Beryllium and Lithium Compound Refractive X-ray Lenses at APS

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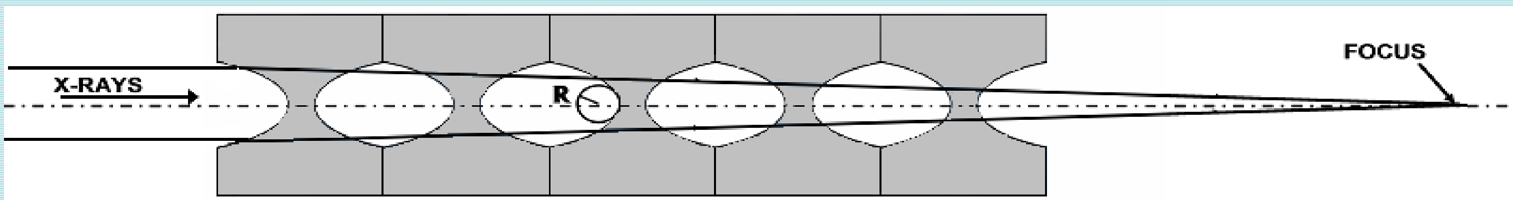
Background

- Mirrors, crystals, zone-plates, lenses, capillaries, and wave guides are used to focus x-rays.
- Selection is based on the applicability, availability, throughput, ease of use, cost, etc.
- Compound refractive lenses (CRLs) are a relatively recent addition.
- CRLs are arrays of (contiguous or modular) concave lenslets used in tandem to focus x-rays.
- CRLs advantages: simple design, ease of implementation and alignment, low cost, insensitivity to surface figure and finish.

Compound Refractive Lens

An CRL with five stacked lenslets



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

Lens Selection

Factors to consider regarding CRLs:

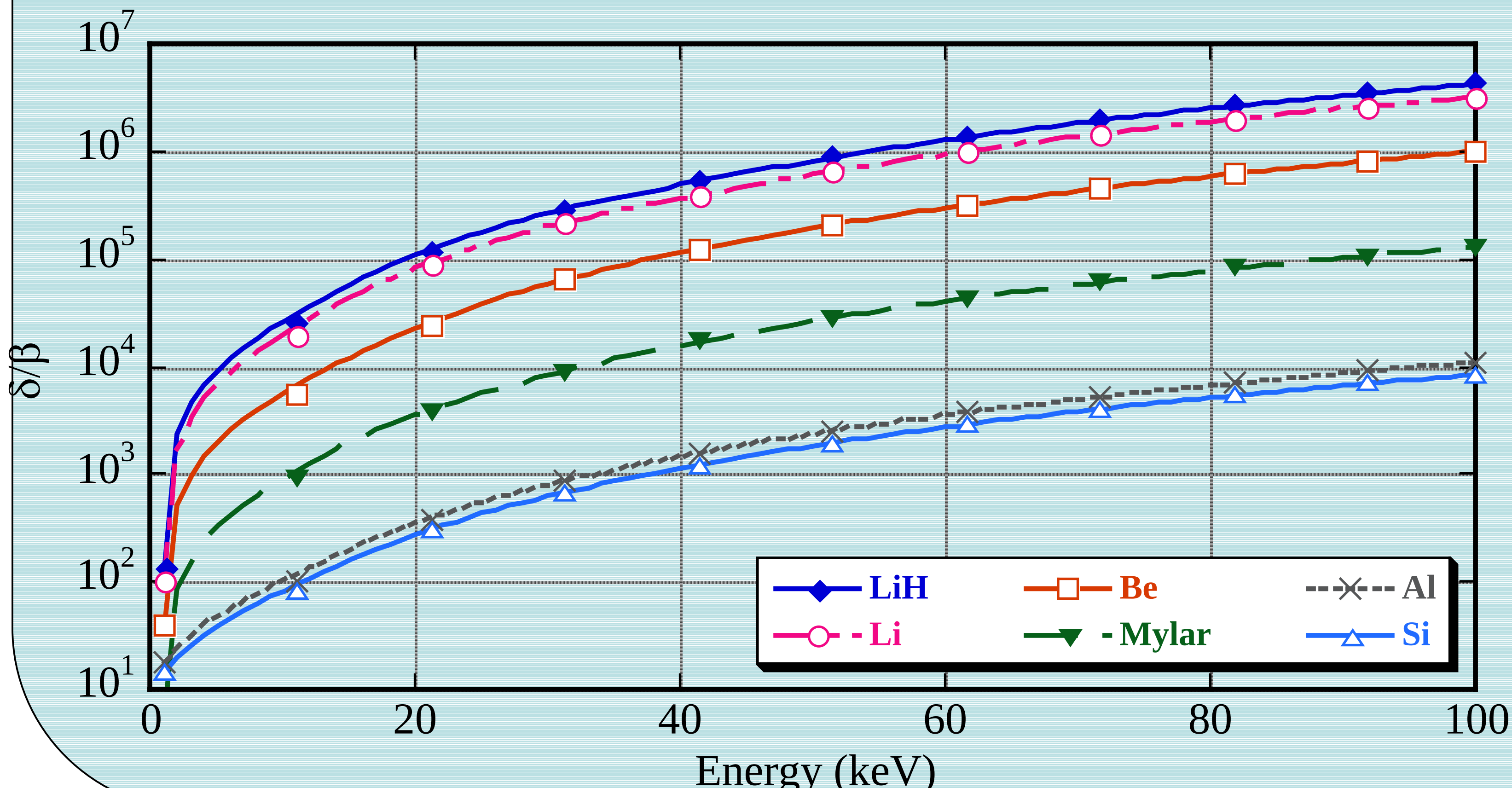
- Photon energy
- Beam size
- Desired focal length
- Desired focus size (and 1-D / 2-D focusing)

These in turn help determine…

- Lens material (absorption is a serious issue)
- Lens design
- Fabrication technique
- Alignment and assembly

Lens materials used include Li, Be, Al, Si, PMMA, Mylar

Material Figure of Merit:Focusing/Absorption



Lithium

- High δ/β over a broad energy range
- Soft and malleable material
- But
- Reacts with oxygen, nitrogen, hydrogen, and strongly with water and moisture
- Tends to adhere to surfaces or forming dies
- Poor surface characteristics

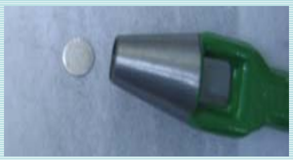
- LiH is the best choice, we would like to explore it.

Beryllium

- High δ/β over a broad energy range
- Readily machinable metal
- High stiffness, strength, and ductility
- Avaible in a variety of grades, including fine-grain
- It can be polished
- Routine handling is safe
- But
- Hazardous material
- Fabrication requires safety measures (a few vendors)

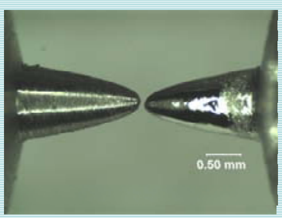
Li Lens Fabrication Process

1. Lithium foil



2. Lithium disk

3. Cartridge unit



4. Parabolic indenters

5. Manual press

Assembled Cartridges

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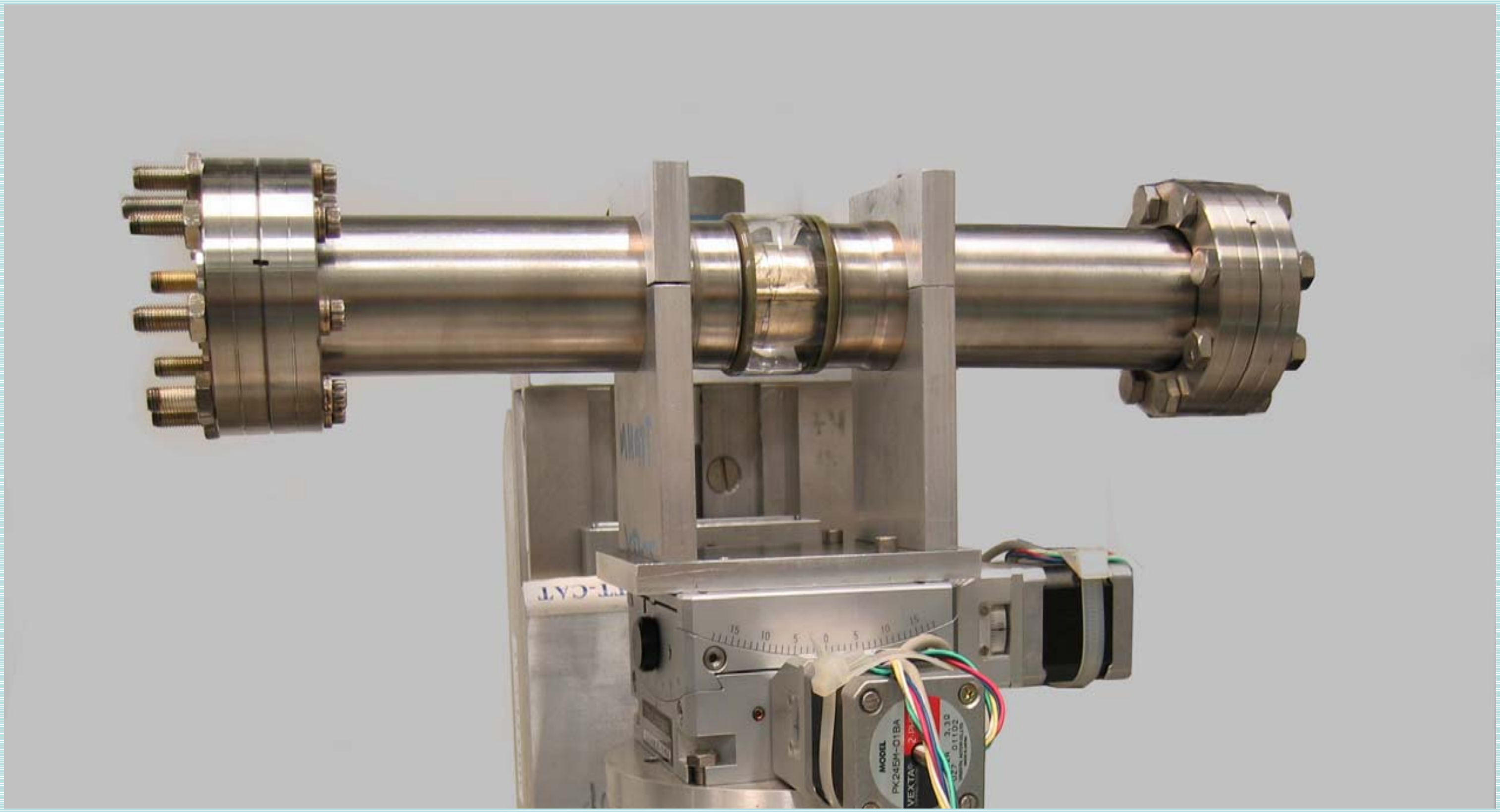
Housing Assembly



Fabrication Process

- Lenslet disks punched out from lithium foil
- Each lenslet disk placed and held in a cartridge unit
- Cartridge is placed in a manual press onto alignment pins
- Lenslet is pressed by a pair of parabolic indenters mounted in the precision press
- Cartridges aligned using alignment pins in an assembly
- Assembled lenslets are set securely in a housing unit having a Be window at each end
- All work is carried out in dry atmosphere

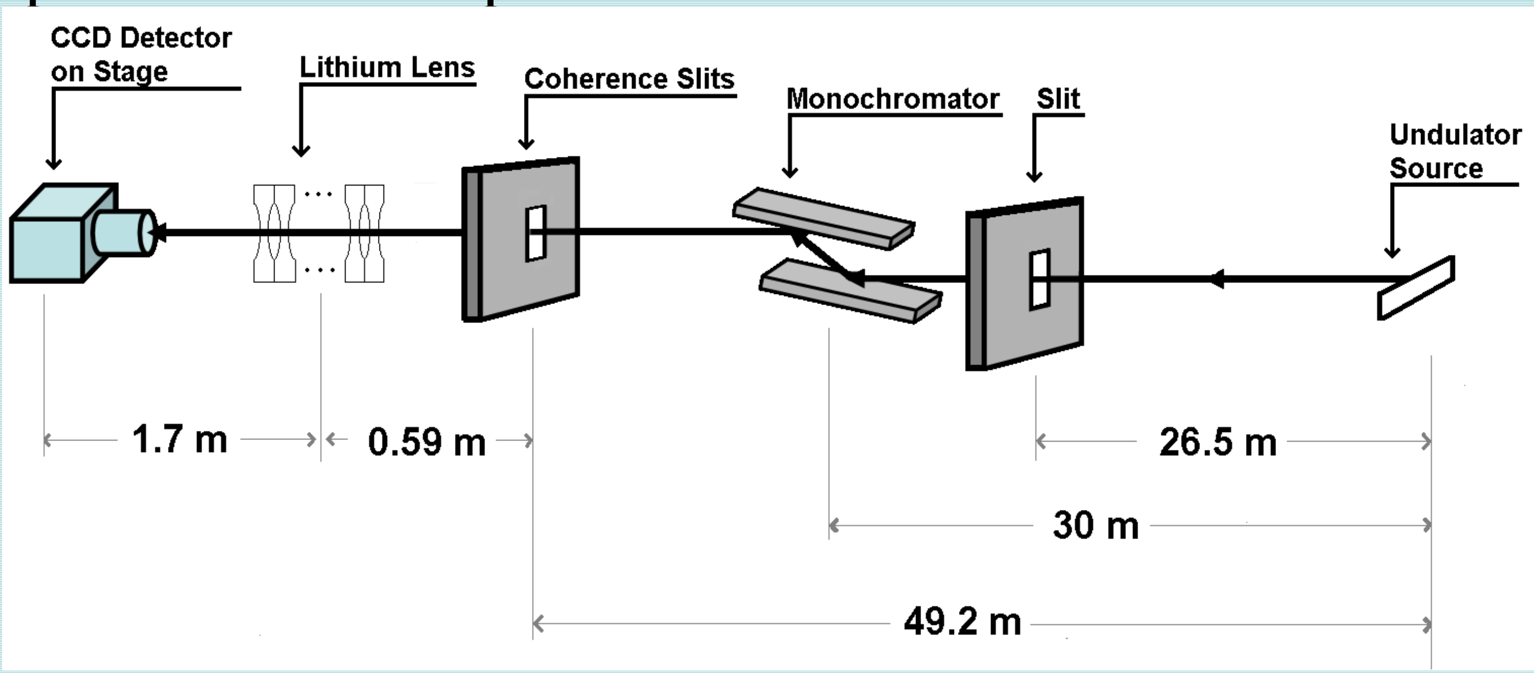
Prototype Li Lens Specifications

- To focus monochromatic (~ 10 keV) x-rays
- Beam size set by ~ 0.5 mm x 0.5 mm slit at 30 m
- Desired focal distance ~ 1-2 m

- CNC-machined stainless steel parabolic indenters
- Indenter tip radius is 100 µm; aperture ~ 500 µm
- A set of 32 lenslets fabricated and assembled
- Expected focal length of 1.7 m at 10 keV

Testing & Evaluation

Experimental setup



Note: Slits do not affect the source size as viewed by the lens

Testing & Evaluation, Cont…

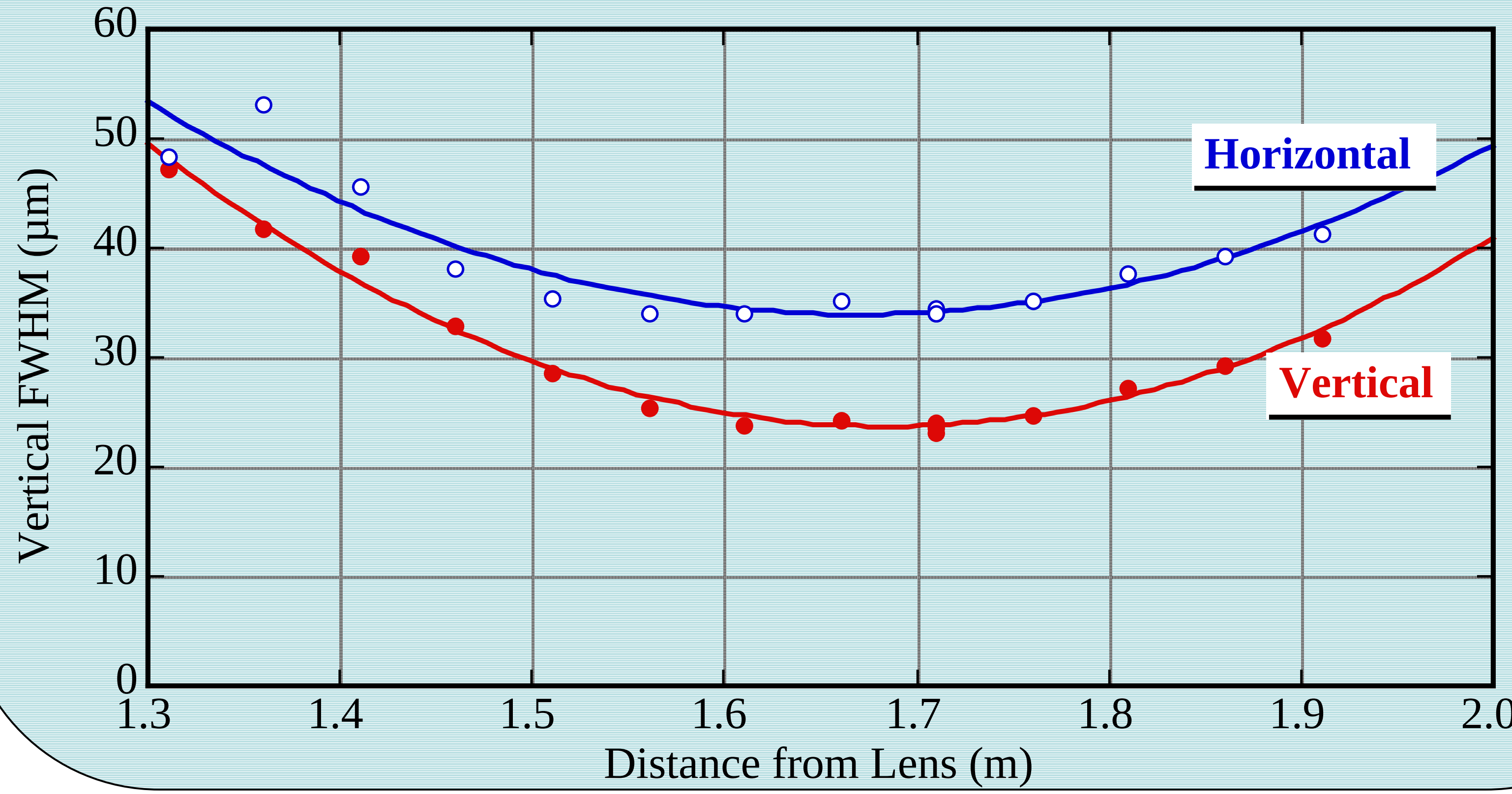
- Experimental goal:
  - Measure location and size of focal spot
  - Measure lens transmission
  - Obtain gain
  - Compare with expectations

  - Note:

Demagnification = 50/1.7 = 1/29

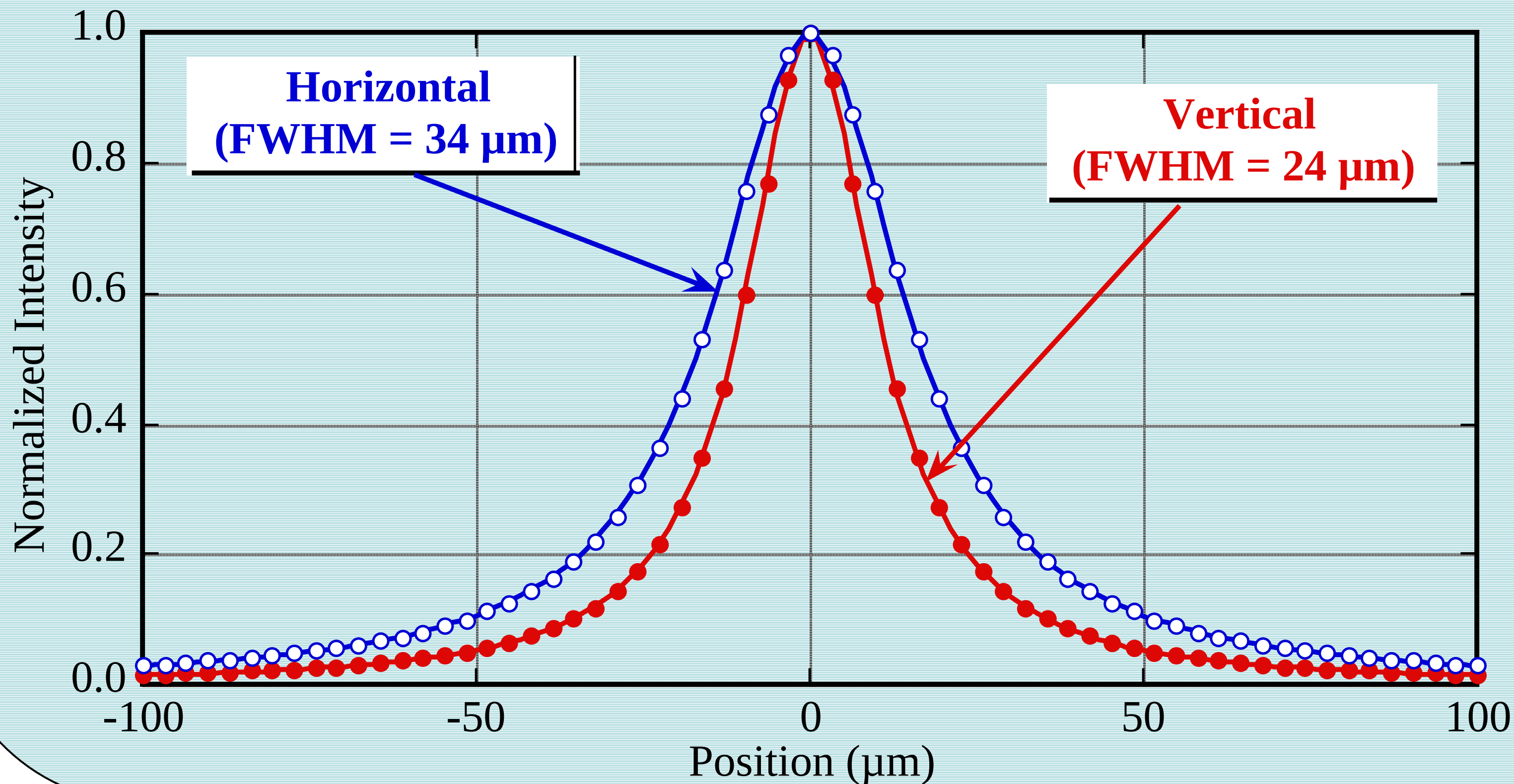
Testing & Evaluation, Cont…

Measuring image size along optical axis

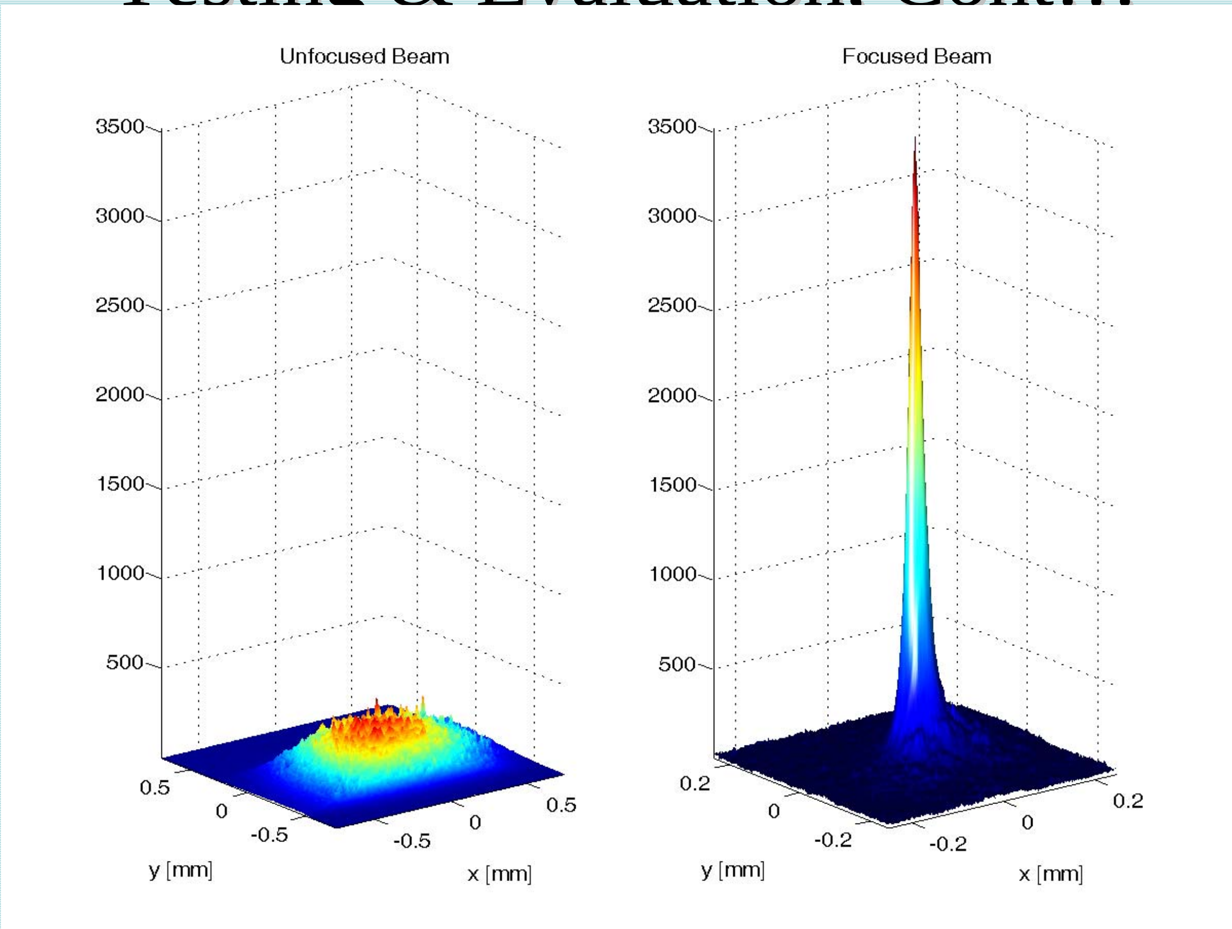


Testing & Evaluation, Cont…

Profile of the beam at the focal spot



Testing & Evaluation. Cont…



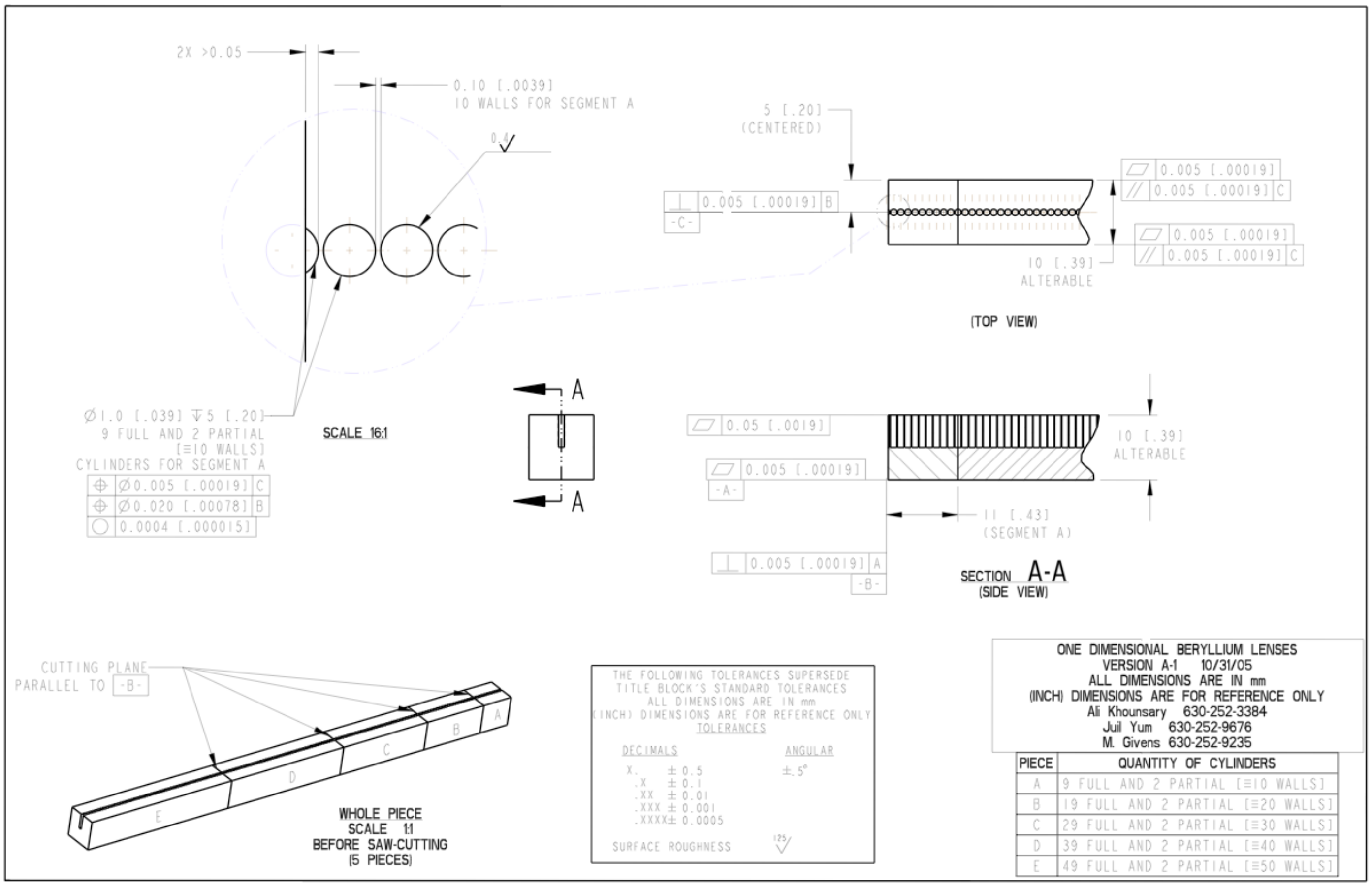
Lithium Lens Summary Results

- Transmission (average)
  - Measured: ~ 85%; Expected ~ 85%
- Focal Distance:
  - Measured: 1.71 m; Expected: 1.70 m
- Gain (increase in peak intensity):
  - Measured: ~ 18; Expected ~ 800
- Focal Size FWHM):
  - Horizontal: Measured: 34 μm; Expected: (634/29) ~ 22 μm
  - Vertical: Measured: 24 μm; Expected: (21/29) ~ 0.7 μm

Beryllium CRL

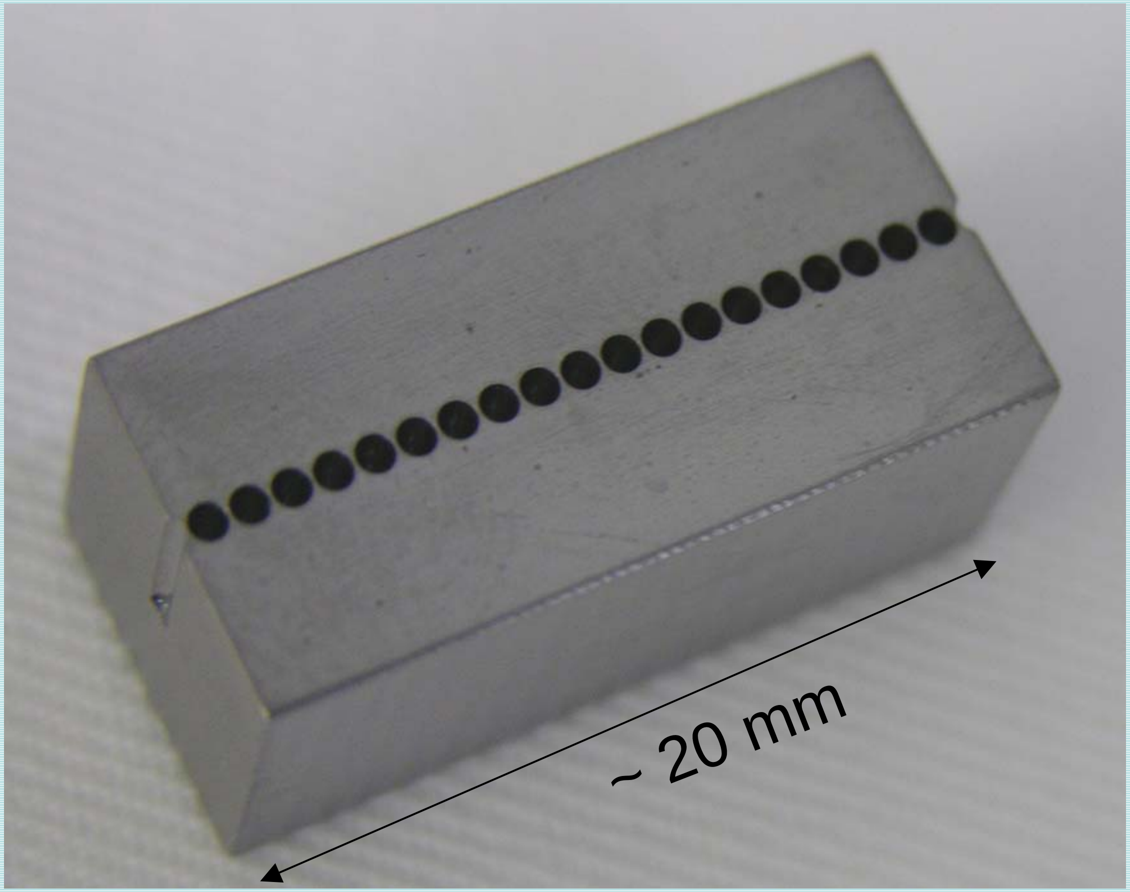
- R = 0.5 mm
- N=10,20,30,40,50, tested only N=50.
- High purity Be used
- Wall thickness ~ 100 µm
- Roughness < 0.1 µm rms
- Conventional CNC drilling
- No post drilling processes

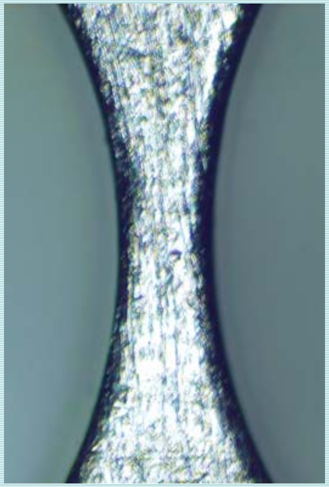
Lens Design



2X >0.05
0.10 [.0039]
10 WALLS FOR SEGMENT A
5 [.20]
(CENTERED)
0.005 [.00019] B
-C-
0.005 [.00019]
0.005 [.00019] C
0.005 [.00019]
0.005 [.00019] C
10 [.39]
ALTERABLE
(TOP VIEW)
Ø1.0 [.039] ↧5 [.20]
9 FULL AND 2 PARTIAL
[≡10 WALLS]
CYLINDERS FOR SEGMENT A
Ø0.005 [.00019] C
Ø0.020 [.00078] B
0.0004 [.000015]
SCALE 16:1
A
A
0.05 [.0019]
0.005 [.00019]
-A-
10 [.39]
ALTERABLE
11 [.43]
(SEGMENT A)
0.005 [.00019] A
-B-
SECTION A-A
(SIDE VIEW)
CUTTING PLANE
PARALLEL TO -B-
WHOLE PIECE
SCALE 1:1
BEFORE SAW-CUTTING
(5 PIECES)
THE FOLLOWING TOLERANCES SUPERSEDE
TITLE BLOCK'S STANDARD TOLERANCES
ALL DIMENSIONS ARE IN mm
(INCH) DIMENSIONS ARE FOR REFERENCE ONLY
TOLERANCES
DECIMALS
ANGULAR
X. ± 0.5
.X ± 0.1
.XX ± 0.01
.XXX ± 0.001
.XXXX± 0.0005
± .5°
SURFACE ROUGHNESS
ONE DIMENSIONAL BERYLLIUM LENSES
VERSION A-1 10/31/05
ALL DIMENSIONS ARE IN mm
(INCH) DIMENSIONS ARE FOR REFERENCE ONLY
Ali Khounsary 630-252-3384
Juil Yum 630-252-9676
M. Givens 630-252-9235
PIECE
QUANTITY OF CYLINDERS
A 9 FULL AND 2 PARTIAL [≡10 WALLS]
B 19 FULL AND 2 PARTIAL [≡20 WALLS]
C 29 FULL AND 2 PARTIAL [≡30 WALLS]
D 39 FULL AND 2 PARTIAL [≡40 WALLS]
E 49 FULL AND 2 PARTIAL [≡50 WALLS]

Be Lens





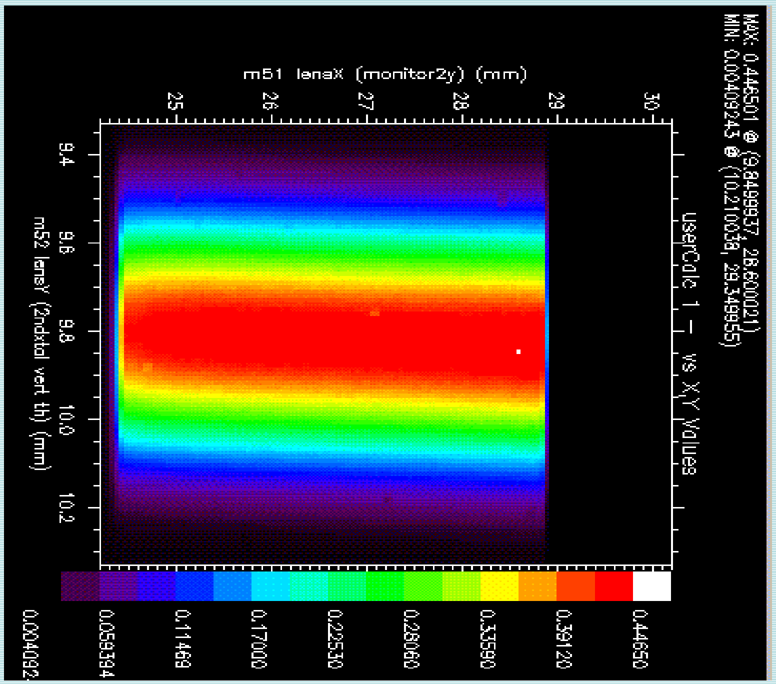
Experimental Procedure

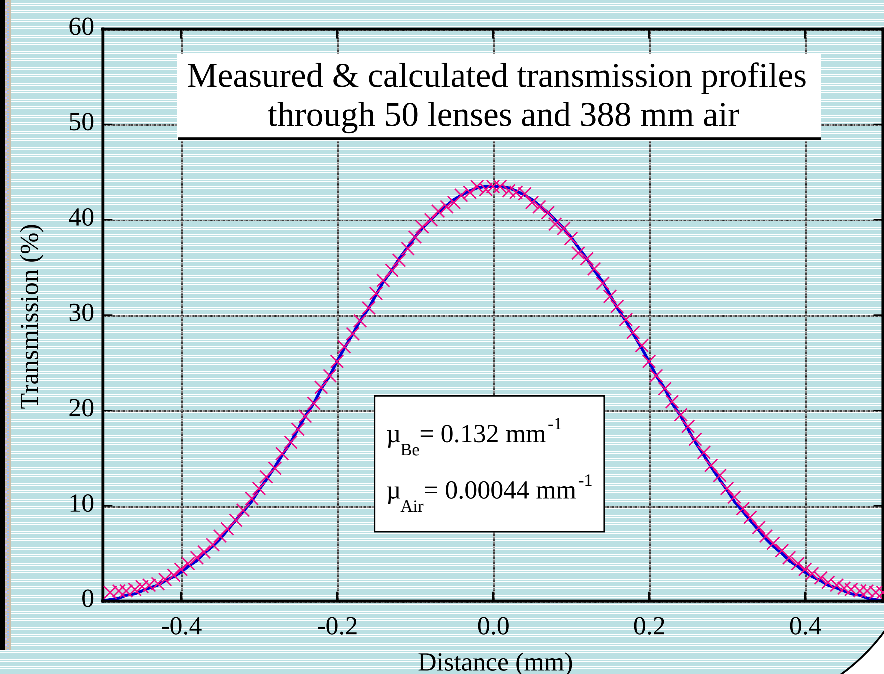
- White beam slit set to 0.5 mm x 0.5 mm @ 26.5 m
- Si (111) monochromatic beam @ 11 keV, detuned by 25%
- Variable opening slit immediately upstream of the lens
- Transmission measurement by scanning the lens across a narrow beam
- Beam size measured by a knife edge scanned vertically
- Best focus determined by moving the knife edge along optical axis
  - Lens 49.8 m from source
  - Vertical source size FWHM ~ 20 μm

Experimental Setup

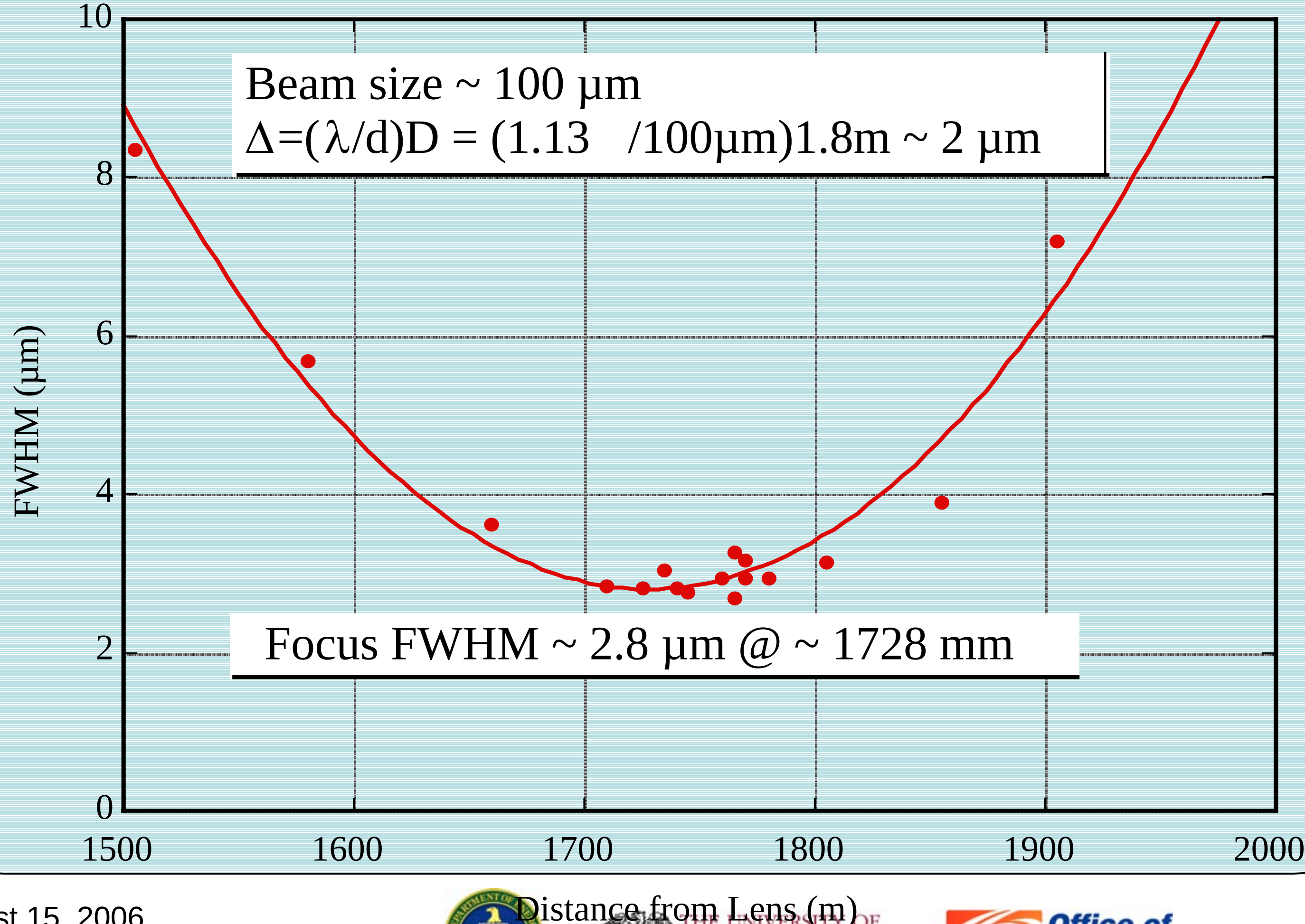
Transmission through the Lens

A 2D scan of the lens over a 30 µm(H) by 10 µm (V) beam.





Focal distance measurements

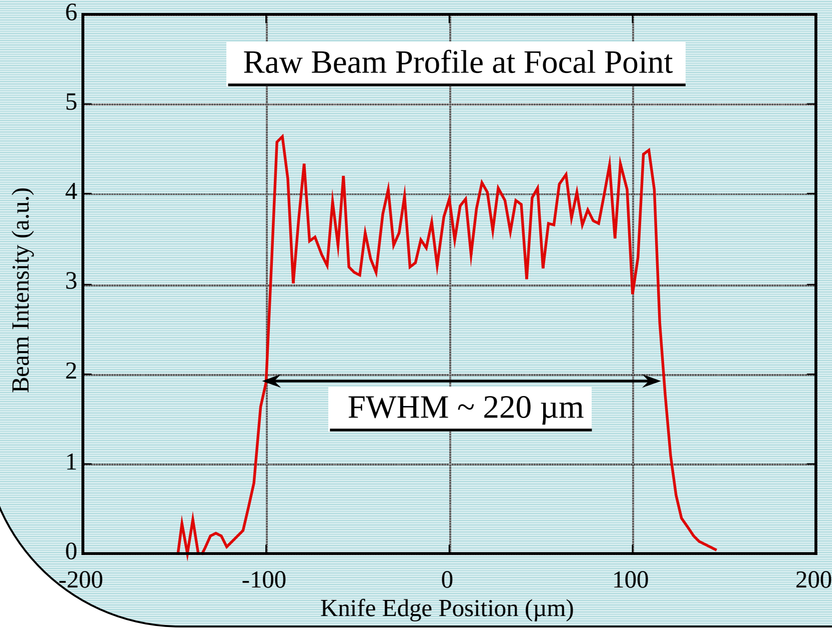


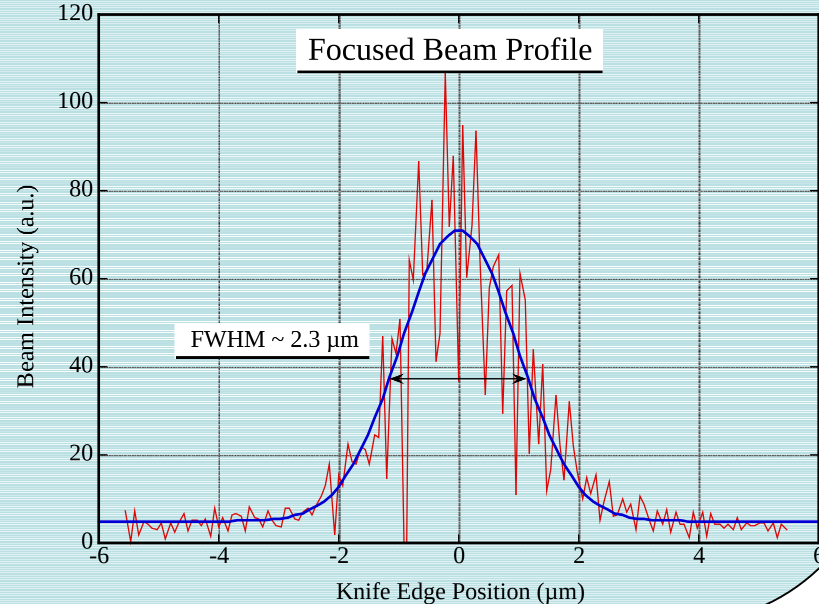
Typical Focused Beams Obtained

Gain ~ 74/3.9 ~ 19

Peak/tail ~ 70/5 =14

FWHM ~ 2.3 µm (diffraction limit ~ 0.9 µm)





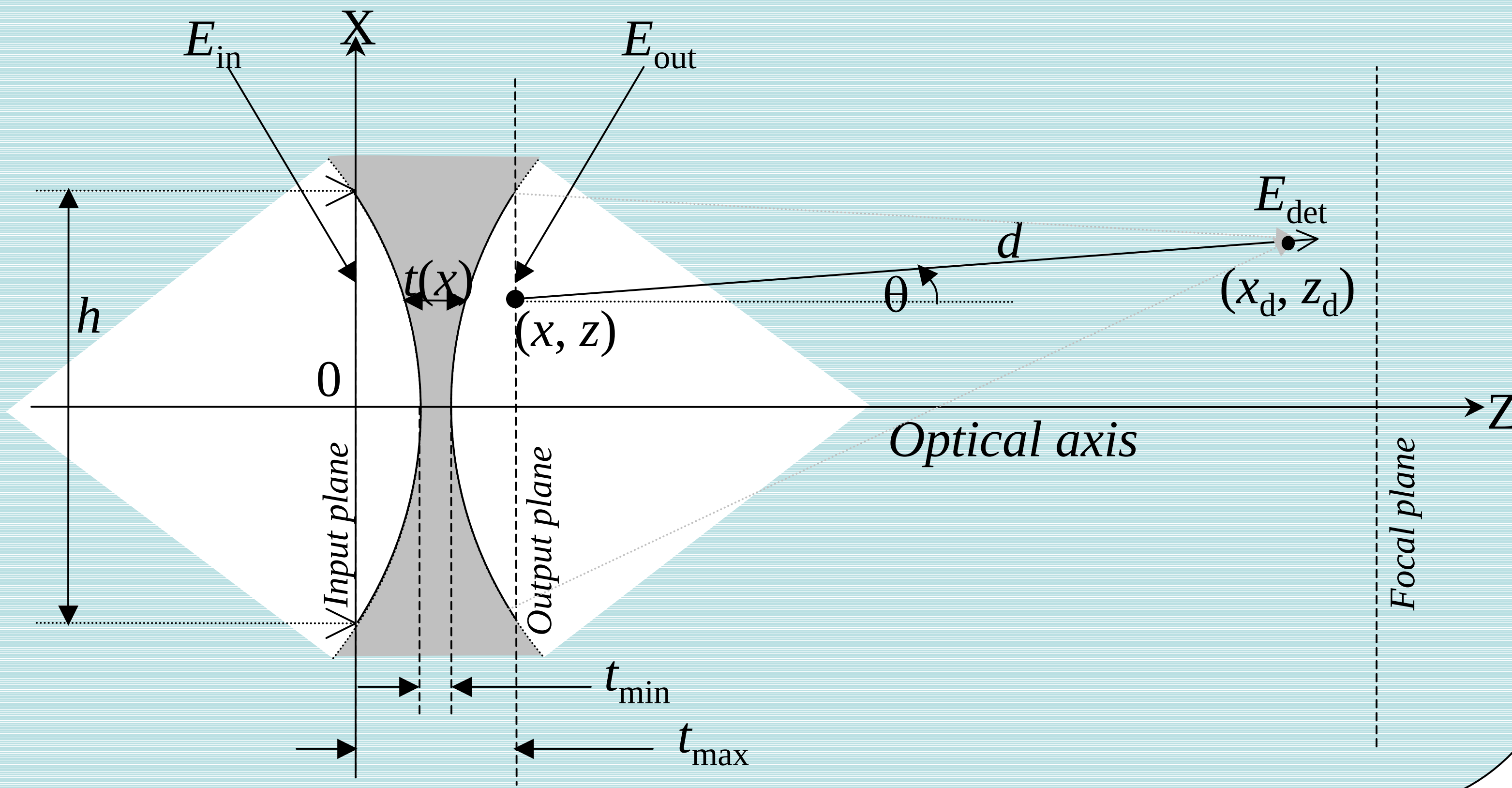
Cylindrical Be lens conclusions

- Peak transmission 43%, as expected with μ_{Be} = 0.132 mm^{-1}
- Focal distance: measured 1.73 m, expected 1.77 m
- Focal size: measured ~ 2.3 µm, expected 20/D = 0.7 µm
- Blurring from GaAs knife edge & horizontal extent of beam
- Gain: Measured ~ 19. Expected ~ 75

$$\frac{\text{Slit size}}{\text{Ideal focus size}}\,\text{Transmission} = \frac{220\ \mu\text{m}}{0.7\ \mu\text{m}}\,0.24 \approx 75$$

- Accurate cylindrical lenses made; surface can be improved

1-D Lens Simulation



Lens thickness profiles

- Circular profile:

$$t_{\text{circular}}(x) = t_{\min} + 2r\left(1 - \sqrt{1 - \frac{x^2}{r^2}}\right)$$

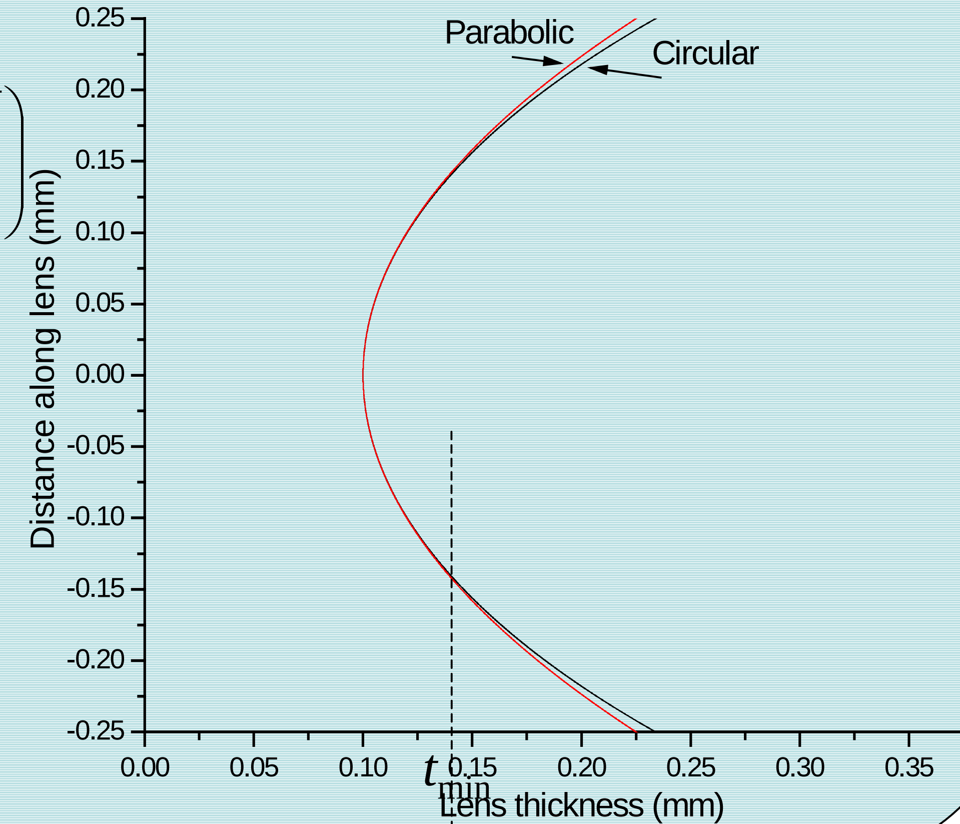
- Parabolic profile:

$$t_{\text{parabolic}}(x) = t_{\min} + \frac{x^2}{r}$$

- Thickness parameters:

$r = 0.5$ mm

$t_{\min} = 0.1$mm



Wave-optics calculations

- Incident (collimated) plane wave: $E_{\mathrm{in}} = E_0$
- Output (refracted) wavefield:

$$E_{out}(x,y) = E_0 e^{iknt(x,y) + ik\left[t_{\max} - t(x,y)\right]} = E_0 e^{ik\left[t_{\max} - \delta t(x,y)\right]} e^{-k\beta t(x,y)}$$

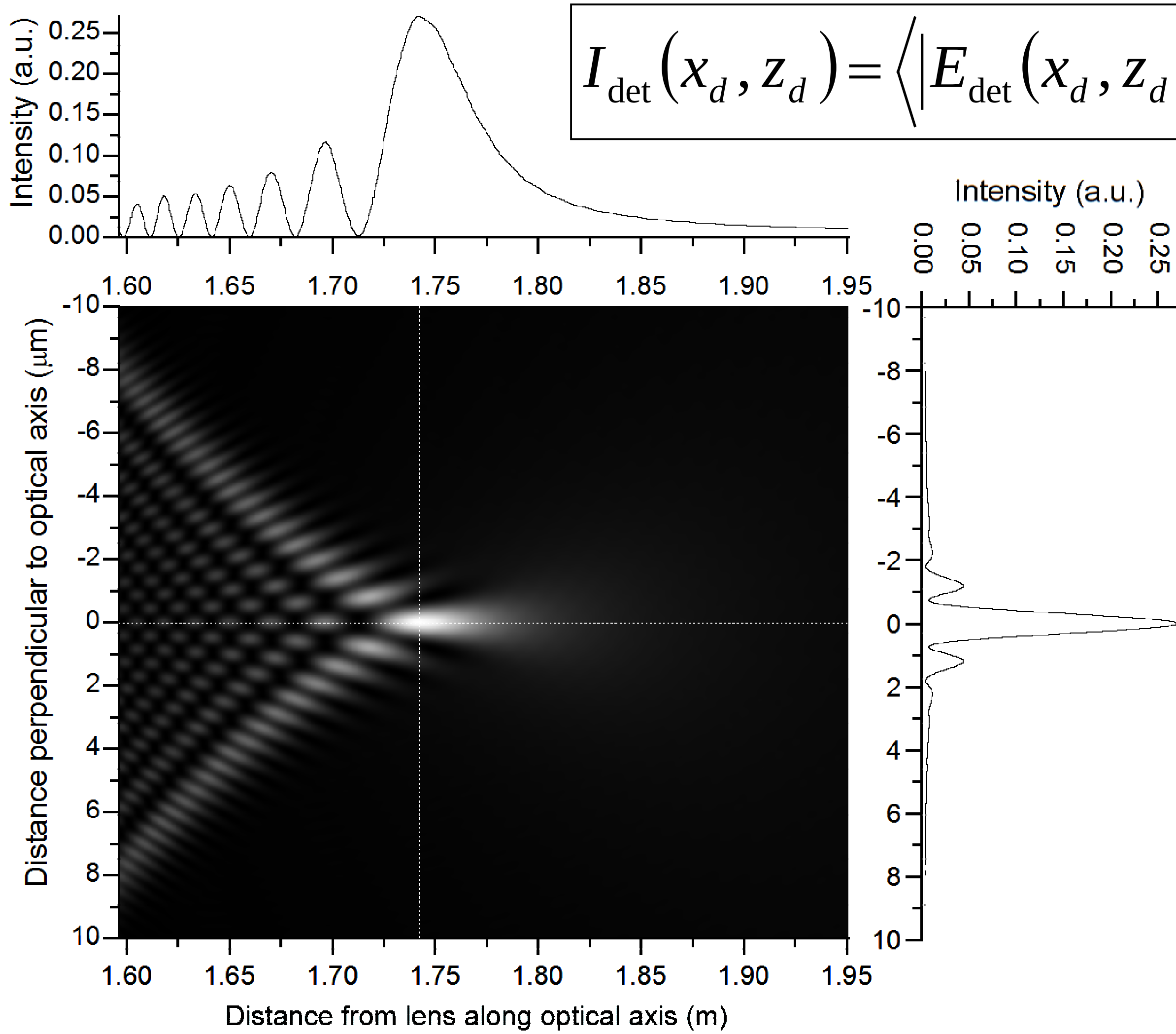
- Detected wavefield:

$$E_{\det}(x_d, z_d) = \frac{-i}{2\lambda} \int_{-h/2}^{h/2} E_{out}(x,z) \frac{e^{-ikd}}{d} (1 - \cos\theta)\, \mathrm{d}x$$

The detection point (x_d, z_d) is moved in the *x*-*z* plane to calculate the complex amplitude in 2D

Intensity map near the focal point of 50 circular profile lenses

$$I_{\det}(x_d, z_d) = \left\langle \left| E_{\det}(x_d, z_d) \right|^2 \right\rangle$$



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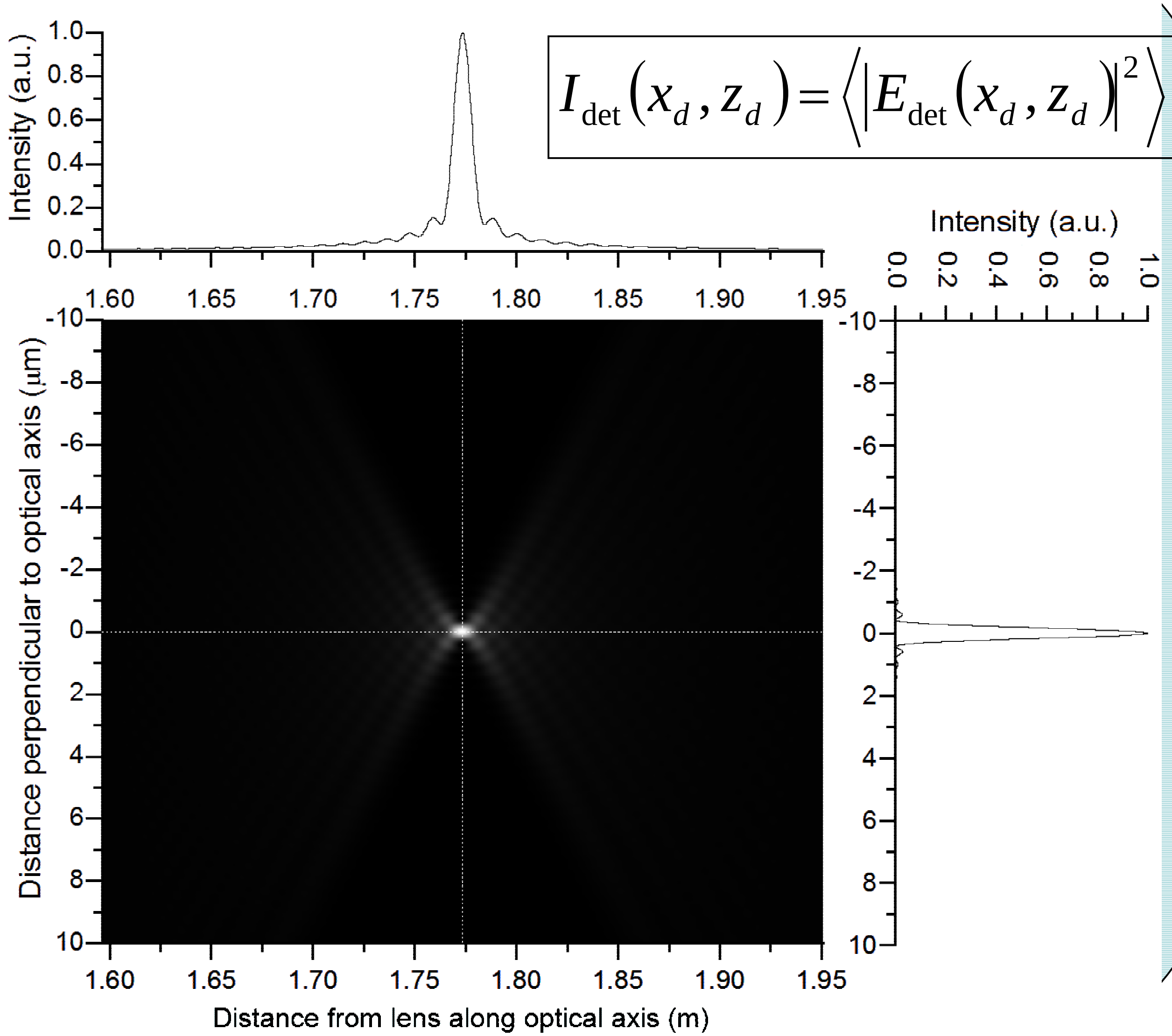
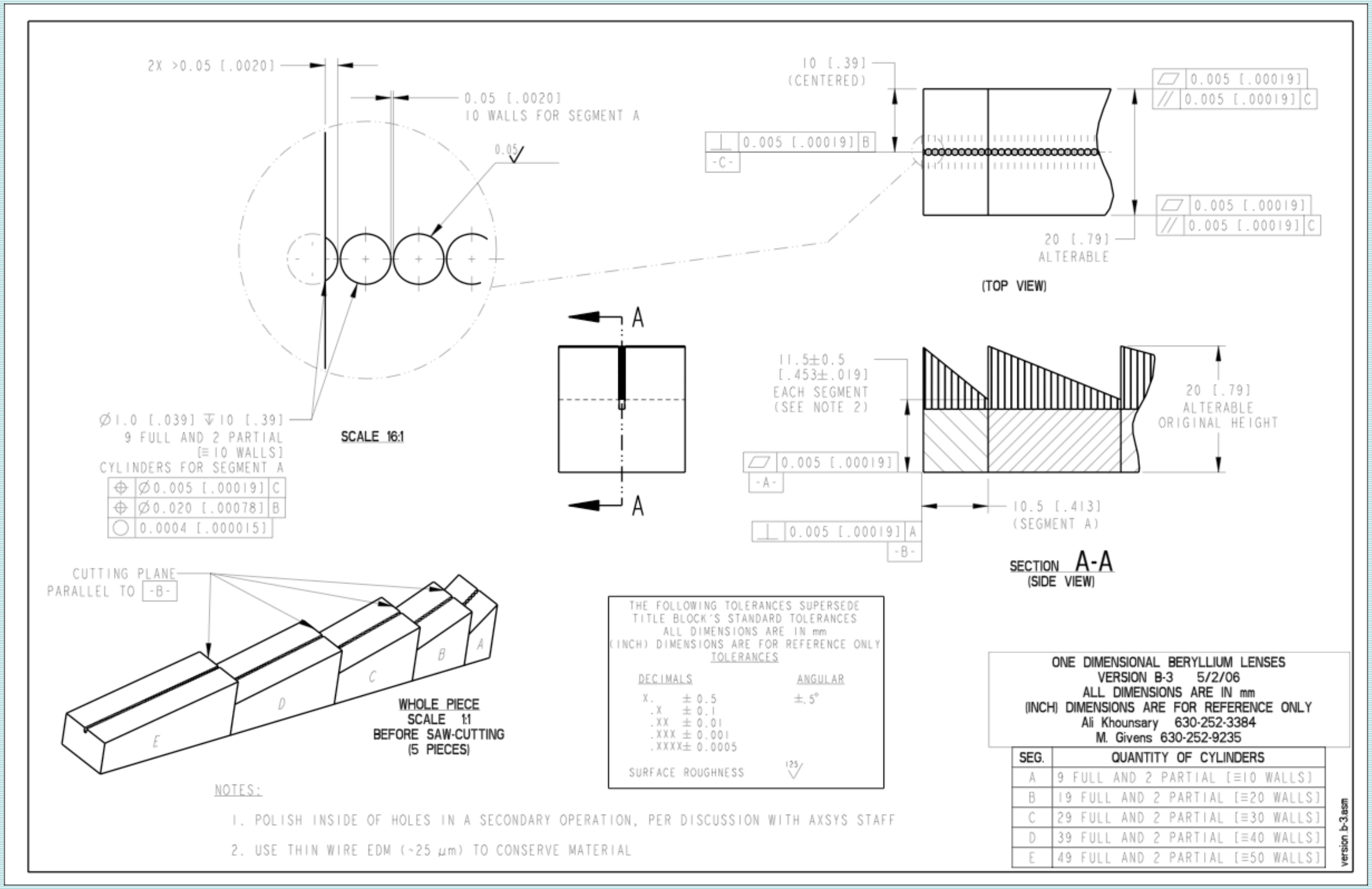
Intensity map near the focal point of 50 parabolic profile lenses



Future Plans

1. Better understanding of mechanical behavior of Li (spring back, flow, adhesion, etc.)
2. Improved indenter (surface profile / polish)
3. Fabricate indenters with smaller tip radii
4. Characterize figure/finish of indenters <u>and</u> indented Li (dry-room metrology or replication needed)
5. Improve precision & alignment in pressing Li process
6. Improve surface finish and wall thickness of Be lenses
7. Carry out wavefield calculations to simulate realistic lenses and features

Second Generation Be Lenses



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Summary

1. Fabrication of parabolic Li lens using a precision press demonstrated
2. First generation Li lens provides reasonable performance and an 18x gain
3. Lens imperfections contribute substantially to focus size broadening, blowing up the image by about 25 µm in both directions
4. First generation Be cylindrical lens 2.5 µm focal spot achieved
5. A gain of ~ 19 with Be lens and a focal size of ~ 2 µm obtained
6. Plan to carry out improvements in Be and Li lenses, as well as simulation of their performance

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