Particle Beam Physics Laboratory

A Permanent-Magnet Quadrupole Final-Focusing Optics at PLEIADES Inverse Compton X-ray Source

J. K. Lim*, P. Frigola, J. B. Rosenzweig
& G. Travish (UCLA)
S. G. Anderson, D. J. Gibson, F. V. Hartemann
& A. M. Tremaine (LLNL)

* jlim@physics.ucla.edu

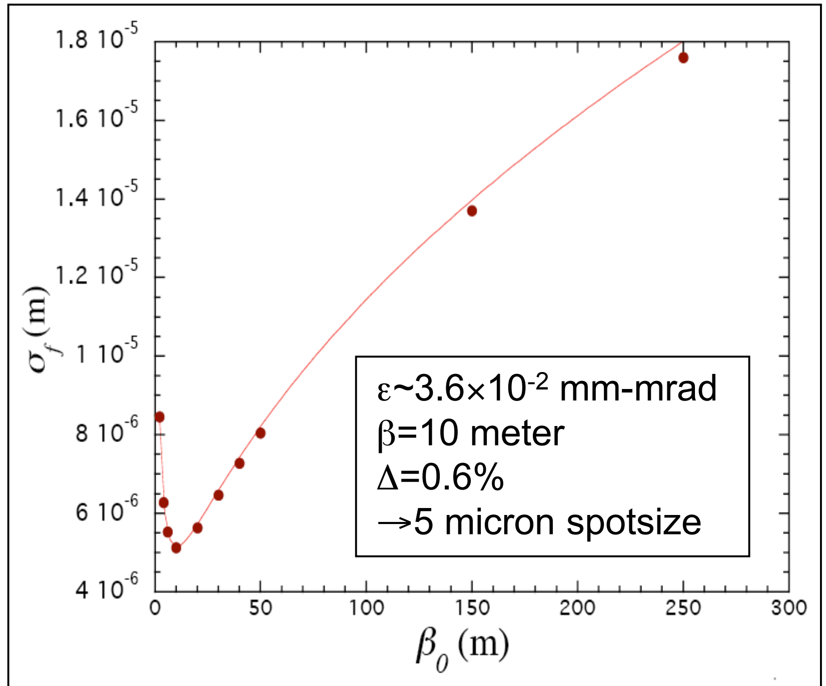
Application of High-Density Electron Beam

- PLEIADES Phase I: Standard EM quadrupole
  - 15T/m in quad strength
  - Over 50 micron spotsize at best
- Phase II: Permanent Magnet Quadrupole
  - Strong quad strength
  - Under 20 micron spotsize
  - Aiming for 5 micron spotsize w/ improved beam quality (~1mm-mrad emittance)
- Inverse Compton Scattering (ICS) x-ray yield upgrades with strong PMQ focusing lens
  - Initial experiment run

(An invited talk given by S. Anderson at this workshop)

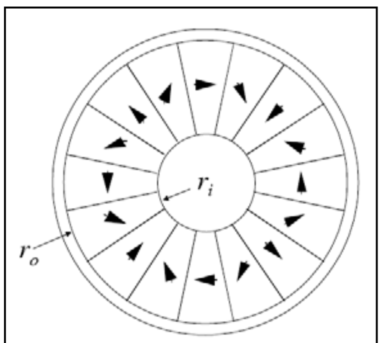
Motivation for Strong Permanent-Magnet Quadrupole

- Chromatic aberration from ratio of final to initial beam-size is



Final spot size vs initial β

- There's minimum in beam-size when $\beta_0/f \cong \delta p/p$, demagnification is $\sqrt{\ }$



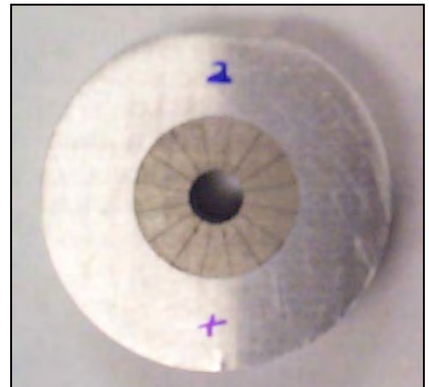
Halbach design

- For a few cm focal length and L_q=1cm, chromatic aberration limits demagnification; need stronger magnet B' (short focal length)

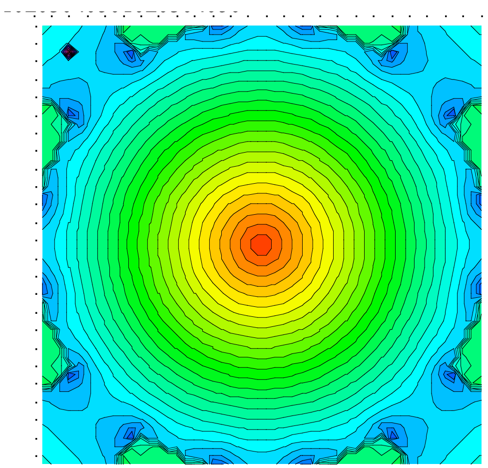
High-field Gradient obtained from PMQ

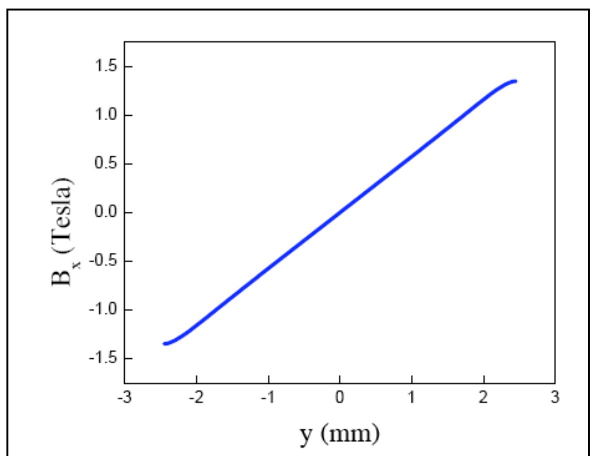
$$B' = 2B_r\left(\frac{1}{r_i} - \frac{1}{r_o}\right)$$

For r_i=7.5mm, r_o=5mm and B_r=1.2T
Field gradient of idealized PMQ is
640T/m

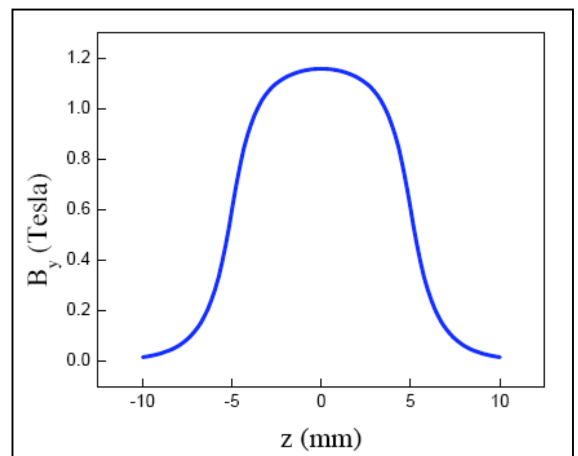

PMQ unit

RADIA – 3D magnet simulation:


2D field plot
in bore region



Linearity good to r ~ 2 mm
B' = 573 T/m

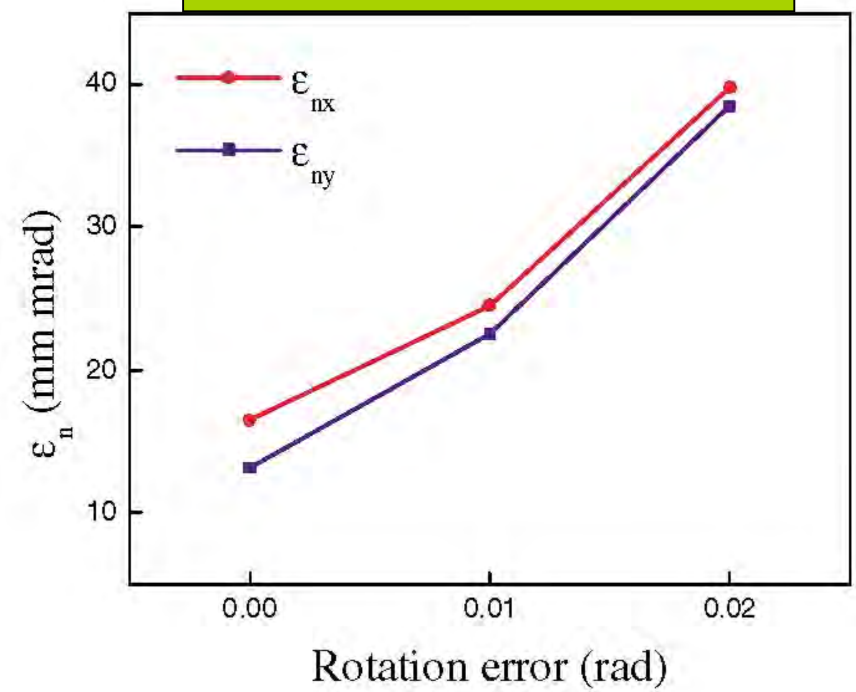


Effective length = 10.4 mm

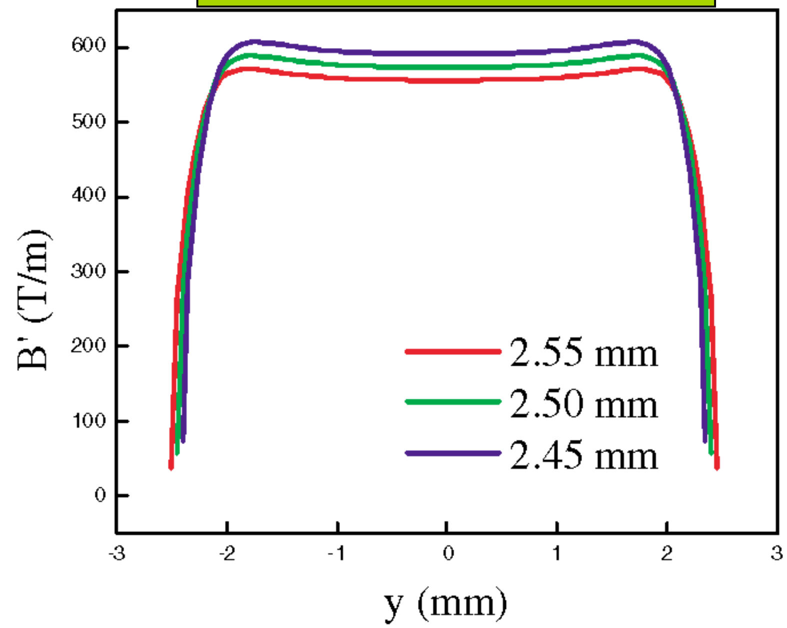
RADIA PMQ Tolerance + ELEGANT

- RADIA magnet error tolerances:
  - ± 50 μm bore radius error ⇒ ± 3% B' variation
  - 2% wedge shape and easy axis orientation allowable

Skew quad (rotation error)

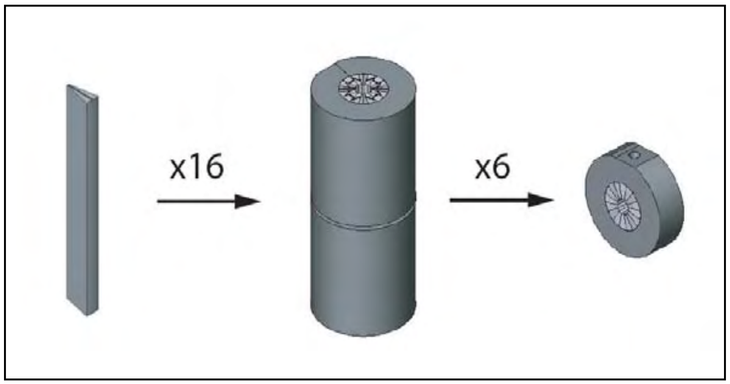


PMQ bore radius error

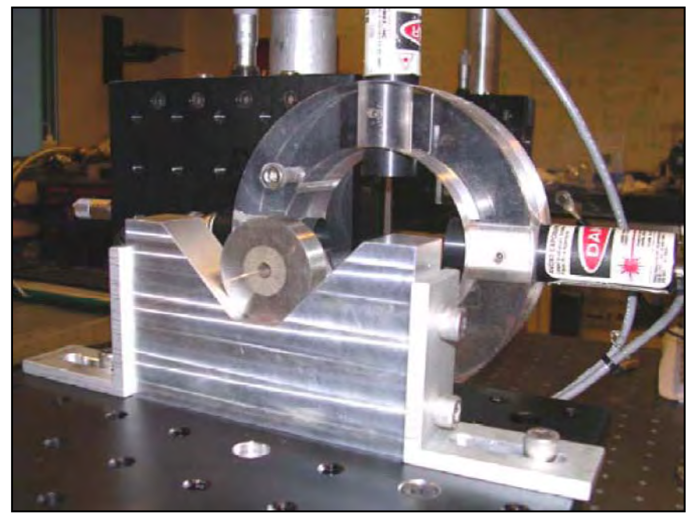


- ELEGANT skew quad effects:
  - Transverse magnet position error has no significant beam effect
  - 10 mrad rotation (skew) error produces significant emittance growth

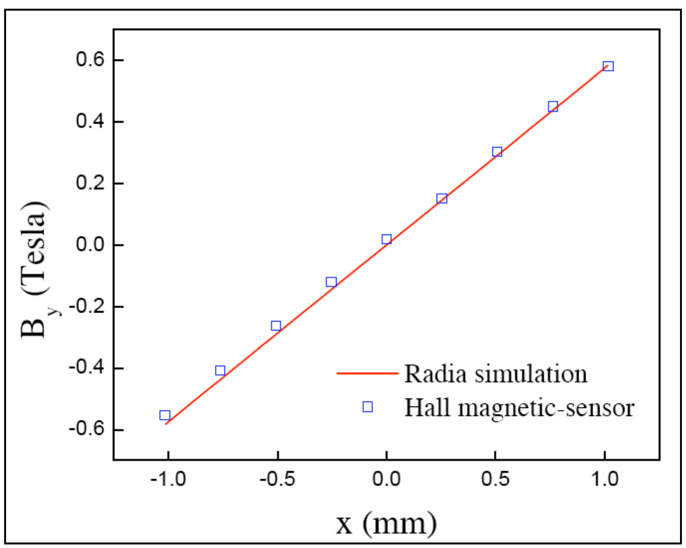
Measurements of built PMQs agree with RADIA simulations



1. Manufacturing process ensures consistency between PMQs, minimizes skew errors.

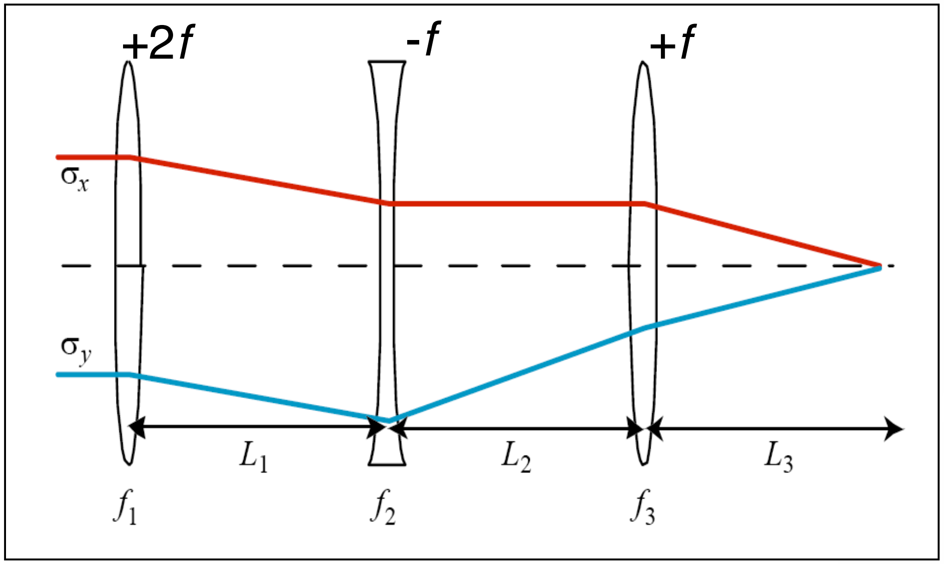


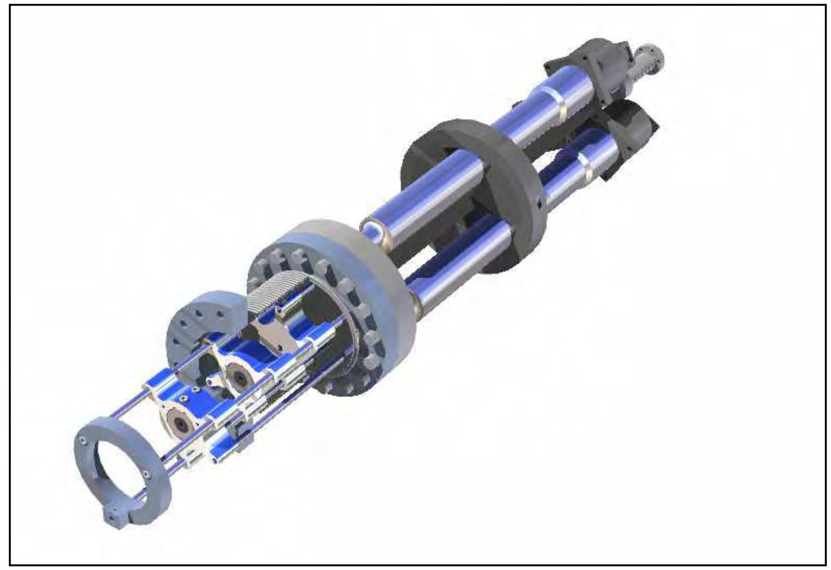
2. Field linearity good to r ~ 2 mm.
3. Magnetic-mechanical centers within 25 μm



4. Hall probe measurement gives B' = 560 T/m

Adjustable PMQ Final Focus System

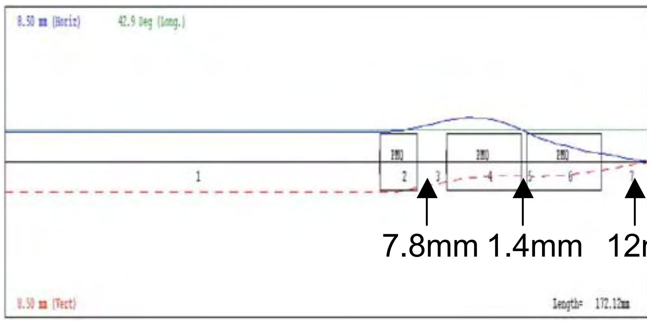




- Final focus system can't tune with B'
- System adjusted by magnet spacing; L_1, L_2, L_3
  - F-DD-FF configuration
- Experiments showed adjustability of the PMQ beam lens in 30-100MeV beam energy range → *final β-functions in 1-6 mm range*

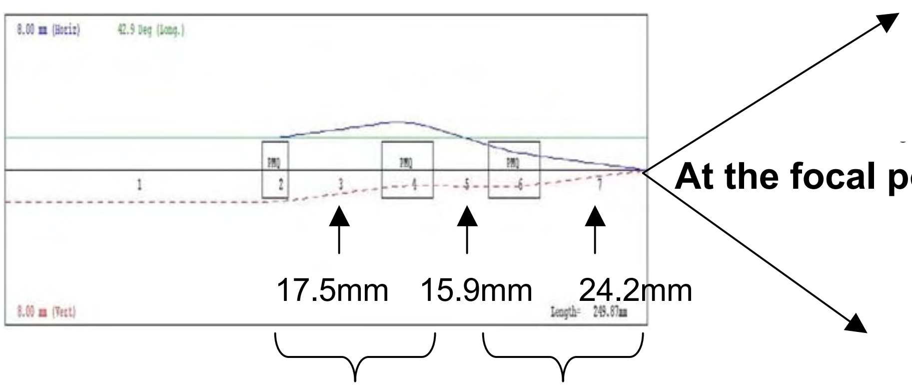
Beam Transport Simulation

Trace3D (particle-transport code)
Electron Beam energy 30MeV

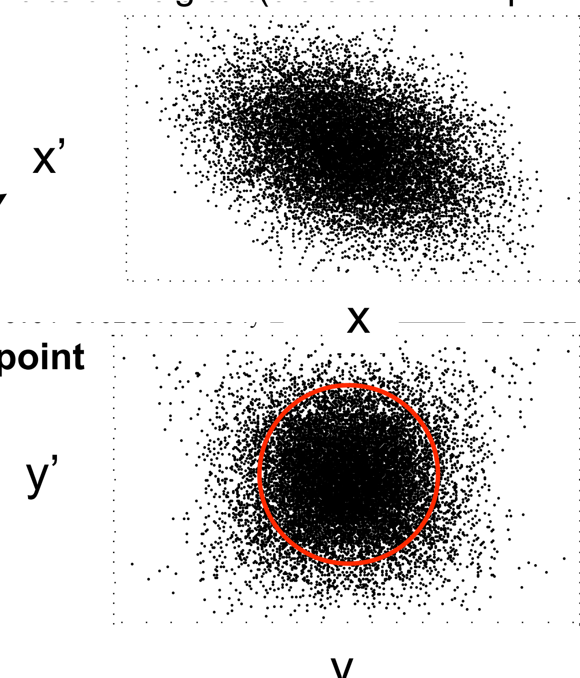


Elegant Input parameters:
$\varepsilon_{xn,yn}$ =10mm-mrad, $\beta_{x,y}$ ~6.5mm/mrad,
γ ~116
Output parameters:
$\beta_{x,y}$ ~1mm/mrad, $\sigma_{x,y}=\sqrt{\varepsilon\beta}$ ~10μm spot size!

Electron Beam energy 60MeV



Elegant (2nd order transport code)

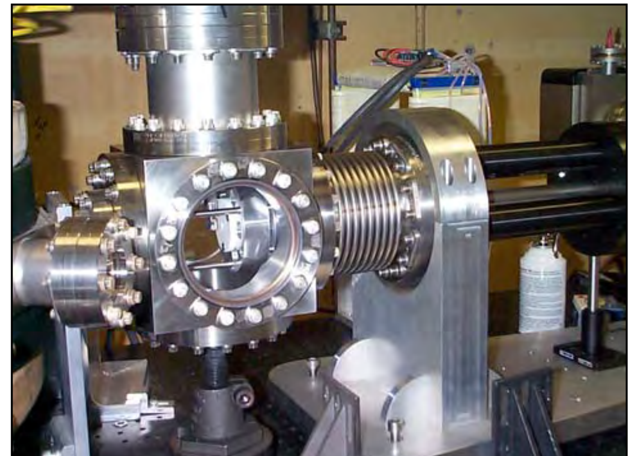


Increase drift space as focal length goes up for stronger triplet quads

(includes chromatic aberration effect)

The PMQ mover system meets experimental requirements

PMQ mover assembly



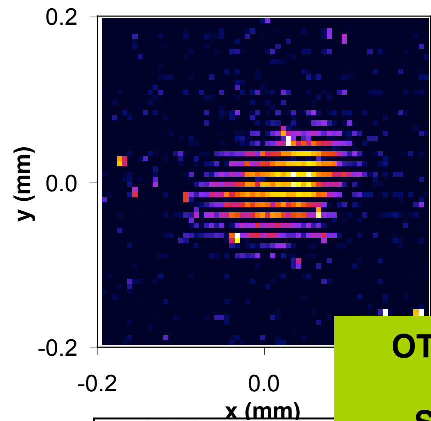
PLEIADES PMQ final focus

- CNC machined “PMQ holders” constrained by rail system
  - < 25 μm PMQ to system center-line throughout range of motion
- Push-rods + stepper motors + LabVIEW for on-line, < 50 μm resolution longitudinal positioning
- Alignment verified optically with theodolite in PLEIADES beamline

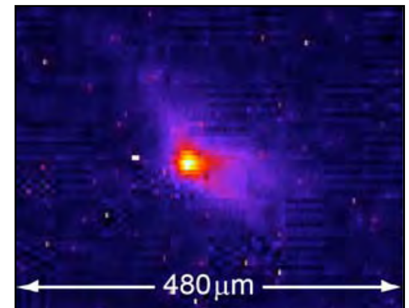
Final focus performance is enhanced with PMQ system

- Final focus procedure:
  - Twiss parameters obtain from quad scan with up-stream magnets
  - Use Trace3D to compute EM quad settings for ~ few meter β_0 and PMQ positions for best focus
- IP spot measured with OTR + 3 μm/pixel video camera
  - < 20 μm spots directly measured
  - Beam image aberration problem?
- PMQ scan analysis indicates σ^* = 15 μm

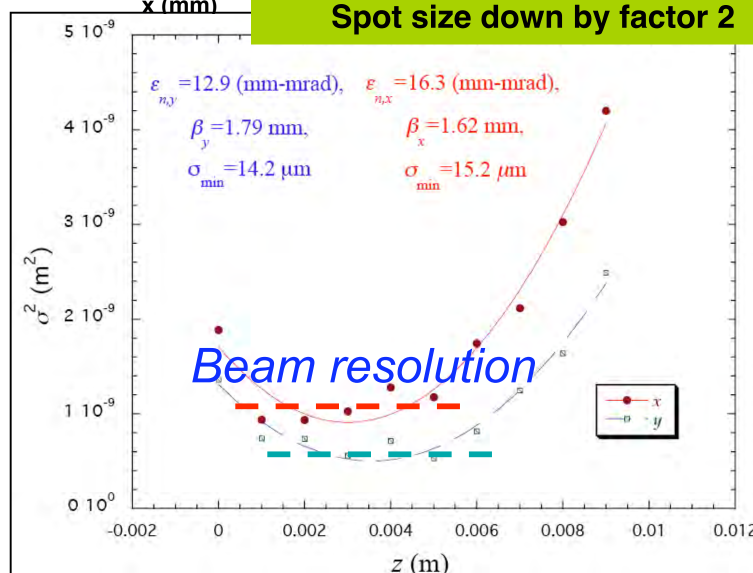
EM Quad(15T/m)



PMQ(560T/m)



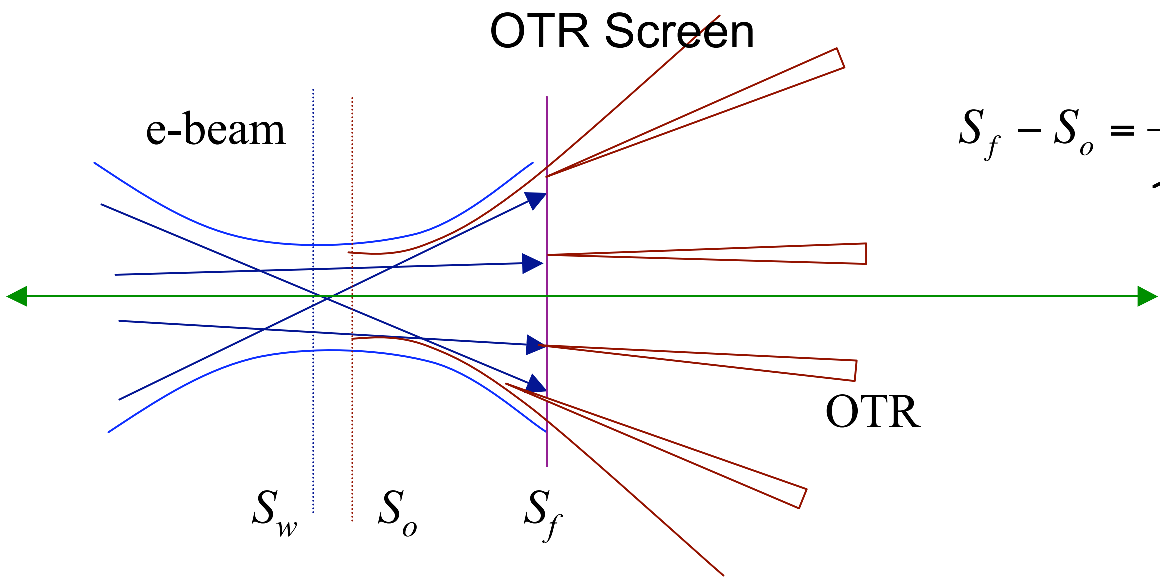
OTR image of 70 MeV, 200pC, 20 μm (rms) final focus. Spot size down by factor 2



PMQ scan shows β^* = 3 mm

Camera depth-of-focus/OTR aberration limit?

- Is the camera lens depth-of-focus longer than quad-scan range?
- OTR 1/γ angular divergence + e-beam divergence moves S_o object downstream of e-beam waist to S_w. For 1/γ~30mrad and θ_b~25mrad→actual object 40% closer. What is actually being measured when the PMQ scan?



$$S_f - S_o = \frac{S_f - S_w}{\sqrt{1 + (\gamma\theta_b)^{-2}}}$$

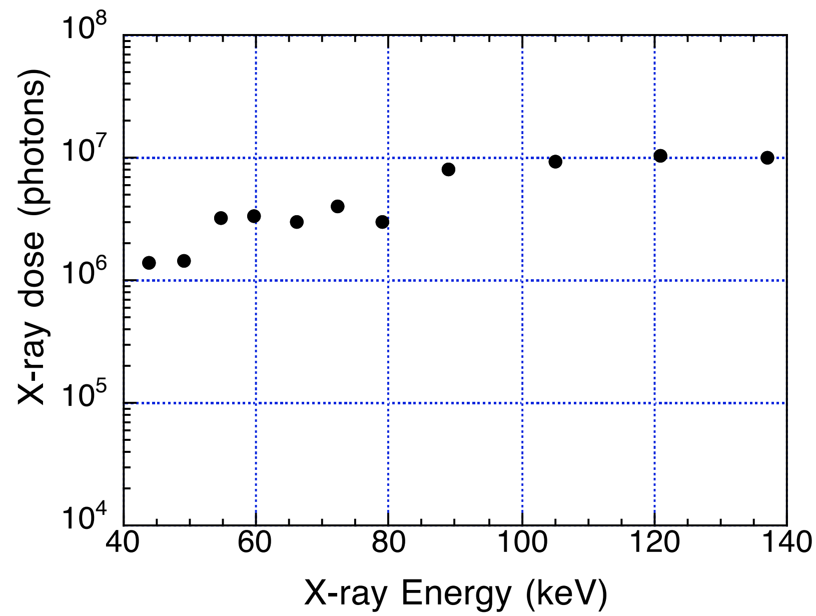
The PLEIADES energy-tunable x-ray source

- Tunable, bright, ICS hard x-ray source
- 810 nm, 250 mJ, 54 fsec, Ti:Sapphire laser
- Under 20 micron beam spotsize w/ PMQ at ICS interaction

RF Gun+LINAC

- ➢ 100 MeV/m
- ➢ Charge = 0.3 nC
- ➢ ε_n = 5 mm-mrad
- ➢ f = 2.85 GHz (S-Band)
- ➢ E = 20 - 100 MeV
- ¬ σ_t = 3 ps (uncompressed)
- ¬ σ_t < 300 fs (compressed)

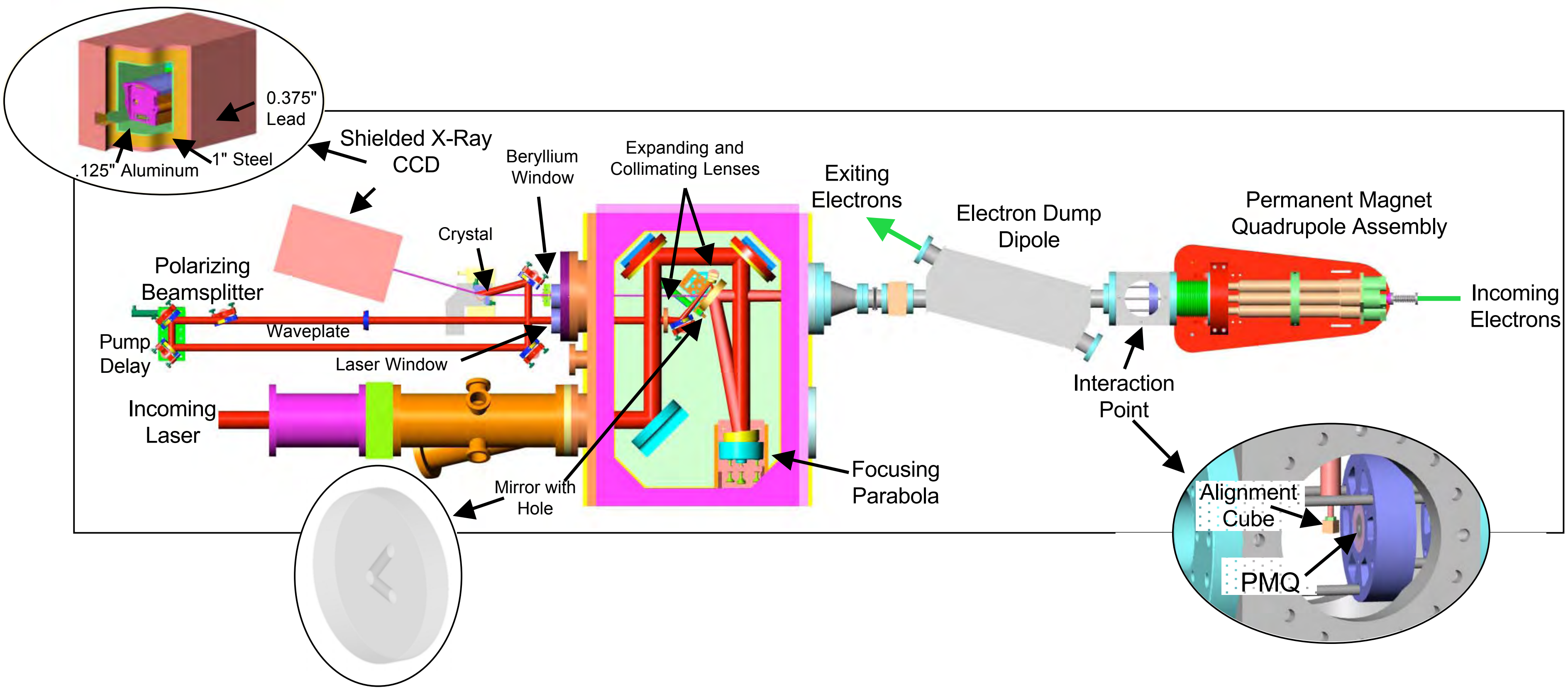
X-ray flux vs. energy



PMQ FINAL FOCUSING LENS has significantly increased source flux and brightness.

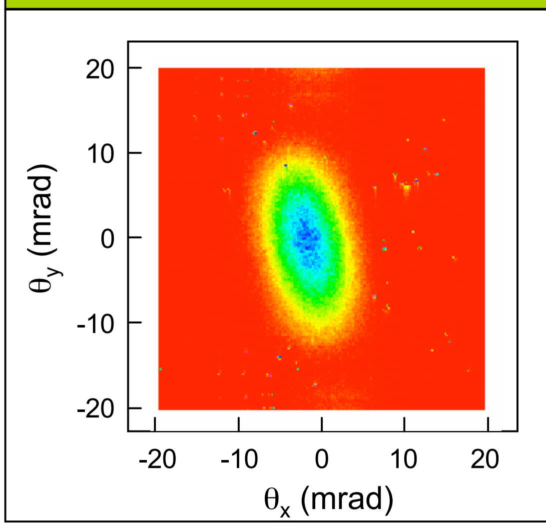
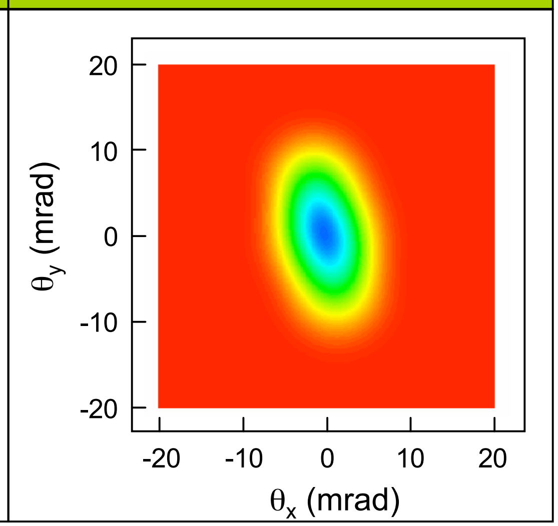
Setup for ICS Production

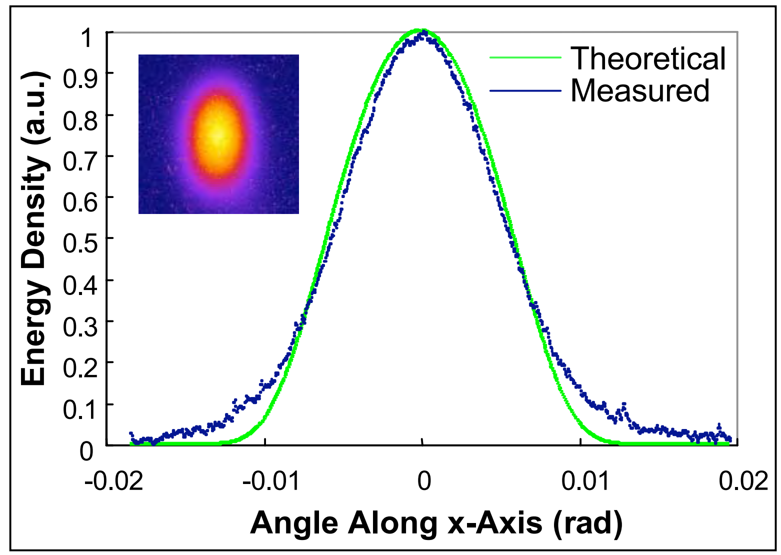
- Layout for the interaction region of the LLNL ICS source, PLEIADES
- A 180° interaction geometry to maximize x-ray flux
- Example: Dynamic diffraction experiments



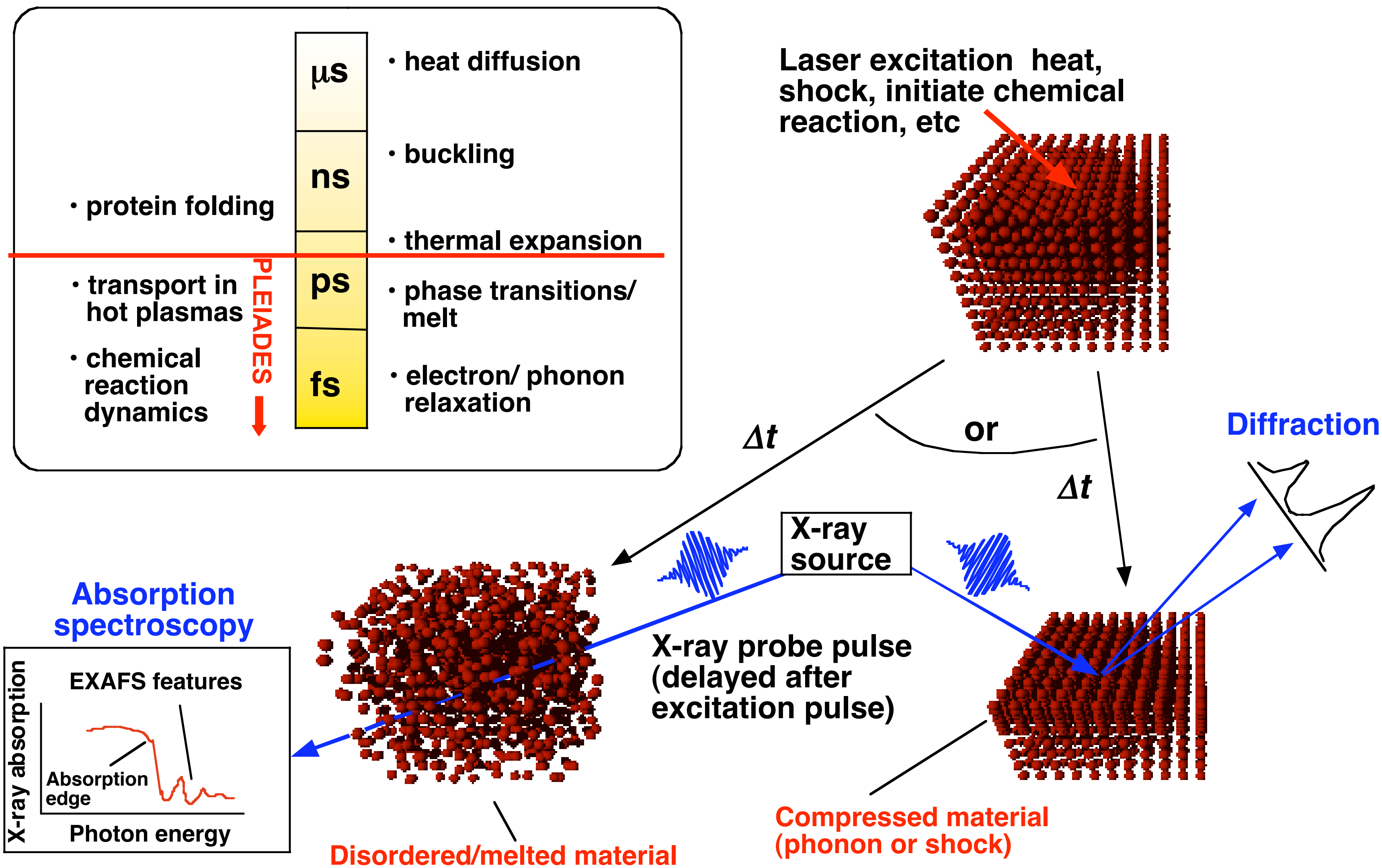
Comparison to Theory

•The x-rays measured with the PLEIADES system matched the theoretical flux and profiles very well, once all the electron and laser beam parameters, material transmission, and CCD response were taken into account

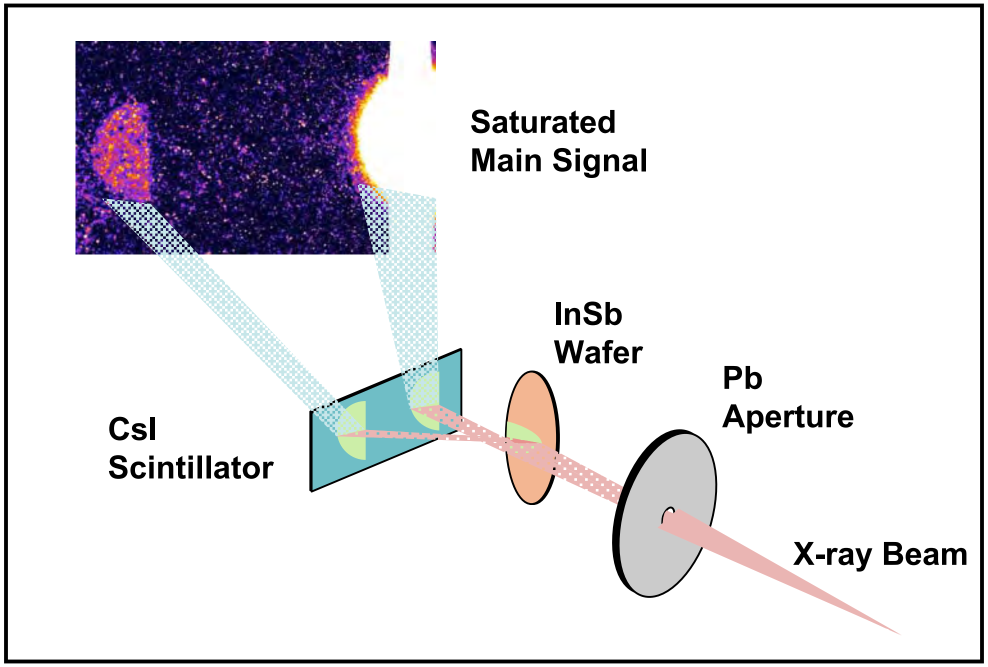
Measured	Theoretical
	



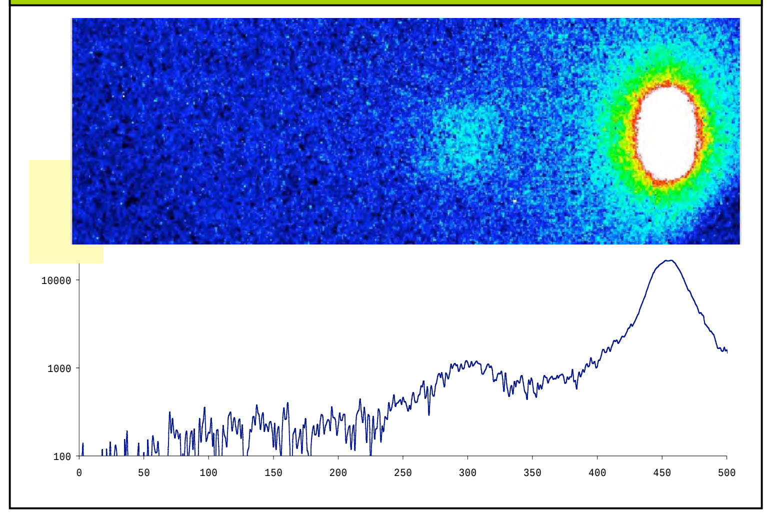
X-ray Diffraction Studies



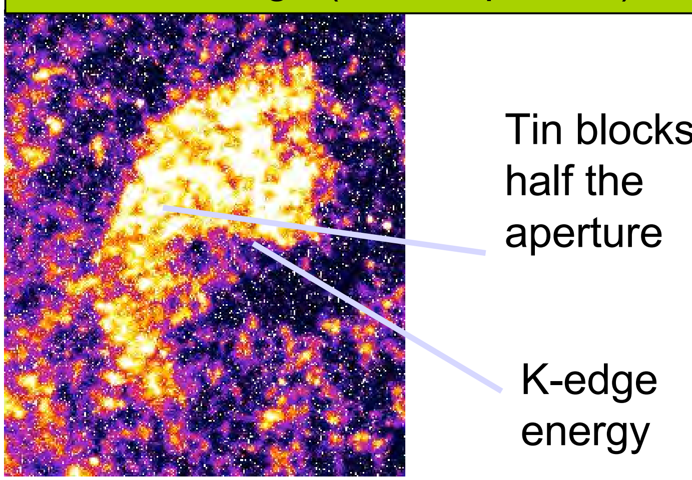
Bragg Diffraction

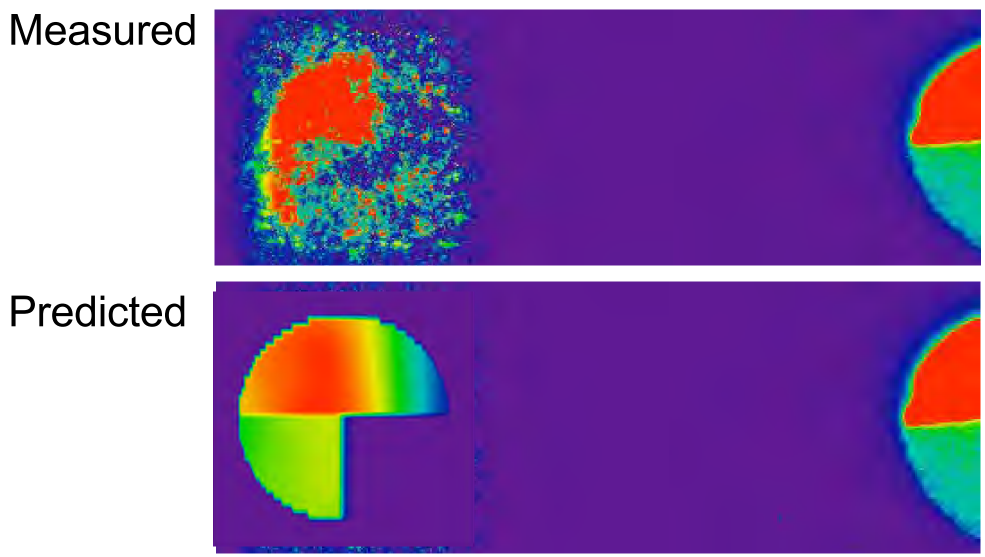


Diffraction from Graphite (HOPG)



X-Ray Diffraction from InSb showing Sn K-edge (round aperture)





Summary

- A tunable final-focusing system based on STRONG PMQ developed
- The system produced 15 micron spotsize
- Increased x-ray yields & diffraction studies performed
- Aiming for 5 micron spotsize with better beam quality