Argonne NATIONAL LABORATORY

Advanced at-wavelength metrology of refractive lenses for APS-U

Xianbo Shi
Advanced Photon Source, Argonne National Laboratory

TWG meeting
Oct. 27, 2022

CONTENT

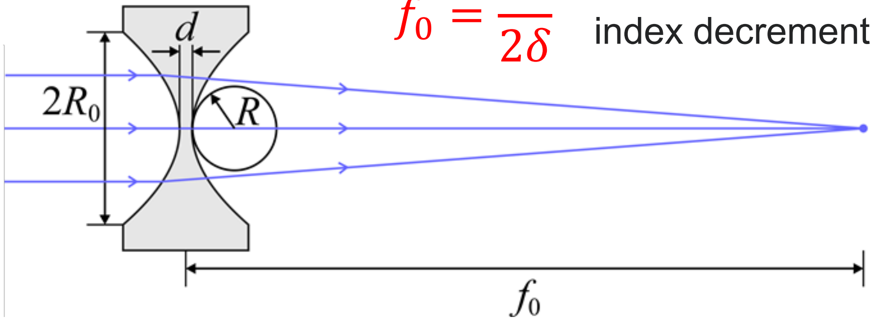
- CRL specifications and vendor status
- At-wavelength metrology: coded-mask-based wavefront sensor
- CRL measurement results
  - APS-U CRL measurements
  - 15-ID Al CRL
  - 23-ID diamond CRL

INTRODUCTION

Single lens

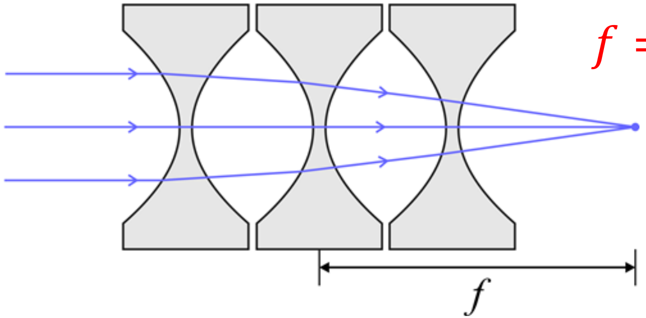
$$f_0 = \frac{R}{2\delta}$$

δ - refractive index decrement

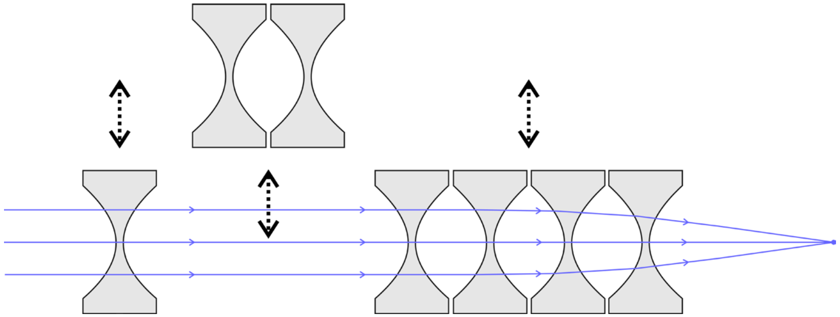


Compound refractive lenses (CRL)

$$f = \frac{R}{2N\delta}$$

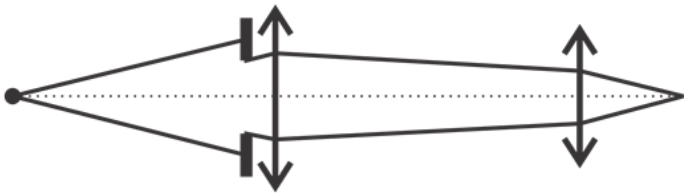


Transfocator



Zoom optics

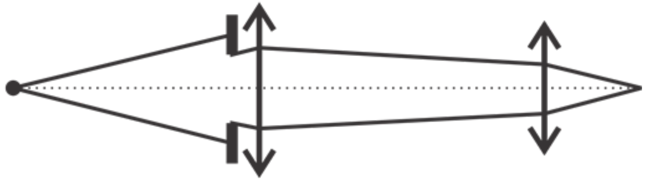
Transfocator 1 Transfocator 2

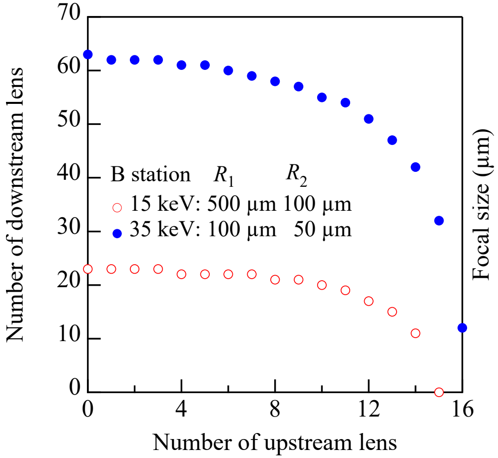


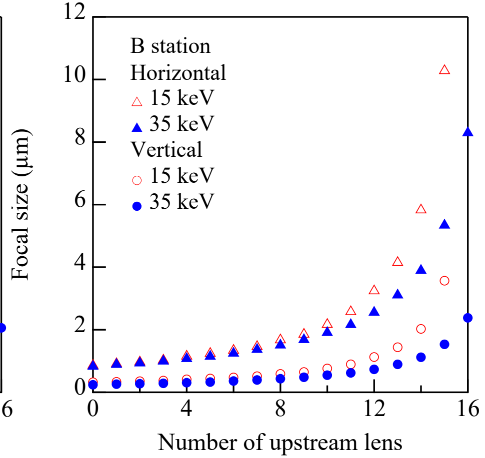
APS-U LENSES

Zoom CRLs

- Combining two sets of transfocators to provide variable focal sizes at fixed sample position







Original plan for APS-U

Beamline	Polar 4-ID	XPCS 8-ID	CSSI 9-ID	HEXM 20-ID	CHEX 28-ID	Enhancements	Total
Transfocators	1 (41)	2 (72)	2 (56)		3 (372)	2 (133)	10
Lens Box					9 (935)	5 (368)	14
Other lenses				7			7
Total number of lenses: (1977)							

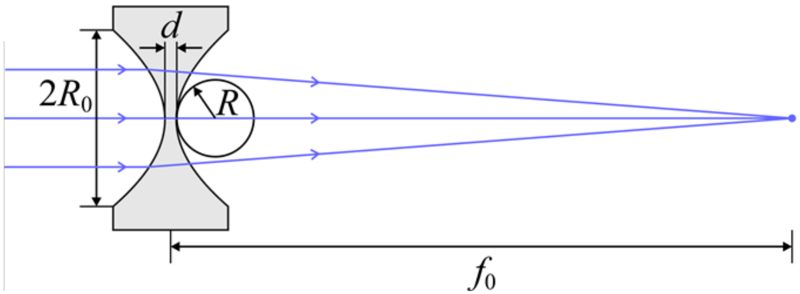
SPECIFICATION OF REFRACTIVE LENSES

Specifications and tests

- Material, highest δ/μ ratio
  – Be (<40 keV)
  – Al (40-80 keV)
  – Ni (>80 keV)
  – Diamond (excellent thermal conductivity and uniform refractive index)
- Profile shapes: 1D parabolic cylinders and 2D paraboloid for point-to-point focusing

$$z(x,y) = \frac{x^2 + y^2}{2R} \qquad f = \frac{f_0}{N} = \frac{R}{2N\delta}$$

- Geometric aperture ($2R_0$)
- Distance (d) between apices: < 30 μm



- Voids in the material:
  – scattering, wavefront distortion
- Thickness profile error

$$\sigma_T \delta \sqrt{N} \leq \lambda/14 \qquad \text{Maréchal criterion}$$

  – σ_T – RMS thickness error of one lens deviated from the ideal thickness profile.
  – <1.0 μm (RMS) after removing the best-fit parabola over the central 2/3 of the lens' clear aperture

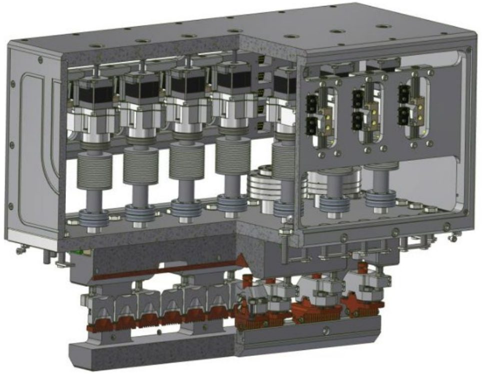
X. Shi, et al., Proc. SPIE **11109**, 111090K (2019).

LENS MANUFACTURERS

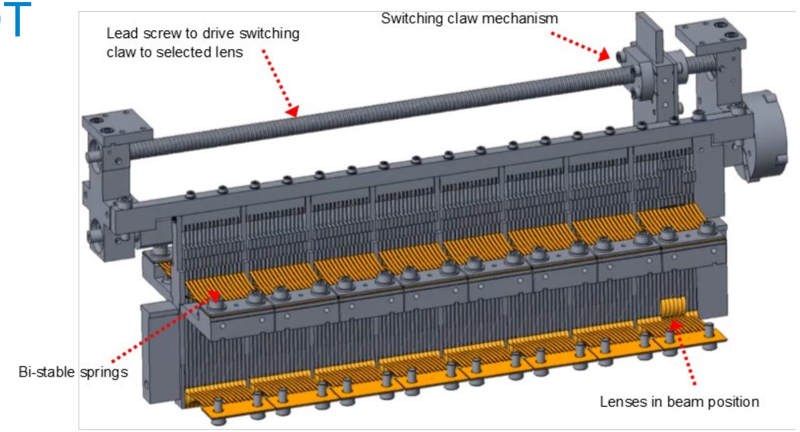
- RXOptics (Not taking new orders now due to company status change)
  - Be, Al, Ni
  - Best (only) Be lens manufacturer
- MATERION
  - Be
  - R&D phase (new project manager)
- ESRF optics group (limited supply)
  - Al (similar or better quality than RXOptics)
  - Can also provide at-wavelength metrology data
- PALM-scientific (Sergey Antipov, used to be at Euclid)
  - Best available diamond lenses (close to the RXOptics Be quality)
- JJ X-ray
  - R&D on diamond lenses (good progress)
  - Maybe buying RXOptics?
- Research institutes
  - polymeric lenses (APS, KIT)
  - Si lenses (APS, other facilities)

TRANSFOCATOR MANUFACTURERS

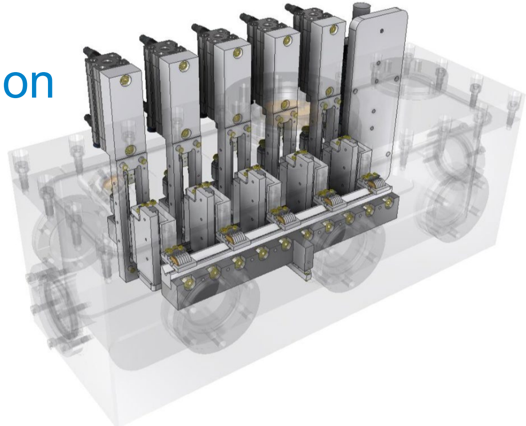
JJ X-ray



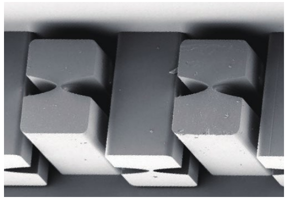
IDT

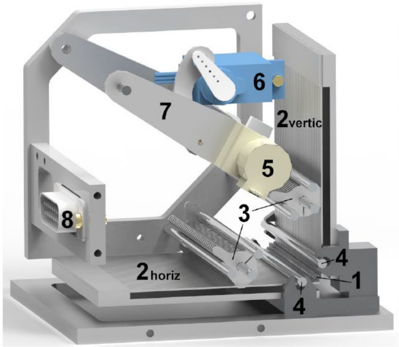


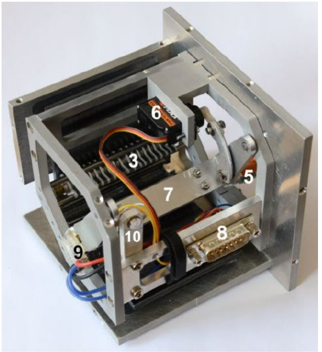
Axilon



KIT (Polymeric)





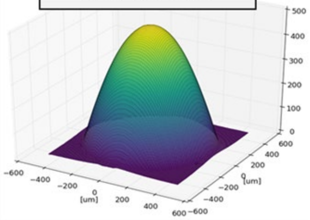


AT-WAVELENGTH METROLOGY

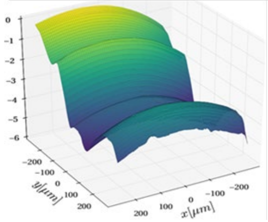
WAVEFRONT SENSING FOR AT-WAVELENGTH METROLOGY

Beamline optics characterization and diagnostics at the APS

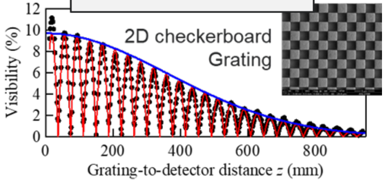
Thickness profile of a Be lens



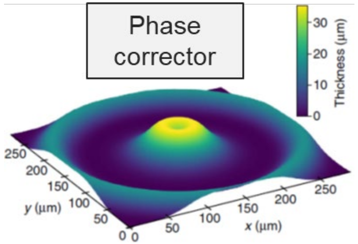
Distorted wavefront downstream of a mirror



Coherence function measurement



Phase corrector



Optics characterization tools
- Grating interferometry
- Speckle tracking
- Coded-mask-based technique

Apply

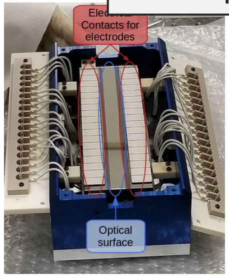
Optics characterization
- At-wavelength metrology
- Wavefront sensing
- Coherence measurements

Support — Extend

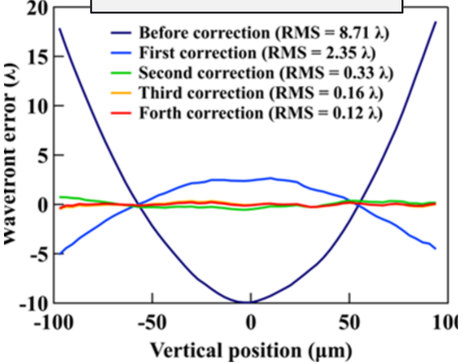
Optics development
- Wavefront-preserving optics
- Adaptive optics
- Phase corrector

Beamline diagnostic
- Wavefront and coherence monitor
- Beamline control and optimization

Adaptive optics



Wavefront correction

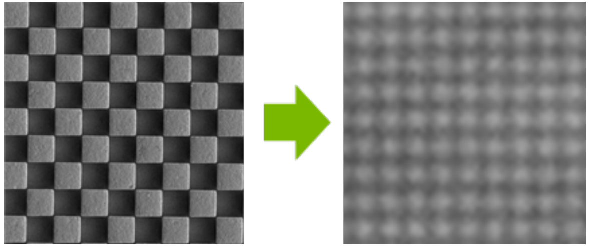


X. Shi, et al., Proc. SPIE 11491, 1149110 (2020).

WAVEFRONT SENSING FOR AT-WAVELENGTH METROLOGY

Grating interferometry

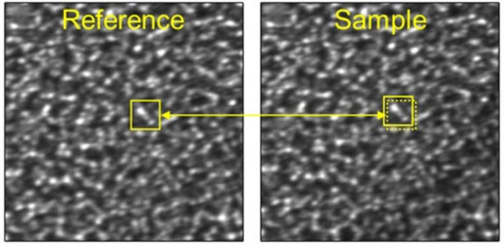
- Phase or absorption gratings (1D or 2D) with periodic pattern
- Fourier-based analysis for grating pattern shifts (fast)



Harold H. Wen et al. Opt Lett. 35, 1932 (2010)
W. Grizolli, et al. Proc. SPIE 10385, 1038502 (2017)
W. Grizolli, et al., AIP Conference Proceedings, 2054, 060017 (2019)

Speckle tracking

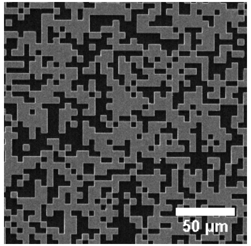
- Speckle generator (sandpaper, membrane filters) with completely random pattern
- Based on near-field speckle pattern shifting



S. Berujon et al., J Synchrotron Radiat, 27, 284 (2020)
S. Berujon et al., J Synchrotron Radiat, 27, 293 (2020)

Coded-mask-based Wavefront Sensor

- Designed non-periodic pattern
- Ultra-high-contrast >30%
- Pre-knowledge of the pattern
- High spatial resolution
- High phase sensitivity
- Better noise robustness
- Flexible and easy to use



Advance data analysis algorithm

- Maximum-likelihood optimization
- Wavelet-transform-based speckle vector tracking
- Speckle-based Phase-contrast Imaging Neural Network (SPINNet)

X. Shi, et al., US patent US20220265231 (2022).
Z. Qiao, et al., Appl. Phys Lett. 119, 011105 (2021).
Z. Qiao, et al., *Optica* 9, 391 (2022).
Z. Qiao, et al., Opt. Express 28, 33053 (2020).
Z. Qiao, et al., J. Imaging 7, 249 (2021).
X. Shi, et. al, Proc. SPIE 12240, 122400H (2022).

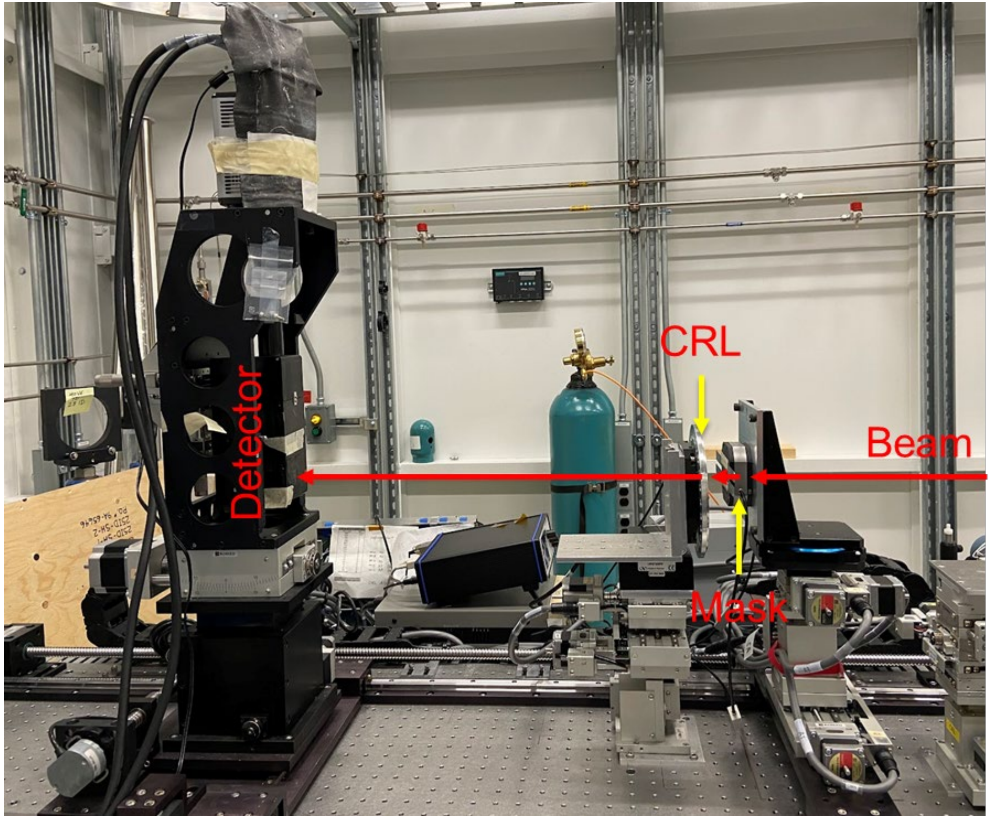
Argonne NATIONAL LABORATORY

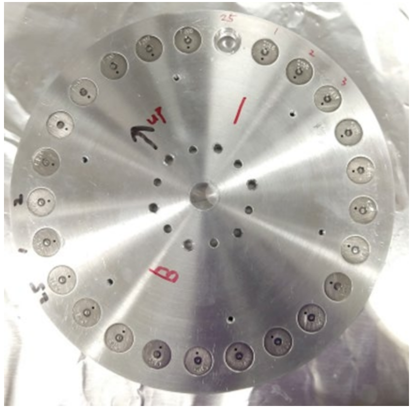
CRL MEASUREMENTS (1-BM AND 28-ID)

APS-U (4-ID, 8-ID, 9-ID, 12-ID): 302 (Be)
15-ID (ChemMatCARS): 95 (Al)
23-ID (GMCA): 179 (Be)
11-ID: 10 (Al)
12-ID: 33 (Be)
32-ID: 12 (Diamond)
CBXFEL: 84 (Be)

Many R&D lenses from ESRF, Euclid, JJx-ray, Materion, KIT, RXoptics, APS-LDRDs

APS-U LENSES MEASURED AT 28-ID-B BEAMLINE





- 20 keV
- Lens-to-detector distance: 0.5 m
- Mask pitch: 5 µm

Lens list (302 total)

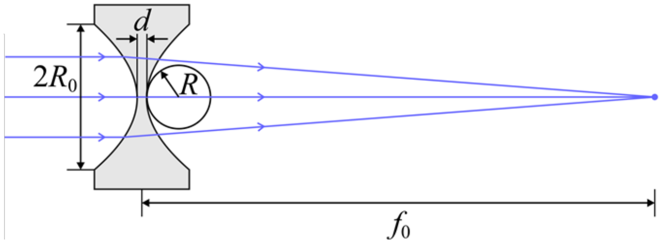
- 132 $R = 100$ µm, 2D
- 133 $R = 200$ µm, 2D
- 4 $R = 300$ µm, 2D
- 7 $R = 500$ µm, 2D
- 6 $R = 1000$ µm, 2D
- 4 $R = 2000$ µm, 2D
- 16 $R = 200$ µm, 1D

Beamlines

- 4-ID (118)
- 8-ID (72)
- 9-ID (56)
- 12-ID (56)

APS-U LENSES MEASURED AT 28-ID-B BEAMLINE

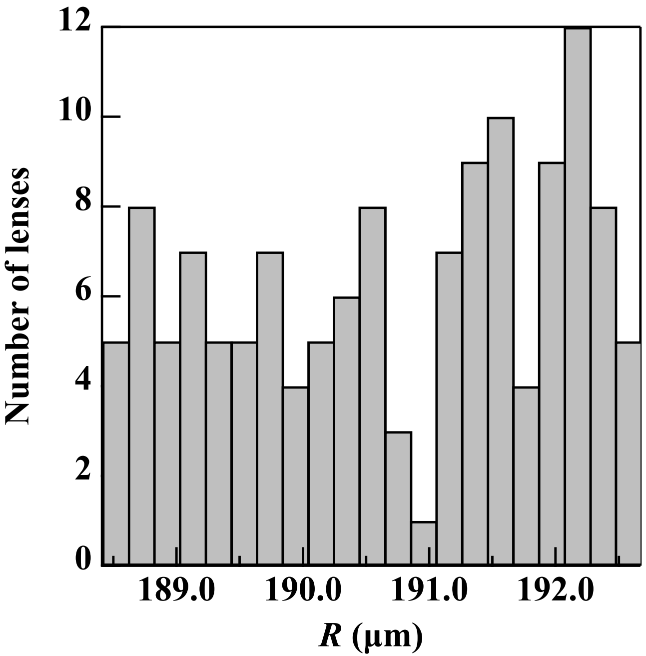
- Clear aperture $2R_0$: acceptable
- Radius of curvature *R*: acceptable
  - Measured mean values are ~5% smaller than specified values, most likely due to systematic measurement error (possibly due to uncalibrated energy, delta value and beam divergence and distance)
  - Radius RMS deviation < 1%, all within ±2.5% of the mean value
- Minimum thickness *d*: not tested



Statistics (R = 200 μm)

Radius distribution (600 μm area)

$\bar{R}$ = 190.7 μm, σ = 1.30 μm



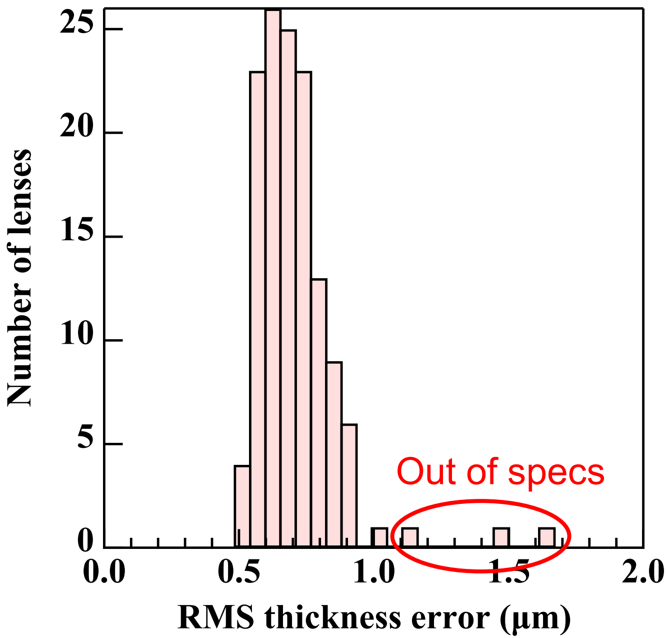
APS-U LENSES MEASURED AT 28-ID-B BEAMLINE

- Defects and cracks
  - 15 lenses were detected with defects >10 µm PV thickness error, request to replace
  - All lenses rechecked after air cleaning, defects remained.
- Thickness error
  - RMS thickness error after removing best-fit parabola over the central two-third of the diameter < 1.0 µm except 3 lenses (already included in the defect rejection list above)
- Optical axis: not tested
- Ventilation hole: not tested

Statistics (R = 200 µm)

RMS error distribution (600 µm area)

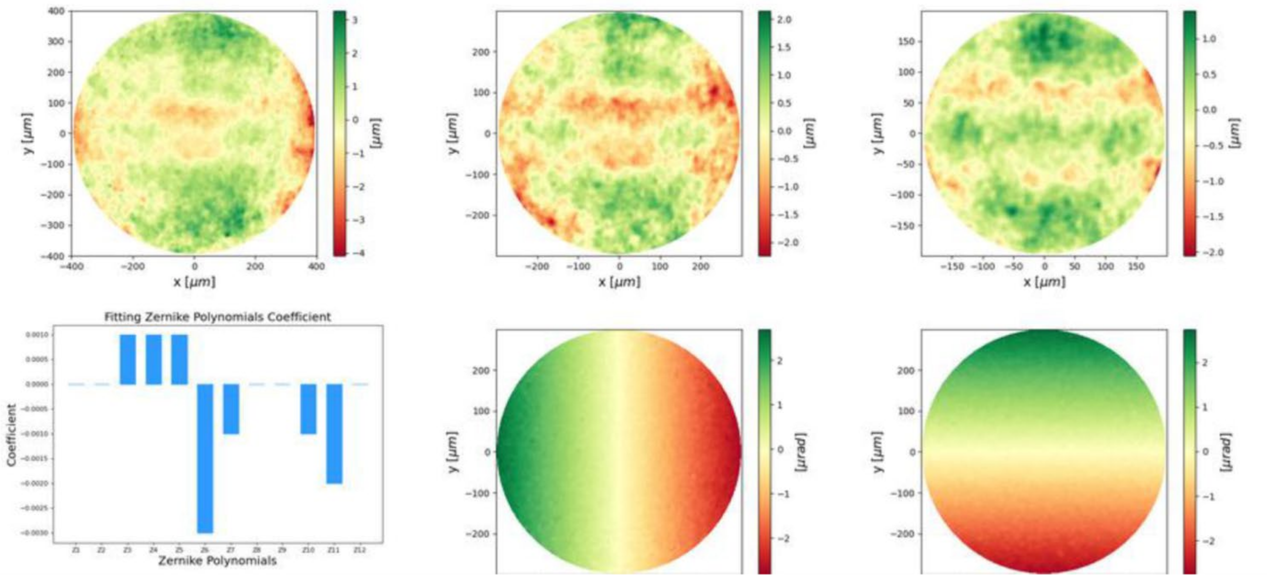
Average RMS error = 0.71 µm

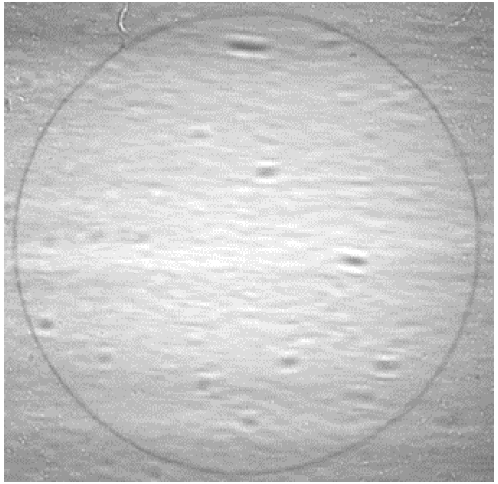


APS-U LENSES MEASURED AT 28-ID-B BEAMLINE

Example good lens

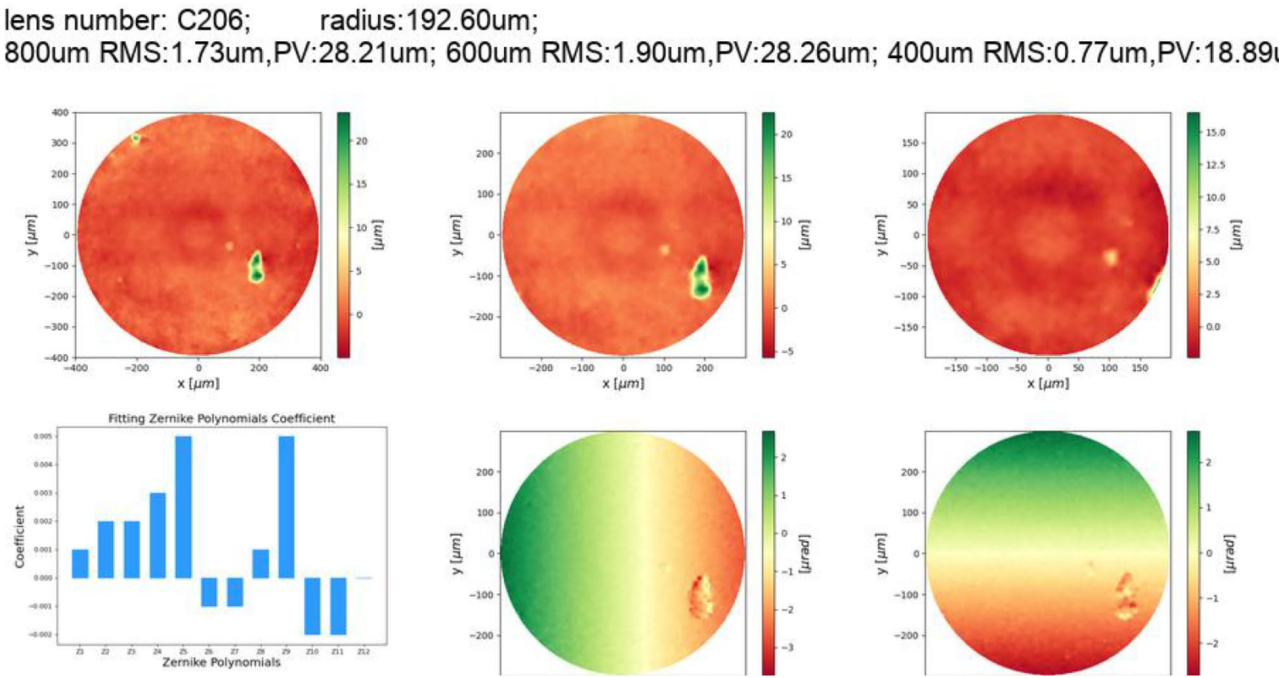
lens number: D102; radius:189.22um;
800um RMS:0.92um,PV:7.36um; 600um RMS:0.62um,PV:4.39um; 400um RMS:0.44um,PV:3.45um

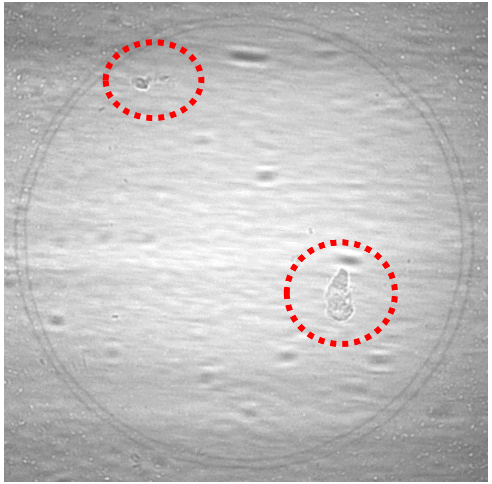




APS-U LENSES MEASURED AT 28-ID-B BEAMLINE

Example rejected lens

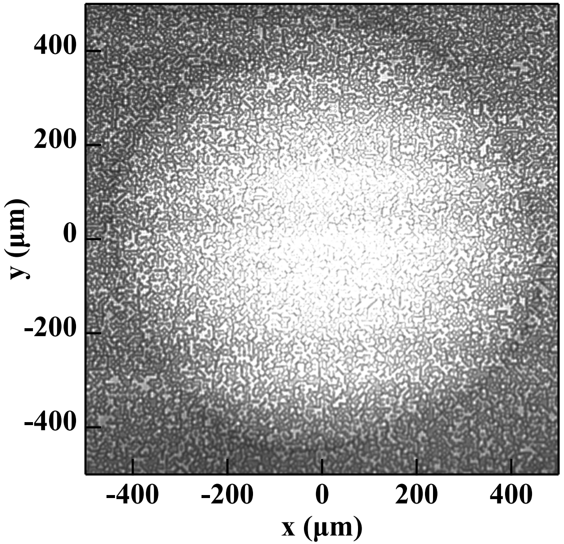




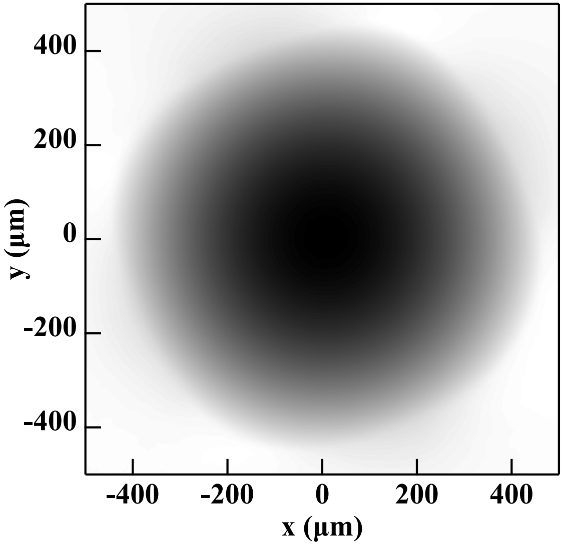
REMEASUREMENT OF 95 AL LENSES FOR 15-ID

- **Quatrefoil error**
  - **Consistent with the lens aperture shape (all lenses seem to have a square-ish aperture)**

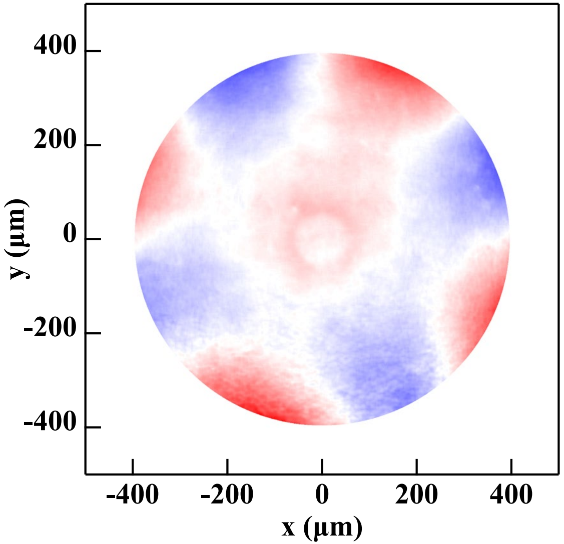
Raw transmission image (with the mask in)



Reconstructed phase profile (same shape as thickness profile)



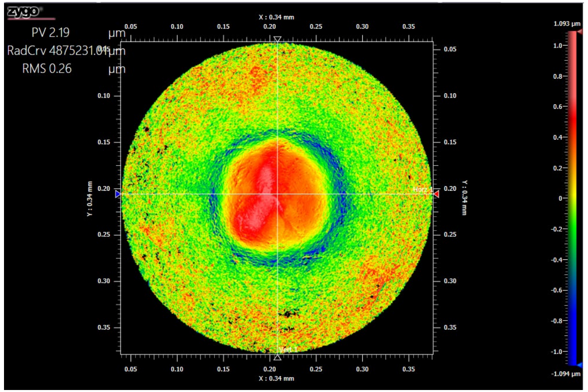
Thickness residual profile removing best fit parabola

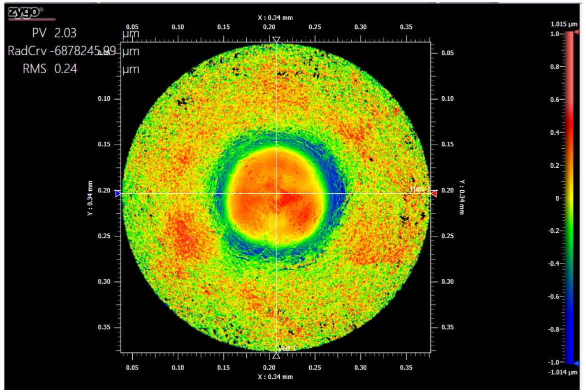


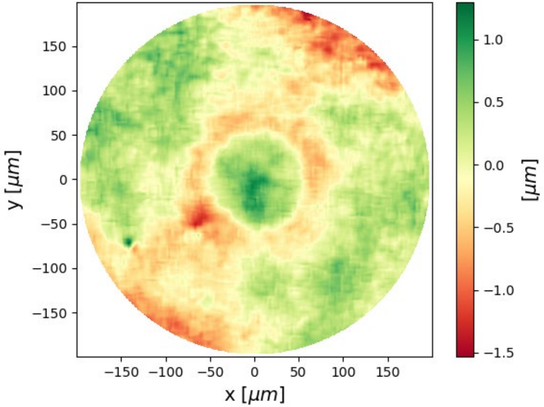
REMEASUREMENT OF 95 AL LENSES FOR 15-ID

- **Zygo interferometer vs 28-ID wavefront sensor**
  - **Within a small aperture (~400 µm) limited by Zygo**

Zygo	**Zygo**	**28-ID wavefront**
Lens 1: face 1	Lens 1: face 2	Lens 1



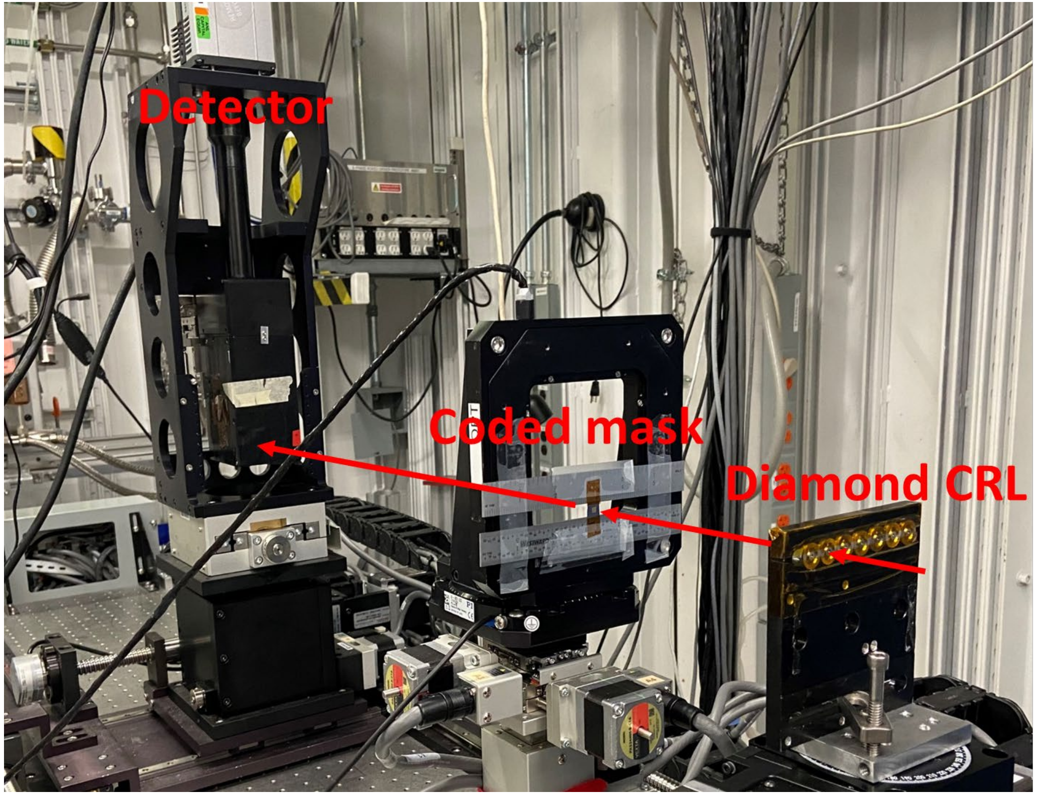




R = 198.11 µm	R = 198.11 µm	R = 189.16 µm
RMS = 0.26 µm	RMS = 0.26 µm	RMS = 0.40 µm

R from x-ray measurement is 5% smaller than from optical measurement: possibly due to uncalibrated energy, delta value and beam divergence and distance.

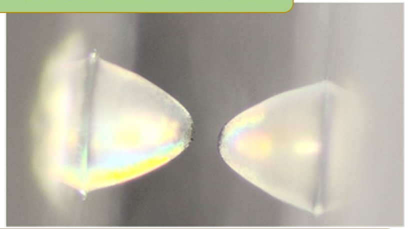
DIAMOND LENSES AT 32-ID



PALM Scientific
(Sergey Antipov)

Diamond press-in

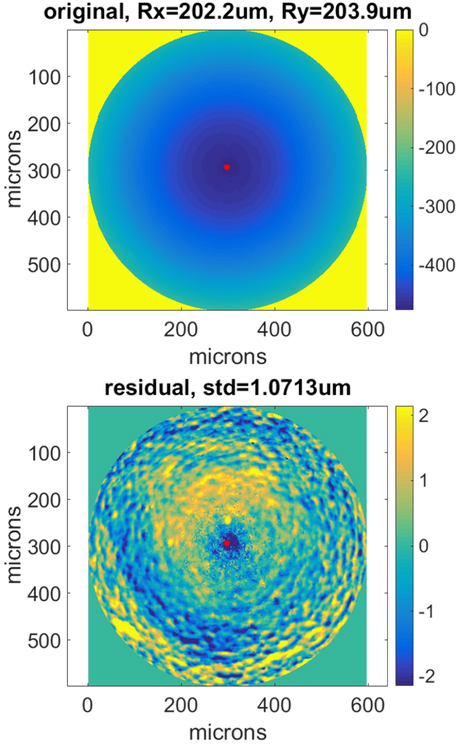
Laser ablation



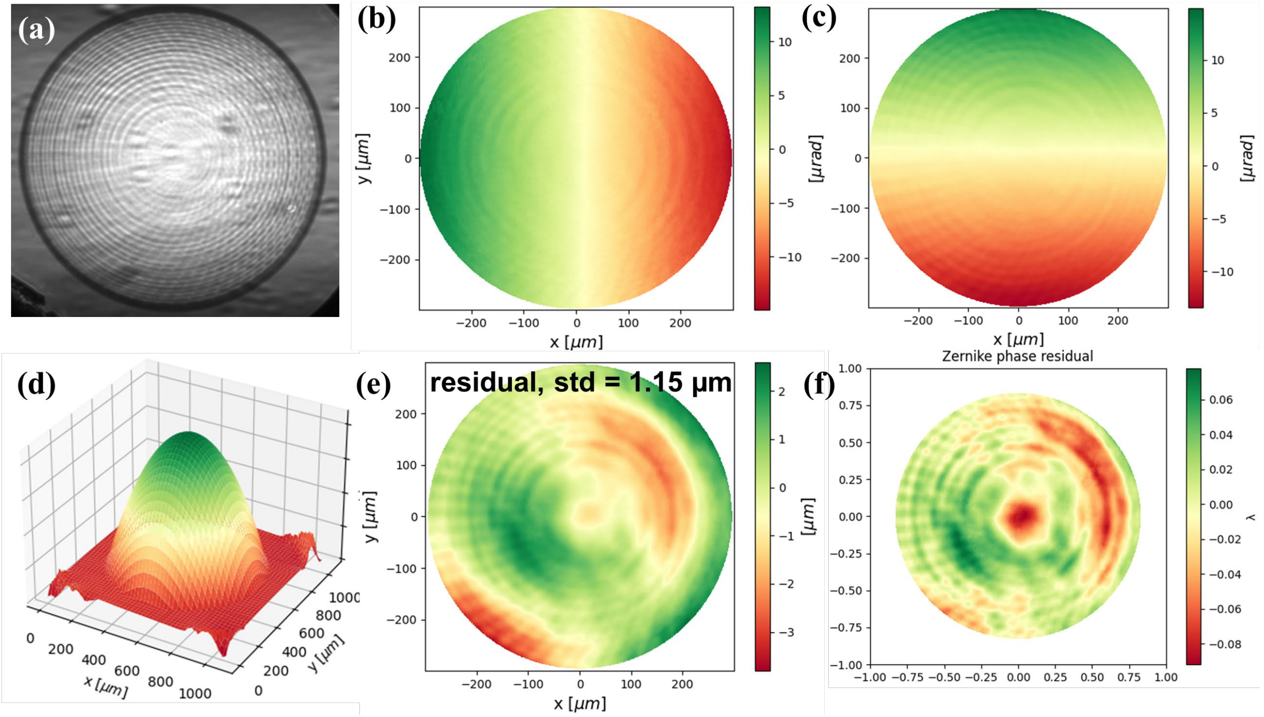
High precision disks

FOCUSING MEASUREMENT AT 32-ID VS SIMULATION

Optical metrology



X-ray metrology

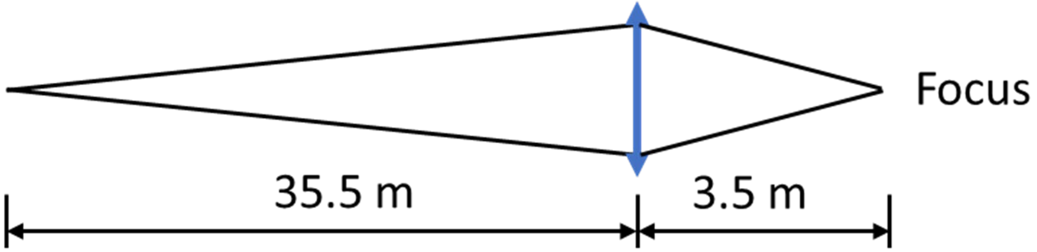


Argonne NATIONAL LABORATORY

FOCUSING MEASUREMENT AT 32-ID VS SIMULATION

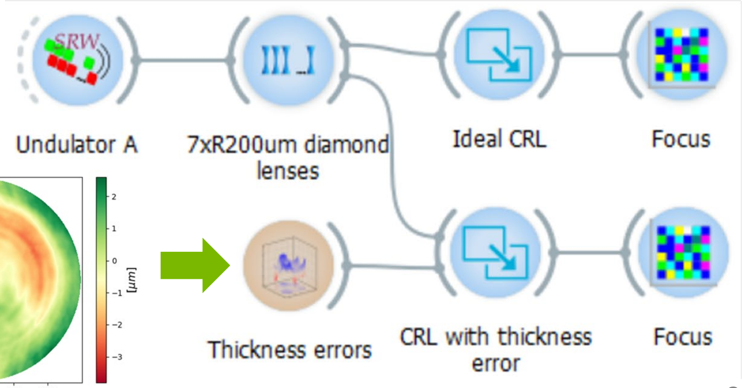
APS @ 8.9 keV

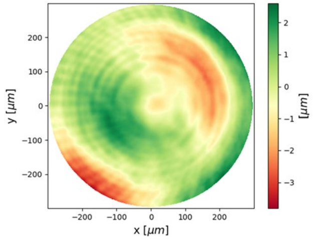
7 diamond CRL (single-sided R = 200 µm)



Measured focus

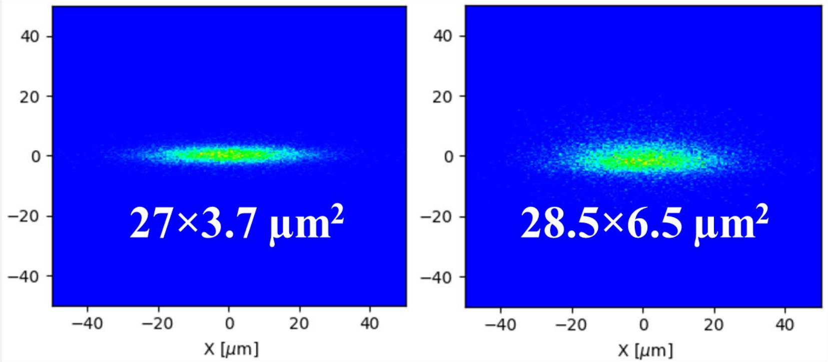
Oasys-Shadow simulation



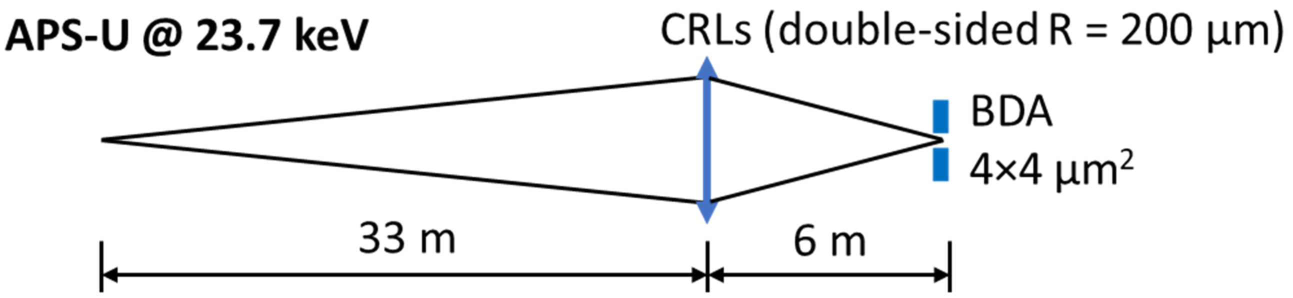


Ideal lens

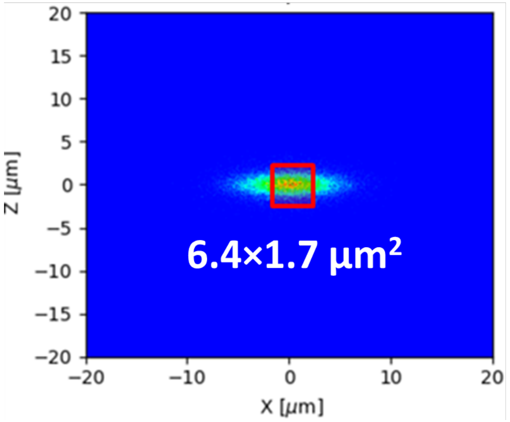
With thickness error



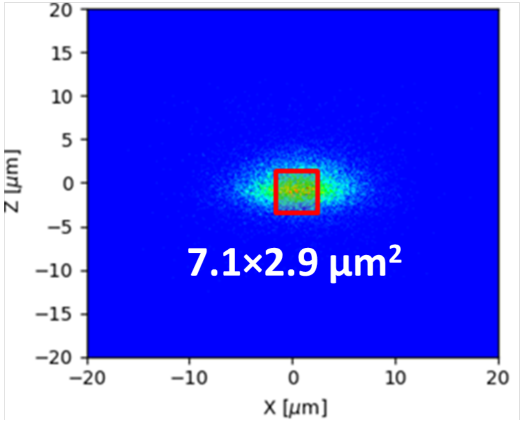
FOCUSING SIMULATION FOR 32-ID WITH APS-U



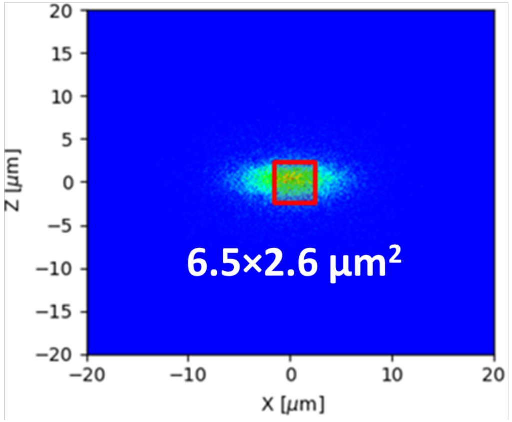
Ideal lenses



15 diamond lenses with thickness errors



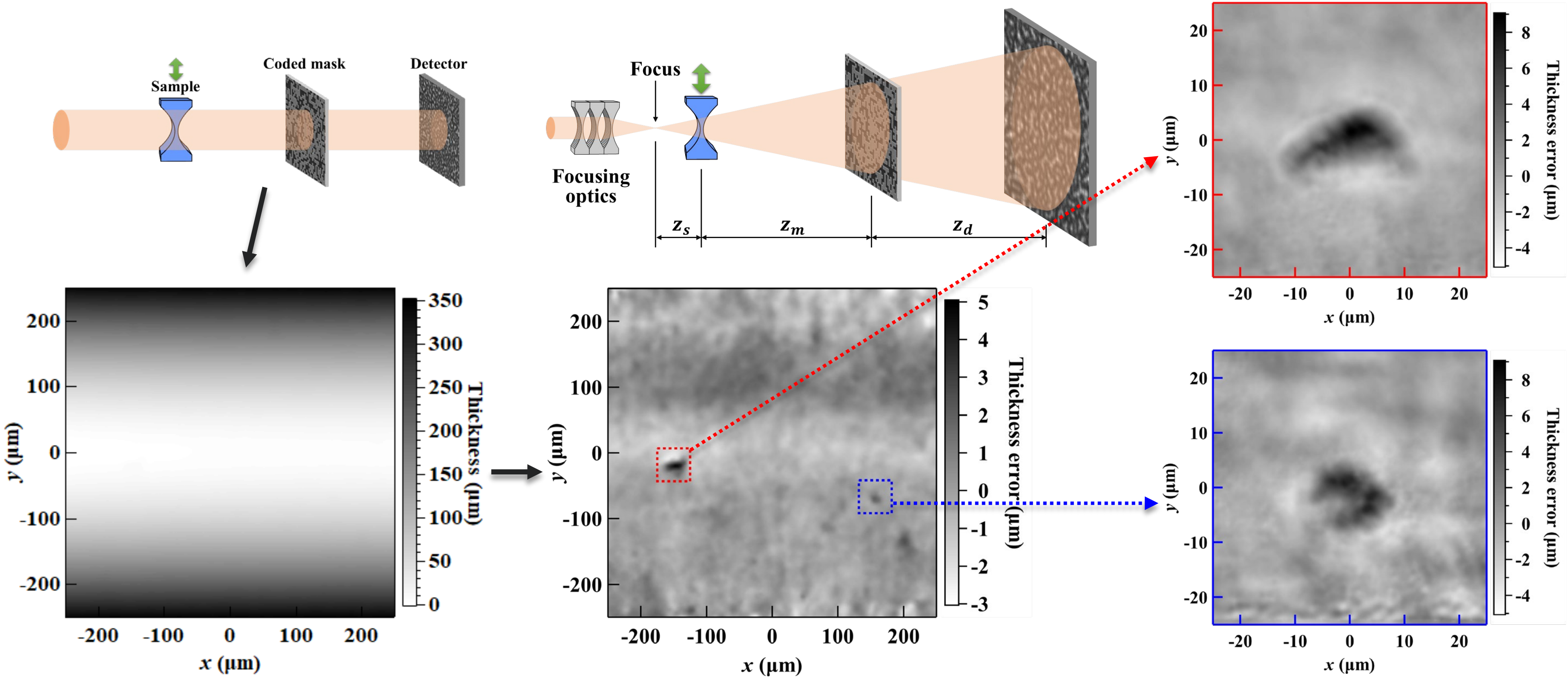
32 Be lenses with thickness errors



VARIABLE-RESOLUTION METROLOGY OF CRL

VARIABLE-RESOLUTION METROLOGY OF CRL

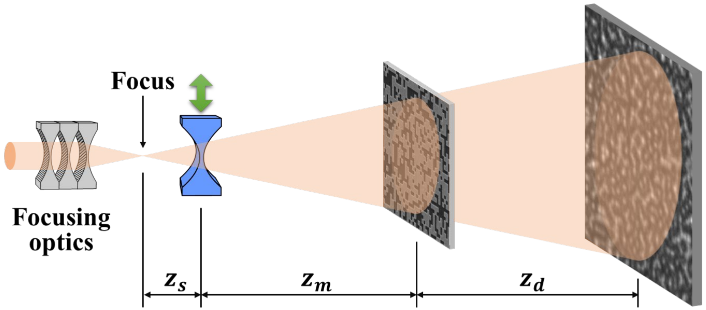
Results: thickness profile measured with diverging-beam setup

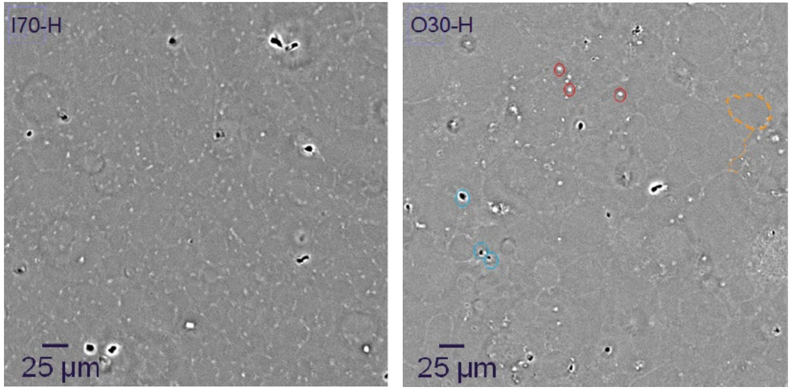


X. Shi, et. al, Proc. SPIE **12240**, 122400H (2022).

VARIABLE-RESOLUTION METROLOGY OF CRL

Results: comparing lenses using different Be grade



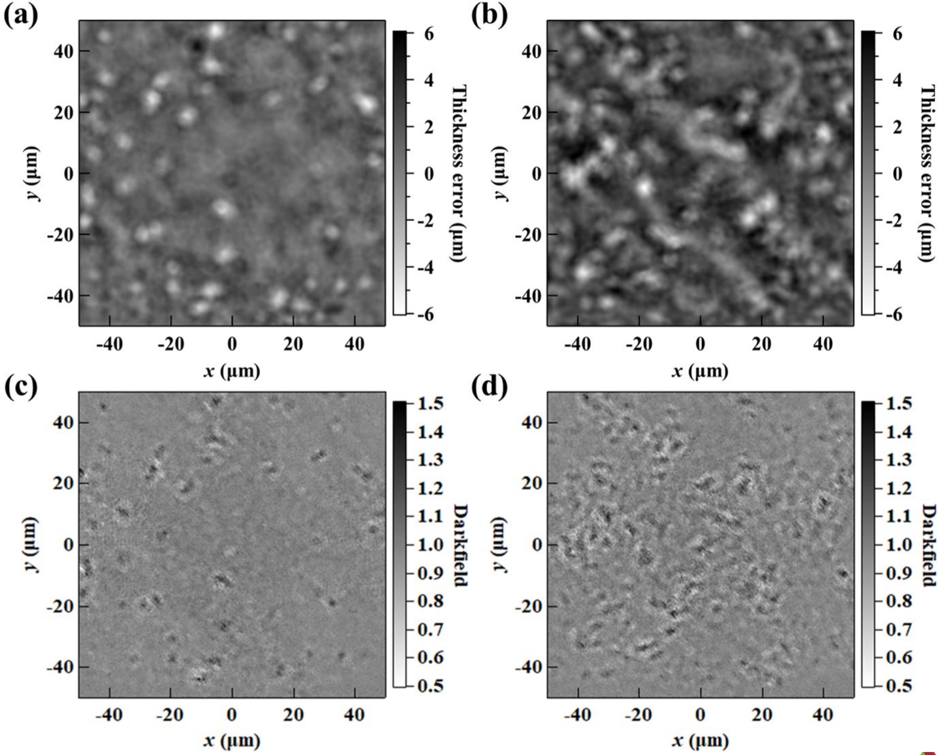


Results using synchrotron laminography

T. Roth, et al., Proc. SPIE 9207, 920702 (2014).

I-70-H

O-30-H



ACKNOWLEDGEMENT

Zhi Qiao
Walan Grizolli
Matthew Highland
Matthew Frith
Michael Wojcik
Luca Rebuffi
Jun Qian
Lahsen Assoufid

Deming Shu
Shenglan Xu
Mati Meron
Binhua Lin
Kamel Fezzaa
Sergey Antipov

This work was supported by the US Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

THANK YOU!

Argonne NATIONAL LABORATORY