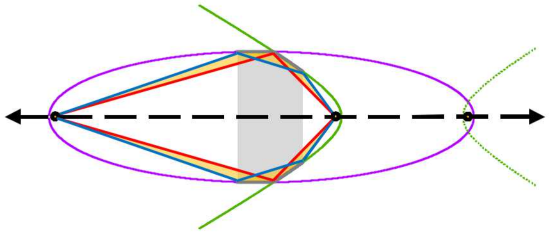
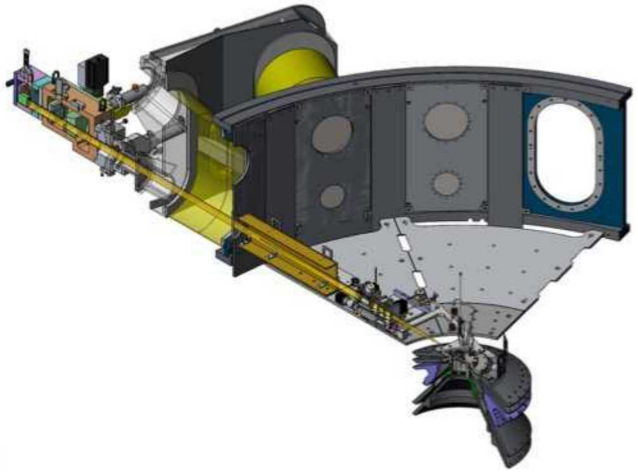
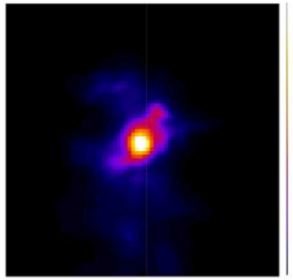
SAND2019-5675PE

Development of a Wolter Imager to diagnose warm x-ray sources on the Z Machine







PRESENTED BY

Jeff Fein, on behalf of the Wolter team

SNL Z Machine Diagnostic Workshop, April 17-18, 2019

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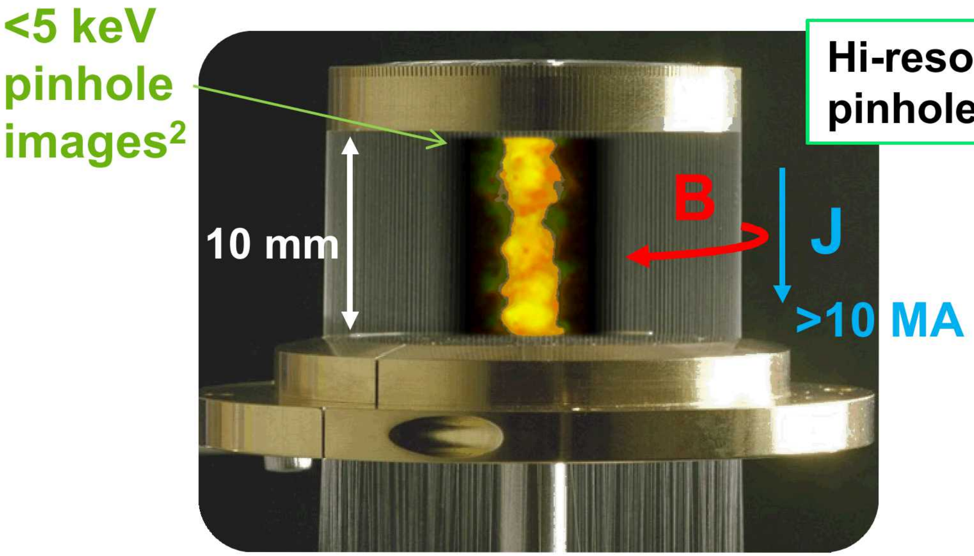
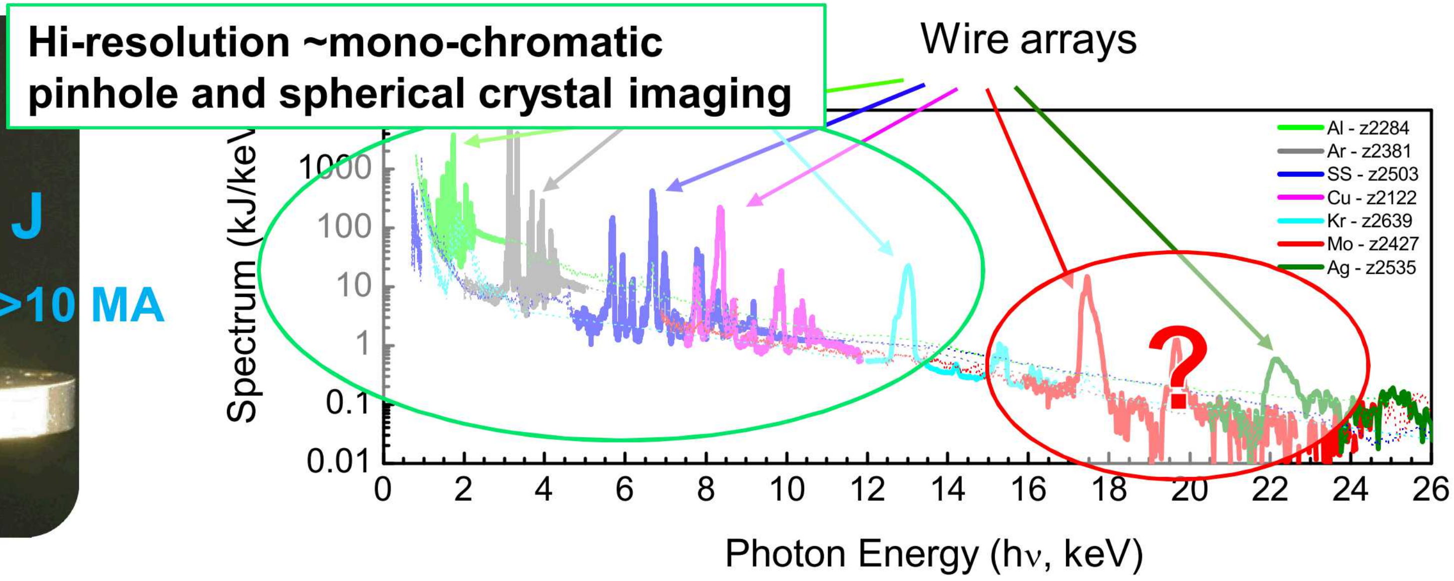
The Wolter optic was developed to image warm K-shell x-ray sources[1] for radiation effects science (RES) on the Z Machine





Previous limitations:

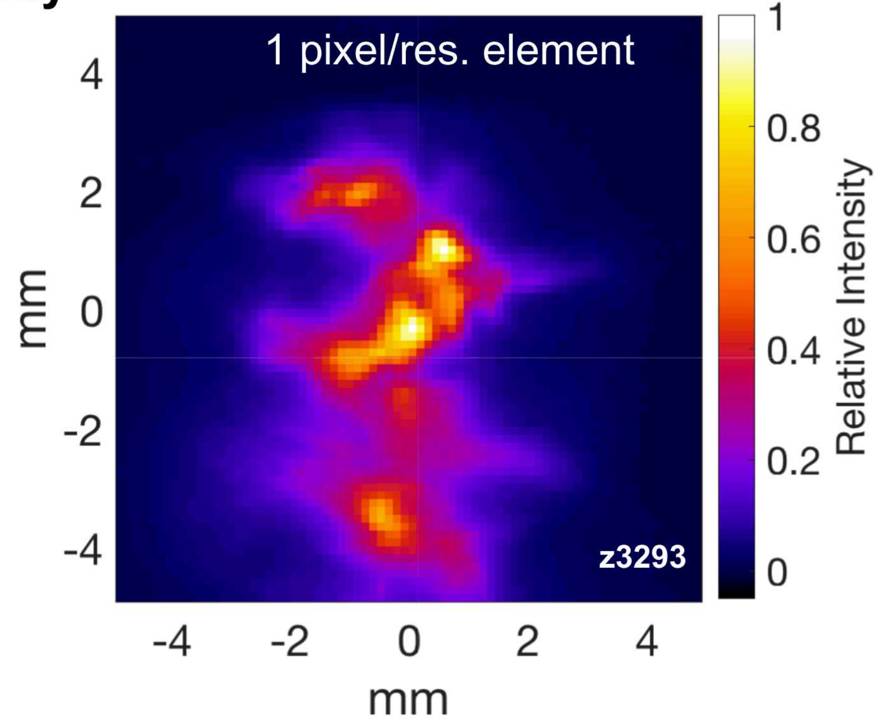
- **Tradeoff between signal/noise and spatial resolution (e.g. pinhole camera)**
- **Low efficiency and strong aberrations at >15 keV photon energies (e.g. spherical crystal imaging)**
- **Small fields-of-view (FOV), sources << 5 mm (e.g. KB microscope, Penumbral imager)**

1. D.J. Ampleford, POP (2014), 2. B Jones, RSI (2008)

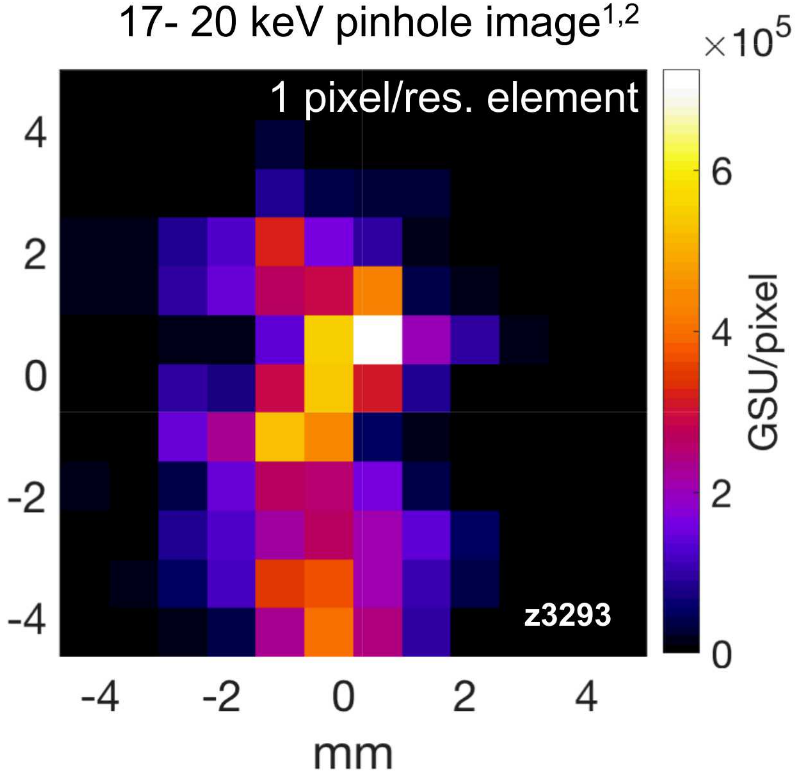
The Wolter optic was developed to image warm K-shell x-ray sources for radiation effects science on the Z Machine

Mo wire-array z-pinch

Wolter, flat-fielded[2]



17- 20 keV pinhole image[1,2]



Wolter optics can overcome several limitations from previous techniques for hi-resolution imaging of large (>5 mm) sources at >15-keV

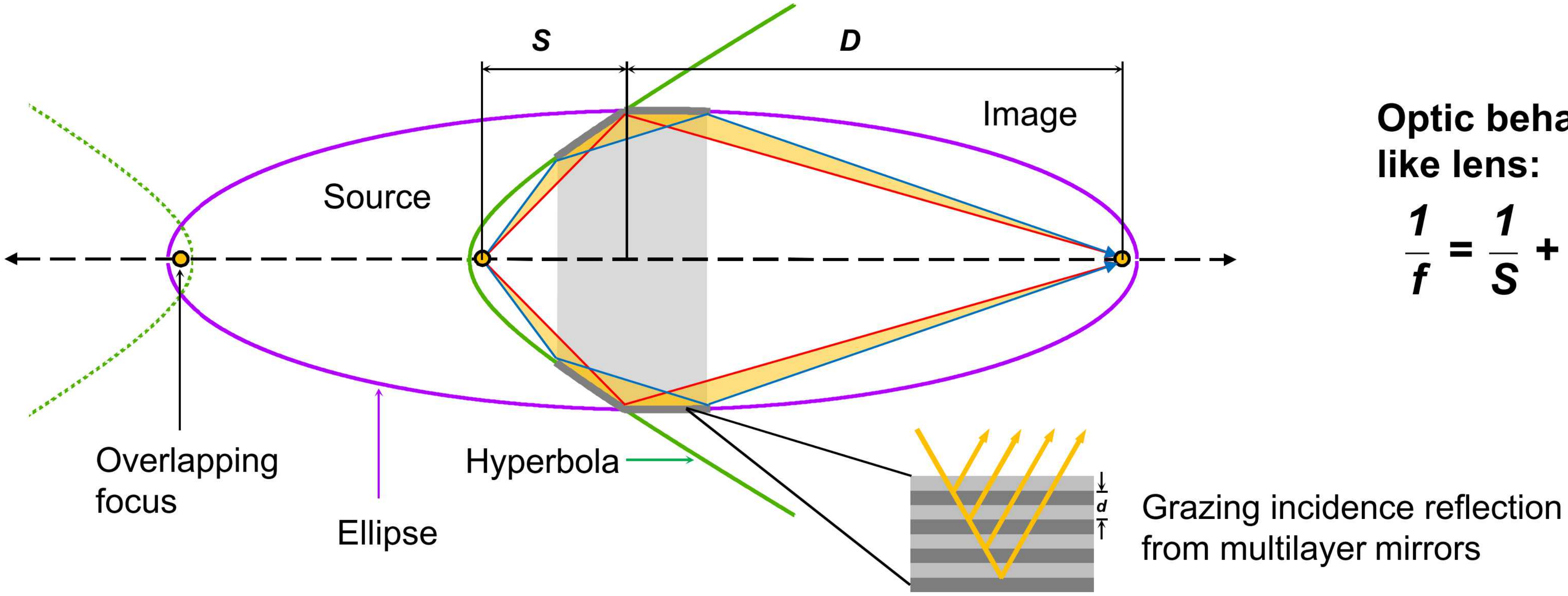
1. L. A. McPherson, 2. J.R. Fein, RSI (2018)

Summary

- The Wolter Imager has successfully imaged x-ray sources on the Z Machine in the 17-18 keV energy band, with development at ~22-keV
- Wolter has demonstrated a spatial resolution better than 150 microns with high signal/noise, significantly improving upon previous imaging capabilities
- Image processing techniques show potential to recover sub-resolution features in recorded images
- New fabrication techniques have been developed, capable of producing even higher-resolution optics

Wolter optics[1] use grazing incidence mirrors to form images of x-ray sources

Wolter type-I microscope:



Optic behaves like lens:

$$\frac{1}{f} = \frac{1}{S} + \frac{1}{D}$$

Key advantages:

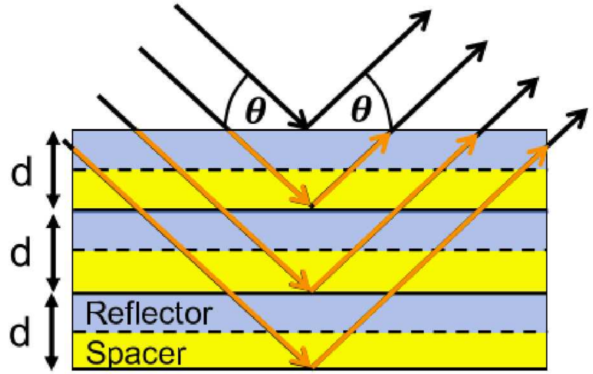
- **Large FOV, good resolution off-axis**
- **Large solid angle, multilayer (high-energies)**

1. H. Wolter, Ann. Phys. (1952), 2. J. K. Vogel et al., Rev. Sci Instrum (2018)

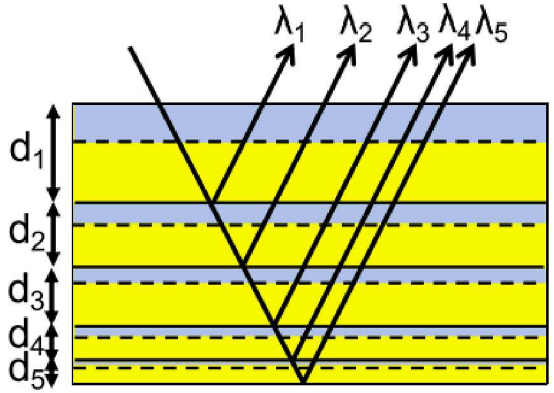
Multilayer mirrors enable high-efficiency imaging of >15 keV sources with tunable band-pass

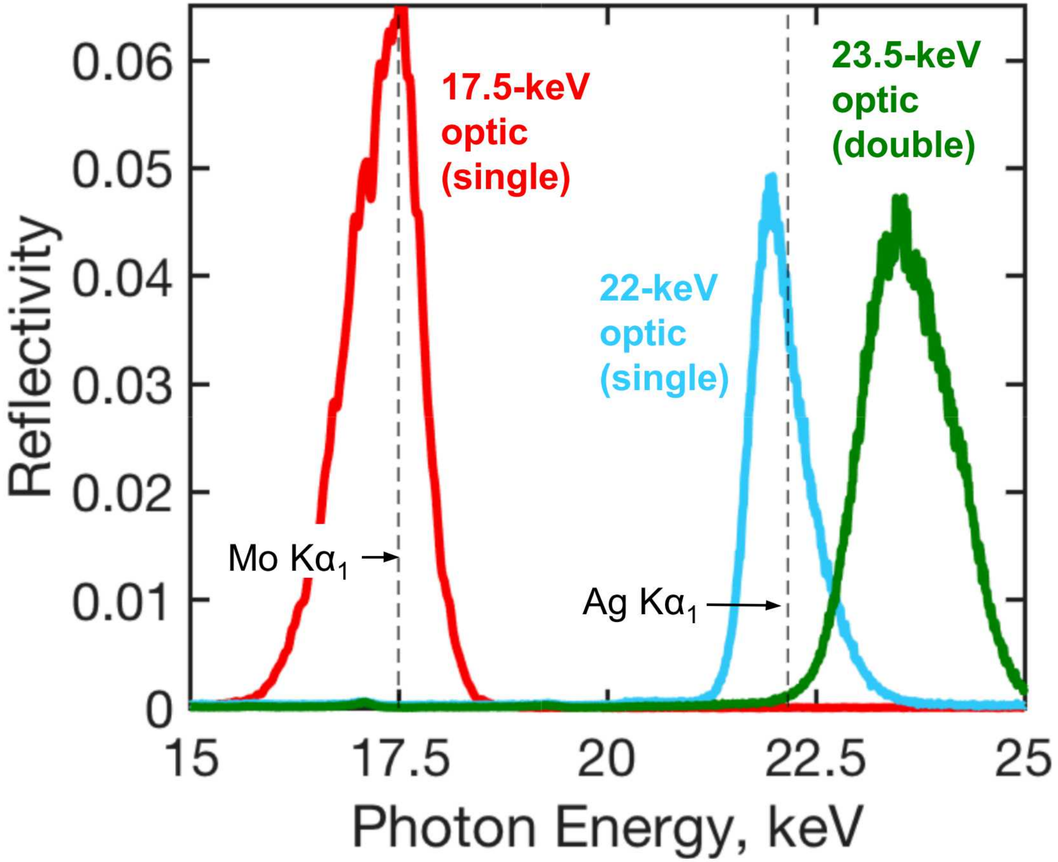
$$m\lambda = 2d \cdot \sin\theta$$

Constant-d[1]:



Graded-d:

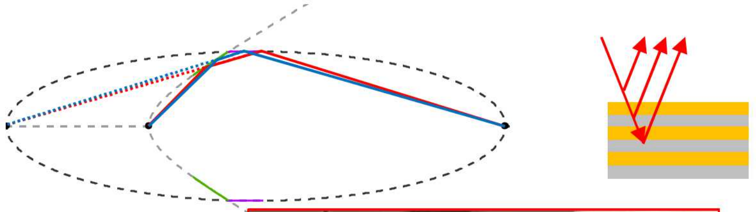




1. J. K. Vogel et al., Rev. Sci Instrum (2018), 2. S. Romaine et al., Proc. SPIE (2013)

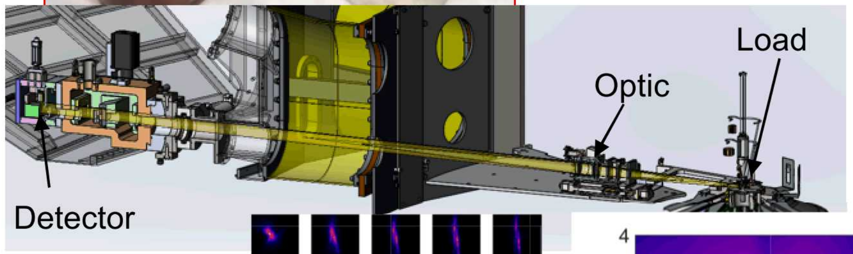
The Wolter Imager at SNL has been a multi-year collaboration between several institutions

Optical design (LLNL):

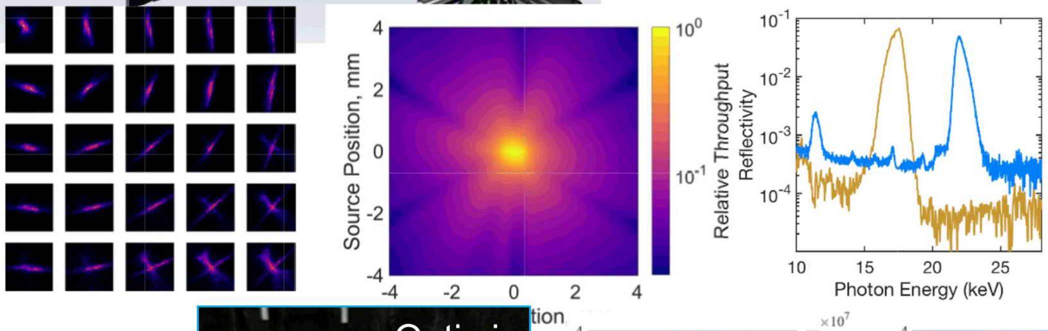


Mandrel & multi-layer fabrication (NASA/Harvard):

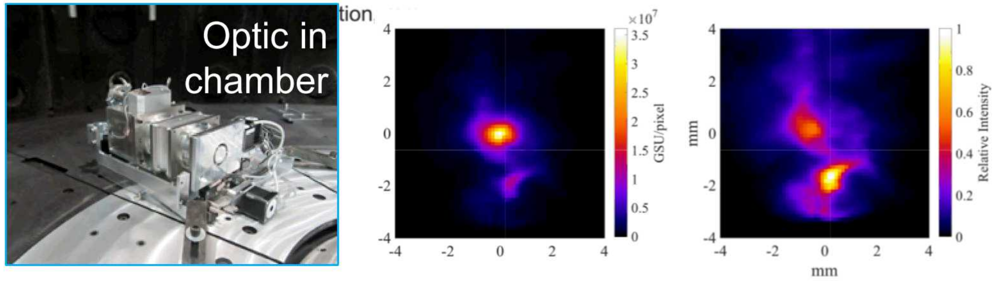
Mechanical design and control systems (SNL):



Calibration (LLNL and SNL):



Commissioning, Fielding, Image processing (SNL):



The optic's design was driven by a requirement to produce ~monoenergetic images at >15 keV energy with 100-µm resolution

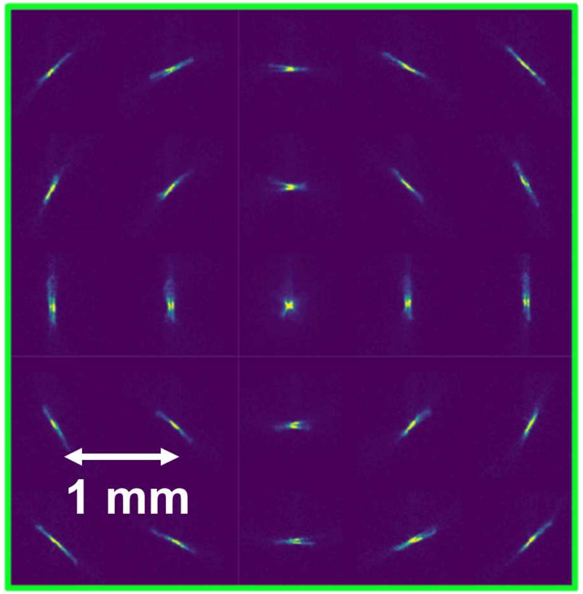
#	Need	Goal for initial fielding	Future aim	Driver
1	Photon energy	Mo Kα : 17.479 keV	Ag Kα : 22 - 23 keV (demonstrated) W Kα : 59.32 keV	Study K-shell radiators from Ag to W
2	Spectral window	~1 keV		Simultaneously view Kα1 & 2 from cold and low-ioniziation states up to Heα
3	Field of View	>5 mm field of view (in x,y and z)	Evaluate performance and setup for 20 mm	Study sources that are 5x5x5 mm size Collect all emission from 2 cm pinch. Kα emission comes from large diameter
4	Spatial Resolution	100 µm	50 µm	Resolve length-scale of structures emitting Kα (don't know what these are)
5	Time resolution	Time integrated initially	~1 ns in 2-4 years (hCMOS)	Resolve evolution over x-ray pulse
6	Sensitivity	800 J/cm^2 at source with 3:1 signal to noise	100 J/cm^2 at source with 3:1 signal to noise	Able to record 100 J (over source area); not diminish resolution with noise
7	Contrast	5:1 (In-band/Out-of-band)	>15:1	Image dominated by relevant signal
8	Flatness of response	<3x variation over FOV		Dynamic range of likely detectors (Image plate, hCMOS)

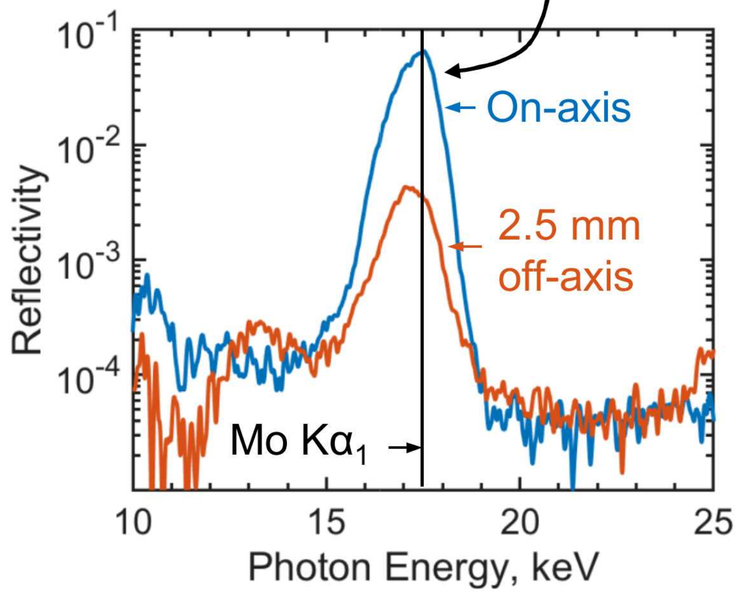
The optic has been characterized extensively in the laboratory to understand its performance and provide measurements for future image processing[1,2]

Initial 17.5 keV optic:

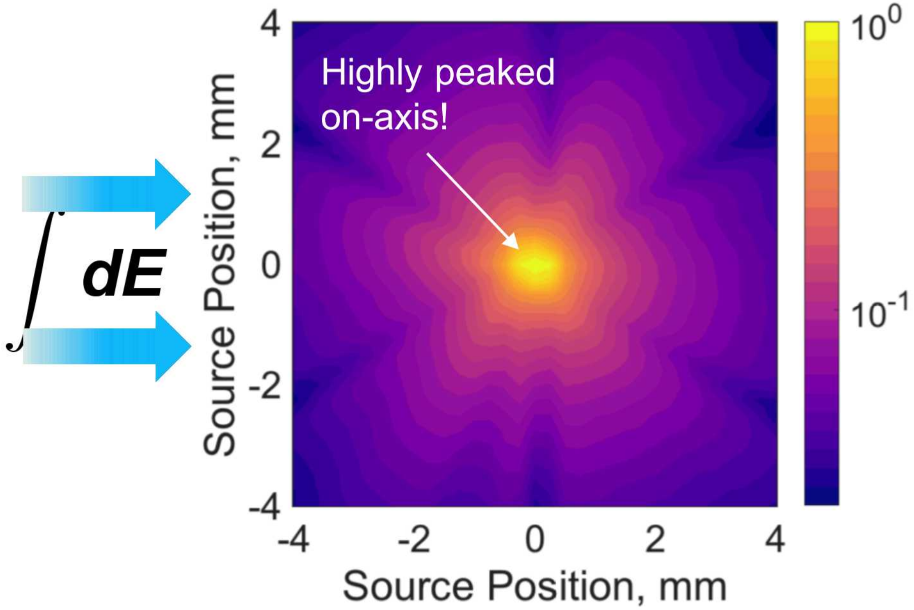
- 75-μm resolution on-axis, 30-μm to 300-μm resolution off-axis
- ~1 keV bandwidth with centroid at 17.3 keV
- In-band/Out-of-band rejection ratio >15:1

Point-spread function (PSF) map:





Relative throughput (flat-field)

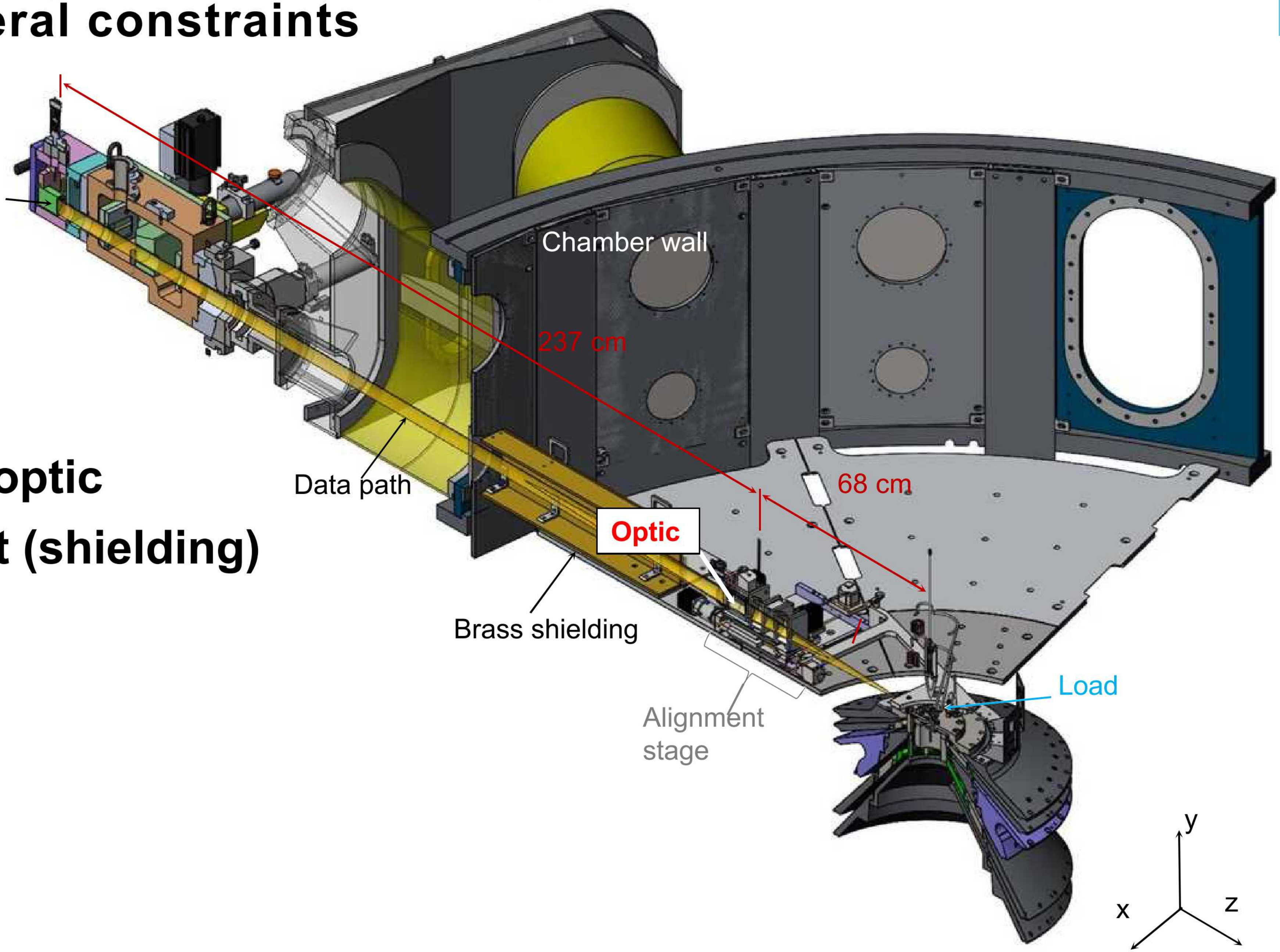


Variation of optic's response over FOV makes it very sensitive to alignment!

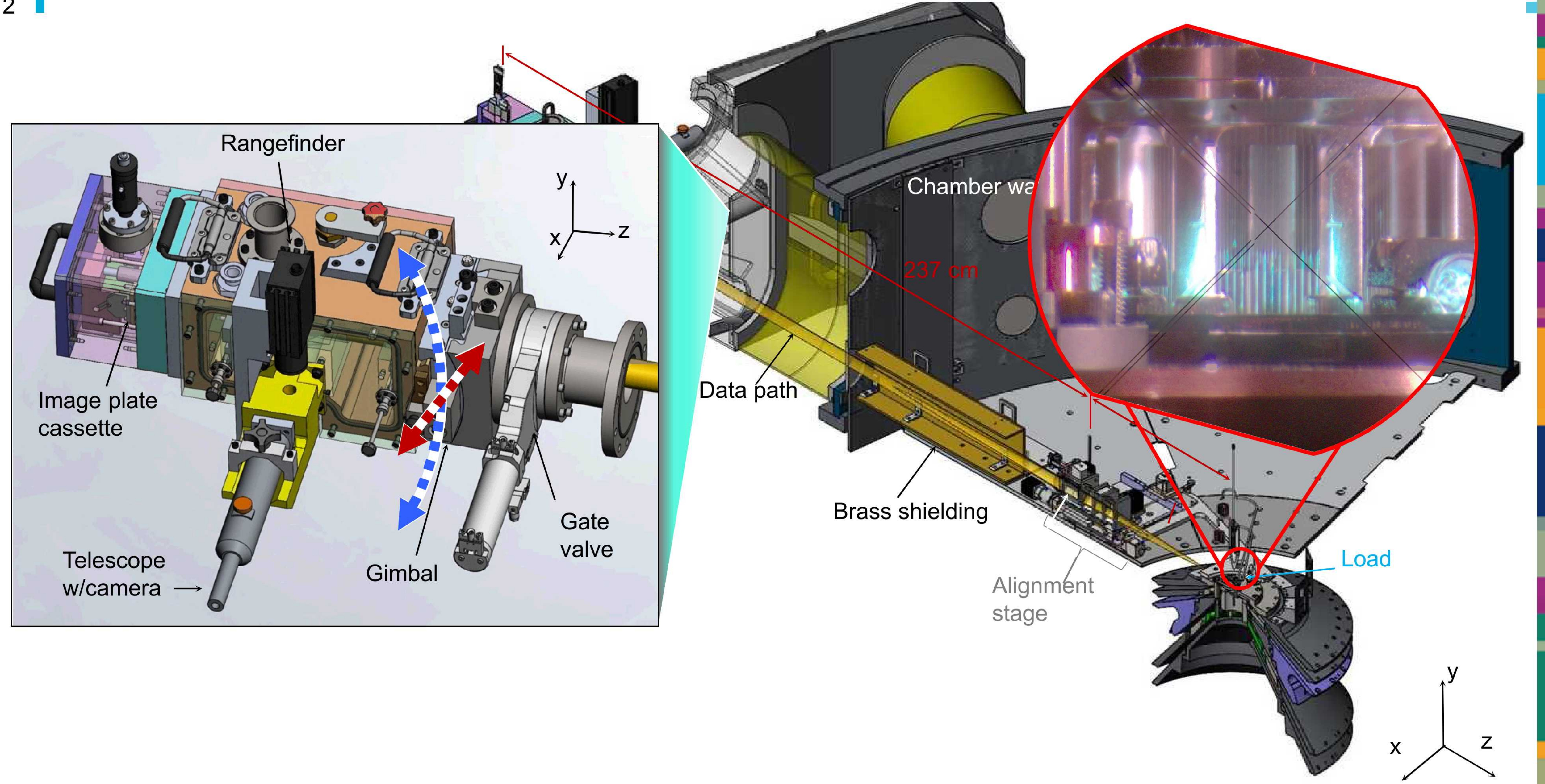
1. M. Wu, et al. Rev. Sci Instrum (2018), 2. B. Kozioziemski, et al. Rev. Sci Instrum (2018)

The mechanical design of the Wolter Imager on the Z Machine was driven by several constraints

- **Stringent alignment requirements of the optic**
- **Harsh Z environment (shielding)**

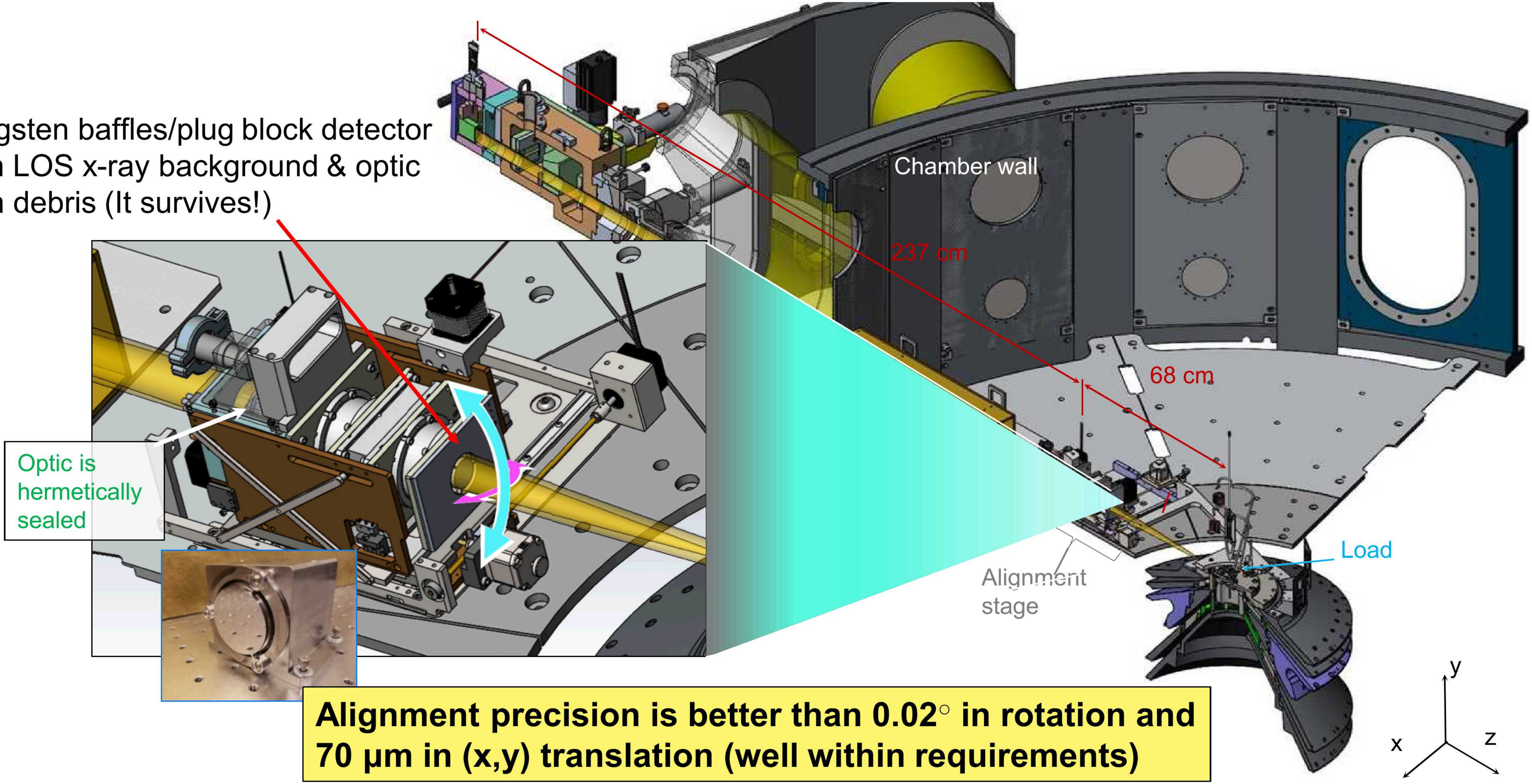


The detector is aligned to the load with a camera and laser rangefinder



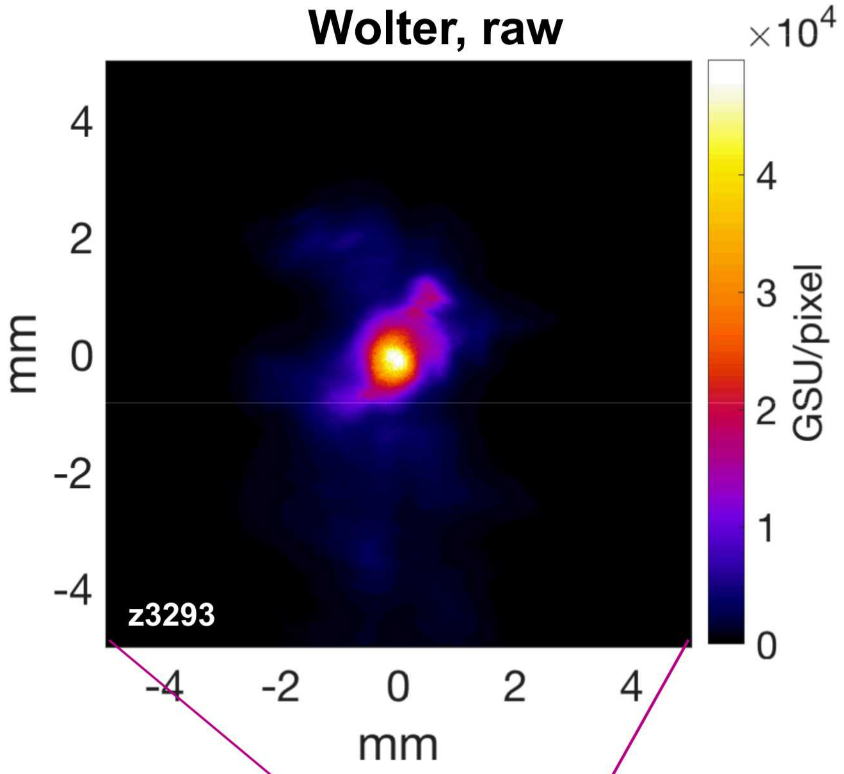
The optic is aligned remotely with a motorized five-axis stage, shielding allows the optic to survive the Z environment

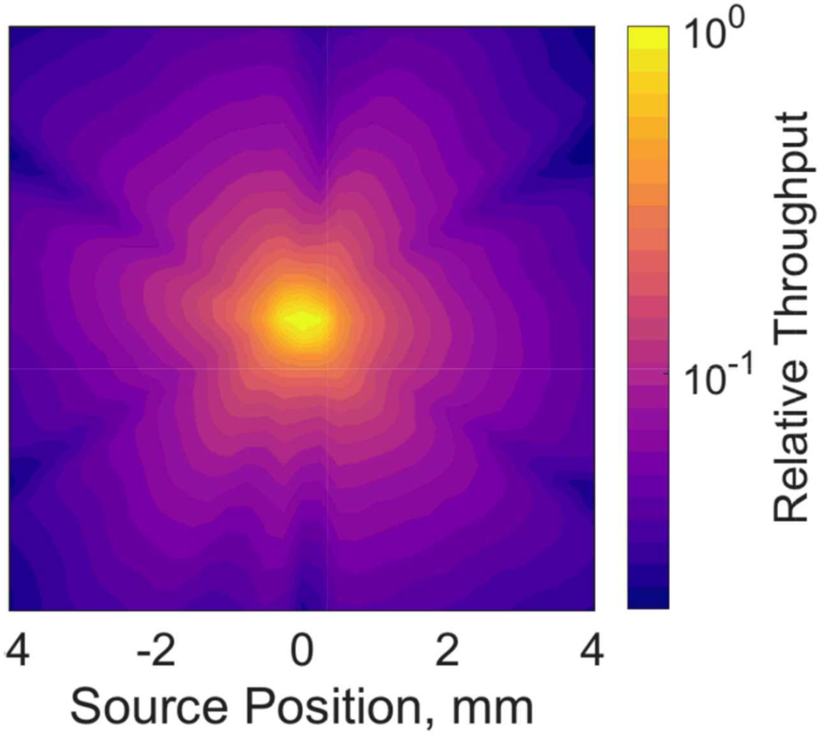
Tungsten baffles/plug block detector from LOS x-ray background & optic from debris (It survives!)

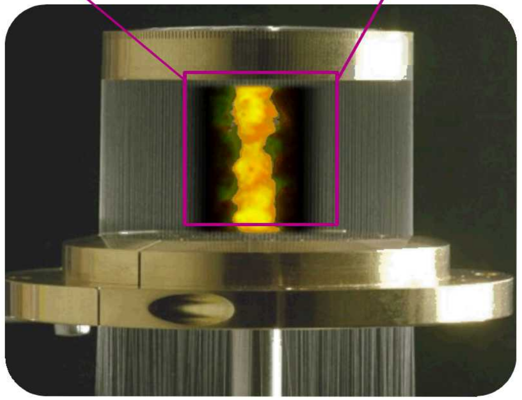


Alignment precision is better than 0.02° in rotation and 70 μm in (x,y) translation (well within requirements)

The Wolter imager was successfully fielded on the Z machine, imaging Mo wire array z-pinches[1]

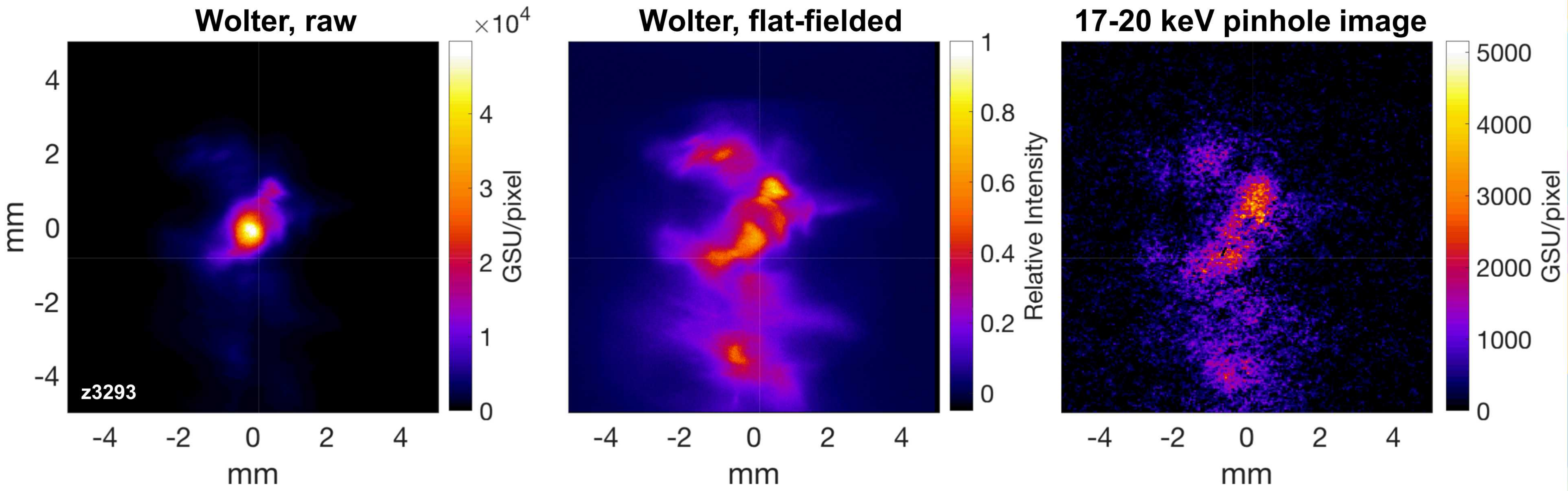






1. J. R. Fein, et al., RSI (2018)

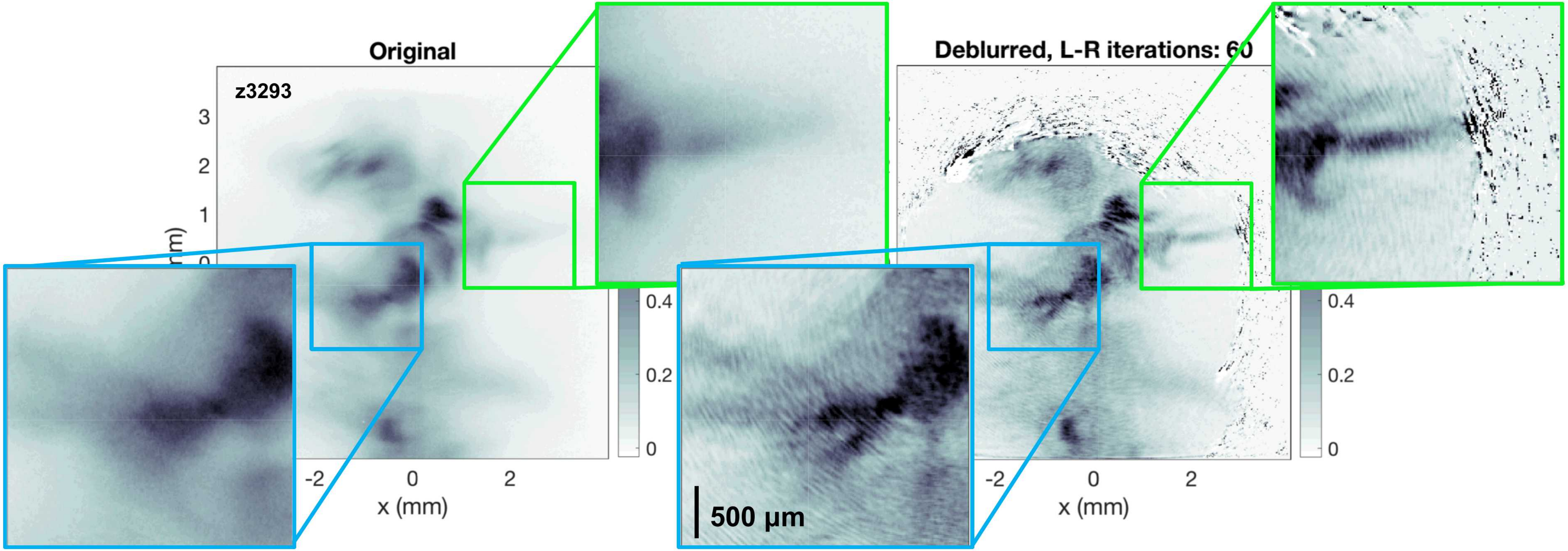
First Wolter images[1] demonstrate drastic improvements in spatial resolution and signal/noise compared to pinhole camera[2]



- **Flat-fielded Wolter images have features similar to those seen in time-integrated pinhole camera[2] (TIPC) images**
- **Wolter demonstrates spatial resolution better than 150 µm, compared to ~1 mm in TIPC, as well as a factor of 19 – 64 increase in signal/noise (helps enable time-resolved)**

1. J. R. Fein, et al., RSI (2018), 2. L. A. MacPherson et al., RSI (2016)

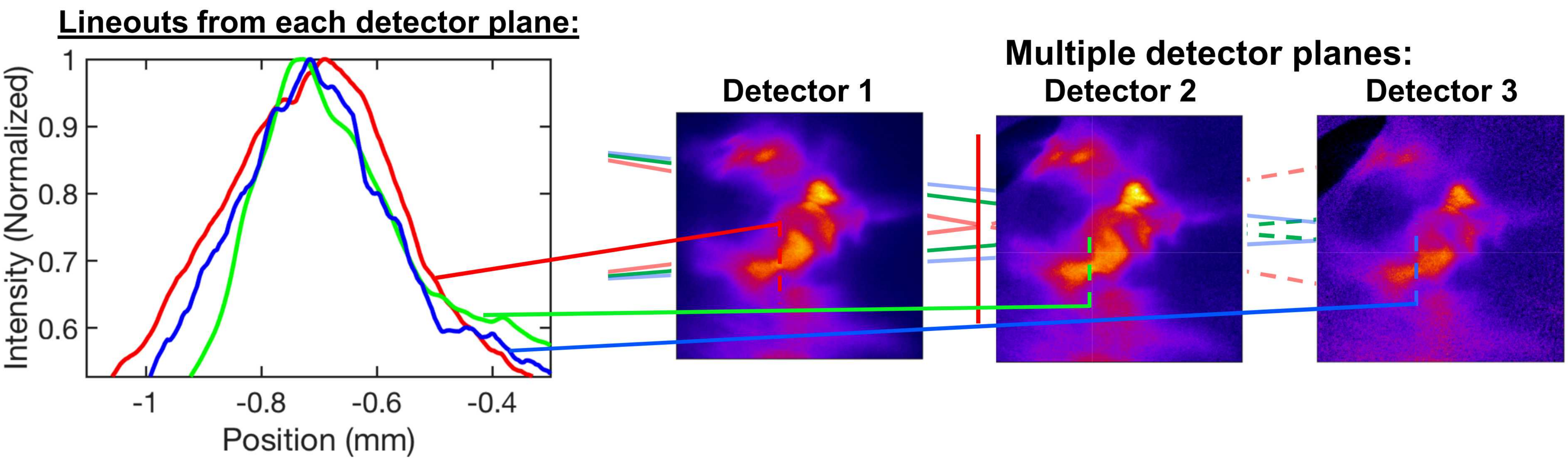
Deblurring of actual Wolter data indicates structures may exist below the resolution limit



- **Deblur using iterative Lucy-Richardson algorithm (maximum likelihood)**
- **Image is computed as sum of convolutions after breaking up (measured) shift-variant PSF into shift-invariant modes[1]**

1. L. Denis, et al., Int. J. Comput. Vision (2015)

Real x-ray sources are 3D…i.e. we need to account for depth

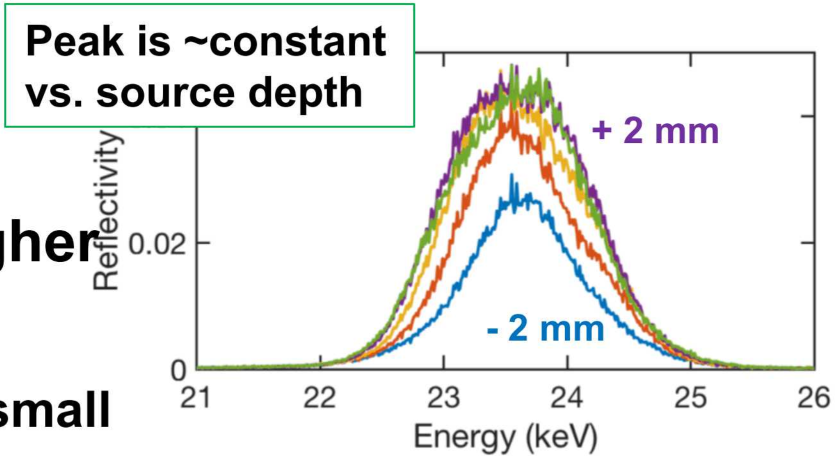


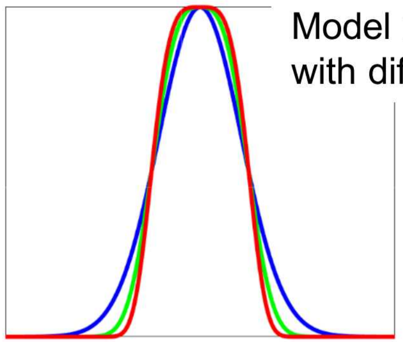
- **Multi-plane detector[1] can help recover depth information**
- **Synthesize information from spatially and spectrally resolved diagnostics at multiple lines of sight**
- **Created Wolter image model for 3D sources that incorporates variation in PSF and throughput over entire FOV**

1. B. Kozioziemski et al., U.S. Patent App., Filed 13 November 2017

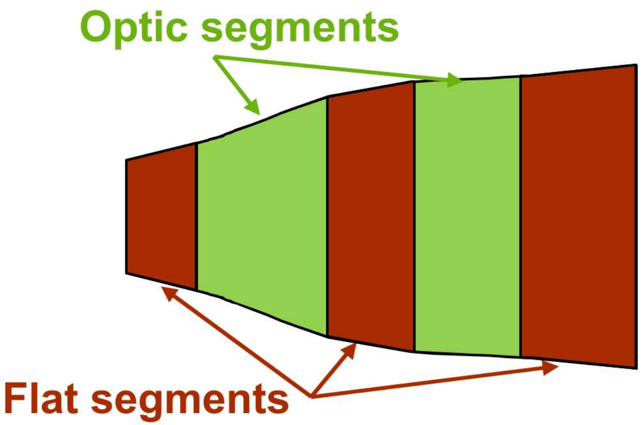
Additional next steps

- We are currently developing 22-keV optics for higher energy sources
  - New optics have less variation over FOV as a result of small tunings in multilayer recipe and improved replication
  - Pursuing new reflectivity shapes to improve In-Band/Out-Band, Signal/Noise, etc.
- Plan to integrate a hCMOS[1] detector for time-resolved imaging (~CY2020-2021)
- Lessons learned from SNL optic are being leveraged to design and fabricate an optic for NIF with even higher resolution
  - Improved polishing and alignment has led to 10x reduction in figure error (optic's shape)
  - Flat segments introduced to mitigate edge curling




Model reflectivities with different shapes

NIF Mandrel:



1. L. Claus et al., Proc of SPIE (2017)

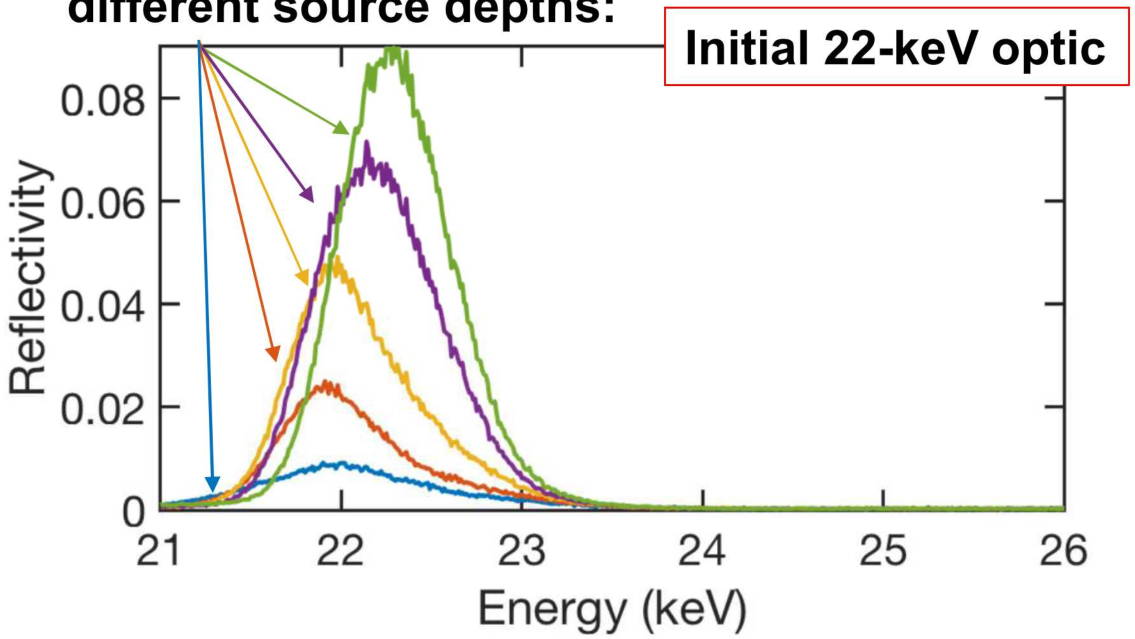
The Wolter optic for the Z Machine is part of an ongoing collaboration to improve x-ray imaging by pushing FOV, resolution and energy

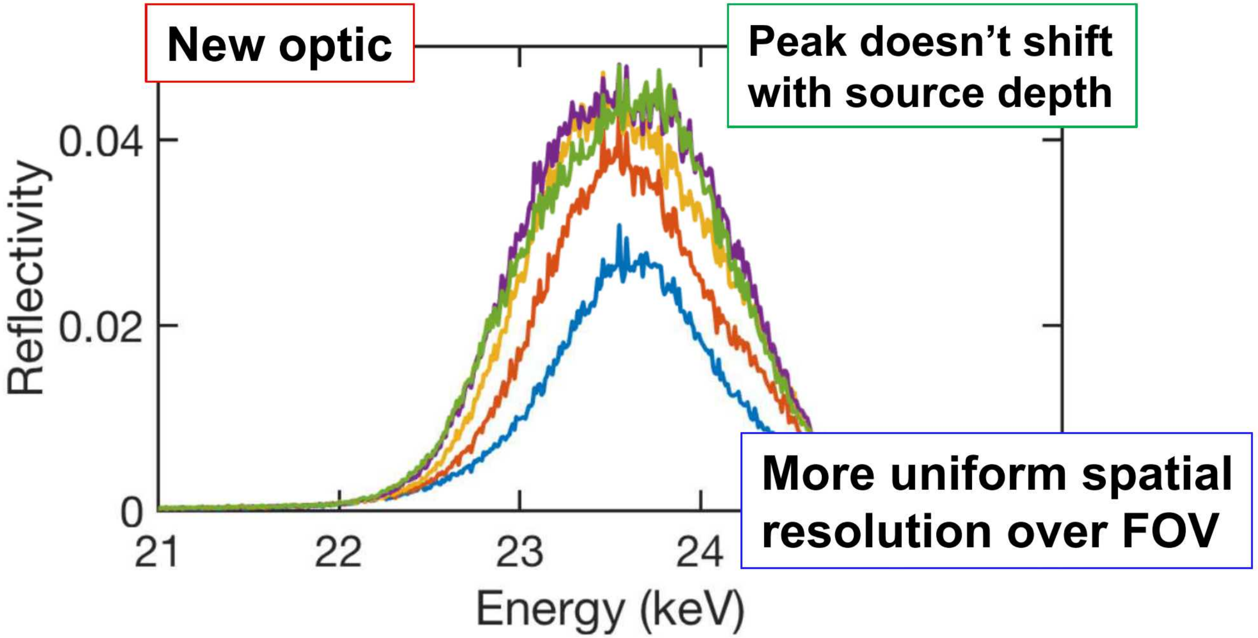
- **The Wolter Imager has successfully imaged x-ray sources on the Z Machine in the 17-18 keV at better spatial resolution (~150 μm) and signal/noise than previous capabilities**
- **Image processing techniques show potential to recover sub-resolution features in recorded images**
- **Leveraging lessons in fabrication and optic geometry/multilayer design to produce better-performing optics for future applications**

Extra material (although not organized as structured slides)

We are successfully fielding 22-keV optics to image even higher-energy sources

Reflectivities at different source depths:

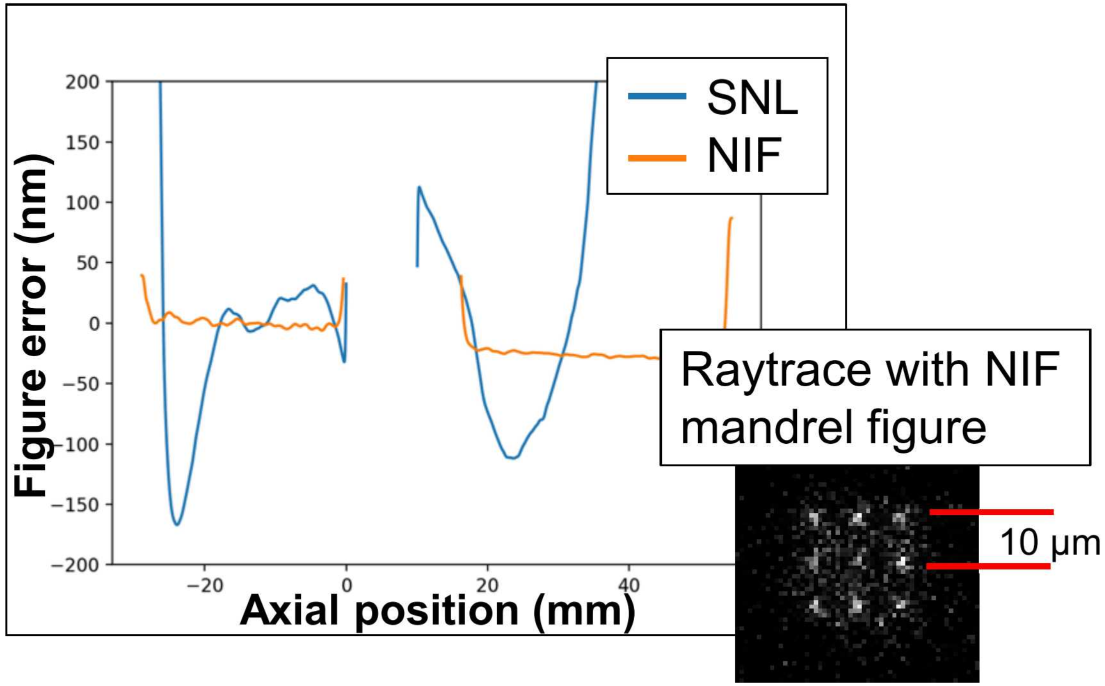




New optics have improved performance as a result of small tunings in the multilayer recipe and improved replication

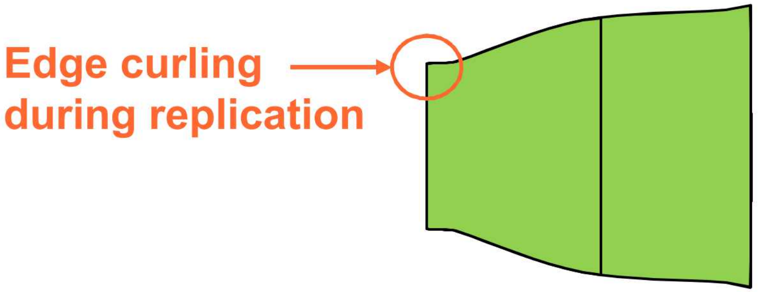
Replicated optic performance is being enhanced by improved polishing and by re-designing the optic’s shape

LLNL and NASA MSFC collaborated to improve lap polishing and figure correction of a test NIF mandrel

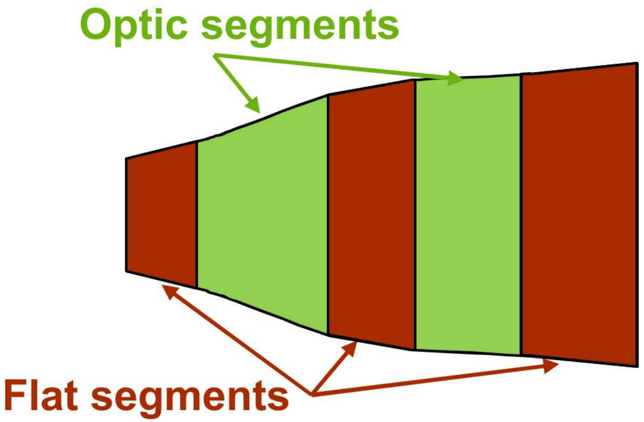


Flat segments introduced on ends/middle of optic to mitigate edge curling during replication

SNL Optic shape:



NIF Mandrel shape:



~10x reduction in figure error, expect < 10-μm resolution:

- Lap polishing improvements = 5x reduction
- Improved polishing slurry, alignment procedure for sub-aperture polisher (Zeeko) = 2x reduction

We are beginning advanced image processing to efficiently calculate Wolter images and deblur them

- **Shift-variant PS means we cannot do simple convolutions to compute images**
- **Break up shift-variant PSF into sum over weighted modes, constructed from measured PSF data:**
- **Image is computed as sum of convolutions over PSF modes after interpolating coefficients at all source positions:**

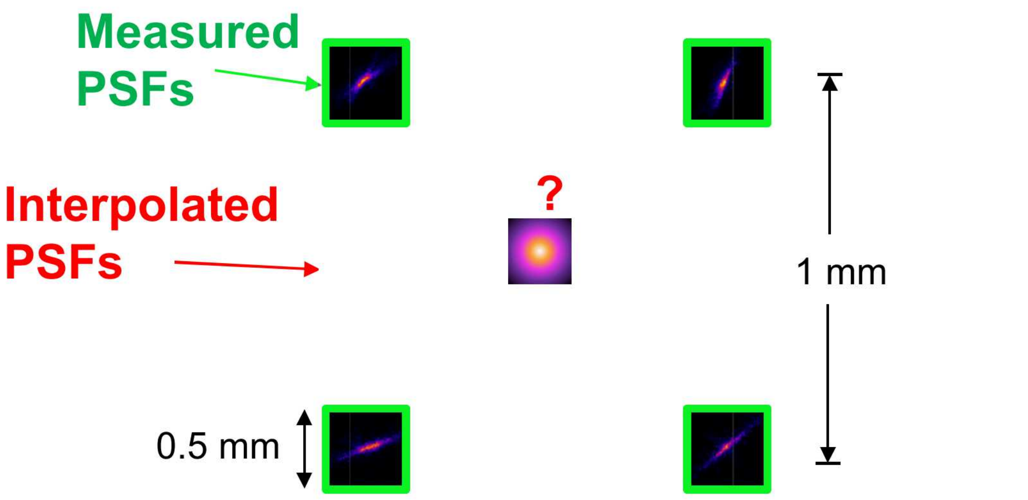
$$\text{Image} = \sum_{p}^{N} c_p * (a_p \times \text{Source})$$

Coefficients (vary over FOV)

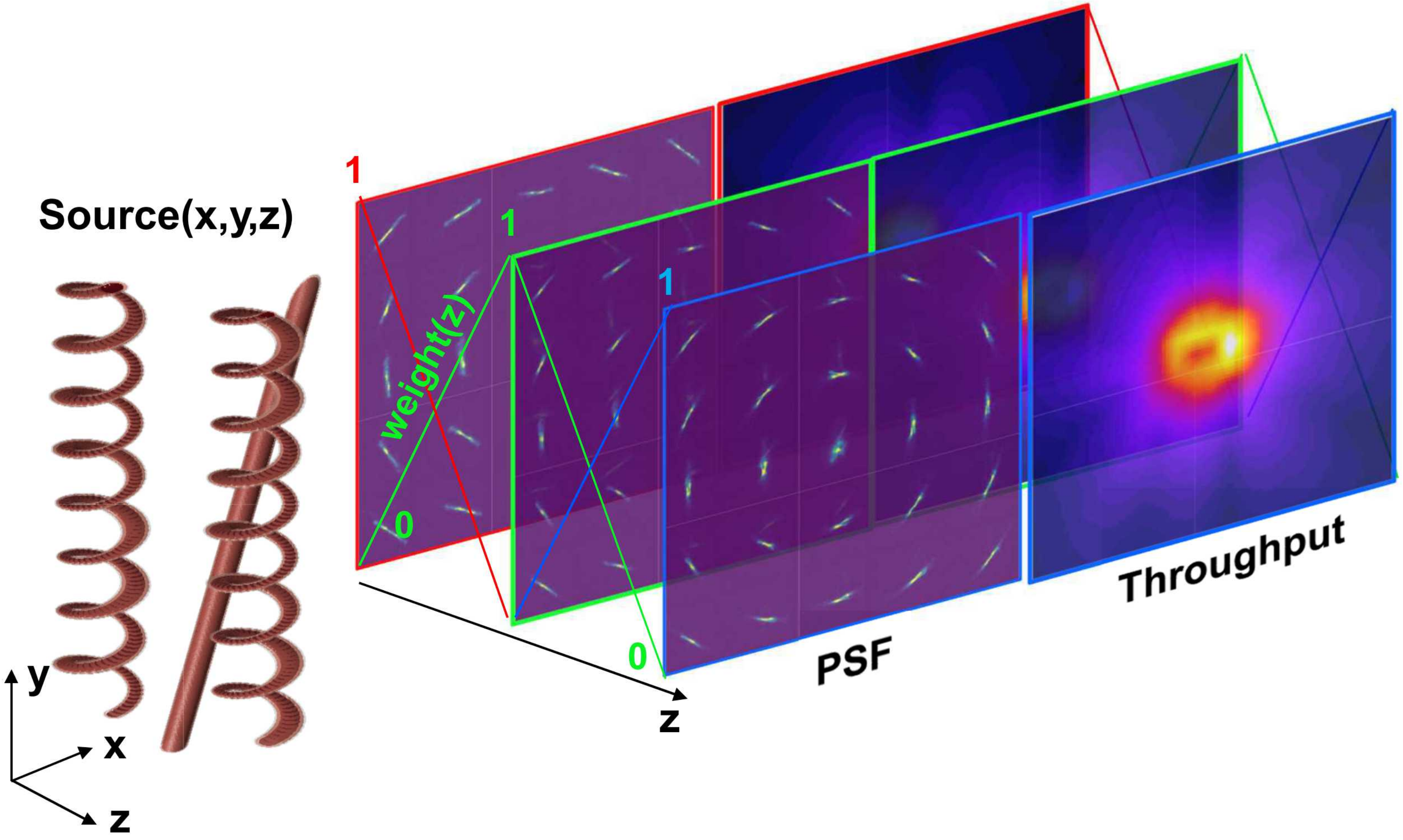
p^{th} shift-invariant PSF mode

$$k(\boldsymbol{r}, \boldsymbol{s}) = \sum_{p}^{N} a_p(\boldsymbol{s}) c_p(\boldsymbol{r})$$

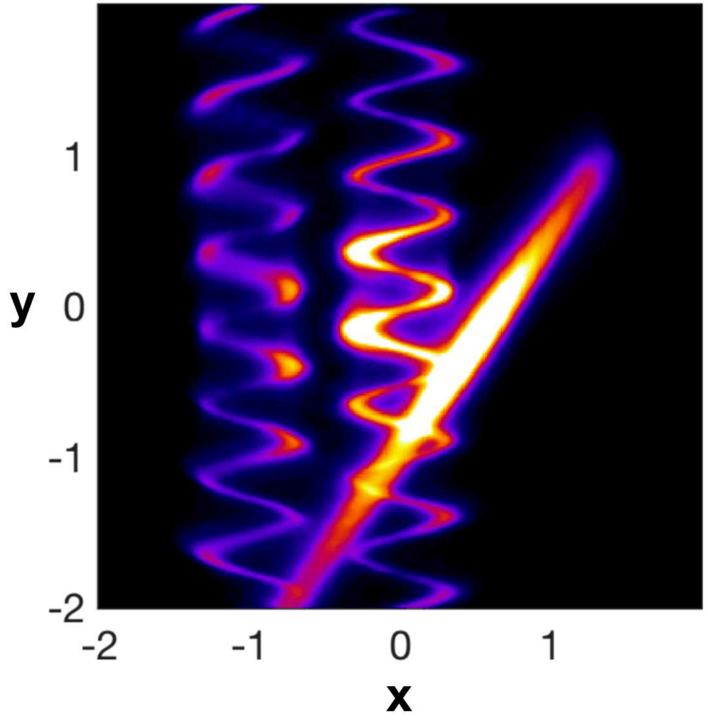
Can calculate from data via SVD



Variation of the optic's response with depth motivates an image model from 3D sources

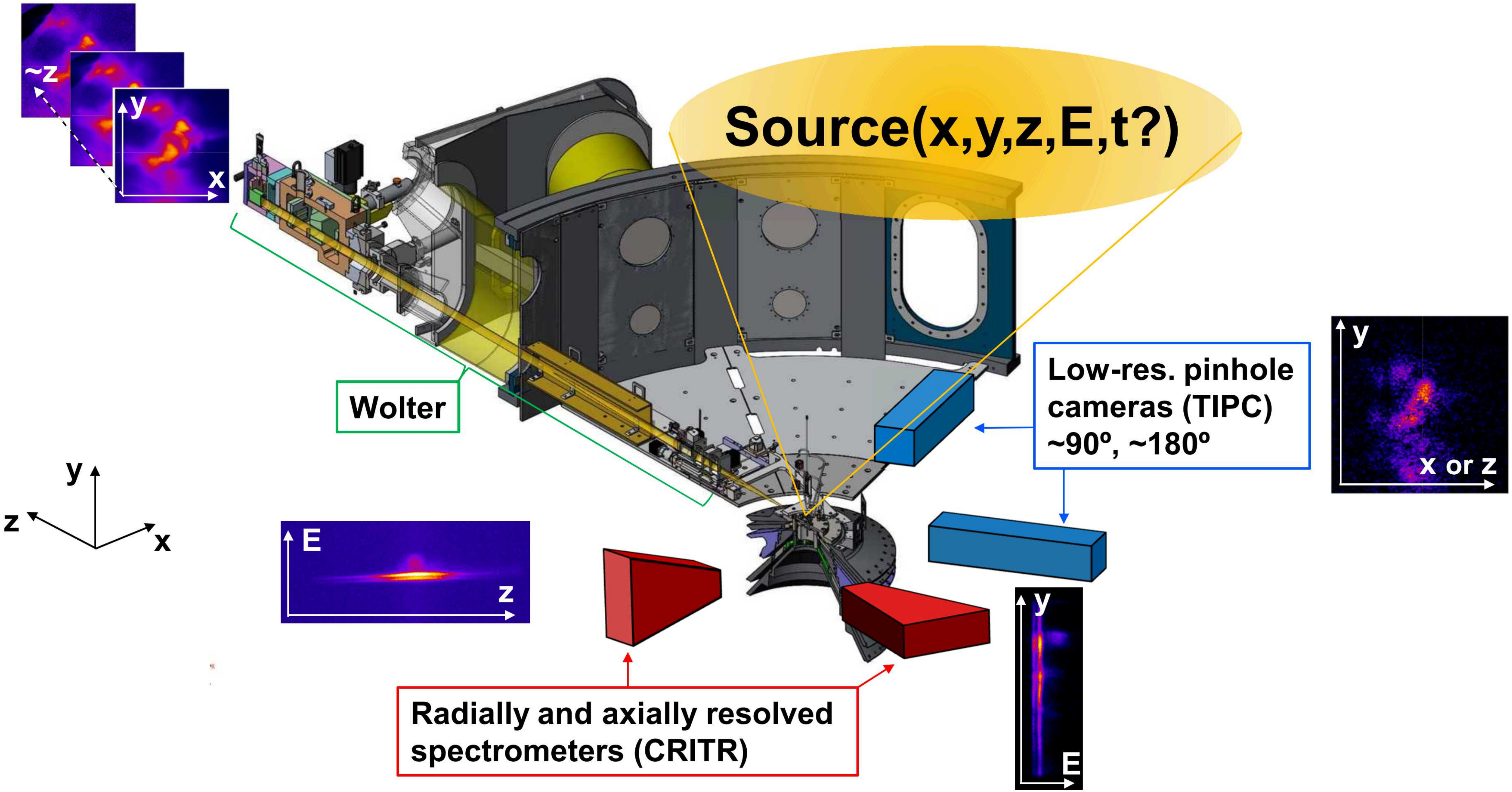


Simulated image from 3D source:

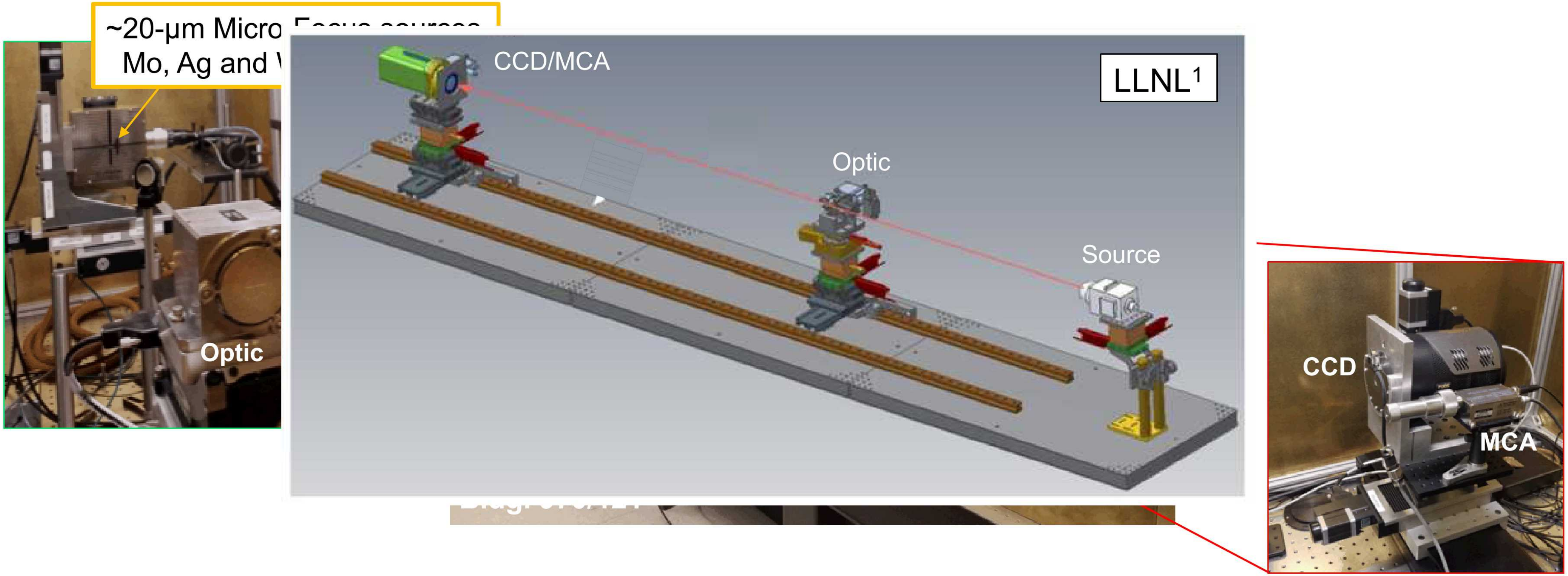


$$Image(x,y) = \int_z Source(z)\,Throughput(z)\,PSF(z)\,dz$$

Upcoming experiments will synthesize information from spatially and spectrally resolved diagnostics at multiple lines of sight



We developed facilities at LLNL[1] and SNL[2] to record calibration measurements for image processing and to inform fielding decisions



- **Resolution/point-spread function over FOV**
- **Spectral reflectivity, throughput/illumination over FOV**
- **Monitor performance degradation (if any) post-shot**

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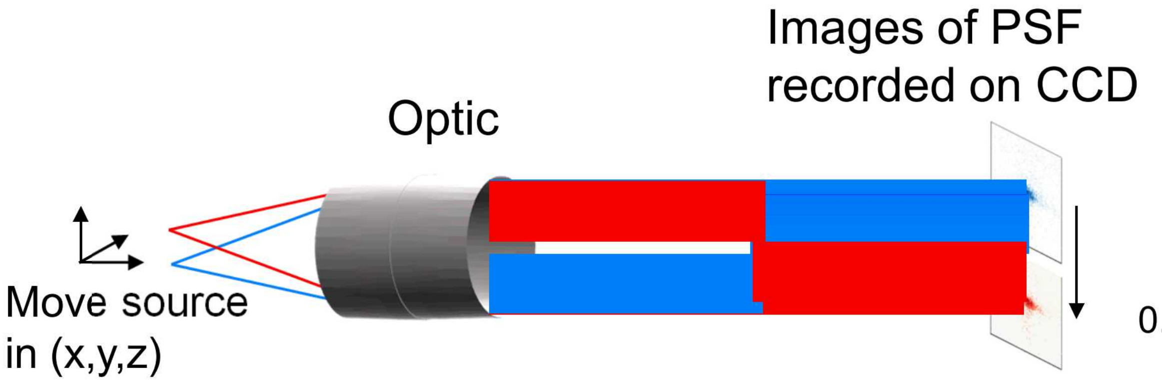
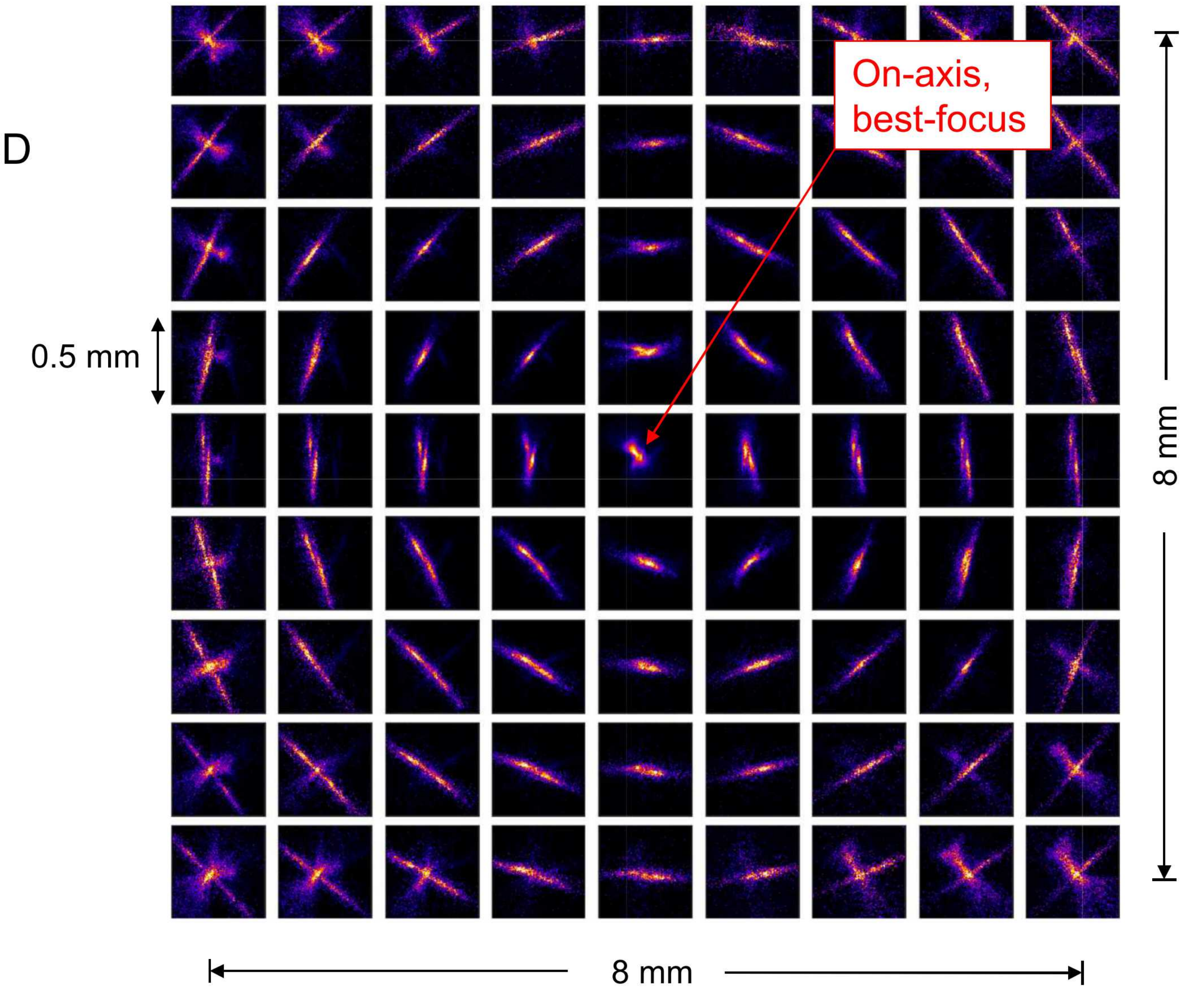
1. B. Kozioziemski, et al. RSI (2018), 2. M. Wu, et al. RSI (2018)

Imaging of a ~point source demonstrates resolution between 75 – 300-μm over a >5x5x5 mm^3 field of view

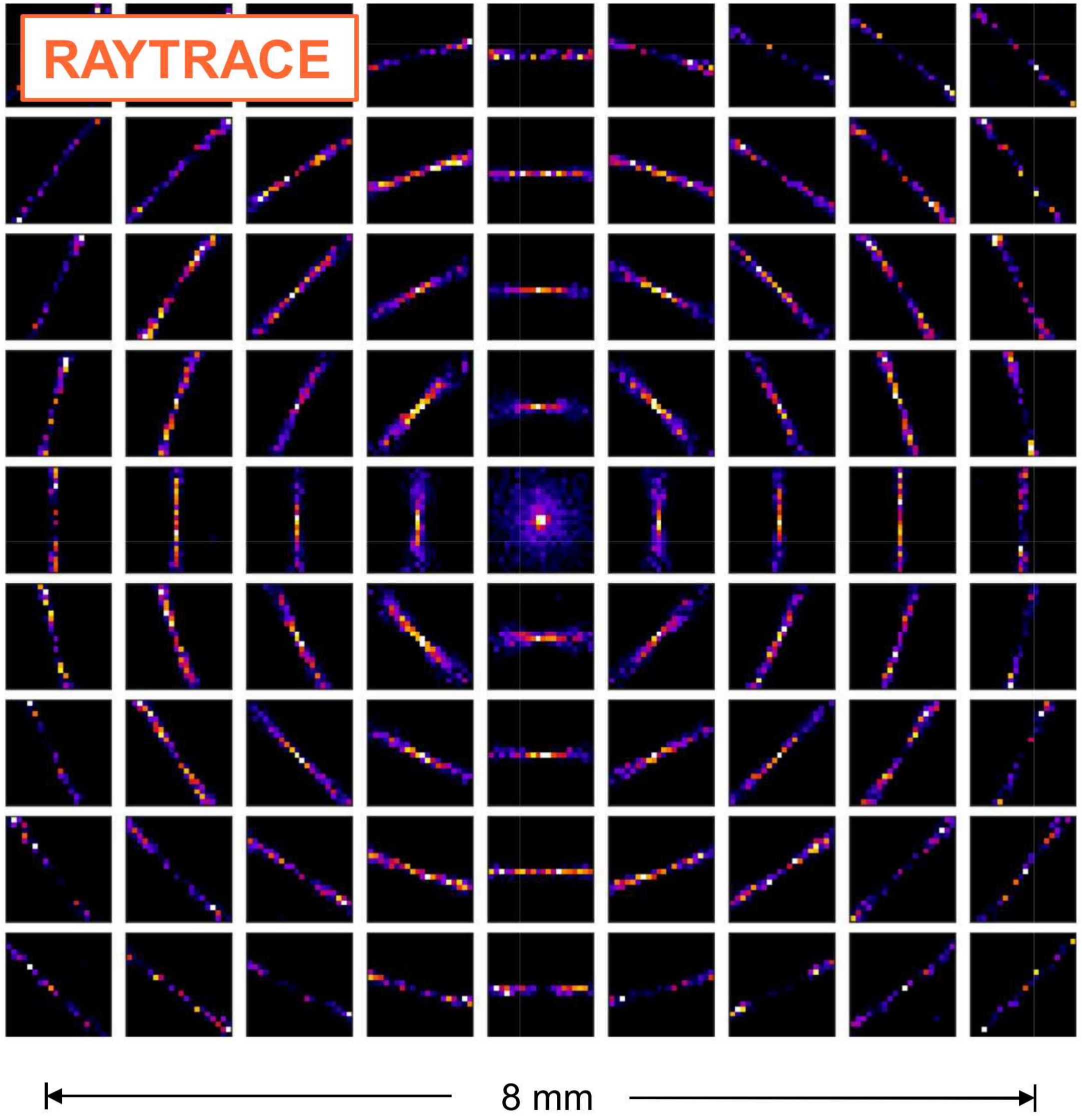


Measured PSF map at plane of best-focus:



- **75-μm resolution on-axis**
- **30-μm x 300-μm resolution off-axis**
- **Depth of field ~ 1 mm**

Measured PSFs agree with raytrace simulations, with deviations likely from optic figure error



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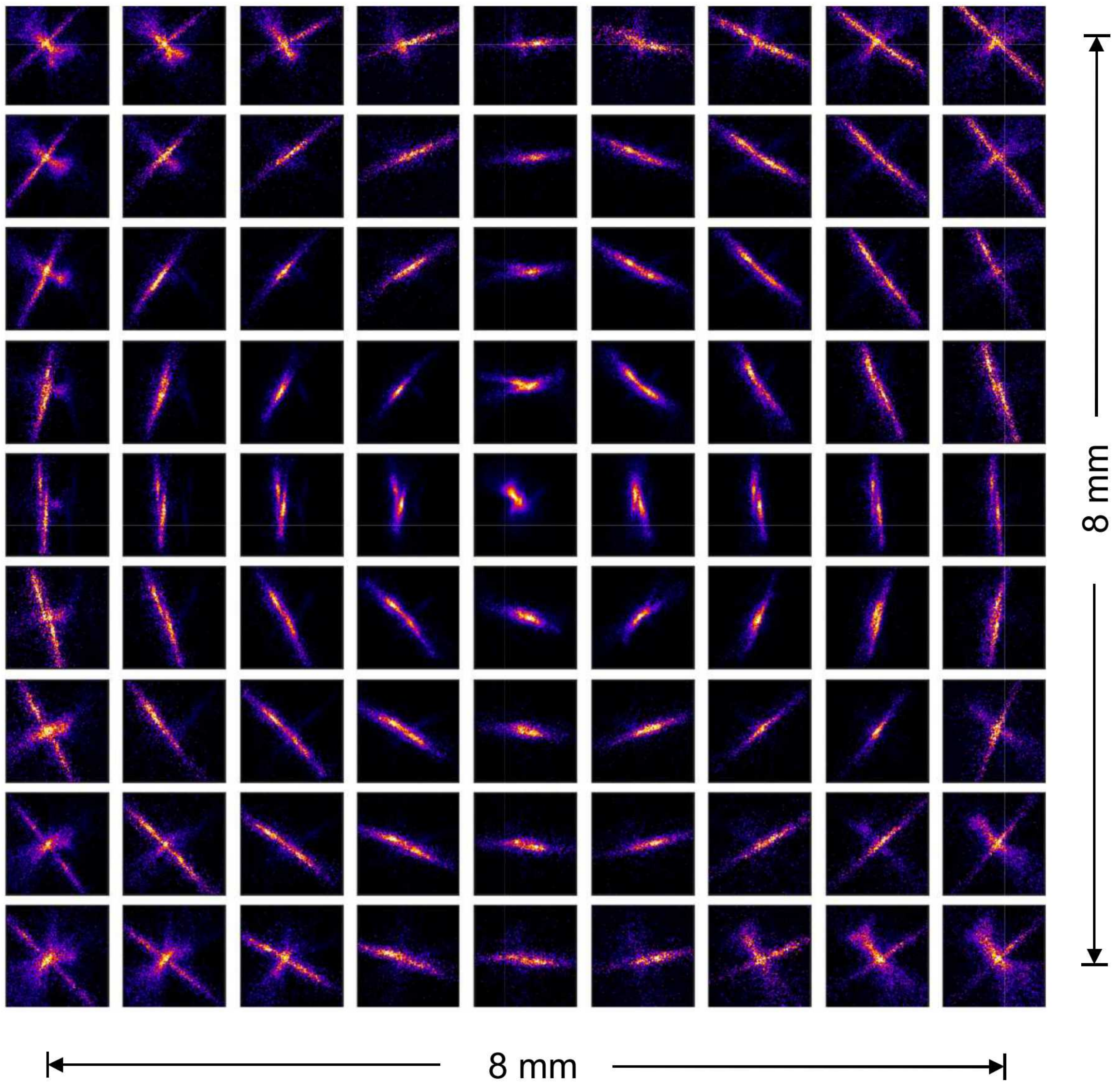

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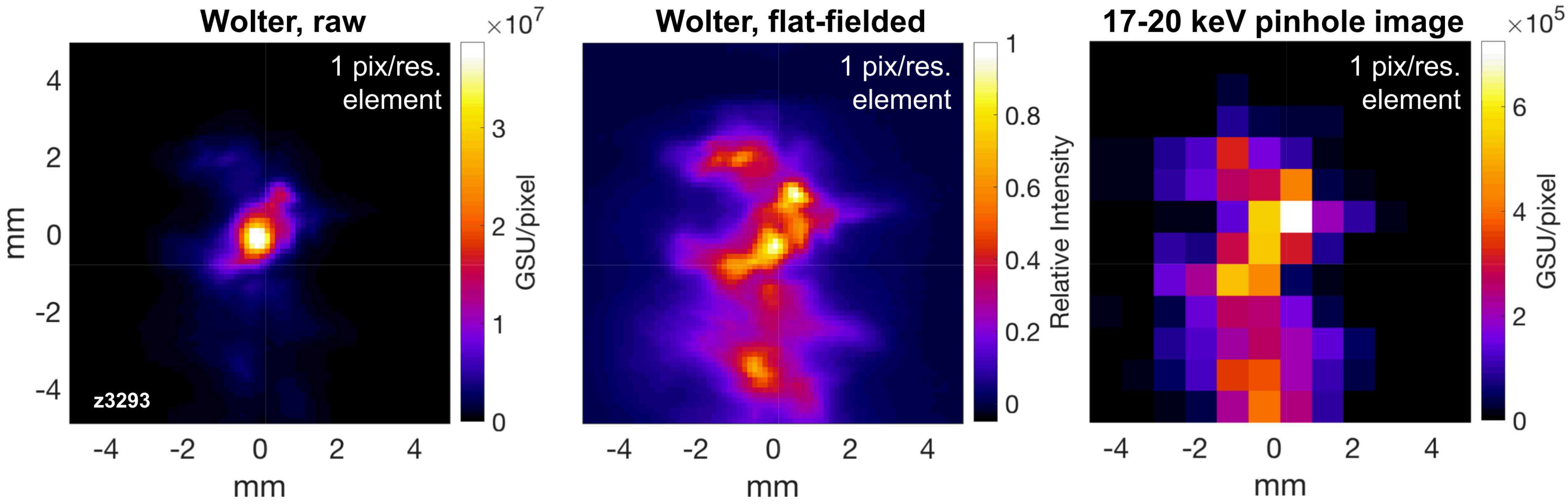

- **Flat-fielded Wolter images have features similar to those seen in time-integrated pinhole camera[2] (TIPC) images**
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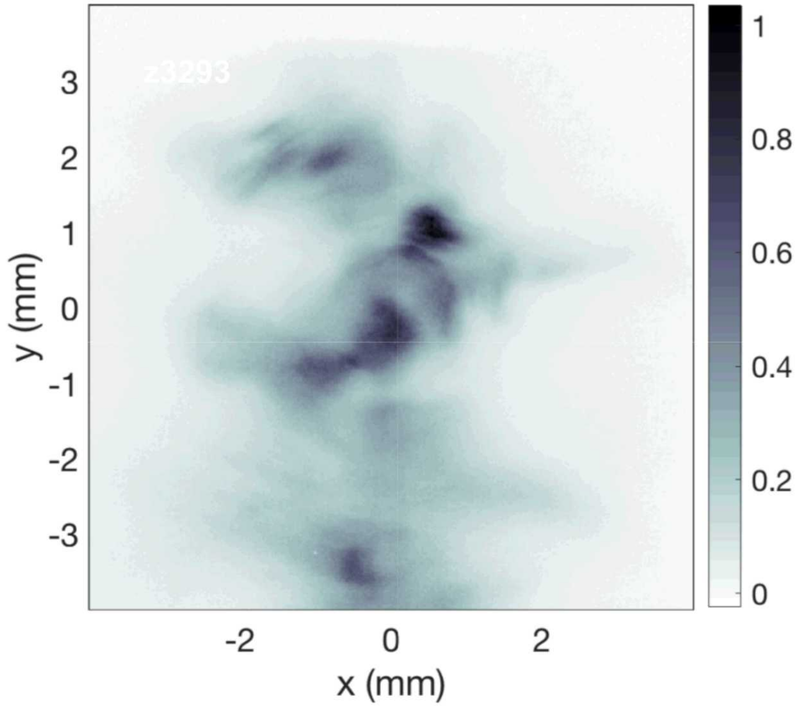


Shift-variant PSF

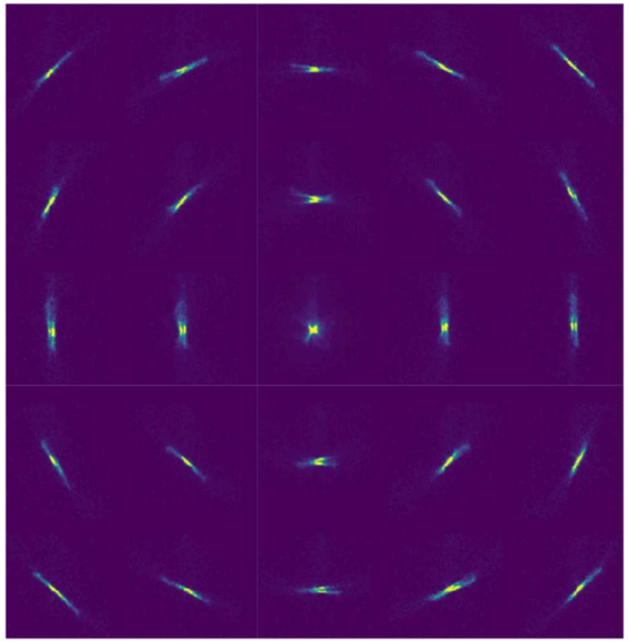


Image is computed as sum of convolutions over PSF modes after interpolating coefficients, $a_p(s)$ at all source positions

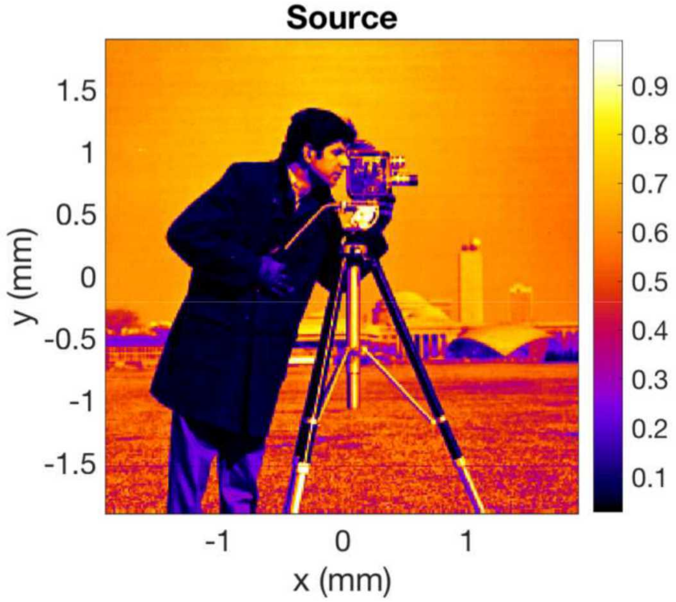
PSF

Coefficients (vary over FOV)

p^{th} shift-invariant PSF mode

$$\boldsymbol{k}(\boldsymbol{r},\boldsymbol{s}) = \sum_{p}^{N} \boldsymbol{a}_{\boldsymbol{p}}(\boldsymbol{s})\boldsymbol{c}_{\boldsymbol{p}}(\boldsymbol{r}-\boldsymbol{s})$$

A Wolter image of a source can be computed using measured PSF data



$$\text{Image} = \sum_{p}^{N} c_p * (a_p \times \text{Source})$$

Iterative deblurring (e.g. Lucy-Richardson)

$$I_n = S_n * K$$

$$C_n = \left(\frac{I}{I_n}\right) * K^T$$

$$S_{n+1} = C_n S_n$$

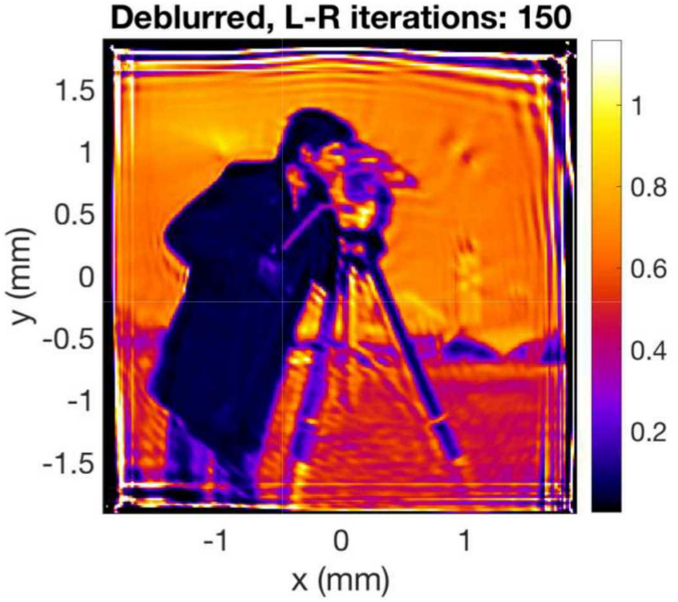
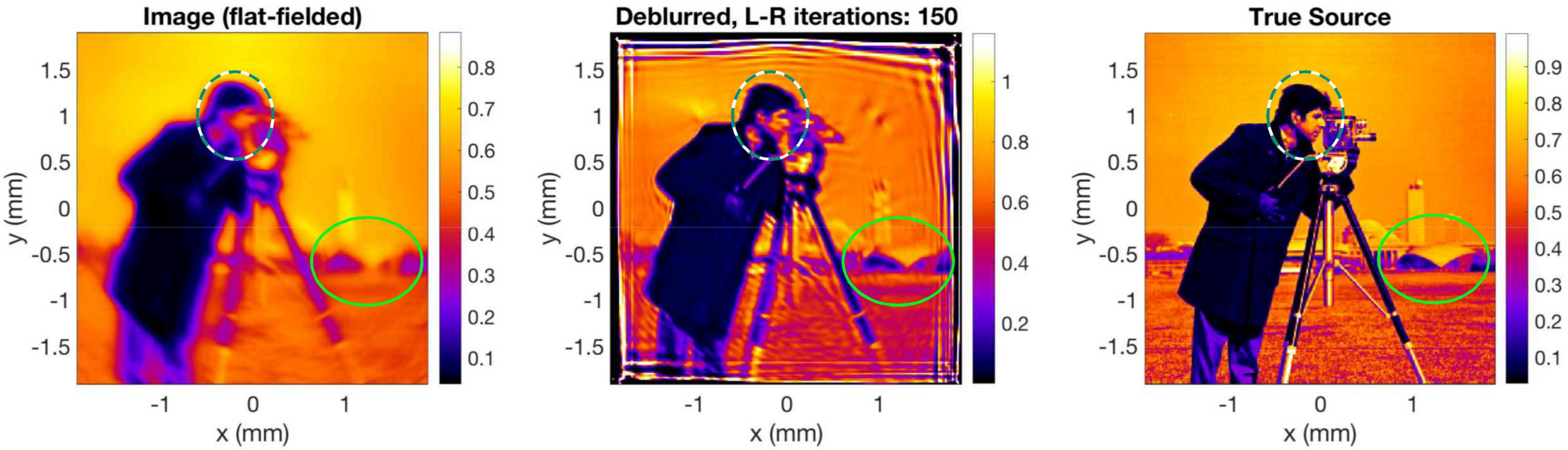
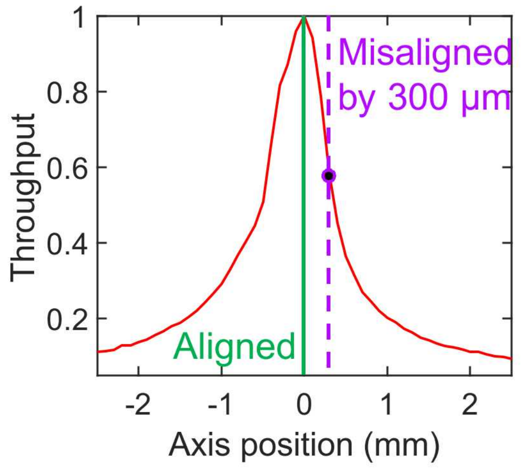


Image deblurring shows potential to recover sub-resolution structure and improved contrast in the source distribution

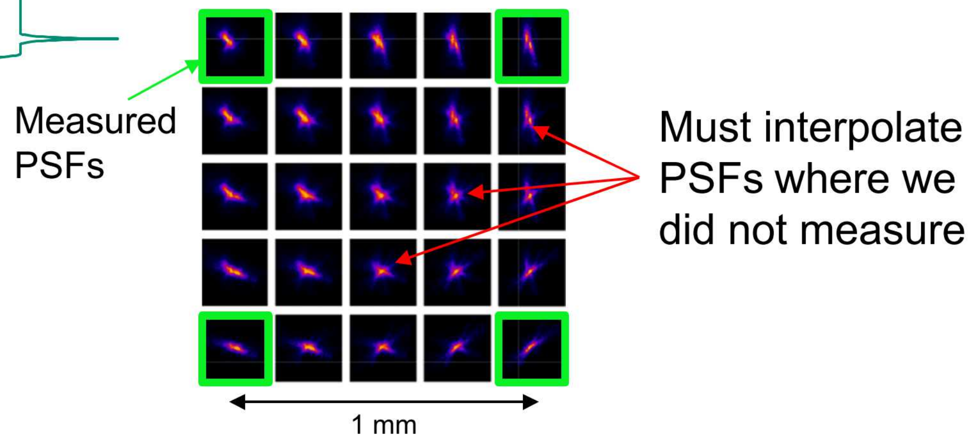


The Wolter optic's spatially-varying response presents challenges for both instrument fielding and image analysis

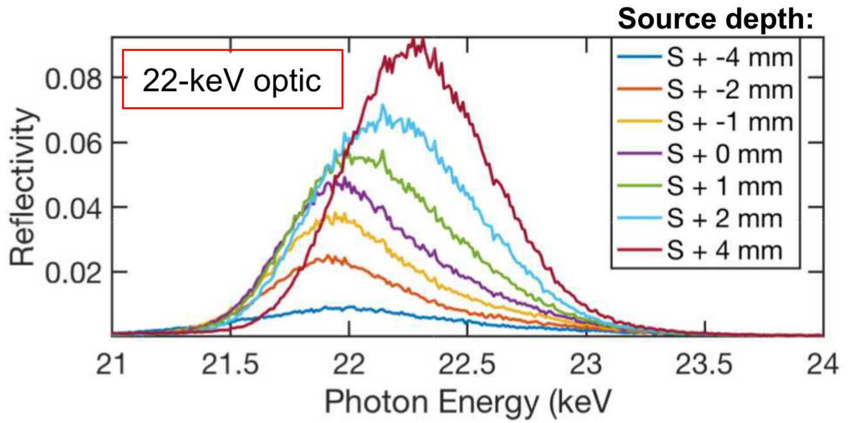
- **Variation of throughput over FOV requires flat-fielding**
  - In image, need to distinguish between high throughput and actual source intensity
  - Alignment must be better than 0.05 deg. and 200 μm



- **PSF is shift-variant (spatially-varying):**
  - convolutions/deconvolutions w/FFTs don't work for deblurring

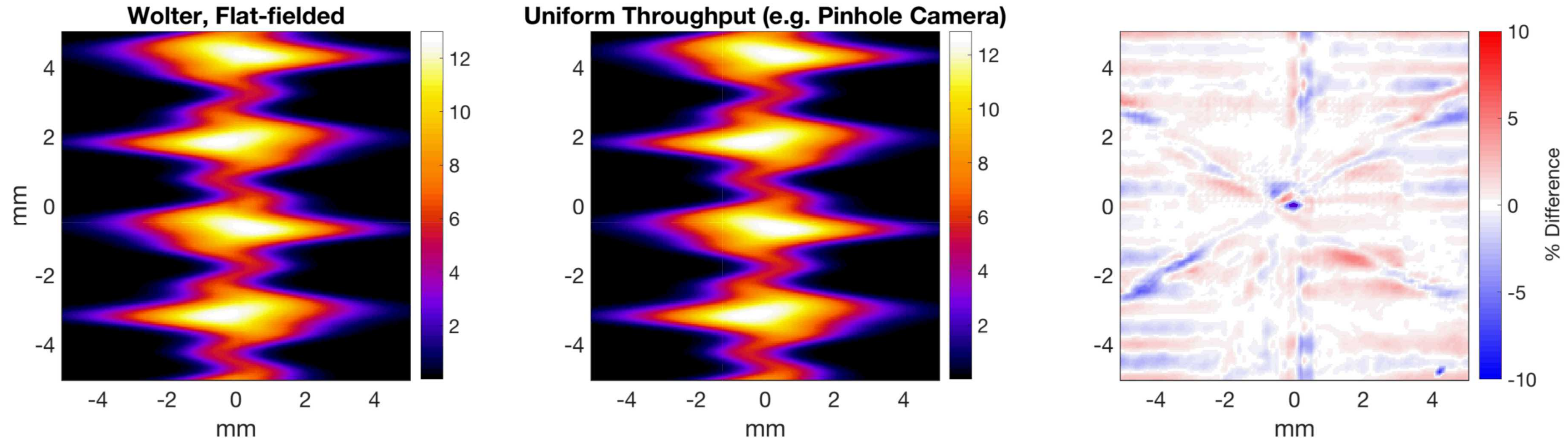


- **Optic's response is different at each depth (unlike simpler pinhole camera)**



Flat-fielding without a 3D model of the source can accurately produce images with uniform sensitivity (e.g. pinhole camera)

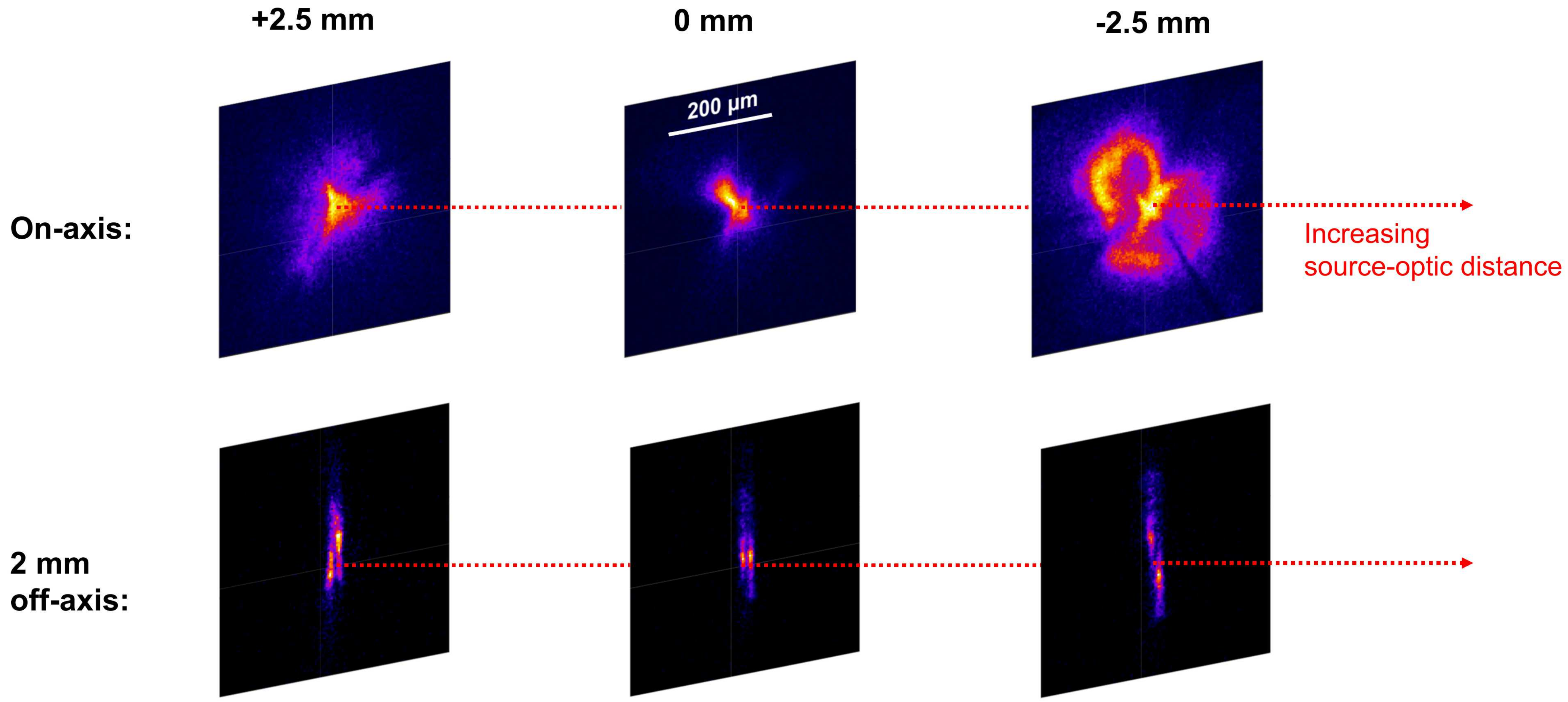
Simulated images (no blurring):



$$\text{Image}(x,y) = \int \text{Source}(x,y,z)T(x,y,z)dz$$

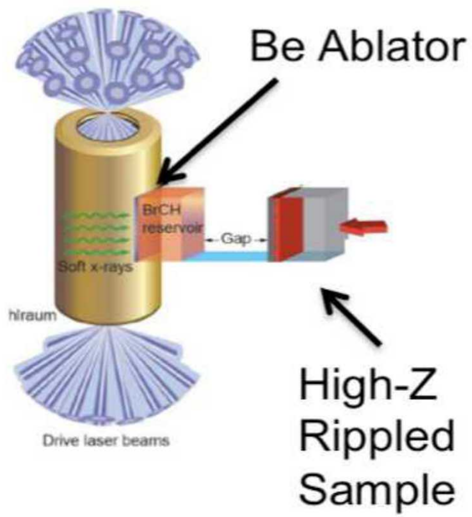
Pinhole image = $\int \text{Source}(x,y,z)dz \approx \frac{\text{Image}(x,y)}{\frac{1}{\Delta z}\int T(x,y,z)dz}$

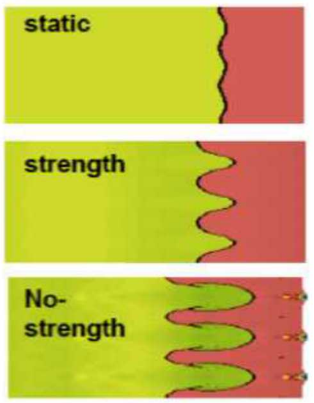
The optic's PSF also varies significantly with depth



Future Wolter optics will enable multi-frame, high contrast imaging with ~5-µm resolution on NIF

RT Strength Platform

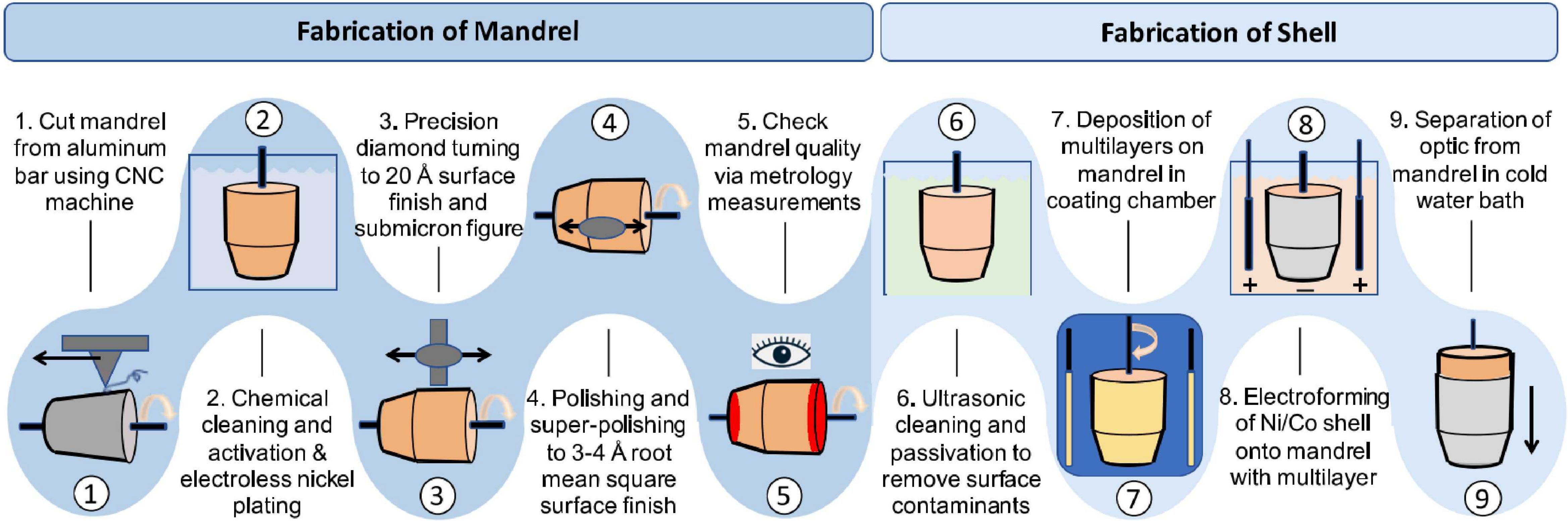




Backlight with x-rays up to 60 keV in energy and image at high resolution with a Wolter optic

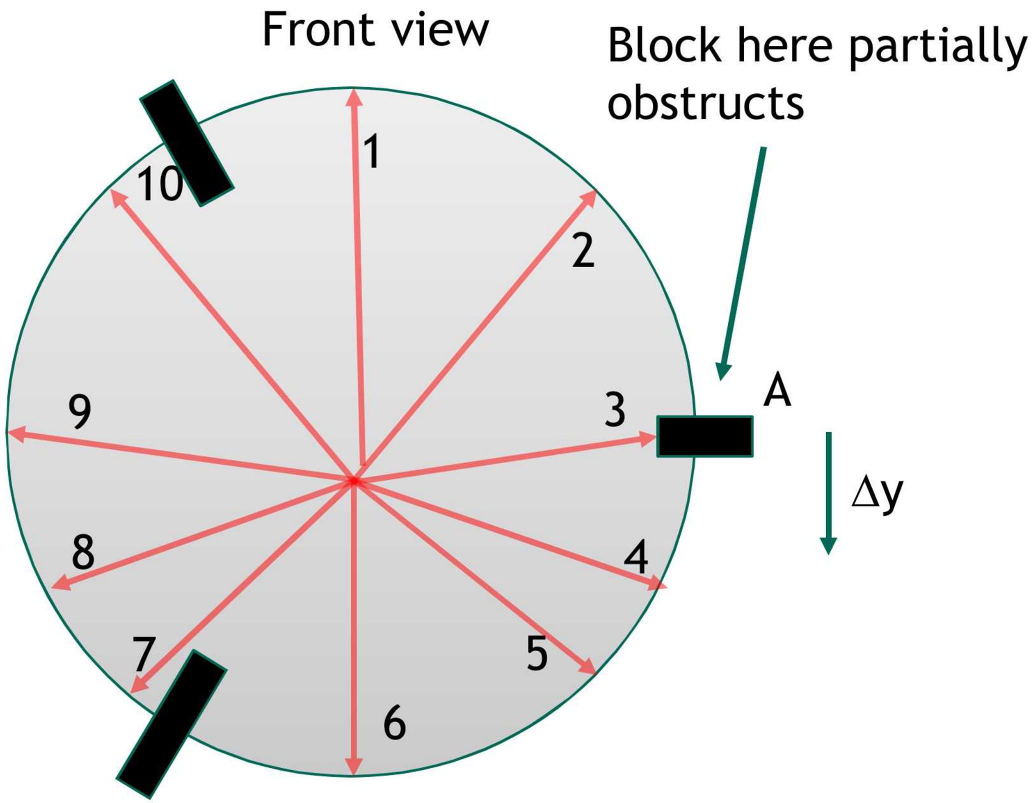
- **~40x increase in signal from large solid angle**
- **Narrowband response improves contrast by reducing out-of-band signal**
- **Enables multi-frame imaging**

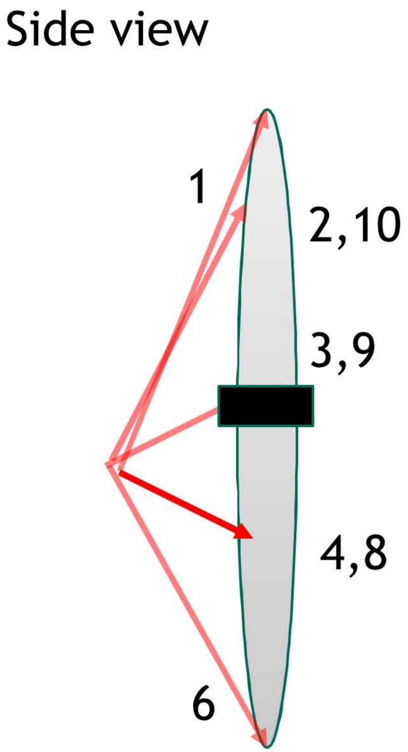
Spec.	Sandia 1st generation	NIF 1st generation	NIF 2nd gen
Resolution	100 µm	5 µm	5 µm
FOV	5 mm	0.5 mm	1 mm
Magnification	3.5	10	10-20
Energy	17-23 keV	<=25 keV	50 keV

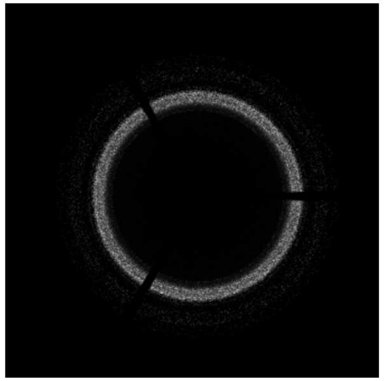


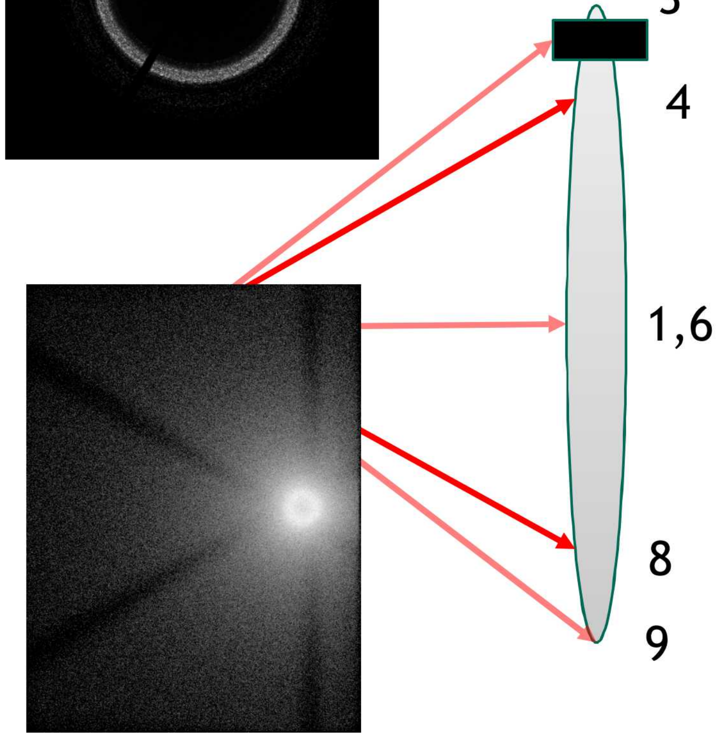
Fabrication of Mandrel
Fabrication of Shell
1. Cut mandrel from aluminum bar using CNC machine
2. Chemical cleaning and activation & electroless nickel plating
3. Precision diamond turning to 20 Å surface finish and submicron figure
4. Polishing and super-polishing to 3-4 Å root mean square surface finish
5. Check mandrel quality via metrology measurements
6. Ultrasonic cleaning and passivation to remove surface contaminants
7. Deposition of multilayers on mandrel in coating chamber
8. Electroforming of Ni/Co shell onto mandrel with multilayer
9. Separation of optic from mandrel in cold water bath
1
2
3
4
5
6
7
8
9
+
−
+

Moving off-axis causes the rays to no-longer meet Bragg condition in the direction of movement



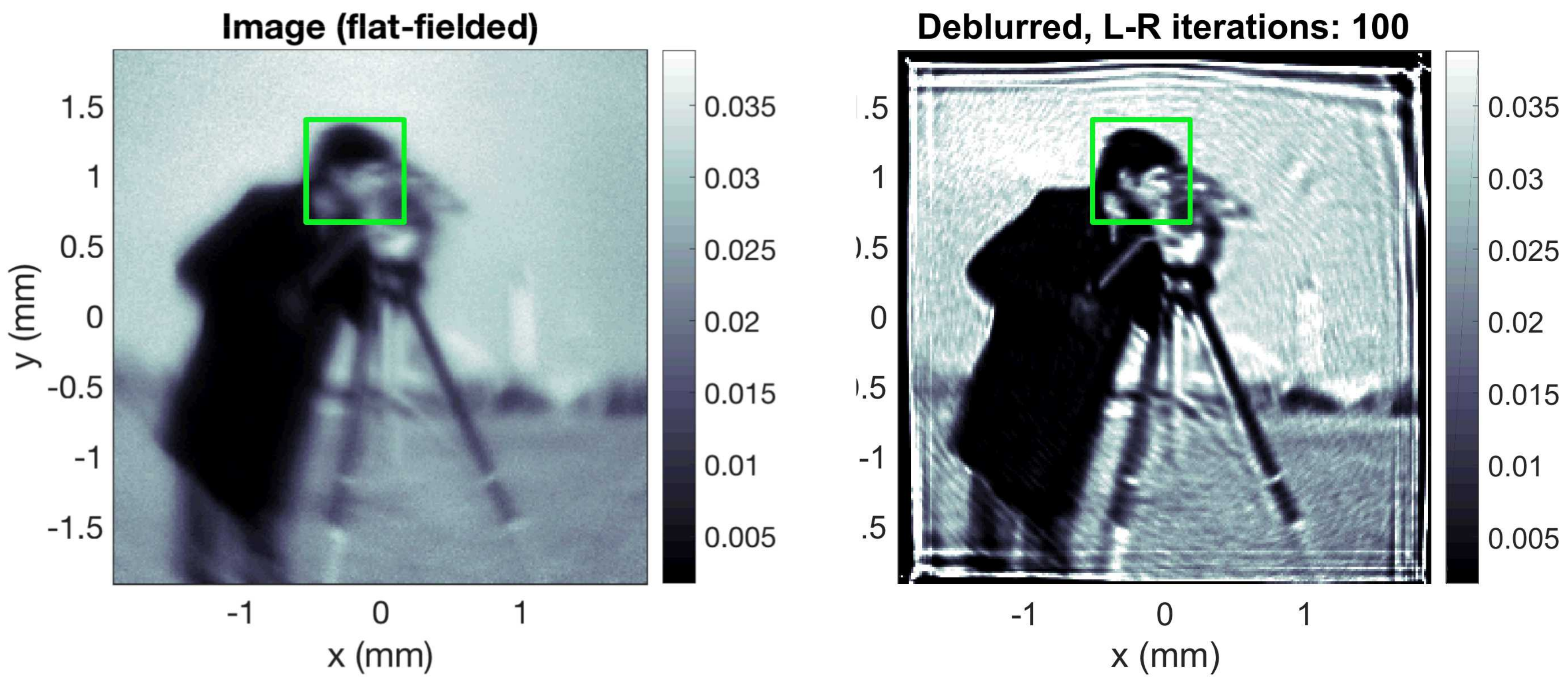






- Rays orthogonal to the movement direction still meet the Bragg condition
- Obscuration “A” blocks rays when the source is moved in either +- y direction so it shows up two times in the throughput map

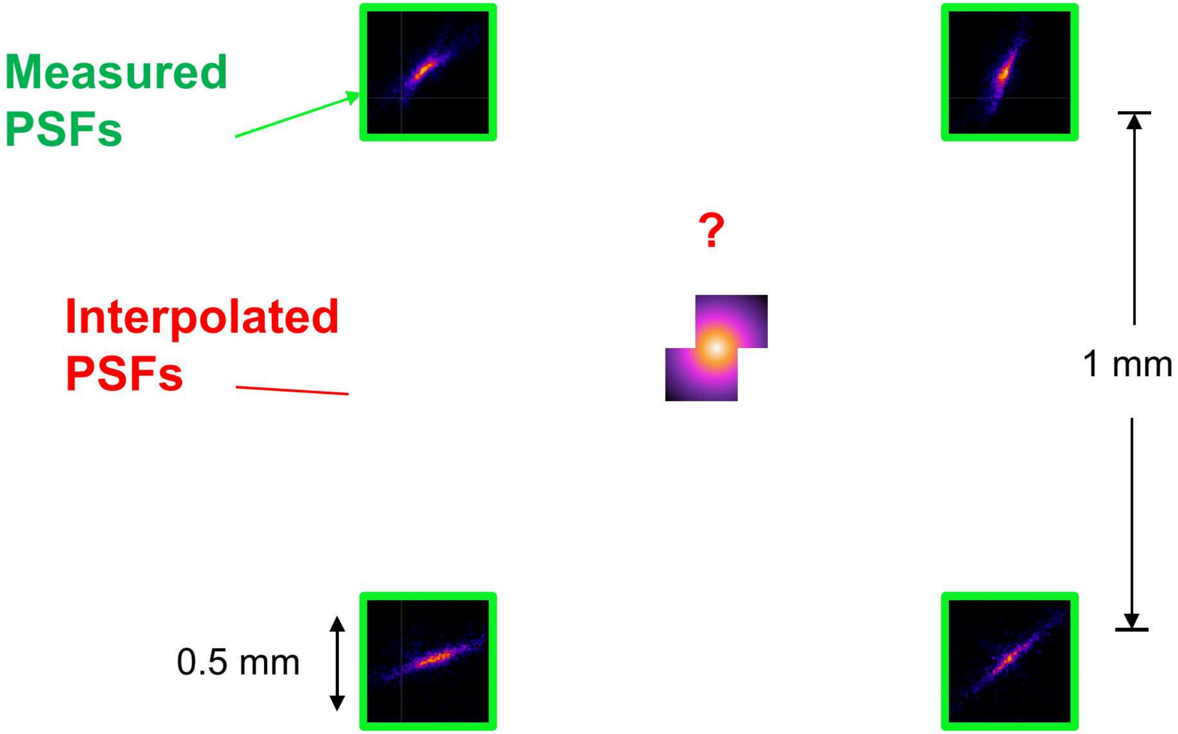
Deblurring with noise



144% mean difference

44% mean difference

Decomposition enables interpolation of PSFs at all source positions for image computation



- Image is computed as sum of convolutions over PSF modes after interpolating coefficients at all source positions:

$$\text{Image} = \sum_{p}^{N} c_p * (a_p \times \text{Source})$$

1. L. Denis, et al., Int. J. Comput. Vision (2015)

Many people have contributed to Wolter…

Science needs, system performance: Dave Ampleford (previous RS), Jeff Fein (current RS), Ming Wu

Engineering design: Chris Ball, Paul Gard (detector subsystem), Andy Maurer (optic subsystem)

SNL Calibration: Ming Wu, Jeff Fein, Pat Lake

Hardware buildup: Pat Lake, Mike Sullivan, Chris Kirtley, Linda Nielsen-Weber, Andy Maurer

Hardware prototyping: Larry Lucero

Stage control: Drew Johnson, Jeff Georgeson, Chris Ball

Calibration/commissioning lab build up: Pat Lake, Ming Wu, Paul Gard

Commissioning and System demonstration: Pat Lake, Dave Ampleford, Jeff Fein, Chris Ball

Fielding in Z: Mike Sullivan, Chris Kirtley, Aaron Citrin, Chris Ball, Dave Ampleford, Jeff Fein, Linda Nielsen-Weber, Antoinette Maestas, Brian Ritter, Dan Folker

Image Analysis: Jeff Fein

Management: Clark Highstrete, Greg Dunham, Chris Bourdon (start of project), Greg Rochau (NDWG)

Thanks to the Z Diagnostics and Operations teams!

External:

Optical design: Julia Vogel, Bernie Koziokiemski, Chris Walton *(LLNL)*

Optic fabrication: Suzanne Romaine, Drew Ames *(Harvard/Smithsonian Center for Astrophysics)*

Optic mounting and testing: Brian Ramsey, Kiranmayee Kilaru *(NASA Marshall Space Flight Center)*

LLNL Calibration: Bernie Kozioziemski *(LLNL)*