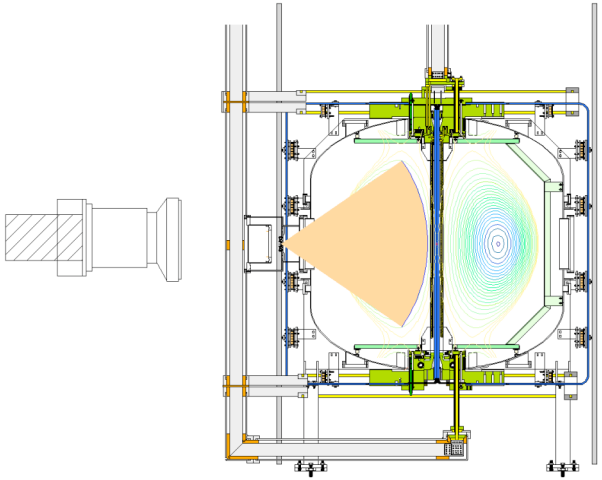
Abstract

An improved soft X-ray pinhole camera for current profile measurement has been installed on Pegasus. With an optical CCD camera and P43 phosphor scintillator that responds to X-ray energies in the range of 100 eV-5 keV, it provides a 2700-fold throughput improvement over the prototype (Tritz et al, Rev. Sci. Instrum., 2003, 2161). The 4k x 4k back-illuminated CCD has a 200 mm diameter active area, giving a spatial resolution of ~3 cm at 1 m and a temporal window of 2 ms. The current profile is obtained iteratively. Abel inversion of the measured intensity is used to obtain an emissivity profile across the plasma midplane. This profile is then used as constraint on an equilibrium reconstruction program, which generates a set of potential current profiles and associated intensity contours. X^2 minimization during the equilibrium fitting identifies the best intensity map. This non-invasive current profile measurement technique offers improved understanding of MHD mode evolution and has potential applications for large scale fusion experiments.

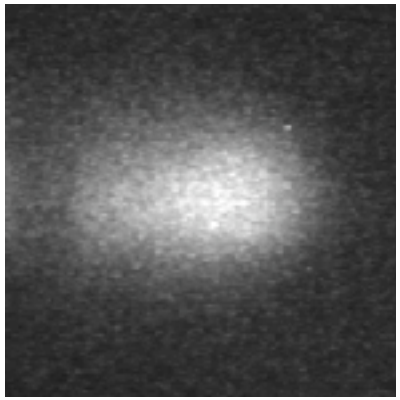
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Motivation

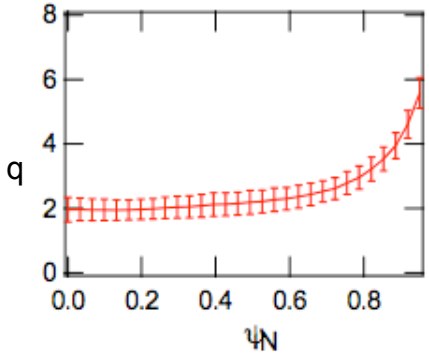
Pegasus is developing a highly sensitive, tangentially viewing soft X-ray camera to determine current profiles using a Grad-Shafranov equilibrium solver.



High sensitivity soft X-ray pinhole camera (with tangential toroidal view) images the plasma.



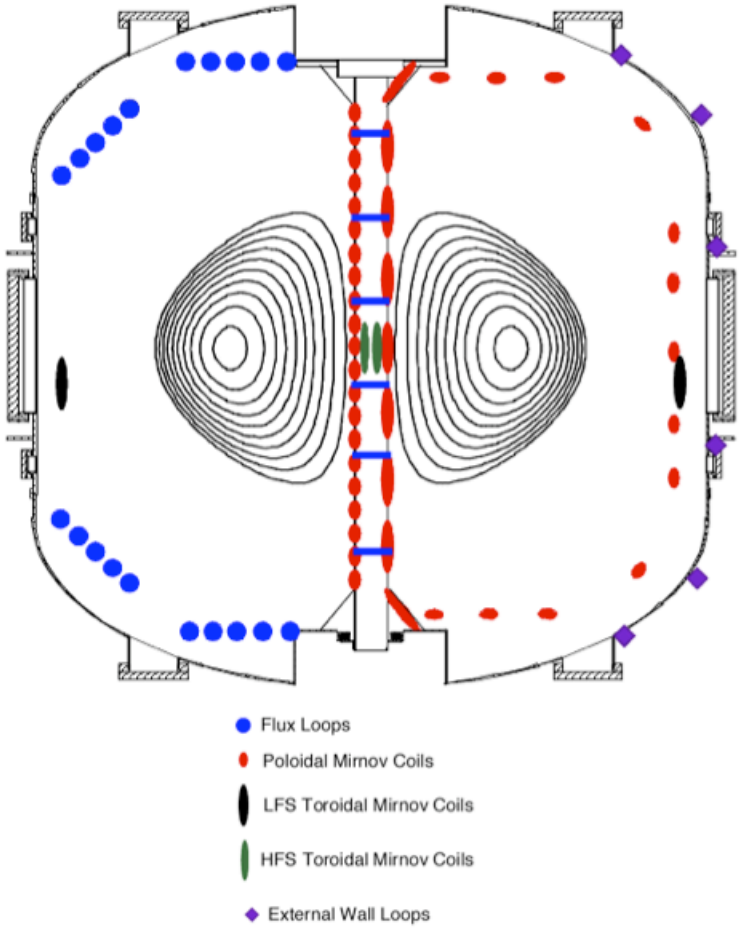
Emissivity profile is determined from X-ray image, then applied to a Grad-Shafranov equilibrium reconstruction program.



Using the one-to-one correspondence between flux surfaces and current profiles, we can obtain the q-profile of the plasma.

PEGASUS is an Ultra-Low Aspect Ratio Spherical Torus

Pegasus Machine Layout Showing External Magnetics



Experimental Parameters

Parameter	Achieved	Goals
A	1.15-1.3	1.12-1.3
R (m)	0.2-0.45	0.2-0.45
I_p (MA)	≤ 0.18	≤ 0.30
I_N (MA/m-T)	6-12	15-20
RB_t (T-m)	≤ 0.06	≤ 0.1
κ	1.4–3.7	1.4–3.7
τ_{shot} (s)	≤ 0.02	≤ 0.05
β_t (%)	≤ 25	> 40
P_{HHFW} (MW)	0.2	1.0

• Magnetics includes Rogowski coils and a diamagnetic loop (not shown here).

Plasma Profiles Inferred From External Measurements Only Are Inaccurate

- Pegasus applies external measurements, such as magnetic fields, as well as estimates for internal parameters, such as density, into plasma equilibrium reconstructions to better understand the physics of our discharges.
- The equilibrium reconstruction infers current, pressure, and q profiles, which can in principle provide insight into the equilibrium and stability properties of Pegasus plasmas.
- Typically j(r) and p(r) are determined only through equilibrium analysis relying on external measurements.
- This leads to poorly constrained profiles in the plasma interior.

Conventional Current Profile Diagnostics Cannot be Used Universally

- Conventional j(r) diagnostics such as Motional Stark Effect (MSE) or Faraday Rotation are problematic for the spherical torus due to its low toroidal field.
- MSE in the plasma interior will be difficult in fusion grade experiments due to beam penetration.
- Tangentially viewing 2D soft X-ray (SXR) imaging offers an indirect and non-perturbative method of measuring q-profiles that is not affected affected by the toroidal field.
- SXR imaging has the potential to scale to fusion devices, potentially manifested as a series of 1D cameras at variable heights.

X-Ray Inversion Technique Relies on Several Assumptions

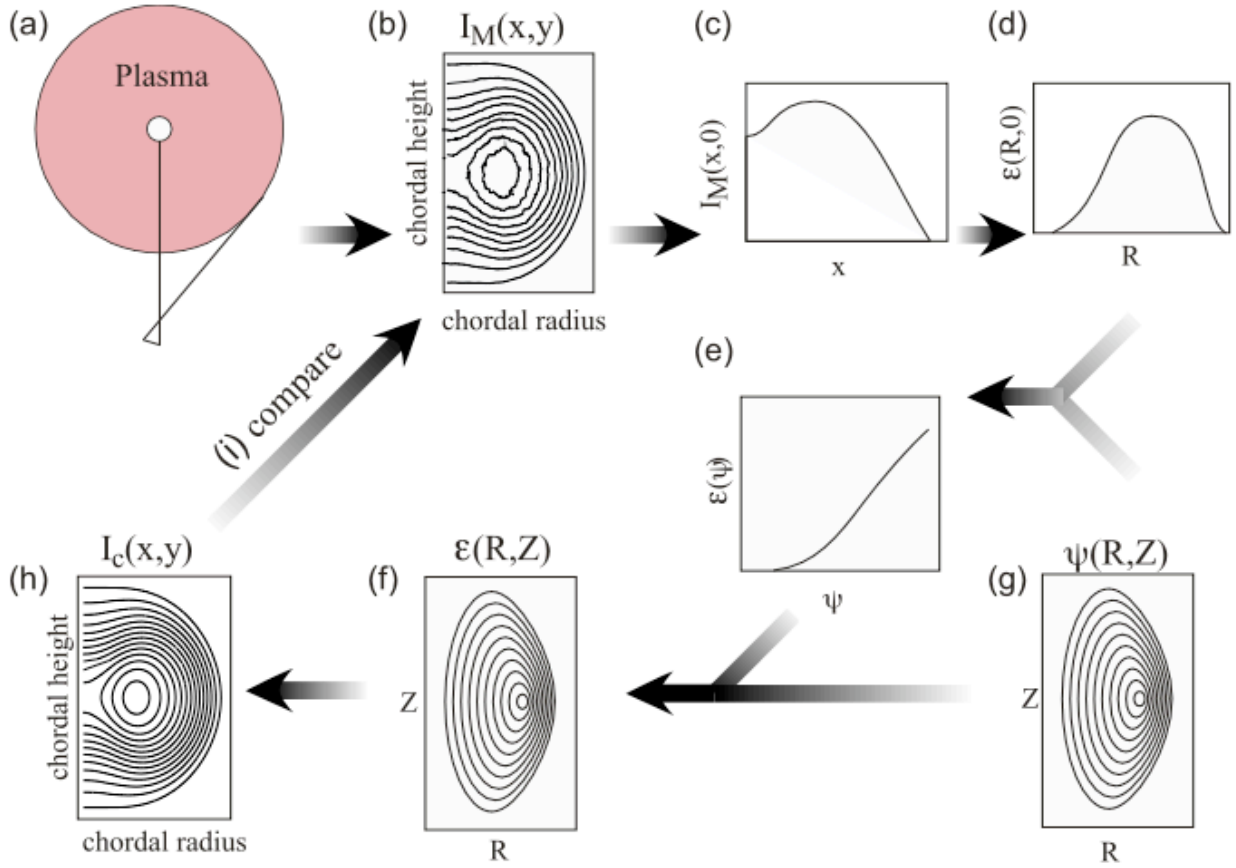
- Using soft X-ray imaging to determine current profiles assumes that plasma emissivity maps directly to flux surfaces.
- This requires there be no variation in density, pressure, or temperature, which may not be valid in plasmas with poloidally anisotropic impurity distributions.
- This measurement also requires clean signal and careful error analysis as inversion techniques magnify errors.

SXR Current Profile Determined Using Equilibrium Reconstruction

Current profiles are measured indirectly from a soft X-ray image:

- The soft X-ray emissivity profile is incorporated as a constraint during equilibrium reconstruction.
- At each iteration, an emissivity profile is calculated and compared to the measured profile. The difference between these profiles is then used as a constraint in the X^2 minimization.
- The equilibrium reconstruction is completed when the X^2 fit is minimized with respect to all measured values. This fit gives the q-profile of the plasma.

The SXR Pinhole Camera Provides Flux Surface Contour Fits



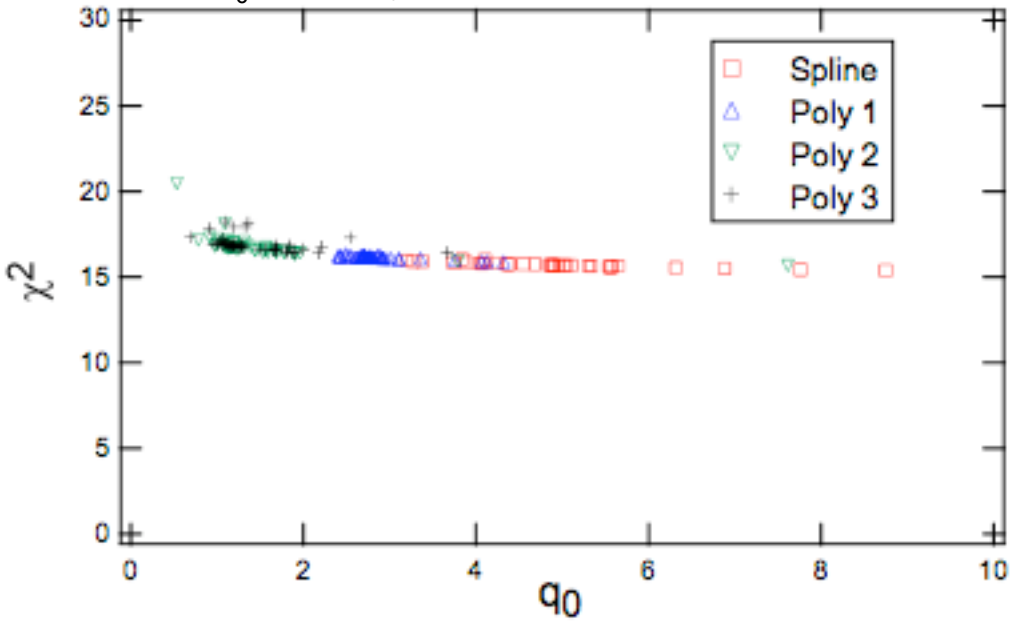
SXR PC Provides Flux Surface Contour Fits (cont)

Fit is performed through iterated equilibrium reconstruction:

(a) SXR Camera has a tangential view of the plasma
(b) Camera measures SXR line integrated intensity
(c) Extract midplane intensity profile
(d) Abel invert intensity profile to obtain emissivity profile at Z=0
(e) Use reconstructed equilibrium flux (g) to map emissivity to local value of y
(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 image

Q Profile Unconstrained by External Magnetics Alone

Reconstructed q_0 fit quality for a randomized set of initial conditions

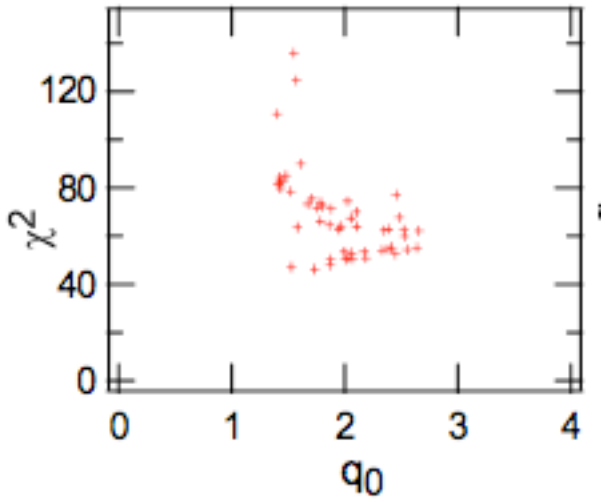


- Monte Carlo scan of equilibrium reconstruction, fixing the general plasma profile but slightly varying initial conditions, should converge on a single value of q_0.

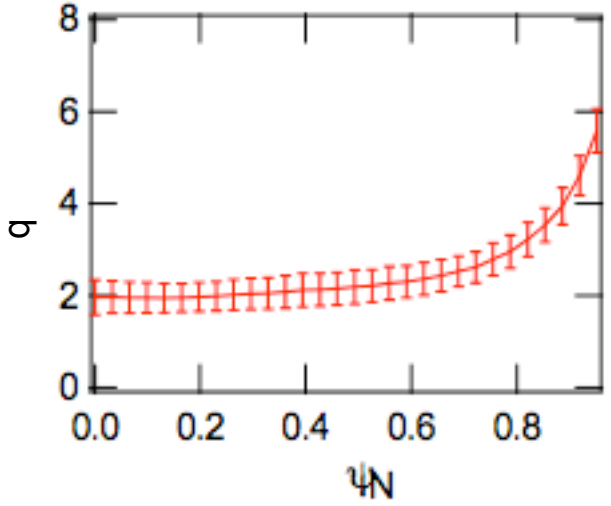
- External magnetic measurements alone give a degeneracy in best-fit q_0, leading to a nearly unconstrained q-profile.

Addition of X-Ray Emissivity Constrains Equilibrium Reconstructed q-Profile

Scatter plot of fit quality for q_0 incorporating emissivity profile

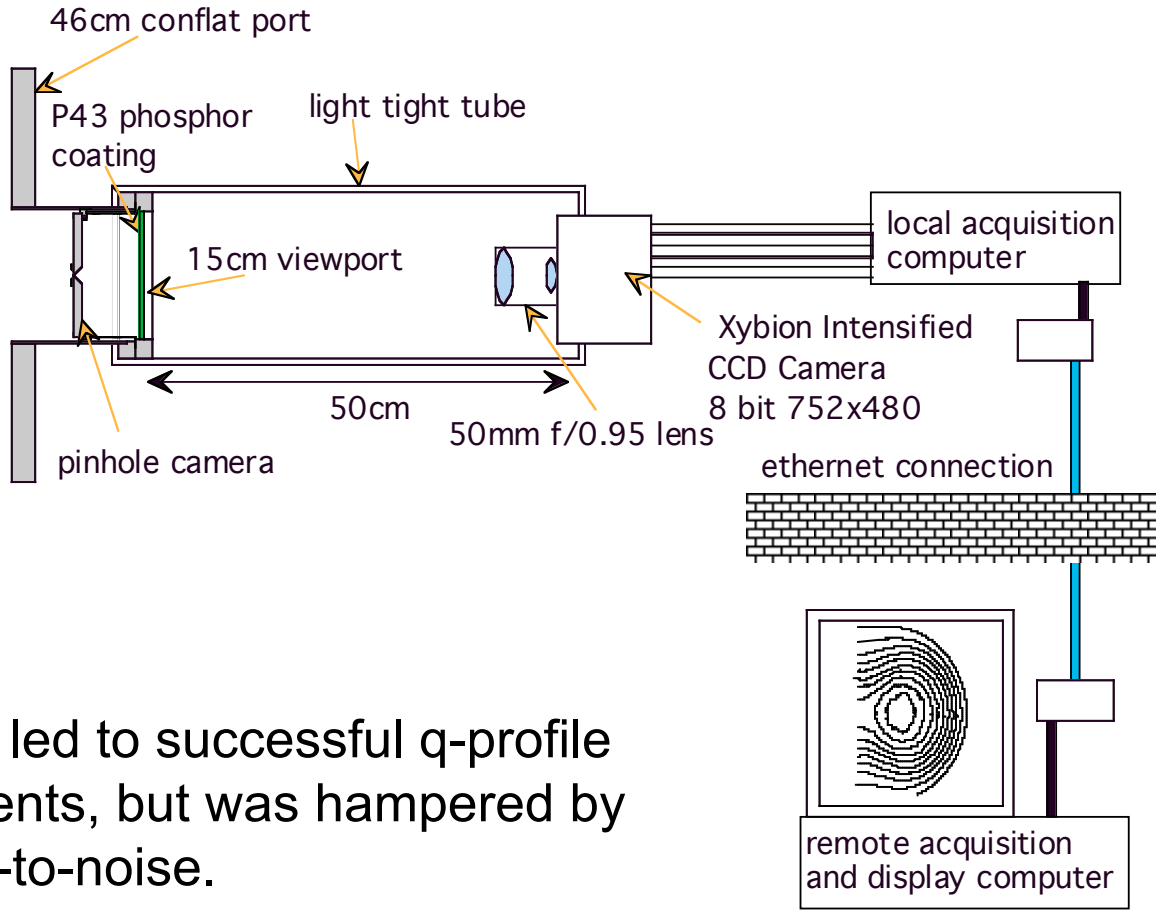


q-profile as a function of normalized flux surface



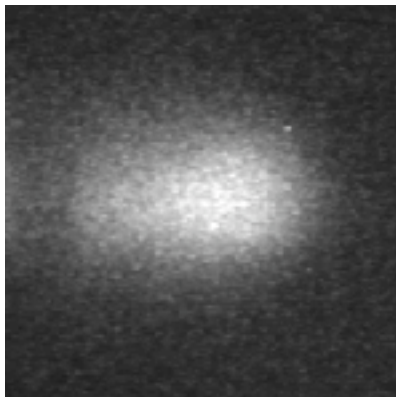
• By using both external magnetics and the emissivity measurement in the equilibrium reconstruction, q_0 is constrained and we calculate a reasonable q-profile.

Prototype System Suffered from Poor Signal-To-Noise

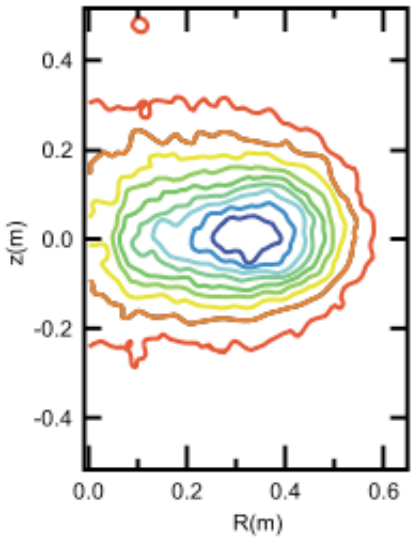


- Prototype led to successful q-profile measurements, but was hampered by poor signal-to-noise.

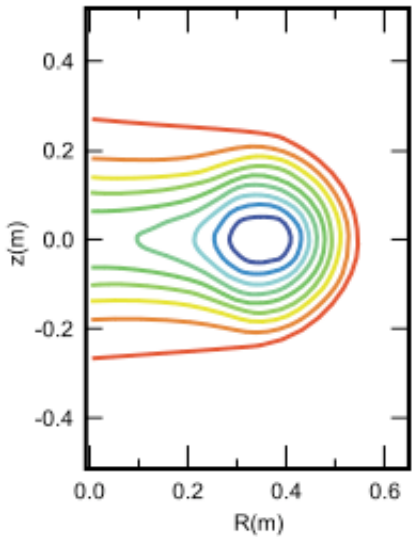
Reconstruction Matches Data from Prototype SXR PHC



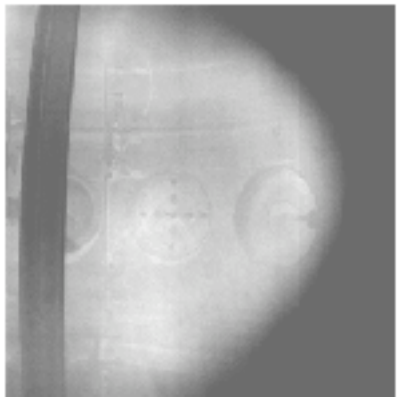
SXR image taken with Xybion intensified CCD camera (step a)



Intensity contours from SXR PHC after processing (step b)



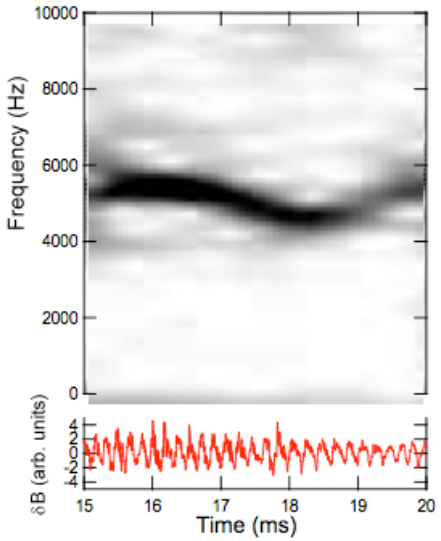
Projection from reconstructed cross-section (step h)



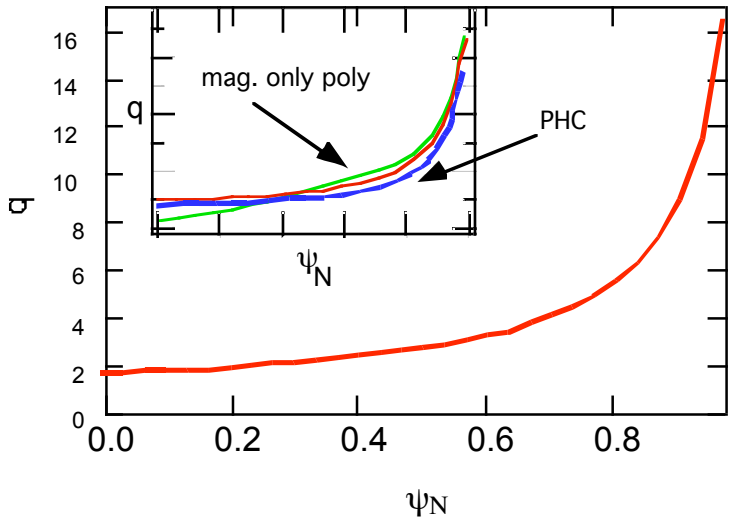
Visible image from Dalsa Shot 9639 (t = 18 ms)

- SXR image obtained with 5ms exposure time.
- Image smoothed using a multi-pass 4x4 Gaussian filter.
- Result used to constrain equilibrium reconstruction of shot 9639.

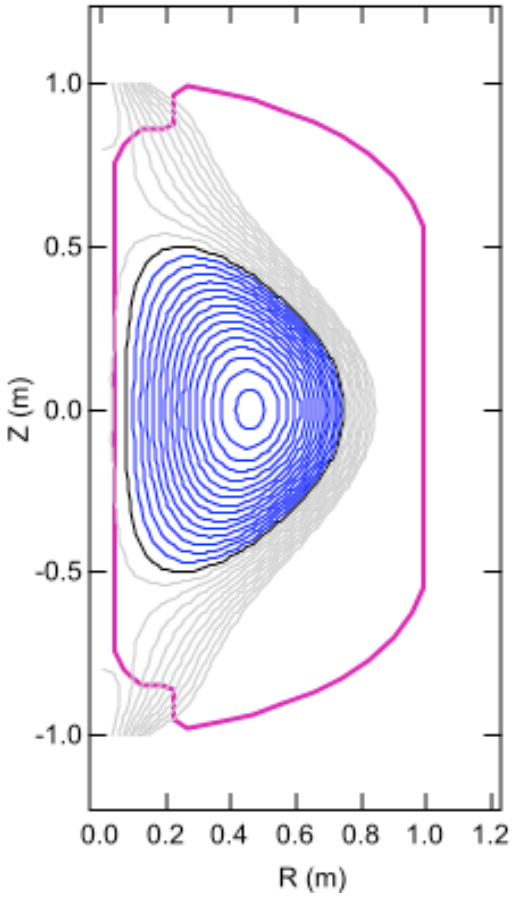
Resulting q-Profile Consistent With Other Plasma Diagnostics



Sonogram and Mirnov coil data showing MHD mode activity



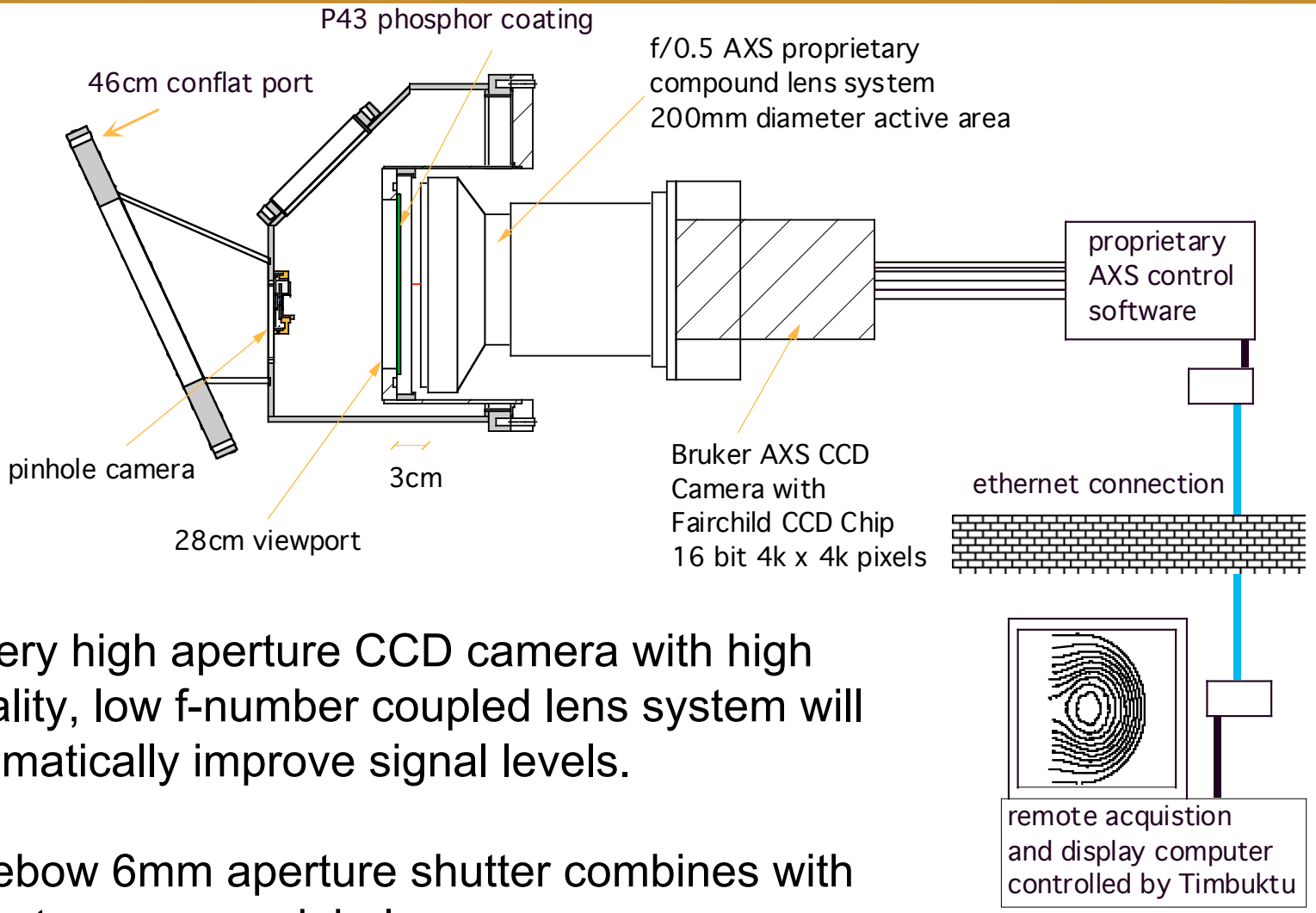
Equilibrium reconstructed q-profile using emissivity constraint.



Reconstructed flux map shot 9639 (step g)

- q_0 reconstruction value ~1.5 consistent with indications of 2/1 mode.
- External magnetics constrain plasma boundary, SXR image provides internal constraint.

Upgraded System Affords Dramatically Increased Signal



- Very high aperture CCD camera with high quality, low f-number coupled lens system will dramatically improve signal levels.

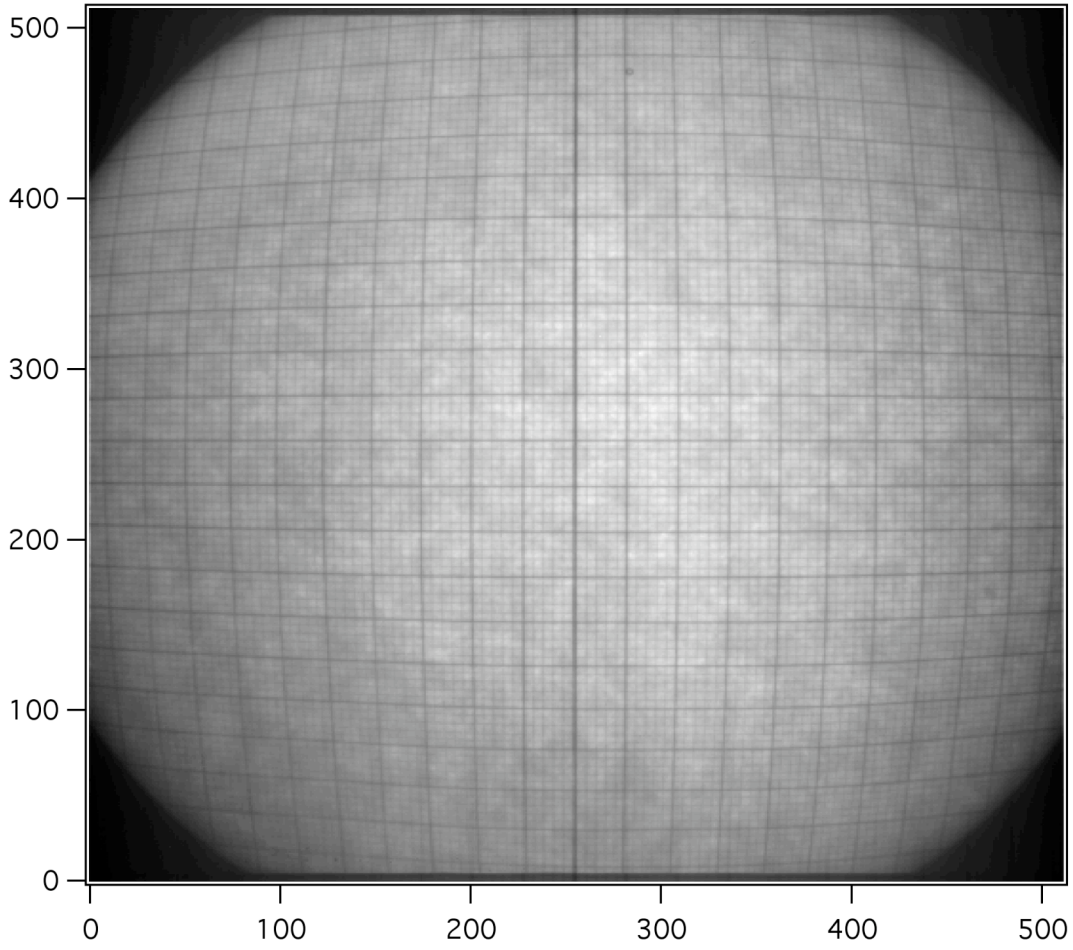
- Lebow 6mm aperture shutter combines with filter to serve as pinhole.

Upgraded Camera Offers Improved Sensitivity

	Prototype	Upgrade	Improvement Factor
Camera Throughput (a_{scint}*a_{ph} /d^2)	0.088cm^2	0.002cm^2	43
f/#	0.95	0.5	4
CCD Effective Area	0.5	1.0	2
Quantum Efficiency	0.1	0.8	8

• We expect a sensitivity improvement of more than 3 orders of magnitude compared with the prototype system.

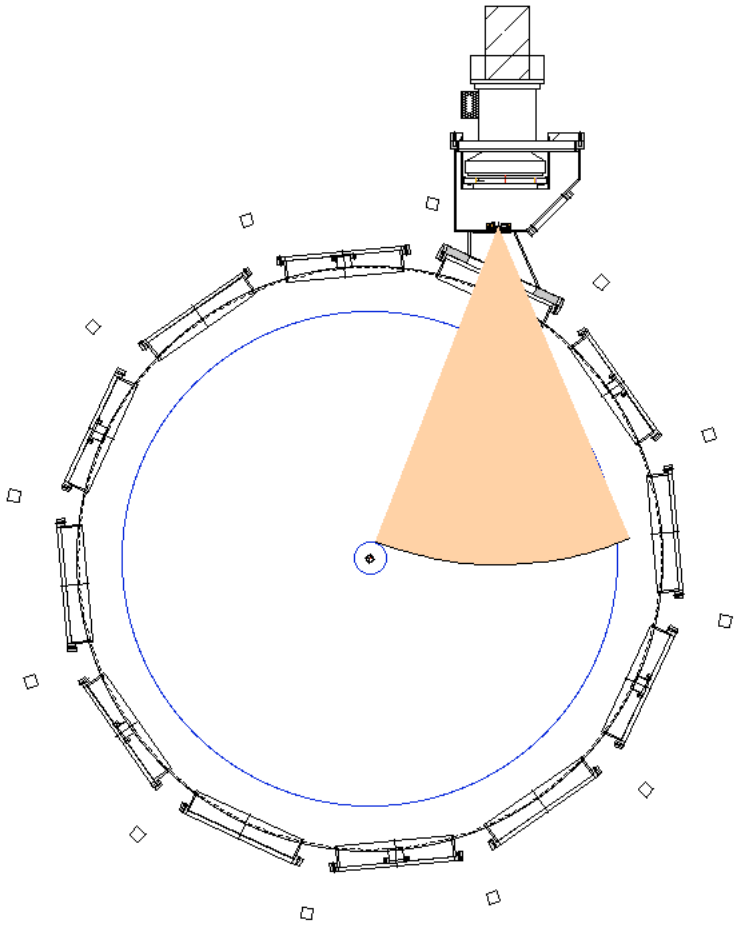
Bruker AXS Camera Has Excellent Optical Resolution



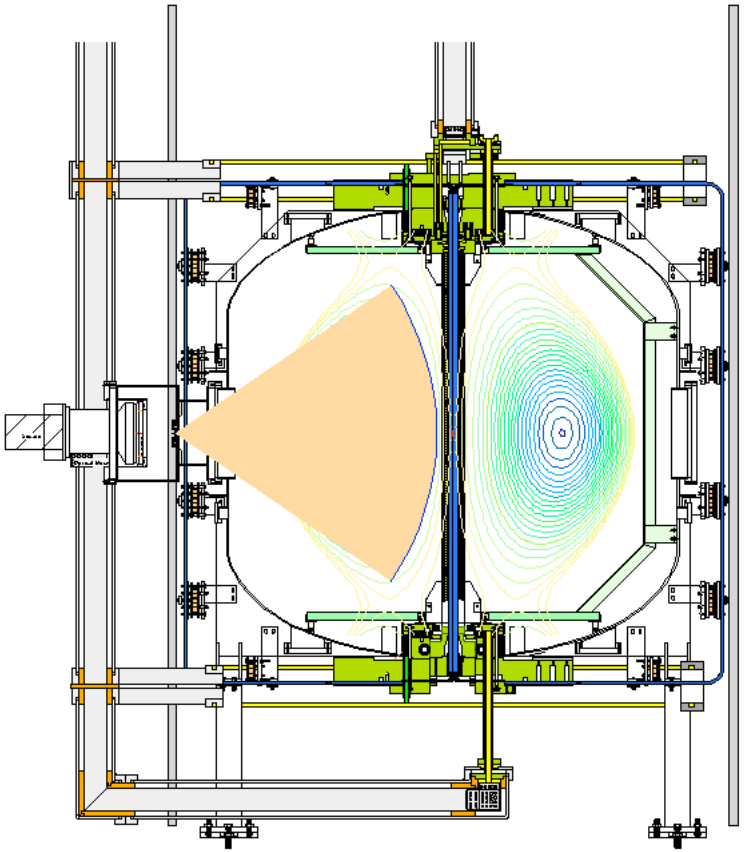
- Unprocessed image of 1cm major grid, 0.2cm minor grid (full FOV >20cm).
- Optical resolution of <1mm at focus (binned 8x8).
- Minimal transmission losses around edges: signal intensity still greater than 70% of peak value across r=0.98*R_max.

Field of View for Upgrade SXR PC

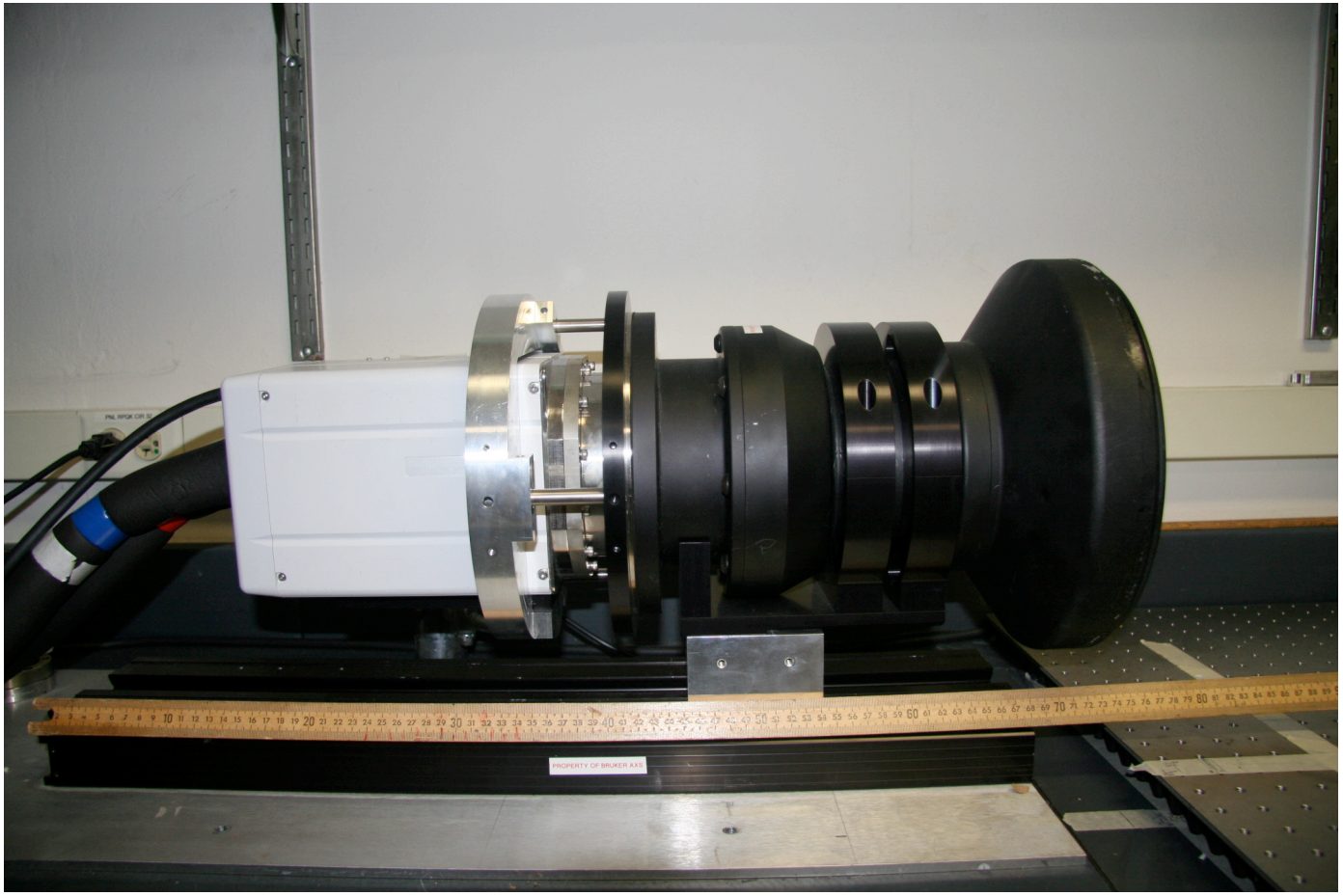
Toroidal View



Poloidal View



Bruker AXS CCD Camera



SXR Pinhole Camera Specifications

- Pinhole Camera:
  - 6mm diameter pinhole
  - 2000A Ni filter
  - 20cm diameter imaging phosphor (P43)
  - minimum shutter exposure time ~2ms
- Bruker AXS CCD Camera:
  - back-illuminated CCD gives good quantum efficiency
  - 6.1cm x 6.1cm chip area with 4k x 4k pixels gives high sensitivity
- Single image acquired per shot (CCD minimum readout time 0.3 sec)

Summary

- Highly sensitive soft X-ray pinhole camera will image with a net sensitivity improvement of >2000 times the prototype version.
- X-ray images, in combination with external magnetics and an equilibrium reconstruction code, will provide us with q-profiles for Pegasus discharges.
- All major components designed and built, system will be commissioned in late November.



Reprints

