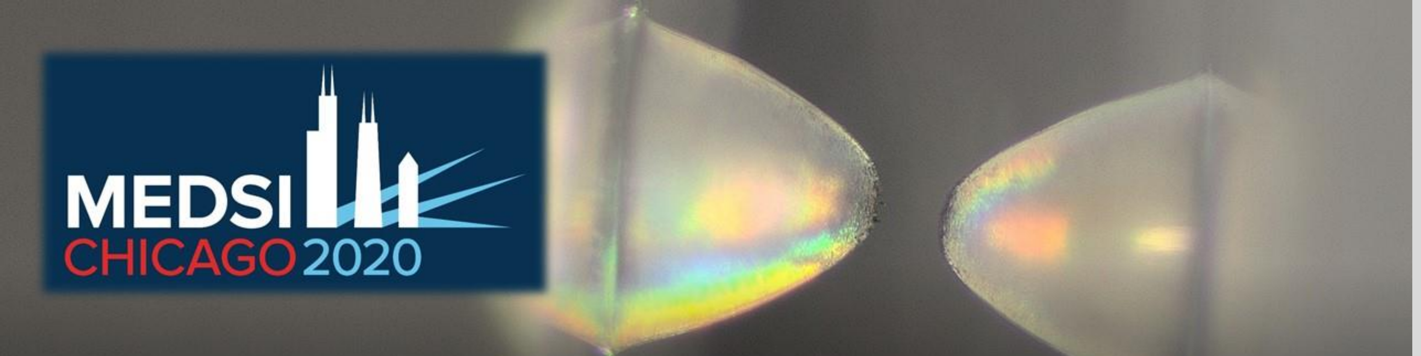

Diamond Refractive Optics Fabrication by Laser Ablation and at-Wavelength Testing

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Funded by DOE SBIR, PM E. Lessner

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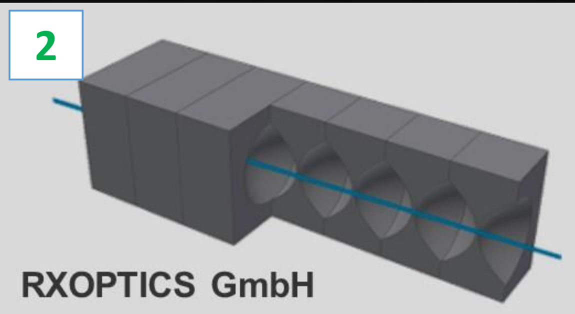
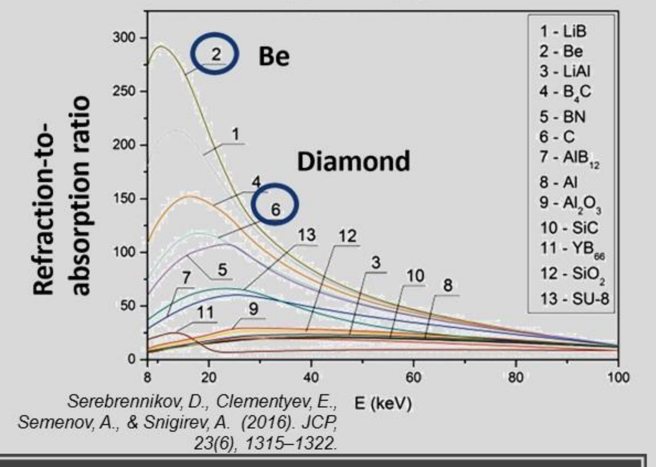


RXOPTICS GmbH

- A. Snigirev, V. Kohn, I. Snigireva, B. Lengeler, A compound refractive lens for focusing high-energy x-rays, Nature 384 (1996), 49-51
- B. Lengeler, C. Schroer, J. Tümmler, B. Benner, M. Richwin, A. Snigirev, I. Snigireva, M. Drakopoulos, Imaging by parabolic refractive lenses in the hard x-ray range, J. Synchrotron Rad. (1999) 6, 1153-1167
- B. Lengeler, Refractive x-ray lenses: New developments, 2012

$n = 1 - \delta + i\beta$; $\delta, \beta \sim 10\text{-}6$



Serebrennikov, D., Clementyev, E., Semenov, A., & Snigirev, A. (2016). JCP, 23(6), 1315–1322

Compound Refractive Lens

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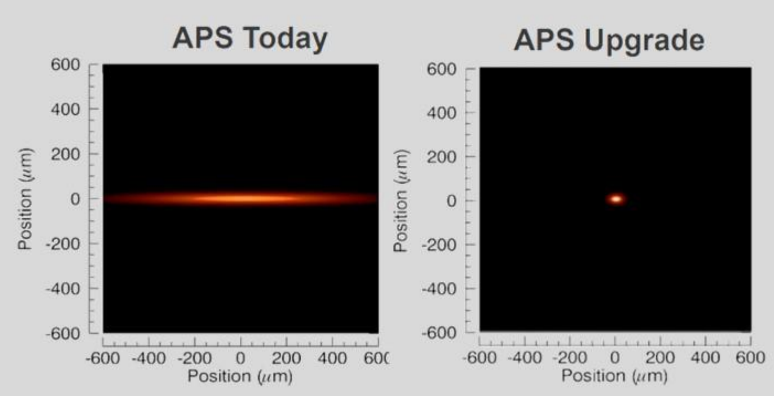
Ultimate Storage Ring – ultra-high brightness

- New generation of synchrotrons MAX IV, ESRF-U, SIRIUS, SPRING-8-U, APS-U
- Round beam (source) – ideal for x-ray microscopy, tomography etc..
- Higher degree of coherence
- APS-U exceeds the capabilities of today's storage rings by 2 to 3 orders of magnitude in brightness, coherent flux, nano-focused flux



- High heat load on the x-ray beamline elements
- Stringent requirements on preservation of coherence

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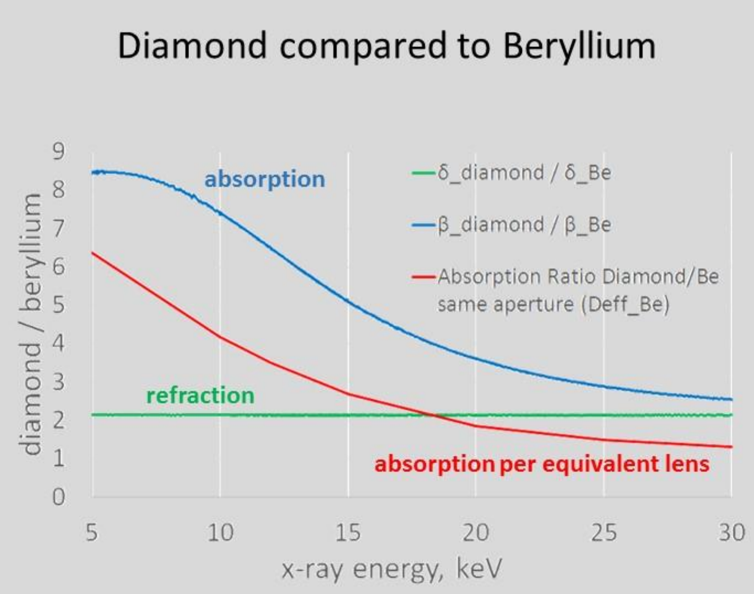
Diamond Compound Refractive Lens?

- Low Z
- Single crystal
- Best thermal conductivity
- Outstanding coefficient of linear thermal expansion
- Radiation hard
- Semiconductor



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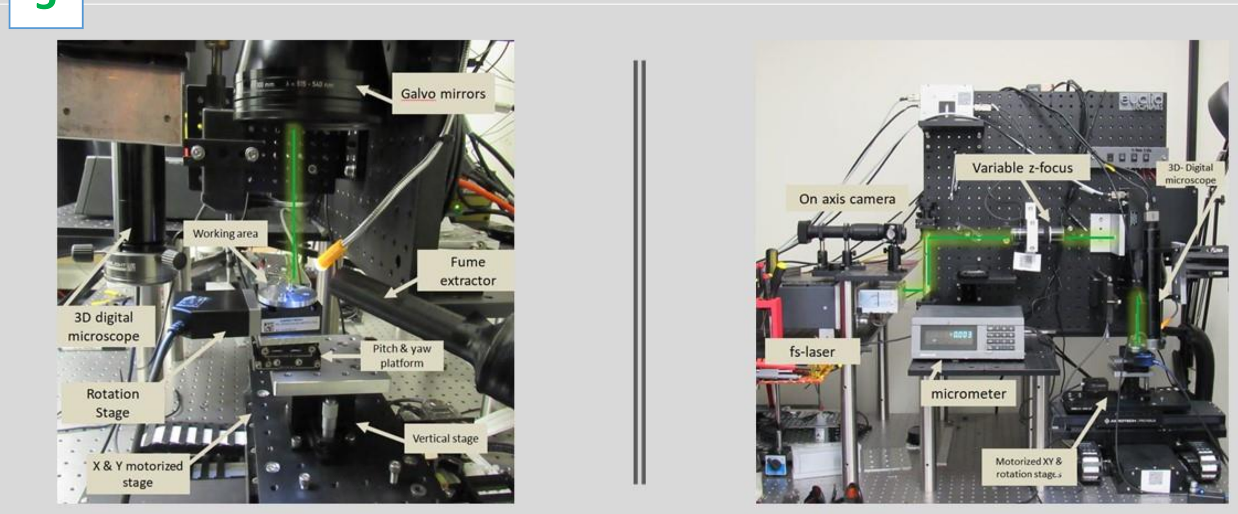

Femtosecond laser microfabrication of diamond

Fs- laser: 515nm, 3W, 60kHz, 200fs

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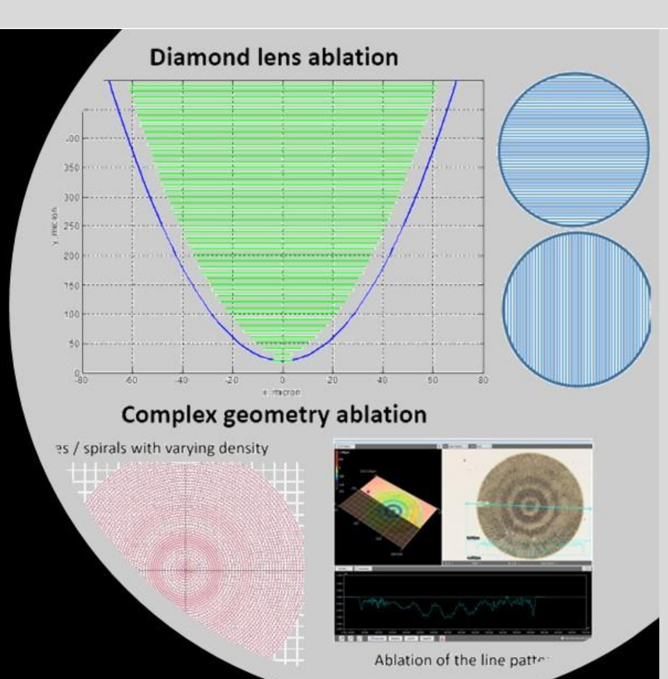
Ablation Scripting

- Profile decomposed in layers
- Layer-by-layer ablation
- Layer symmetrization
- Edge effects
- Laser delay effects
- External motorization
- Focus adjustment



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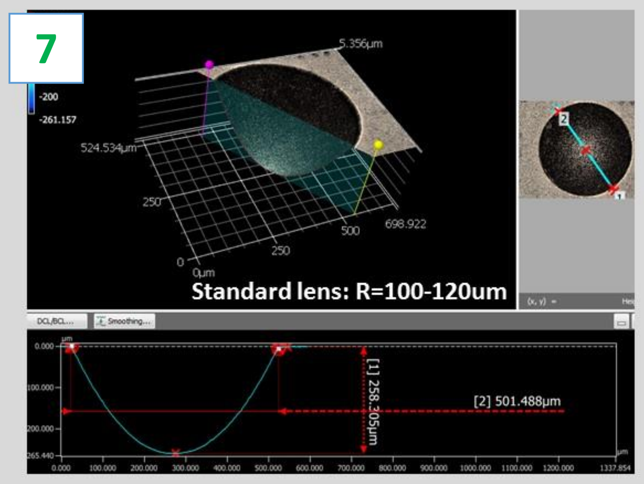

Equivalent to Be lens with R=50 and $2R_0$=450

Metrology in-house

Scanning confocal laser microscopy

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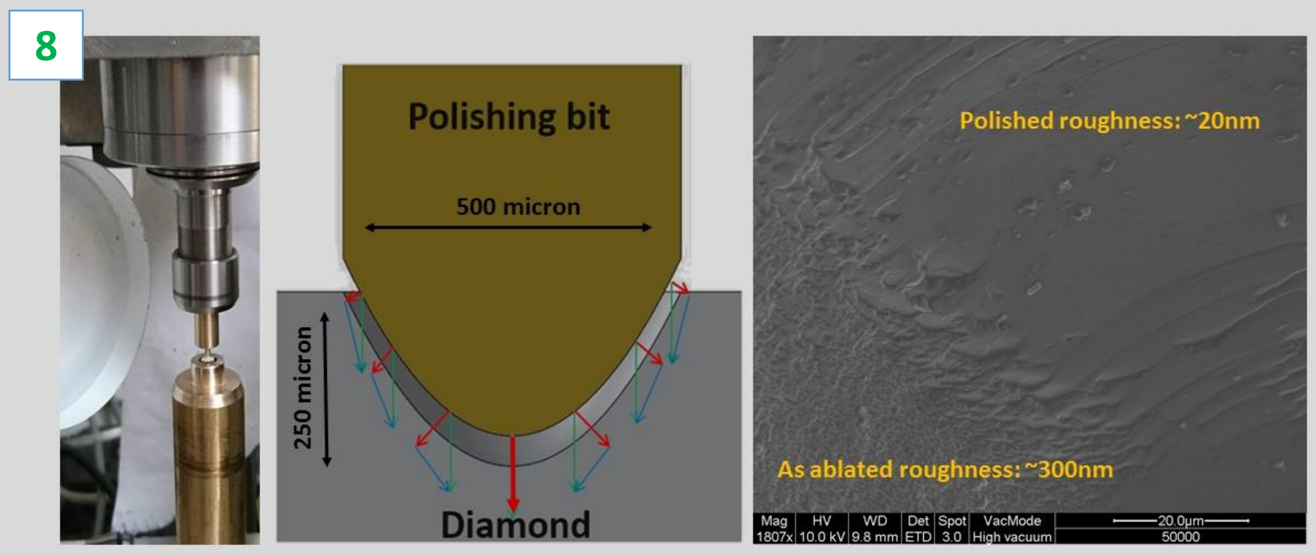

Polishing process

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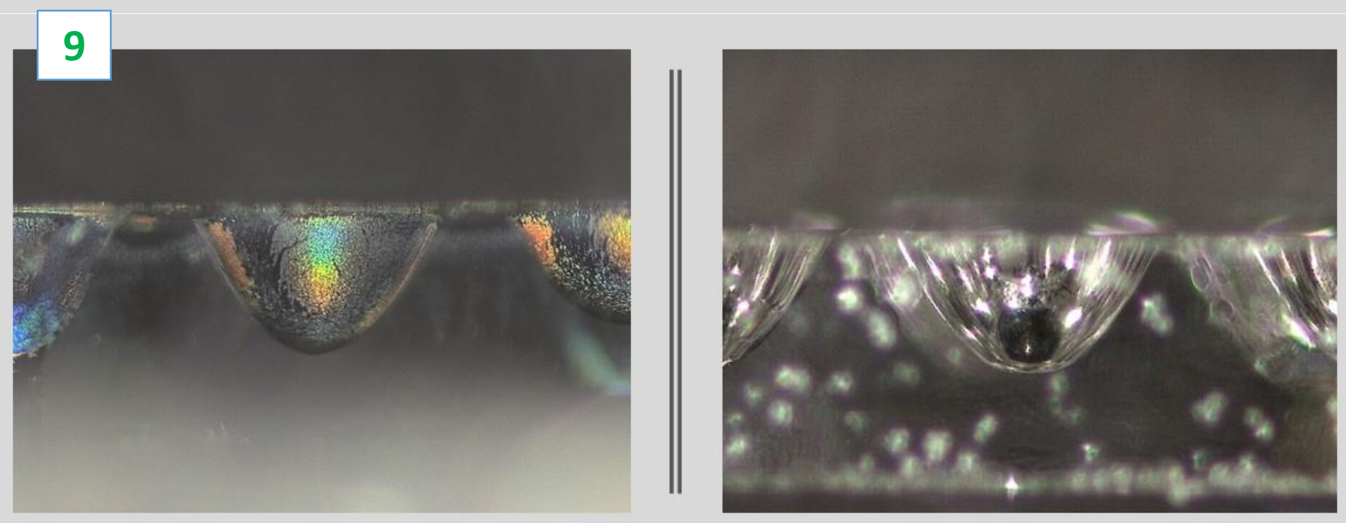

Side view: as ablated vs polished

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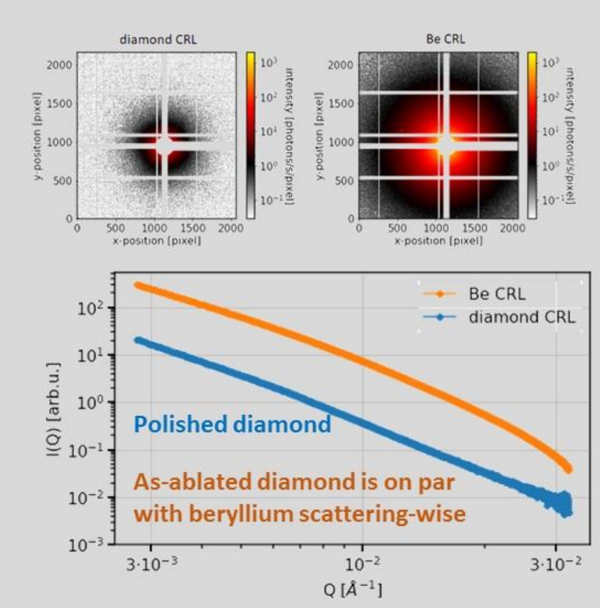
Comparison of Scattering at NSLS-II, CHX beamline

- 2D intensity distributions generated by EIGER detector located at ~16 m distance from the lenses @ 9.65 keV for diamond and Be CRLs
- azimuthally averaged scattering curves
- 200 x 200 μm^2 aperture before the CRL

"The low X-ray scattering produced by diamond CRLs is one of its very attractive features, that may allow to extend the range of applications of the CRL optics to the areas / experiments that are very sensitive to background scattering (e.g. where coherent diffractive imaging reconstruction of weakly-scattering samples is performed), where Be lenses are not currently used, or are not considered as the optics of best choice"



"Analysis of hard x-ray focusing by 2D diamond CRL" O. Chubar, et. al., SPIE conference proceedings 2020, https://doi.org/10.1117/12.2568980

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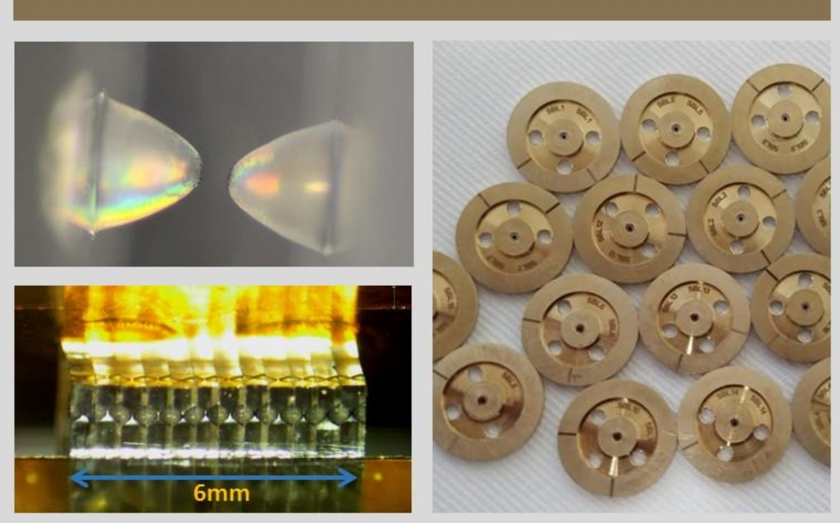
Lens Packaging



- Aluminum – bronze vacuum compatible tight tolerance 12mm "coin" is available
  - Diamond pressed in
  - Diamond brazed in* (ongoing) - thermal
- Octagonal coin – large aperture, 1D lens
- Retrofitting / adding into existing Be lens holder
- Ultra-small diamond stack brazed into heatsink – 10mm long CRL

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Diamond Lens	Optical metrology	17 keV BM05 metrology	Notes
R (apex)	~95.35 um average (on each side)	48.1 um average (96.2 um per side)	Equivalent to Be lens with R=50 and $2R_0$=450
$2R_0$ (aperture)	410 um	350um usable	
d (neck)	19.7 um average		
As-ablated roughness	~300nm		
As-ablated figure error (350um aperture)	0.64um average	1.09um average (for both sides)	0.082um – standard deviation
Polished roughness	~20nm		
Polished figure error	0.91um average	1.19um average (2 sides)	
Form-factor	2-sided lens	Full lens measurement	
Alignment	<3um		

Tested Diamond Lens Quick Stats

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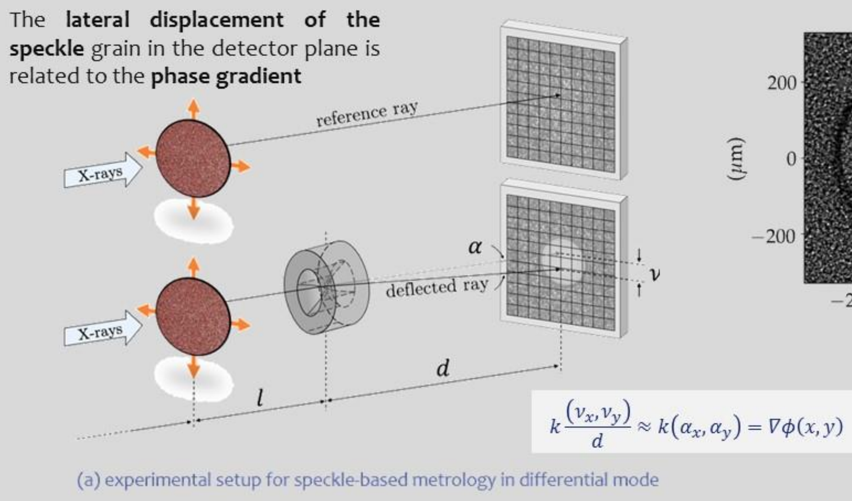
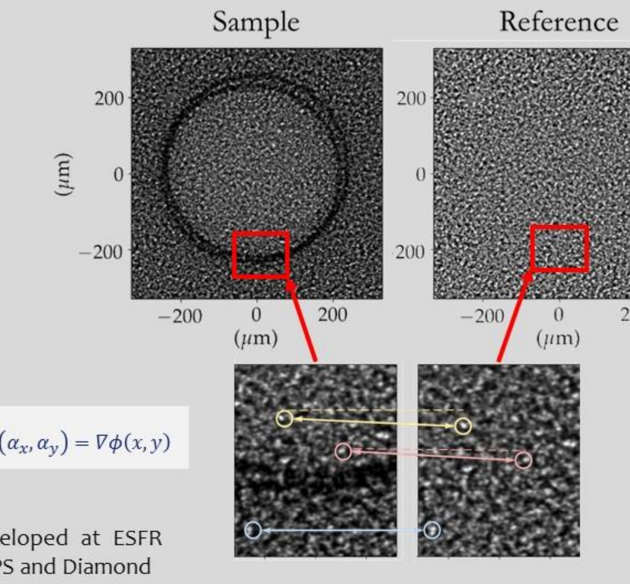
At-Wavelength Lens Metrology: X-ray speckle vectorial Tracking (XSVT)

The **lateral displacement of the speckle** grain in the detector plane is related to the **phase gradient**



$$k\frac{(\nu_x,\nu_y)}{d} \approx k(\alpha_x,\alpha_y) = \nabla\phi(x,y)$$

(a) experimental setup for speckle-based metrology in differential mode



S. Berujon et al, *J. Synch. Rad.* (2020). 27(2), 284
S. Berujon et al, *J. Synch. Rad.* (2020). 27(2), 293

Standard metrology developed at ESFR with variations used at APS and Diamond

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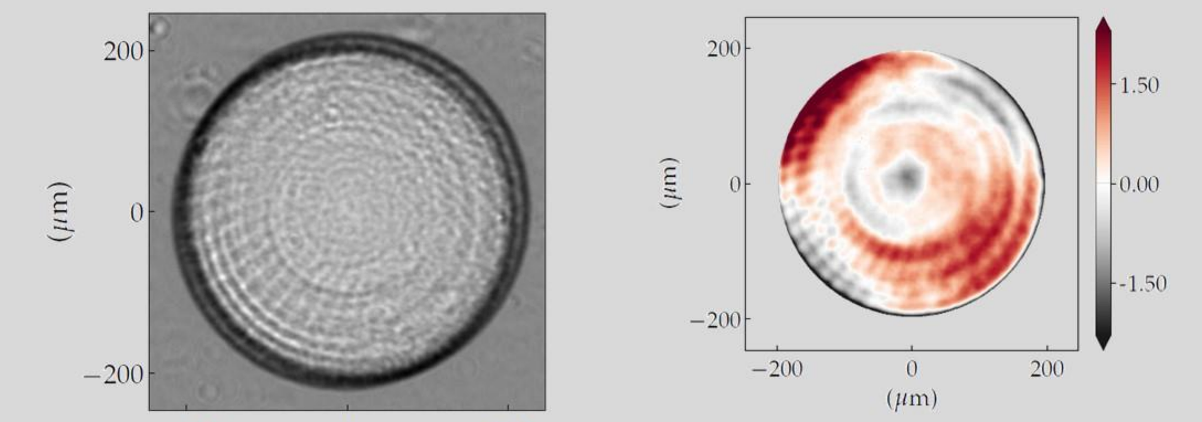
Radiography and cross-correlation peak



(a) figure errors 2D distribution

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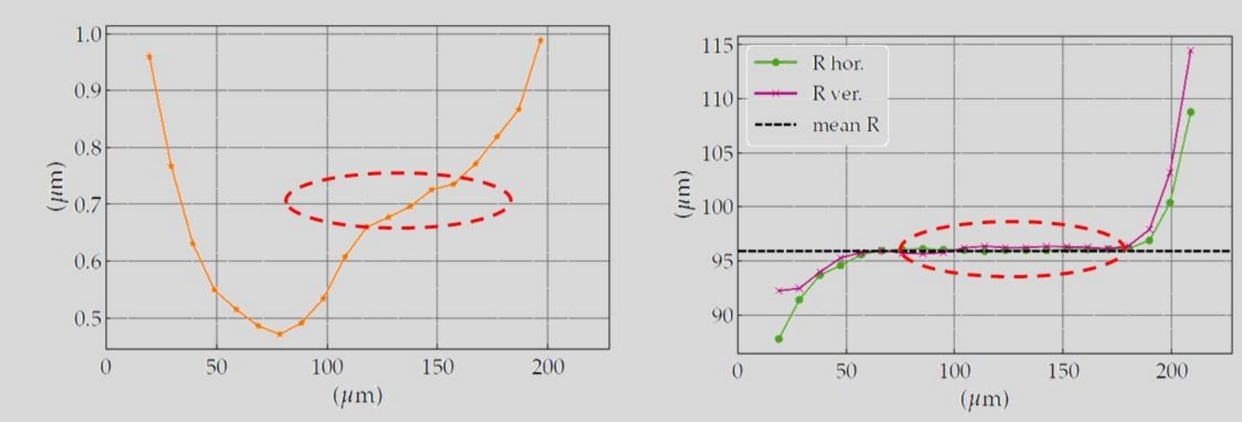
Paraboloid fit vs aperture



(b) figure errors vs. aperture size

(c) R vs. aperture size

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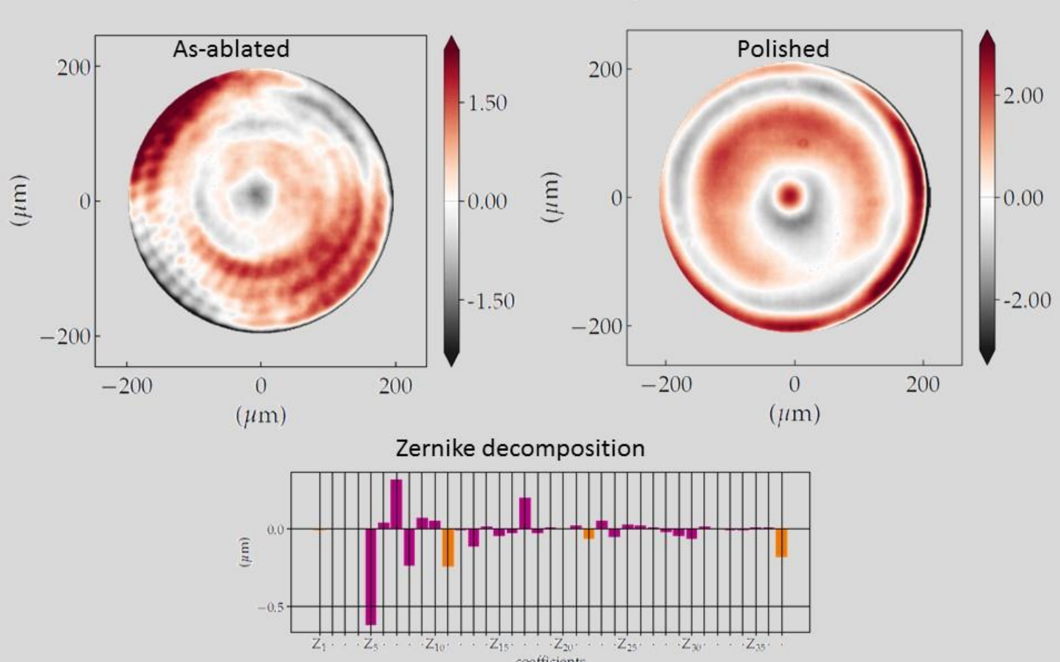
Profile decomposition



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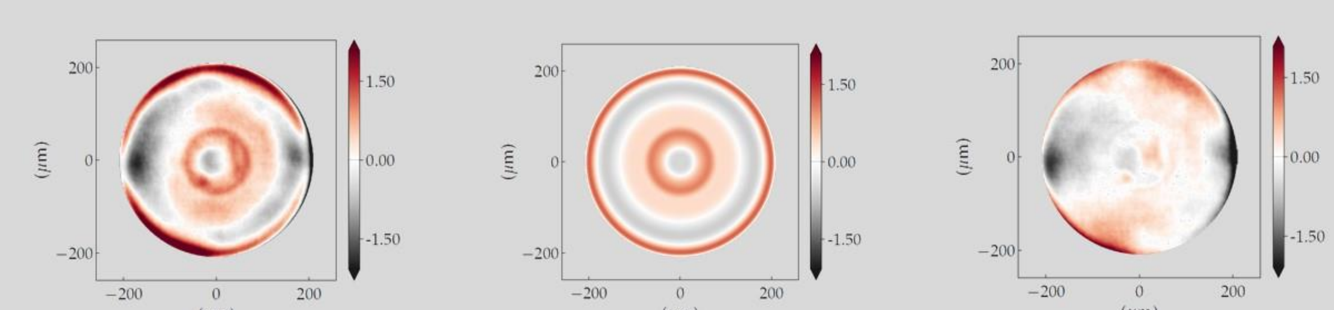
Correctable profile



(a) figure errors (σ_{rms} = 0.85μm) (b) averaged profile (σ_{rms} = 0.58μm) (c) fit residues (σ_{rms} = 0.62μm)

Rotationally-symmetric (spherical) aberrations can be corrected by a correction phase plate. In future it may be possible to correct other aberrations. At this point this is difficult given the stringent alignment requirements for non-spherical features.

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Summary

- Diamond refractive lenses
  - <1um figure error is achieved
  - 300nm roughness as ablated, 20nm roughness polished
- "Coin" - packaging equivalent to industry standard Be-lenses is available

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- DOE SBIR funding (PM E. Lessner)
- Collaborators:
  - X-Ray Optics group (ESRF)
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  - S. Stoupin (*now at LLNL) (CHESS, Cornell)
  - P. Chow (High Pressure CAT, APS, ANL)