Some observation of chromatic aberration and coherence effects using Be Compound Refractive Lenses.

Eric M. Dufresne

X-ray Science Division,

Advanced Photon Source Sector 7

February 19, 2015, 10am

Technical Working Group, APS .

Outline

Performance of a 1-D parabolic Be Compound Refractive Lens to focus a pink beam

- Introduction, motivation
- Brief overview of APS 7ID current capabilities
- Monochromatic beam performance
- White/Pink beam performance
- Discussion

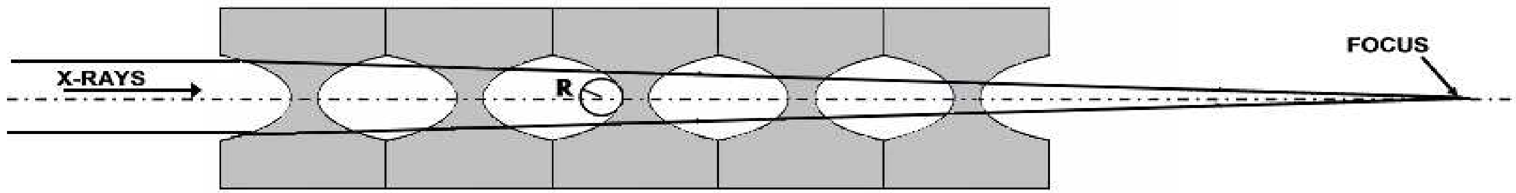
Producing a round beam with a 2-D parabolic Be Compound Refractive

- Introduction, motivation
- Optical modeling and experimental method
- Results
- Discussion

1-D Compound Refractive Lens review

An CRL with five stacked lenslets.

(First demonstrated by B. Lengeler et al., J. Synchrotron Rad. 1999)



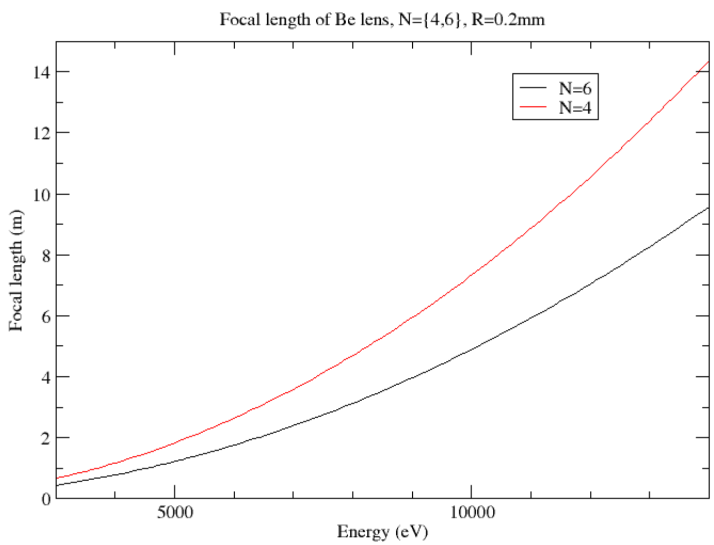
Focal Length → $$f = \frac{R}{2N\delta}$$

- Radius → R
- Index of Ref. decrement → δ
- Number of lenslets → N

Focal Size → $$S'_{h,v} = \frac{S_{h,v}}{D}$$

- Source Size → $S_{h,v}$
- Demagnification Factor → D

Focal length, R=0.2 mm, N=4 and 6



For 8 keV, f= 3.13m for N=6.

The 2nd harmonics will focus beyond 10m from the lens because of the strong chromaticity of CXRLs.

- Advantage: inline focusing, ease of alignment, inexpensive
- Disadvantage: the focal length goes as E^2, so strong chromatic aberrration
- How well would this work with pink beam?

Be lens parameters for one experimental condition

Energy	8 keV
δ	5.33222e-06
1/l	2.08 (cm^{-1})
L	0.00481 m
Radius of curvature R	0.2 mm
N	6
$F=R/(2N\delta)$	3.126 m
Re (source-xprmt distance)	38.3 m
σ_a rms absorption aperture	0.283 mm
Expected focal spot FWHM	0.0027 mm

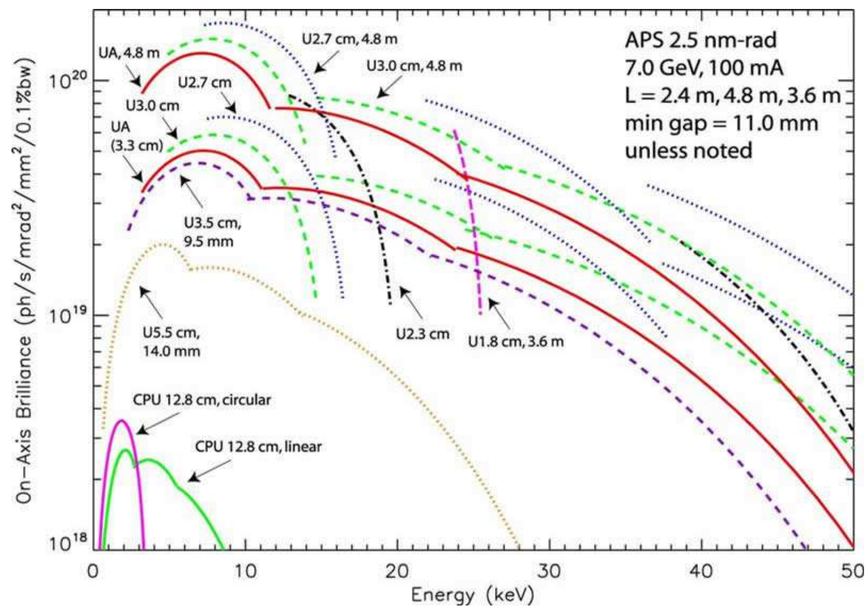
What is the wall thickness [m]?
The wall thickness t between the holes is 0.1 mm(?).
What is the slit opening before the CXRL [m]?
You entered 0.72 mm.
The focal length is 3.12565 m
f = 3.12565, so = 34.8666, si = 3.43345, Re = 38.3 (all m)
The absorption aperture is 0. 283069 mm
The lens radius of curvature is 0. 2 mm
The magnification is 0.098474 (10.155:1)
The RMS beamsize before the lens is 0. 239394 mm
The RMS beamsize after the lens is 0. 18279 mm
The FWHM beamsize at the experiment without the lens is 0. 617852 mm
The FWHM diff. limit. spot size is 5.44392e-07 m
The FWHM image size is 2.71637e-06 m
The wall transmission is 0.882673
The total transmission (walls, absorption, aperture) is 0.673914 (assuming walls of 0.1mm)
The theoretical gain is 153.285
The transverse coherence length in the plane of the lens is 0. 132551 mm

Peak power density of focused pink beam

- From XOP calculations, one expects the peak power density to be around 510 W/mm^2 at 8 keV, about twice the power density at closed gap, in a vertical FWHM of 0.016 mm.
- This will create a lot of thermal gradients and stress in many materials, including scintillator screens used to profile the beam.
- The response of scintillators is also temperature dependent, so if the screen survives, its response may be non-linear.
- This presentation shows how one can sample such high power density with a fast CCD and x-ray choppers.

Refresher on Coherent X-ray diffraction

- Modern 3rd generation sources provide enough partially coherent flux to illuminate a sample of say $(10\mu m)^3$ coherently.
- The coherent flux for a source like the APS, F ~ 4×10^{10} ph/s/eV, 50m from source in a 8.2μm x 197μm aperture at 9 keV.
- Pink beam provides factor 200 or more.

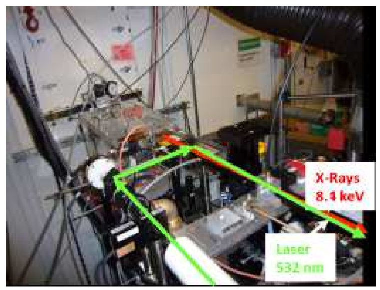


Lower red curve: 1 Und. A

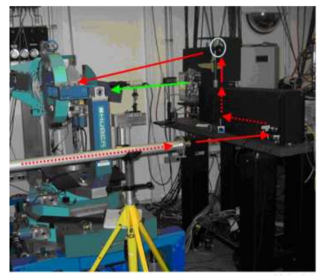
7ID capabilities: 3 Hutches serve time-resolved experiments

- **Focus on Ultrafast Experiments**
  - Laser-pump x-ray-probe spectroscopy
  - Ultrafast Diffraction and microdiffraction
  - Ultrafast imaging
- **Pump types**
  - Laser
  - Electrical pulses
  - Mechanical pump

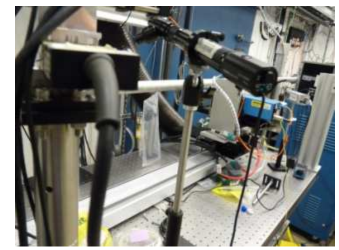
TR Spectroscopy

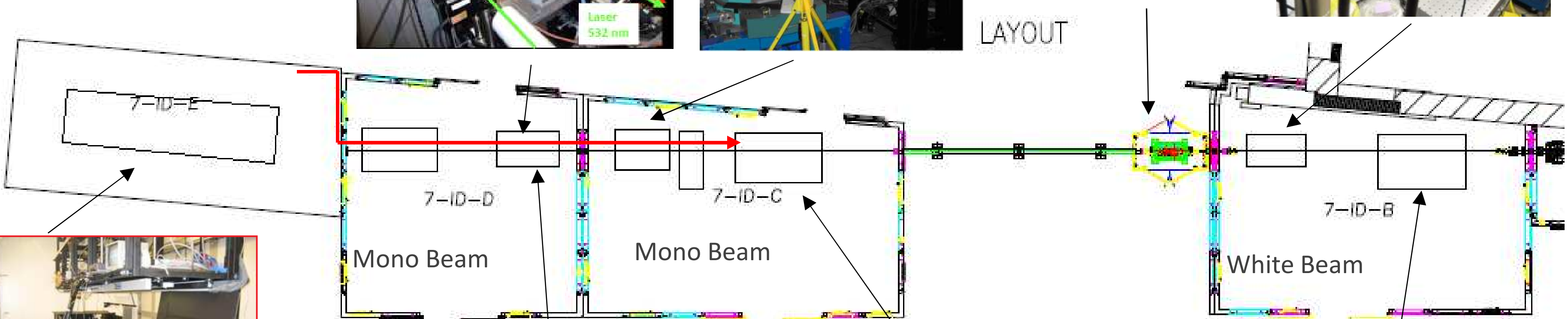


TR Diffraction

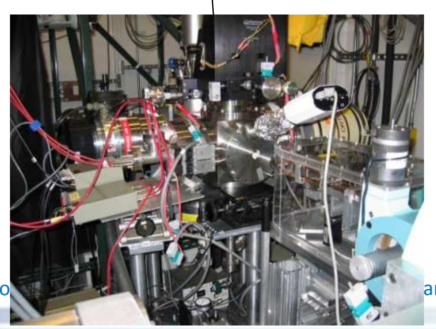


WB Imaging

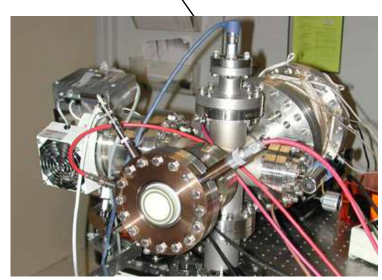




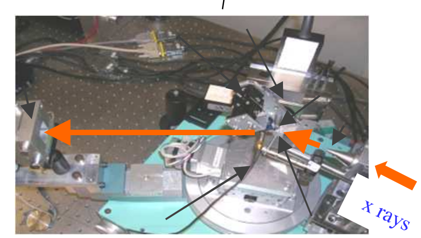
Lasers



AMO chamber



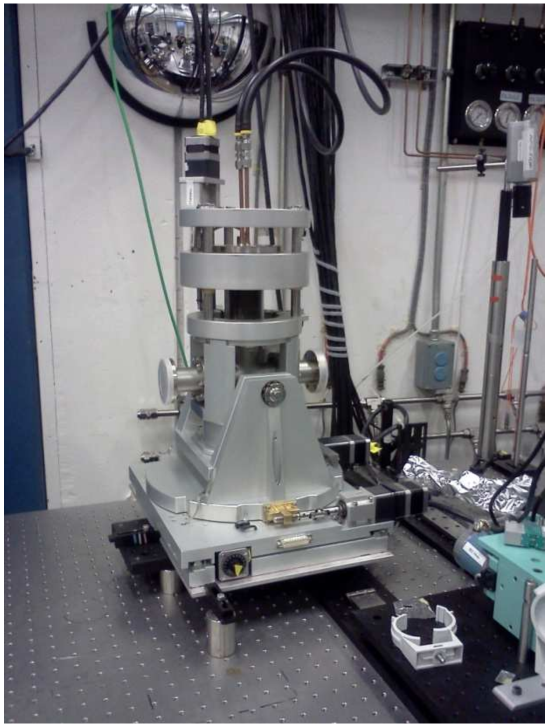
Streak Camera



Nanodiffraction

Monochromatic beam experimental set up

- Experiment in 7ID-B, lens ~35 m from the source, camera about 3.3 m from the lens
- Single Undulator A, Monochromatic beam, diamond (111) set around 10 keV
- Lens: N=10, parabolic coins with R=0.2 mm, and impression is 1D to focus vertically
- Camera: Cooke Sensicam, 1376 x 1040 pixels, 6.4 microns, with X5 or X2 objective, and Lyso single crystal scintillator.
- JJ X-ray cooled CXRL system with 4 motorized axis.

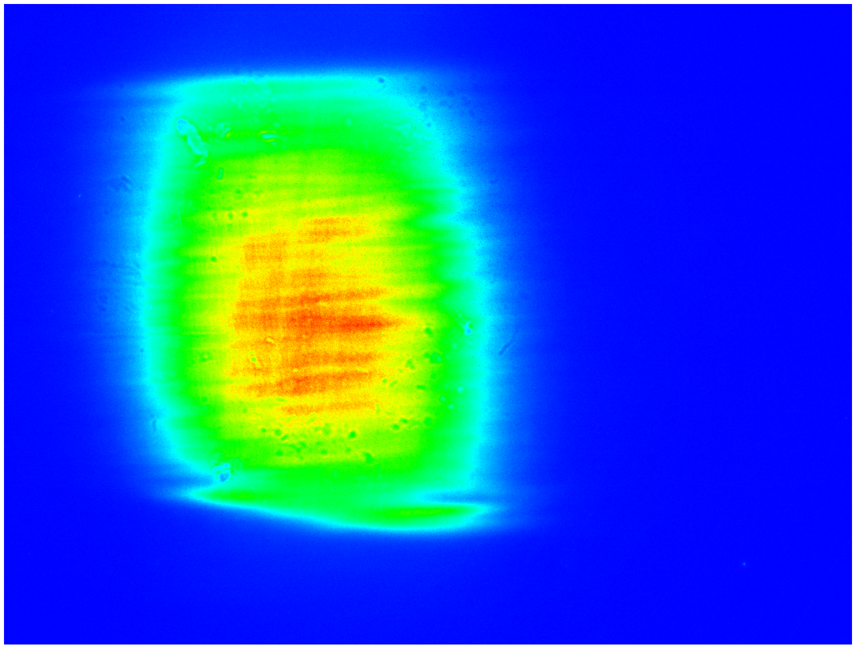


Source and beam sizes

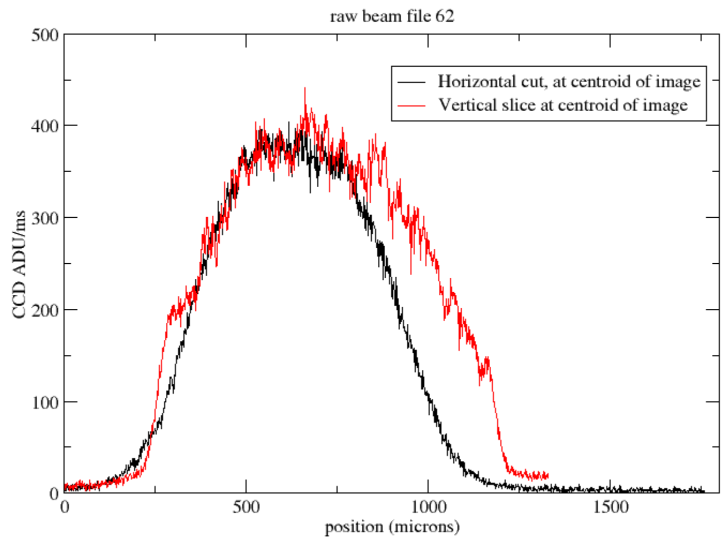
Source parameter	value
RMS Source Size X	0.27 mm
RMS Source Size Y	0.0117 mm
RMS Source Divergence X	13.1 μrad
RMS Source Divergence Y	6.88 μrad
RMS Beam size X in 7ID-B	0.53 mm
RMS Beam size Y in 7ID-B	0.241 mm

- Beam size in 7ID-B at the lens includes the divergence of the electron beam and the ID at 8 keV.
- See Sec. 7 web site Publications/report section for details

Raw 7ID monochromatic beam

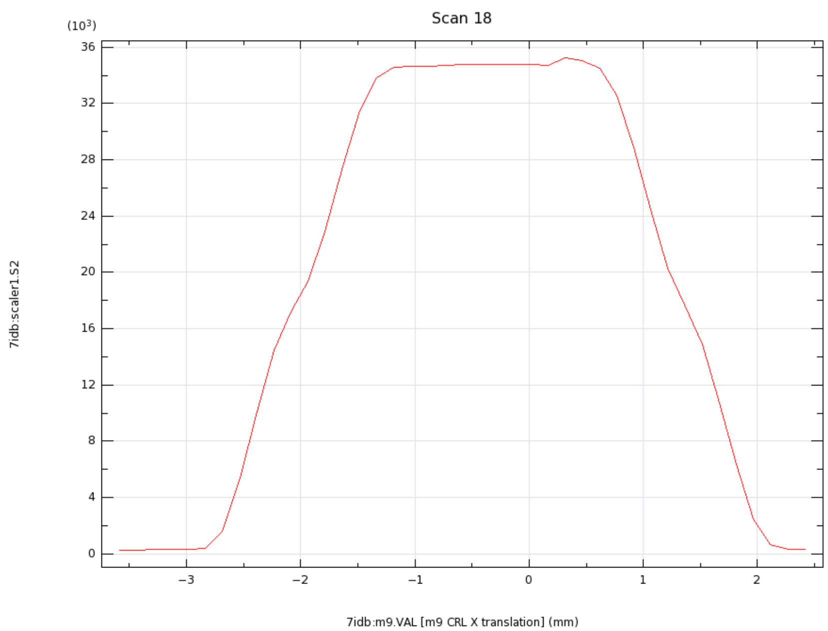


Integrated count 1.03E8/ms, X5 objective, 1.76 mm x 1.33 mm. Color scale from blue to red from 0 to 445 ADU/ms.

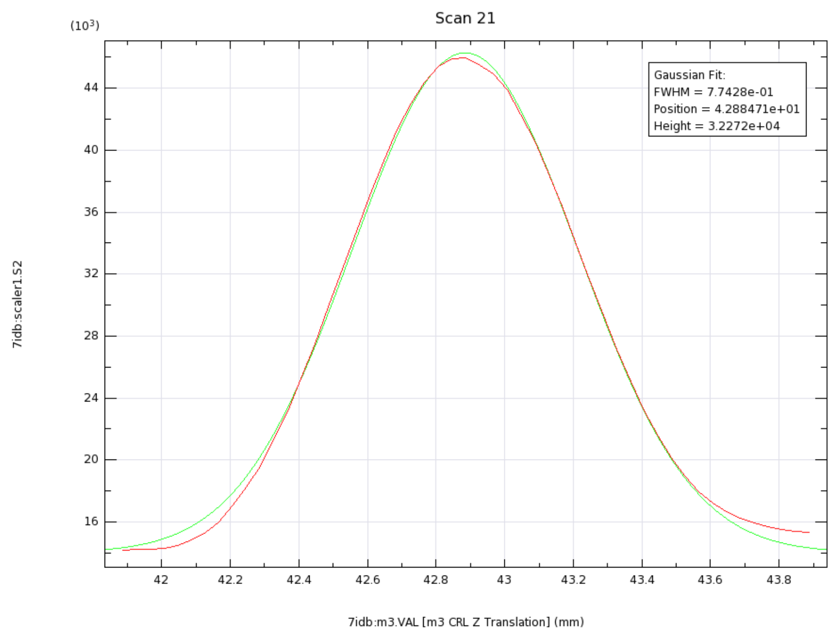


The horizontal FWHM is 0.58 mm. The edges on the vertical beam profile are 0.93 mm apart, likely caused by our white beam slits.

Lens alignment

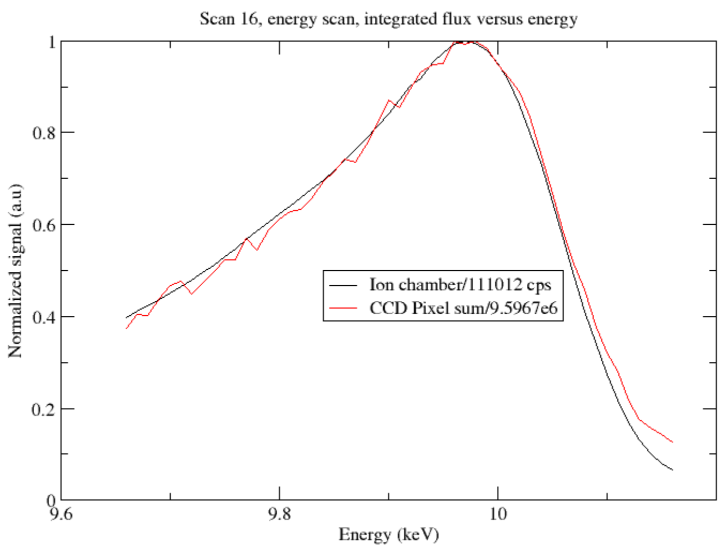


Horizontal acceptance of lens about 2 mm

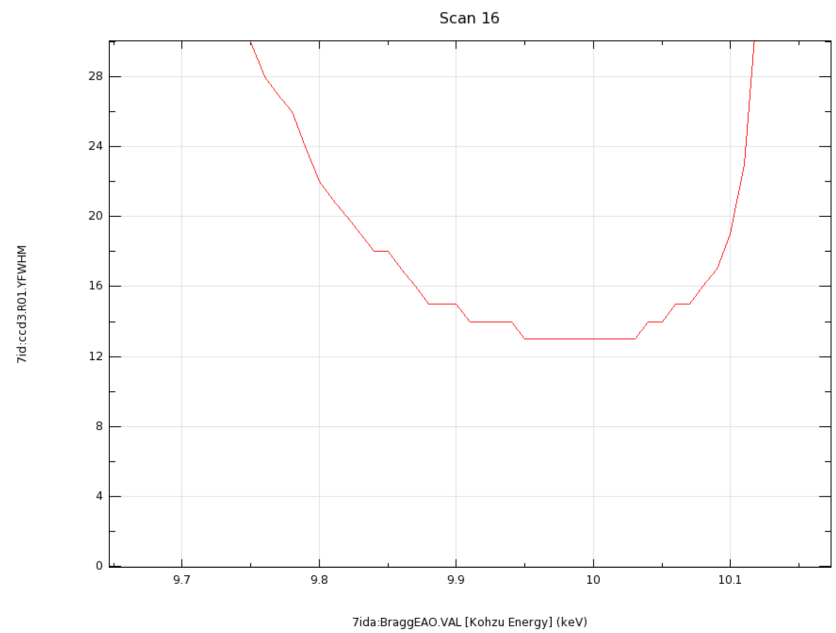


Vertical scan to align lens, red is data, green a fit

Energy optimization for fixed distance

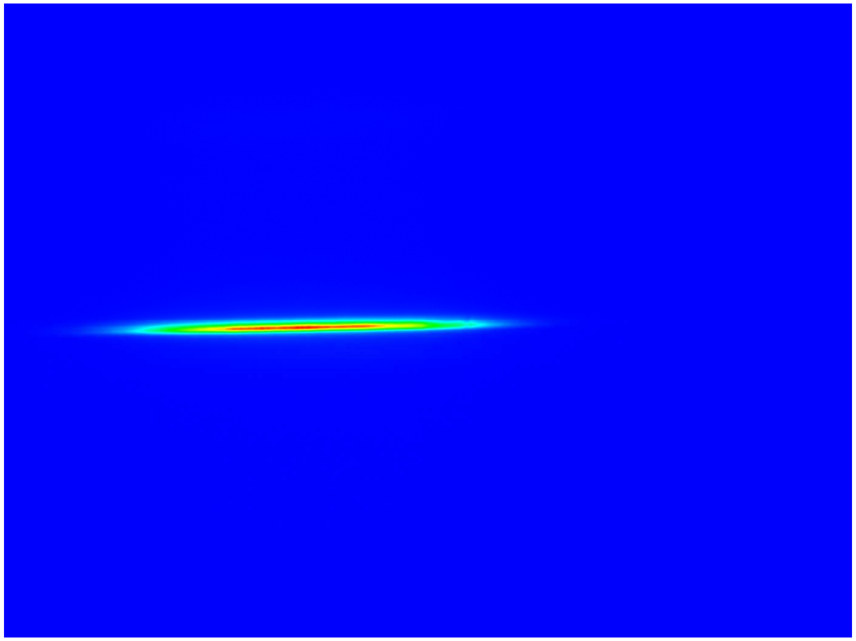


Ion chamber and CCD Integral normalized to their respective maxima.

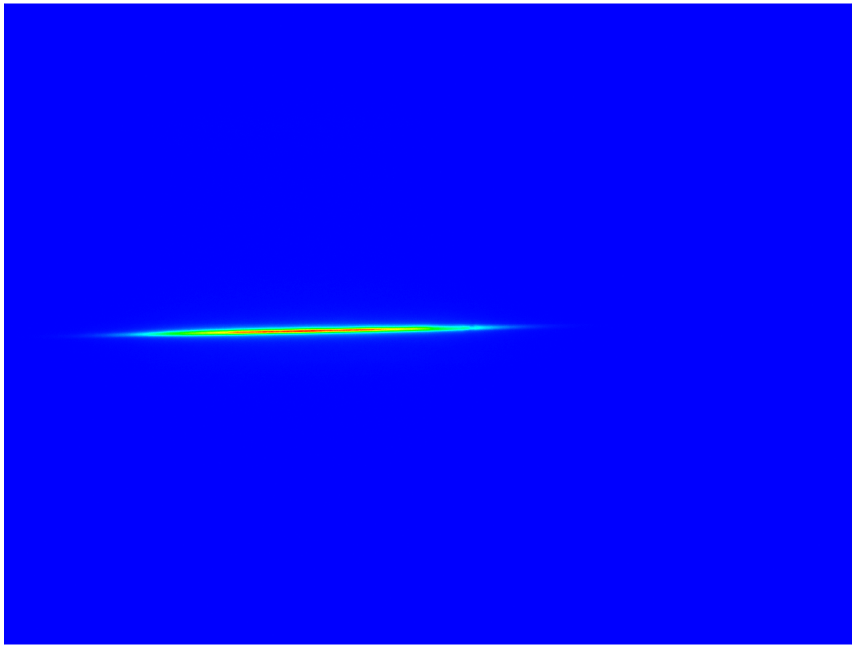


FWHM of vertical profile vs energy, Set to 9.96 keV here (in pixels).

Average image over 500 eV scan versus best focus at 9.96 keV

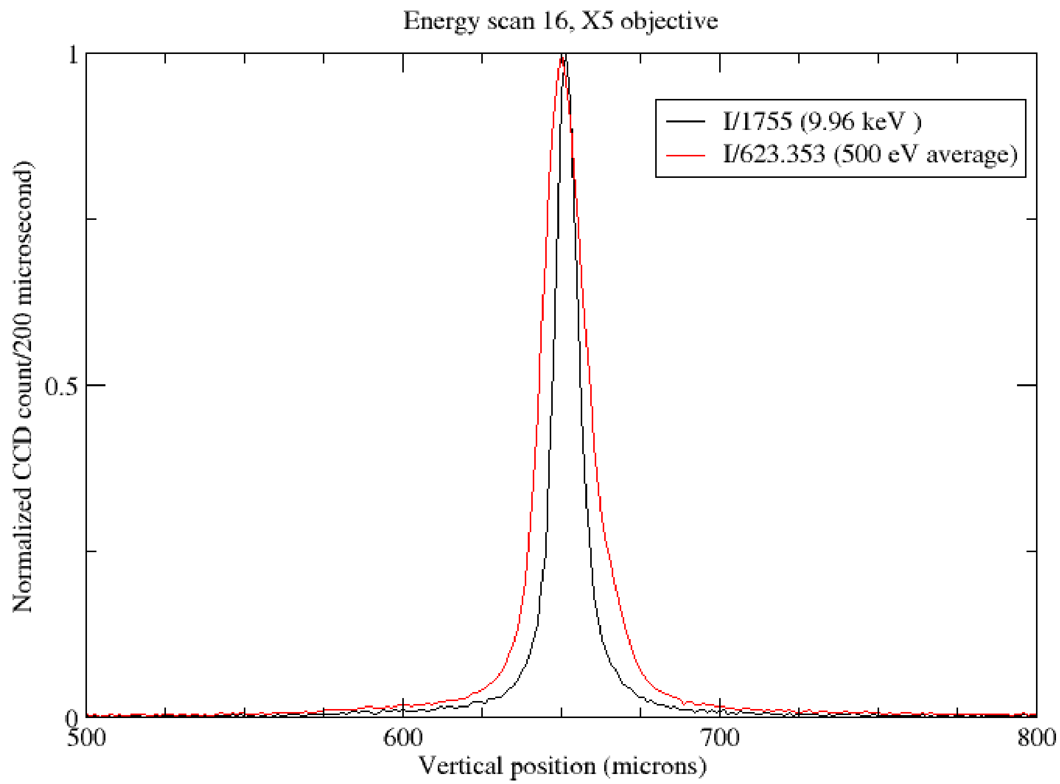


Average from 9.66 to 10.16 keV, 51 pts in scan 16



Single energy, monochromatic beam at 9.96 keV, integrated intensity 9.5967e+06 ADU/0.2 ms, thus the **total transmission is 46.6%.**

Vertical slice of focal images



Average and single image have fwhm of 16.1 and 8.6 μm respectively.

Monochromatic beam discussion

- The vertical source size FWHM is 27.3 microns.
- We imaged the source with magnification 3.3/35.5, thus one would expect a focal spot size fwhm 2.5 micron high.
- We observe a factor 3 worse than the image of the source, which must be due to aberrations.
- About 47% of the incident beam is transmitted through the lens.
- This lens is expected to perform well with focusing a pink beam as shown in the average focus over 500 eV. The average had a focal spot size of 16 microns, well below the required 80 microns for the EBIT experiment.

Using the Phase Contrast Imaging set up in 7ID-B to sample the high power density of the pink beam

Fig. 1 from Ref[2], two chopper are available in 7ID-B to reduce the power. In 324-bunch mode, the total transmission of the two choppers multiplies and should thus be about 0.009%.

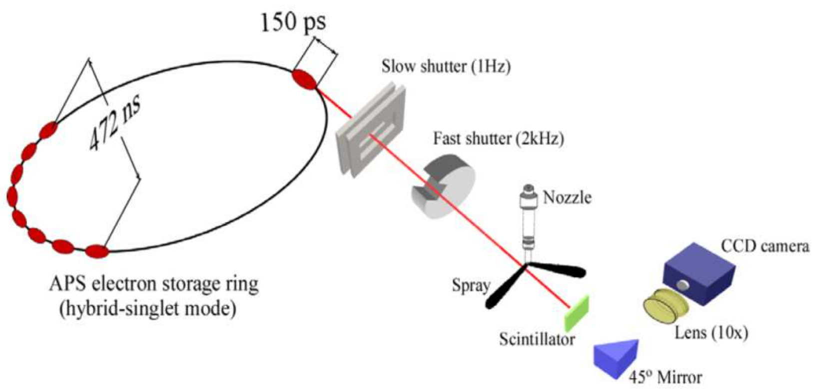


Figure 1. Experimental setup for phase-contrast x-ray imaging

Chopper parameters

	Slow chopper	Hybrid mode chopper
Frequency (Hz)	1	1000
Opening time (ms)	10	0.009
Transmission (%)	1	0.9

White/pink beam set up

- White beam focused with Be refractive lens, R=0.2 mm
- Cases with N=4 and 6 were tested, adjusting the undulator fundamental energy to optimize the focus
- 2 microsecond CCD exposure,
- CCD Cooke Sensicam 6.4 micron pixels, X5 objective, imaging YAG:Ce fluorescence
- YAG:Ce was used as it is more robust to large power densities than Lyso:Ce.

1 Hz electromechanical chopper driven by solenoid used with microsecond chopper (next slide)

Lens safe operation apertures for this JJ system

- Maximum safe angular acceptance of lens:

0.8 mm/35.5 m = 22.5 μrad (V), 2.5 mm/35.5m = 70.4 μrad (H)

- Maximum Acceptance of beamline

2mm/25.5m = 78.4 μrad (V), 3mm/25.5m = 118 μrad

- White beam slits are essential here to act as a mask, the beamline fan is 3.5 times the lens vertical fan, and 1.7 times its horizontal fan.
- Useful operation of lens in 7ID-B, use 3 sigma acceptance of beam size 1.6 mm (H) by 0.72 mm (V).

Overview of current APS chopper

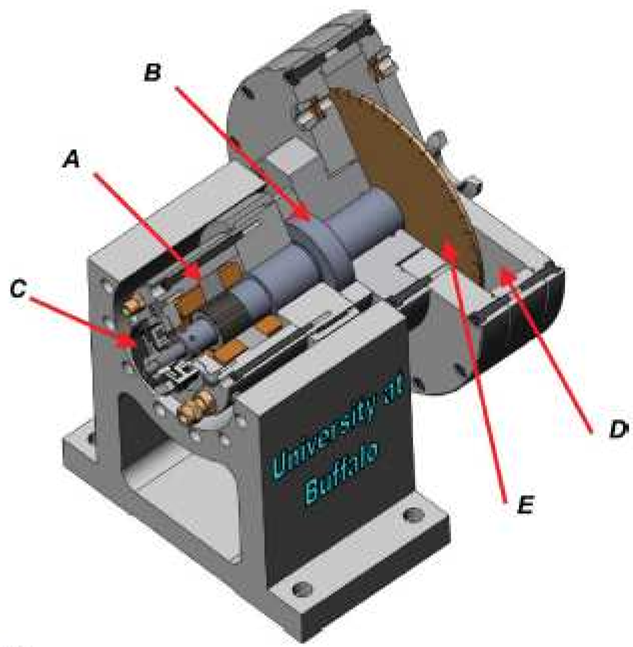
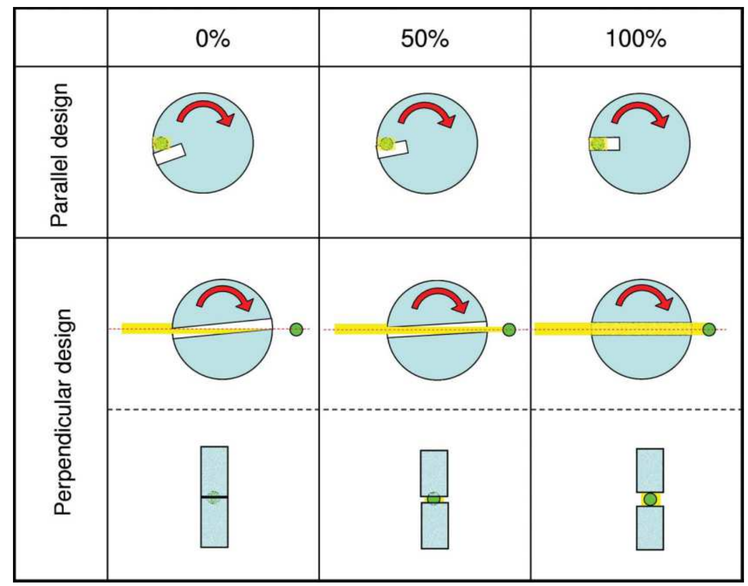


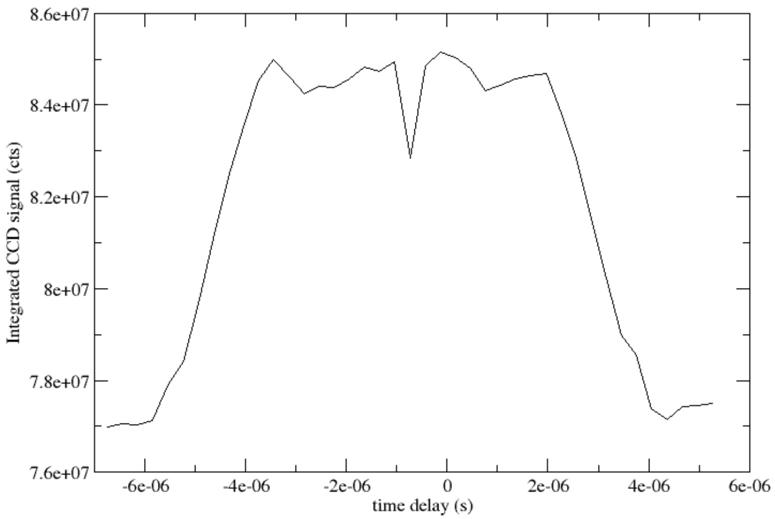
Figure 2
Cross-section view of the chopper with mounting bracket. See text for marked items.

From Gembicky et al, JSR 2005
A servo motor
B air bearing
C optical encoder
D vacuum chamber
E wheel



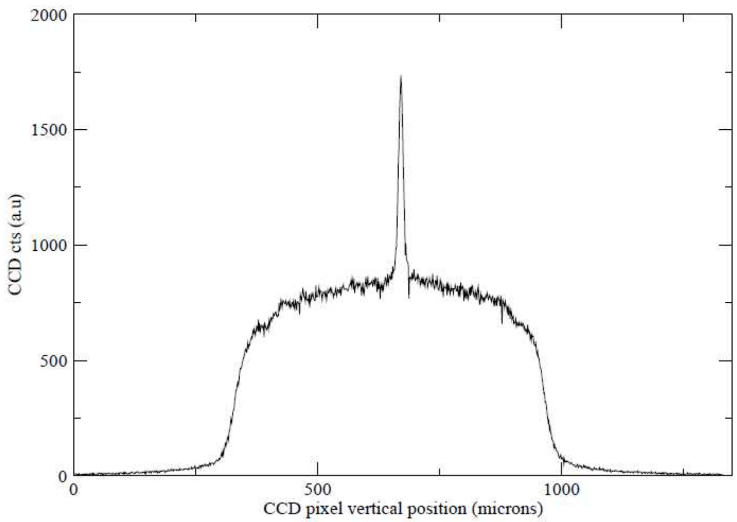
From J. Synchrotron Rad. (2007). 14, 133–137. Note that perpendicular design is twice as fast for opening time

Chopper opening



- Chopper opening, showing a delay scan between the camera trigger and the wheel arrival.

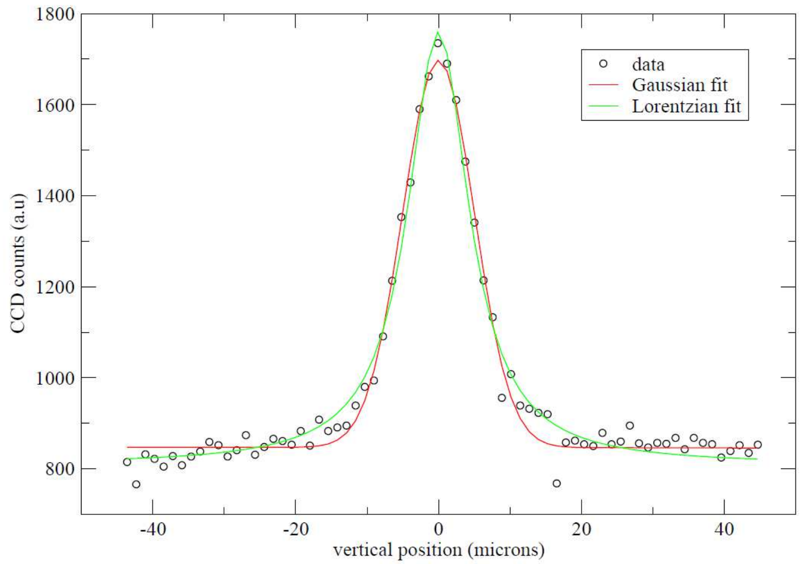
Typical vertical focus with pedestal, N=4, 6.1 keV



CCD exposure 2 microsecond, not overexposed.

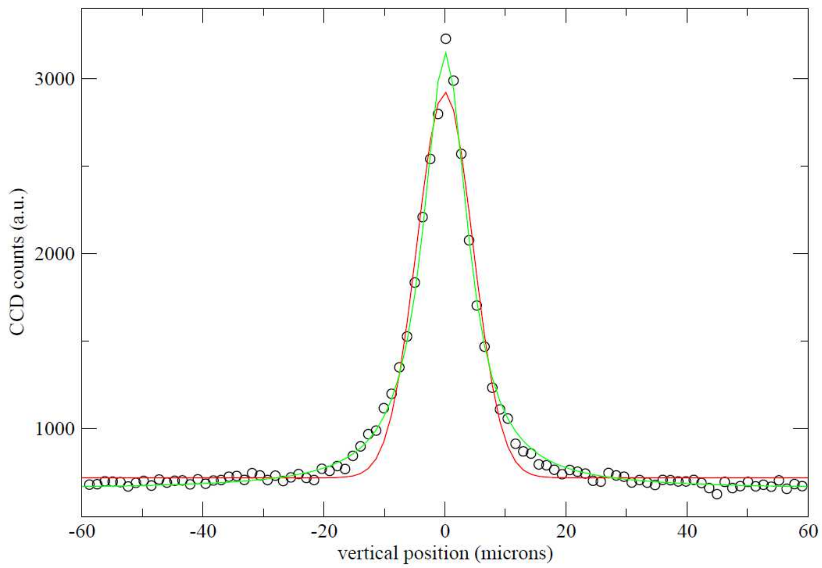
- Fundamental focus over a large pedestal caused by higher harmonics.
- This is not a concern for the experiment planned for this optics.
- Background could be removed with flat grazing incidence mirror.

Pink beam focal spot size at 6.1 keV, N=4



- Data best fit to a Gaussian (xsqr=915 vs 1067 for Lor.)
- Gaussian FWHM is 11.8 µm (10.4 µm for the Lorentzian)

Pink beam focal spot size At 7.47 keV, N=6



- Best fit is Lorentzian
- FWHM is 9.1 μm (Gaussian fit is 10.6 μm)
- Signal to background ratio is 3.8 at this energy, versus 1.2 at 6.1 keV.

Discussion

$NA = \sigma_a/f$. Typically the physical aperture of a refractive lens

$$\sigma_a = \sqrt{f\delta l}, \quad (2)$$

is limited by the absorption length l, materials properties and geometry. Adding this latter broadening in quadrature with σ_i, we expect the pink beam focal spot size to be

$$\sigma_{ip} \approx \sqrt{\sigma_i^2 + (2\sigma_a\sigma_E/E)^2}. \quad (3)$$

Table II shows the expected broadening from focusing a pink beam. Here $R = 0.2$ m, $\sigma_s = 11.6$ μm, $r_s = 35.5$ m, and $\sigma_E/E = 1\%$. The rough estimate of the focal spot size of the pink beam is significantly larger than σ_i, but remains in this example below 10 microns. This beam size would suite many modern synchrotron experiments, and is adequate for the proposed EBIT experiment.

Energy (keV)	N	f (m)	δ	l (mm)	σ_a (μm)	σ_i (μm)	σ_{ip} (μm)
6.1	4	3.3	9.178e-06	2.46	273	1.08	5.6
7.47	6	3.3	6.117e-06	4.75	310	1.08	6.3
9.97	10	3.3	3.432e-06	12.2	372	1.08	7.5

TABLE I. Expected spot size from simple theoretical estimate, assuming $\sigma_E/E = 1\%$.

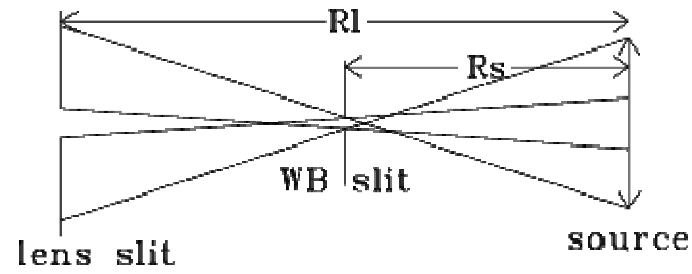
- Theory estimating effect of chromatic aberration for Gaussian energy spread is in good agreement with the data.
- Even for energy spread of a few percent, focal spot sizes around 10 microns were achieved.
- These aberration would be smaller with X-ray FEL pink beams where the energy spread is typically 0.1%.

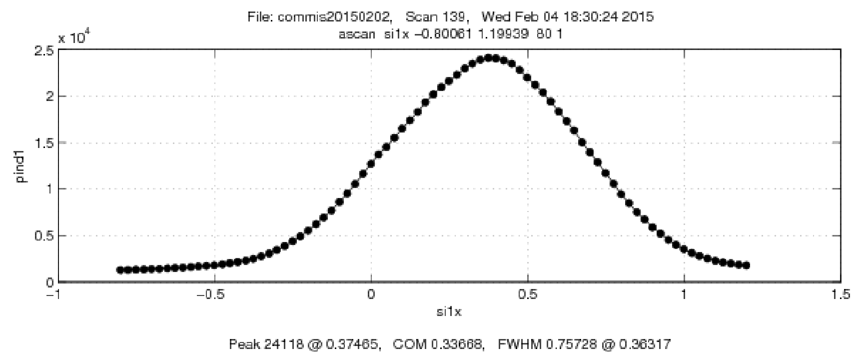
2D diffraction limited focusing with Be lens on 8-ID

- Vertical focusing in X-ray Photon Correlation Spectroscopy is a routine procedure to reshape the coherence area to make it more square.
- For some XPCS experiment, it may be advantageous to focus also in the horizontal direction to produce a round coherent beam. It has been done in the past at the APS on beamline 2-ID-B, 2-ID-D, and 8-ID-E with zone plates.
- It could be beneficial to use instead CXRL because it increases the transmission of the lens, and can produce gentler focus, a few microns wide.
- 2D focusing also can increase the speckle contrast when using large Pixel Array Detector (PAD) such as the Pilatus from the detector pool.
- At 7.35 keV, a Quantum Medipix pixel of 55 microns at 1 meter from the sample will subtend one speckle if the focus is below 3 micron.
- To achieve diffraction limited focusing horizontally, we must reshape the horizontal transverse coherence length to match the vertical coherence lens ~125 microns typically used on 8-ID.
- This is typically done with a slit acting as a spatial filter.

Horizontal beamsize at the lens, for one Und. A at 11 keV.

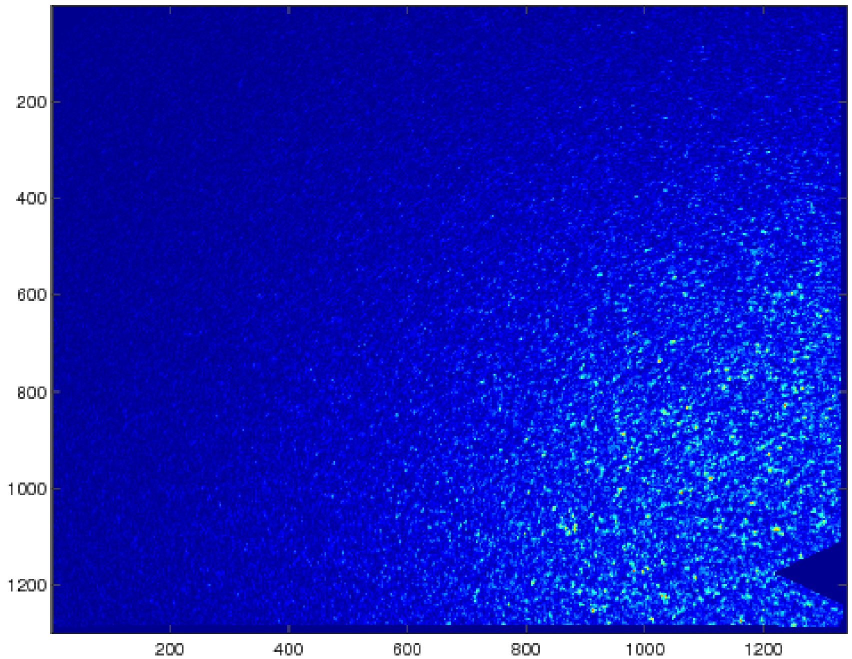
- Lens illuminated with a coherent fan set by a 32 micron slit 27 m from the source producing a 125 micron diffraction pattern at 66.9 m.
- White beam slit reduces flux but diffracts a coherent fan matching the vertical coherence length.
- Beam profile at the lens is a pinhole camera image of the source.



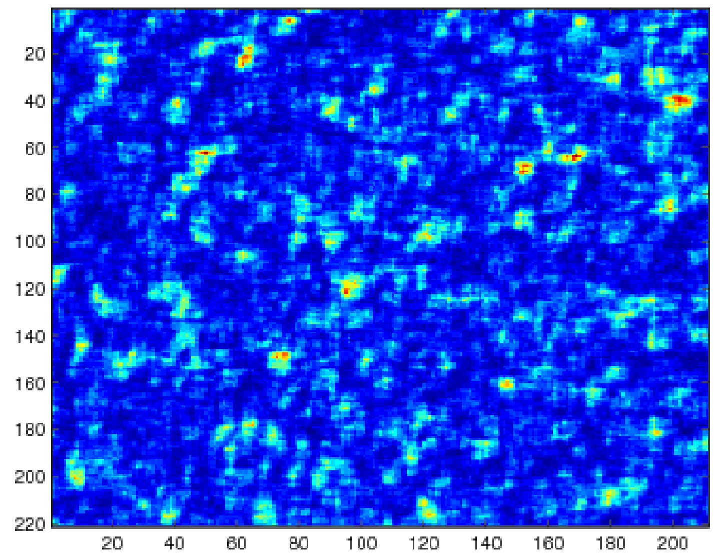


Horizontal beam profile before the lens, FWHM = 0.76 mm.
Calculate a FWHM of 0.95 mm from the pinhole camera image of the source.

Speckle from an aerogel will change as a function of the spot size.

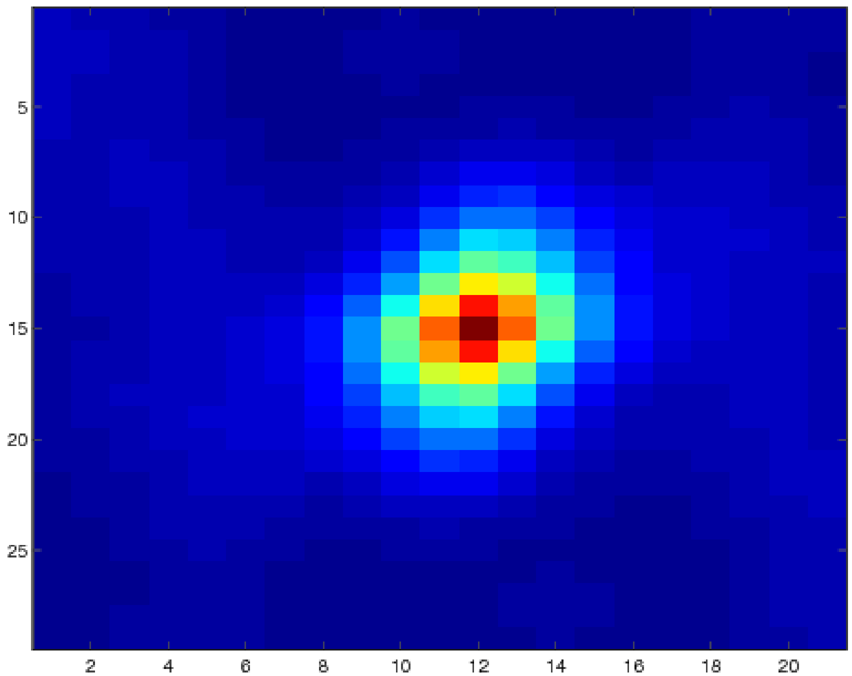


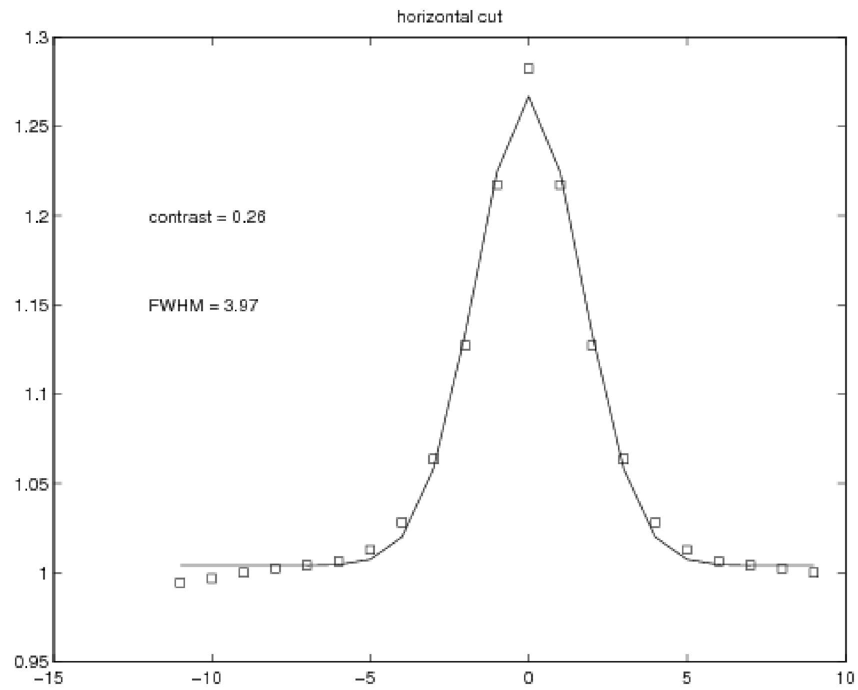
Speckle from an aerogel on 8-ID-I near 11 keV



Smaller area of LHS speckle pattern

Spatial autocorrelation function: a tool to measure speckle size.

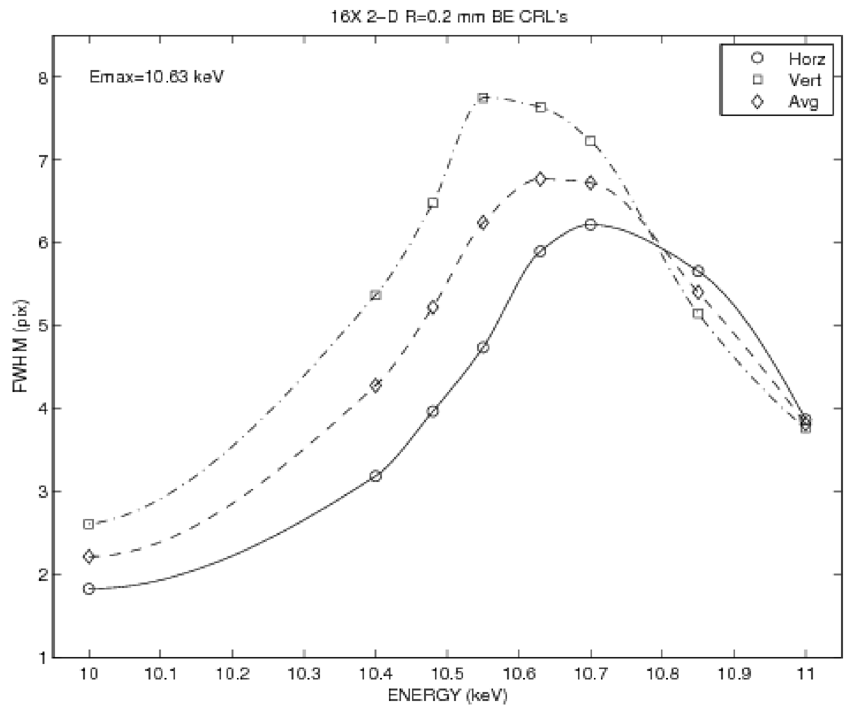


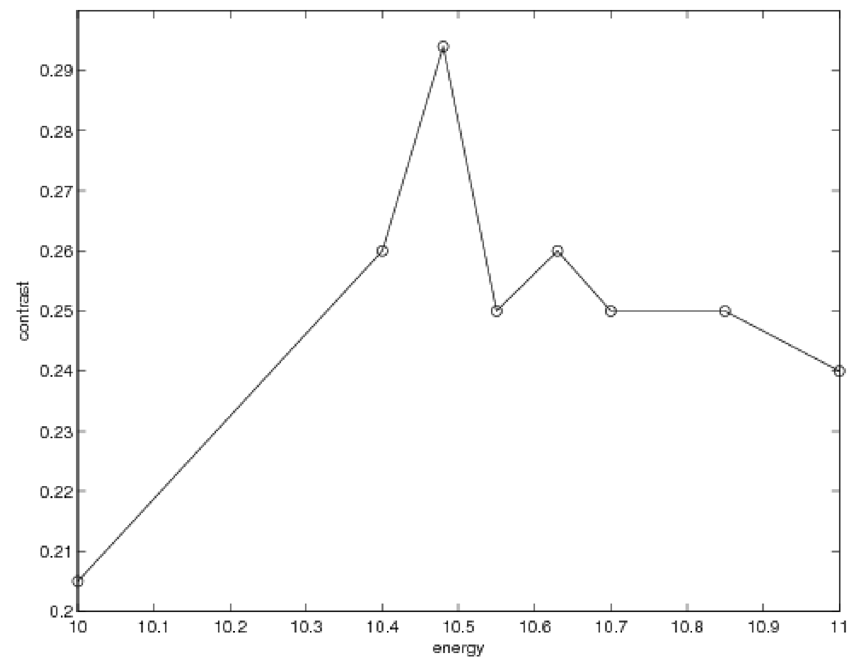


$C(\Delta x,\Delta y) = \langle I(x,y)I(x+\Delta x,y+\Delta y)\rangle_{x,y}$

The bracket is a 2D spatial average.

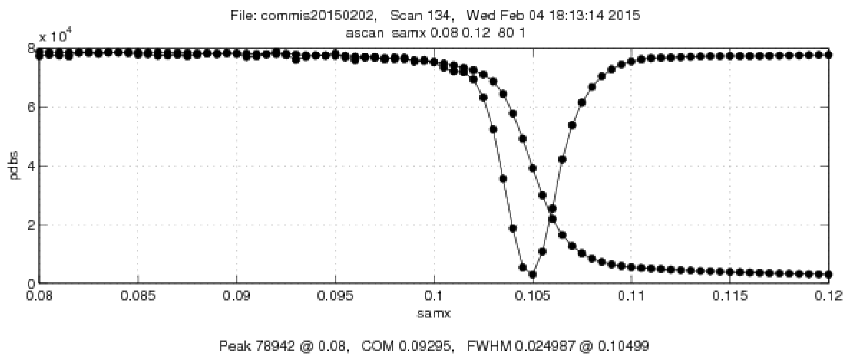
Tuning the focal length with an energy scan between 10-11 keV.

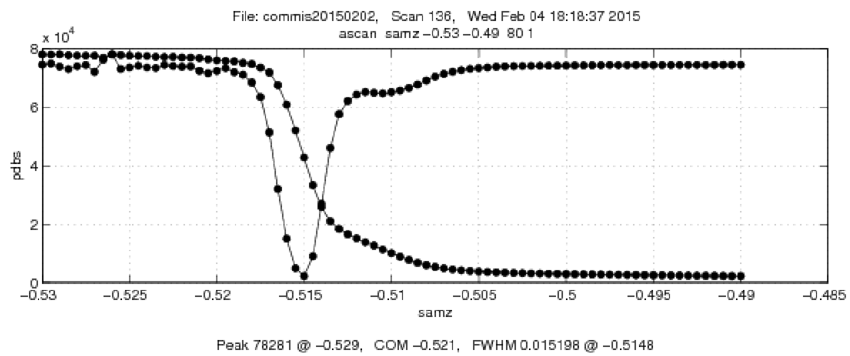




Ge (111) DCM in 8-ID-I scanned with undulator to move the focus before (low energy side) and after the sample.

Observed focus, step size 0.5 microns, with knife edge transmission scan



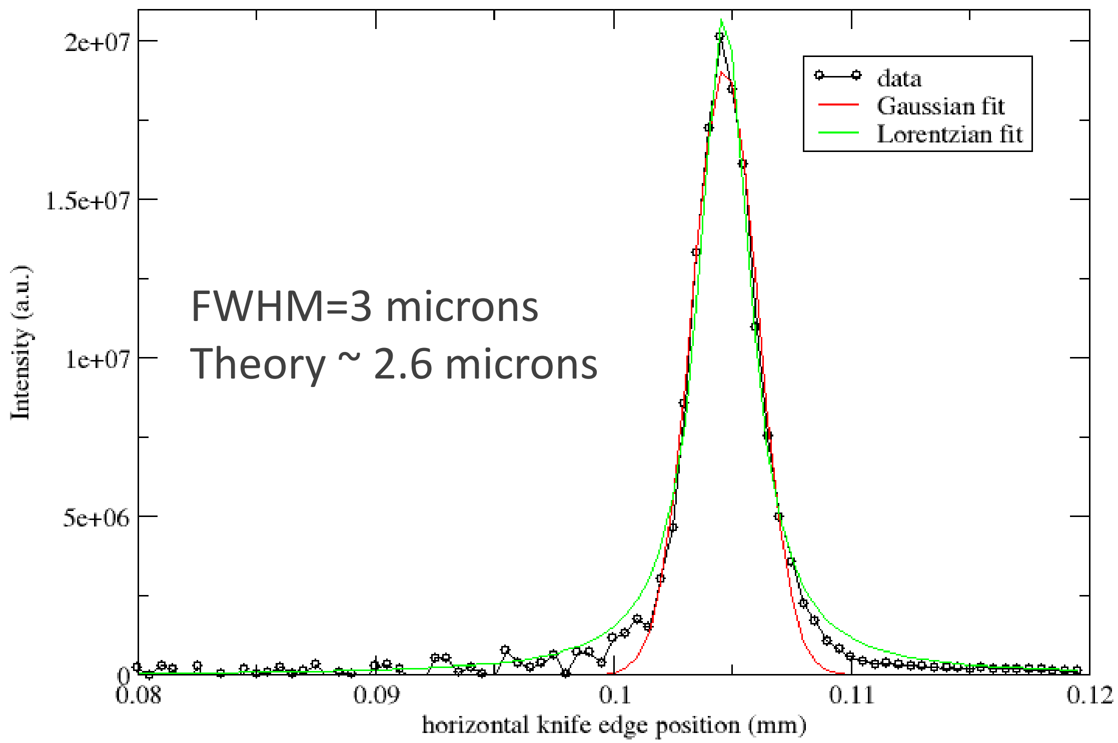


Horizontal focus about 3 microns

Vertical focus, also ~3 microns

Horizontal focus lineshape

Coherent flux: 1.32 x 10^{10} ph/s at 10.6 keV, 1 Und. A



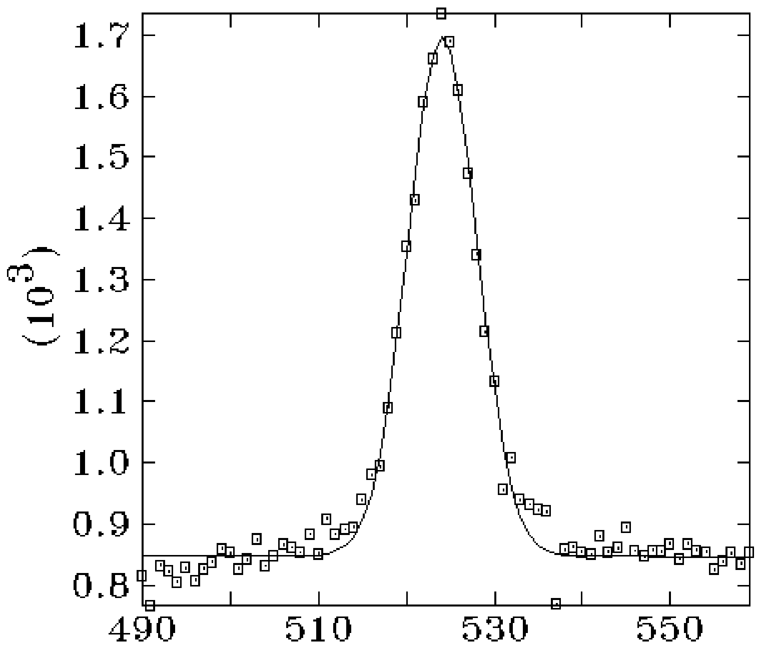
Discussion

- The experimental work was guided by Shadow ray traces including coherent diffraction. These were performed at another energy and beamline, but are qualitatively in good agreement with these results.
- This approach delivered a flux at 10.6 keV a factor 2.9 higher to the 8-ID-I coherent flux without focusing (13.4x13.4 μm^2) but with a round beam of 3 microns.
- We could gain also by increasing the slits to match the vertical transverse coherence length (x1.77).
- This may be advantageous to use with Modern PAD with larger pixel size than CCD.
- It would be well suited for sample insensitive to radiation damage.
- For sample that are sensitive to radiation damage, one would likely benefit in longer focal lengths. Although we note that as the lens aperture becomes closer to the white-beam slits, the collimation effect would be reduced.

Acknowledgements

- On 7-ID, Robert Dunfort, Yuan Gao, Harold Gibson, Elliot Kanter, Seoksu Moon, Don Walko, Xuseng Zhang (XSD).
- On 8-ID, Suresh Narayanan, Ruben Reininger, Alec Sandy, Ray Ziegler (XSD), Larry Lurio (NIU), and Michael Fischer (AES).
- This work was performed on beamline 7 and 8-ID of the APS. Use of the Advanced Photon Source, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science by Argonne National Laboratory, was supported by the U.S. DOE under Contract No. DE-AC02-06CH11357.
- This work was also supported by an Argonne LDRD 2009-146-R1 “Laboratory Simulations of Plasma Conditions near Active Galactic Nuclei and Black Holes, E. Kanter, R. Dunford, L. Young.

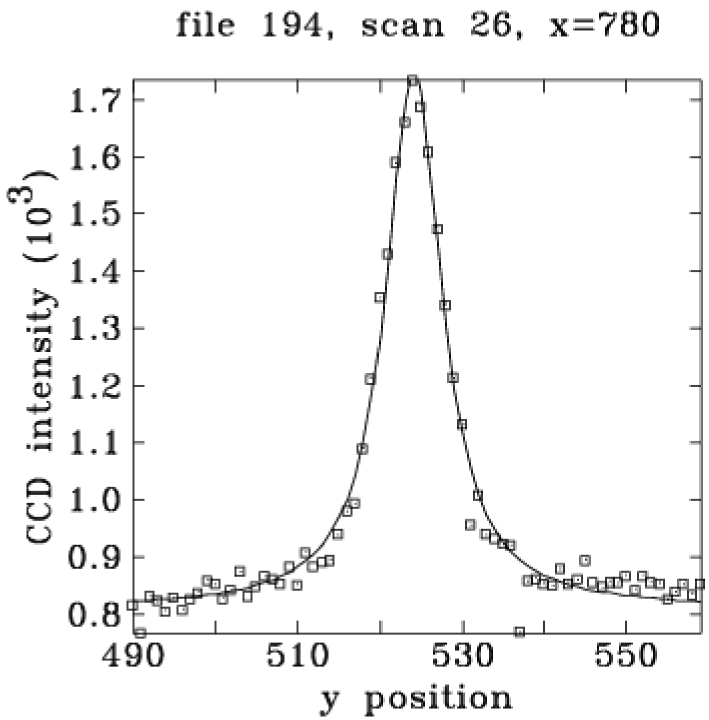
Gaussian fit of 6.2 keV fit



File 194, slice x=780, data from row 490-560 , FWHM is 2.35*3.92*6.4/5 microns or 11.8 microns

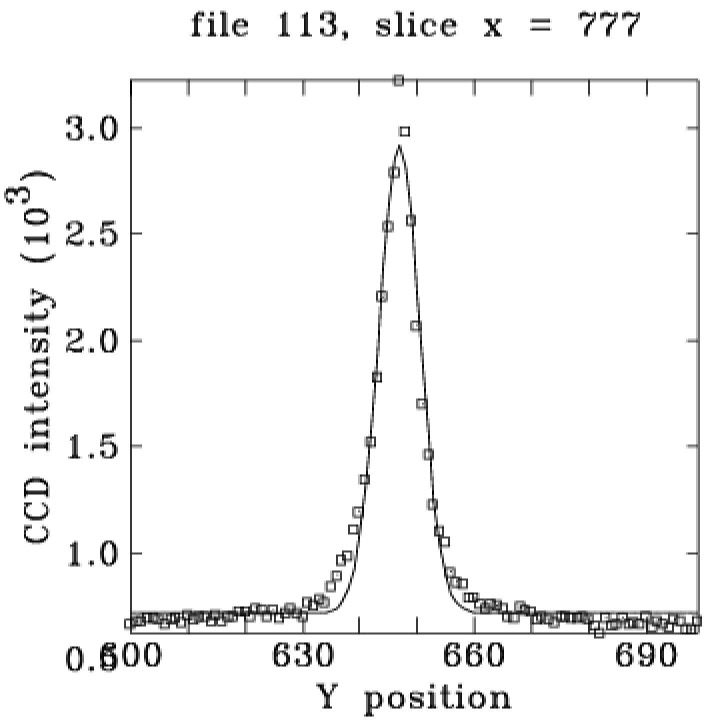
- xisq = 915.084 param = 0
- I1 b[0] = 850.49 +/- 14.0488
- CENTER1 b[1] = 524.07 +/- 0.0748411
- SIGMA1 b[2] = 3.9237 +/- 0.0748406
- I2 b[3] = 847.26
- CENTER2 b[4] = 500
- SIGMA2 b[5] = 1000

Lorentzian fit at 6.2 keV



- xisq = 1061.79 param = 0
- INT b[0] = 951.19 +/- 18.3085
- WIDTH b[1] = 4.0704 +/- 0.134879
- CENTER b[2] = 524.09 +/- 0.0779908
- BACKGROUND b[3] = 808.76 +/- 5.73251

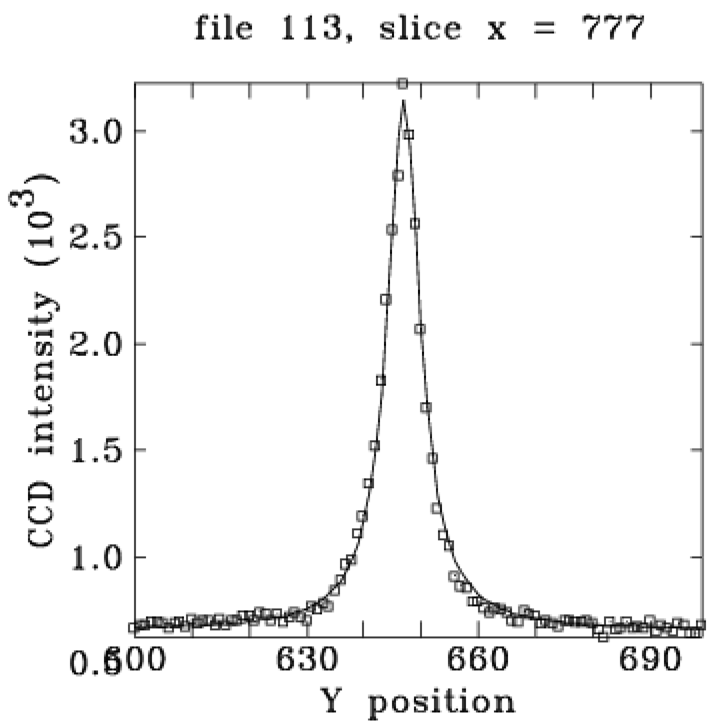
Gaussian fit at 7.47 keV



File 113, slice x=777, data from row 600-700 , FWHM is 2.35*3.62*6.4/5 microns or 10.9 microns

- xisq = 5842.68 param = 0
- I1 b[0] = 721.17 +/- 8.50552
- CENTER1 b[1] = 647
- SIGMA1 b[2] = 10000
- I2 b[3] = 2199.8 +/- 37.4565
- CENTER2 b[4] = 646.88 +/- 0.0702061
- SIGMA2 b[5] = 3.6176 +/- 0.0729392

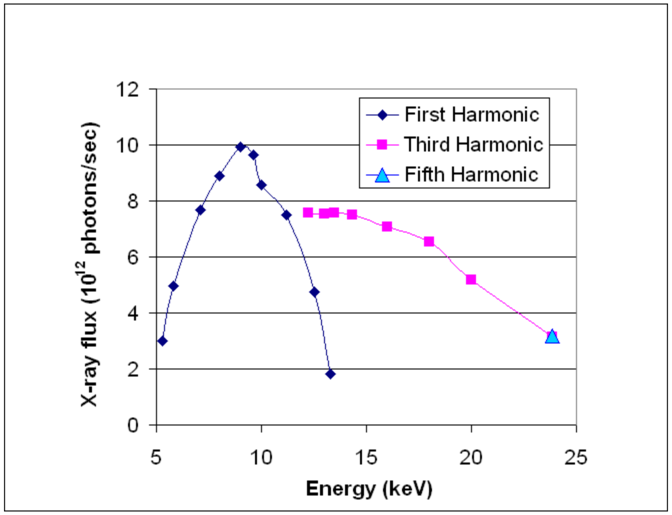
Lorentzian fit at 7.47 keV

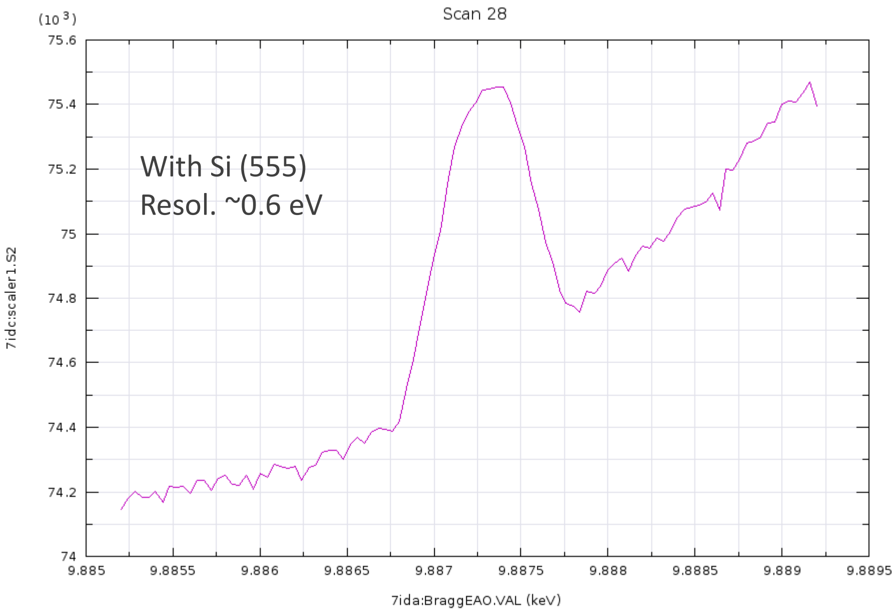


- xisq = 1217.38 param = 0
- INT b[0] = 2490.8 +/- 20.9496
- WIDTH b[1] = 3.5378 +/- 0.0473106
- CENTER b[2] = 646.95 +/- 0.029731
- BACKGROUND b[3] = 656.29 +/- 4.39397

7ID capabilities

- 7ID uses an APS Undulator A, with a 3.3 cm period and 72 poles.
- 7ID-A hutch houses a Kohzu HLD4 with good diamond (111), with a range from 5-24 keV. Many Be windows reduce the flux at low energies.
- An APS P4-20 Mode shutter allows white or mono beam in 7ID-B, allowing some **white beam experiments in 7ID-B** without lasers.





Why is this the first talk?

This is the Title of the Abstract: style is in 14-point Arial font*

First Author[1], Second Author[2], Third Q. Author[3] Author List style is in 11-point Arial font

[1]Affiliation of First Author, Address, City, Country Affiliations style is in 11-point italic Arial font
[2]Affiliation of Second Author, Address, City, State, Zip Code, Country
[3]Affiliation of Third Author, Address, City, State, Zip Code, Country

* Work Support Statement style, if required, is in 10-point Arial font. Referencing asterisk is located on the abstract title.

Abstract:
This is the abstract that will appear in the SRI2010 Conference Program Book. The easiest way to use this template is to type your abstract in another Word file or a text file. Then open this template and 1) copy each separate section in the original document, 2) select the corresponding section in the template, and 3) use Edit → Paste Special → Unformatted Text to paste your text over the text in this template [1].

For the text of the abstract; use Abstract Text style in 11 point Arial font, justified text. Use the styles provided for each section as indicated in the yellow highlighted text [2]. If the Work Support Statement (above) is not needed, you should delete it together with the asterisk following the title of the paper.

The complete abstract may not exceed one page in length. References and figures are permitted (but not required), and if included should conform to the guidelines below. However, color figures cannot be included in the abstract.

References:
[1] Ngoc T. Nguyen, Brandon Howe, Juliana R. Hash, Nicholas Liebrecht, Paul Zschack, David C. Johnson, Chem. Mater. **19**, 1923-1930 (2007) References style is in 10-point Arial font.
[2] D.A. Arms, E.M. Dufresne, R. Clarke, S.B. Dierker, N.R. Pereira, D. Foster, Rev. Sci. Instrum. **73** (3), 1492-1494 (2002).
[3] Y.Z. Yoo, O. Chmaissem, et. al., Appl. Phys. Lett. **89** (24), 124104-1-124104-3 (2006).

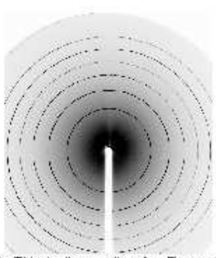


Figure 1: This is the caption for Figure 1 of this abstract. Figure Caption style in 10-point Arial font.

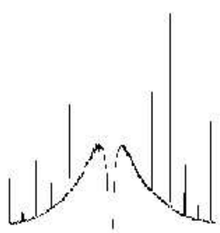


Figure 2: This is the caption for Figure 2 of this abstract.

Performance of a 1-D parabolic Be CRL to focus a pink beam from an undulator at the Advanced Photon Source.

Eric M. Dufresne[1], Elliot Kanter[1], Robert Dunford[1], Yuan Gao[1], Seoksu Moon[1], Donald A. Walko[1], and Xuseng Zhang[1]

[1]Advanced Photon Source, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL, USA.

* Use of the Advanced Photon Source, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science by Argonne National Laboratory, was supported by the U.S. DOE under Contract No. DE-AC02-06CH11357.

Abstract:

We have tested the performance of a cooled Be compound refractive lens (CRL) [1] in the Advanced Photon Source (APS) 7-ID-B hutch to enable vertical focusing of the pink beam in that hutch and permit the x-ray beam to spatially overlap with a 80-micron-high low density plasma. This well-controlled plasma is produced by an electron beam in a new Electron Beam Ion Trap (EBIT) that is designed to simulate astrophysical environments [2]. Focusing the fundamental harmonics of an insertion device white beam increases the APS power density; here we calculate a power density as high as 510 W/mm^2. Fortunately, a CRL is chromatic so it doesn't efficiently focus x-rays whose energies are above the fundamental. Only the fundamental of the undulator focuses at the EBIT experiment. A chopper system designed for white-beam phase contrast imaging, made of two choppers, reduces the power density on the imaging system and lens by 4 orders of magnitude, enabling imaging without any x-ray filter. We report the method to measure such high power density as well as the performance of the lens in focusing the pink beam.

References:
[1] D.A. Arms, E.M. Dufresne, R. Clarke, S.B. Dierker, N.R. Pereira, D. Foster, Rev. Sci. Instrum. **73** (3), 1492-1494 (2002).

[2] Work Towards Experimental Evidence Of Hard X-Ray Photoionization In Highly Charged Krypton, E. Silver, J. D. Gillaspy, P. Gokhale, E. P. Kanter, N. S. Brickhouse, R. W. Dunford, K. Kirby, T. Lin, J. McDonald, D. Schneider, S. Seifert, and L. Young, AIP Conference Proceedings **1336** 146-149 (2011).