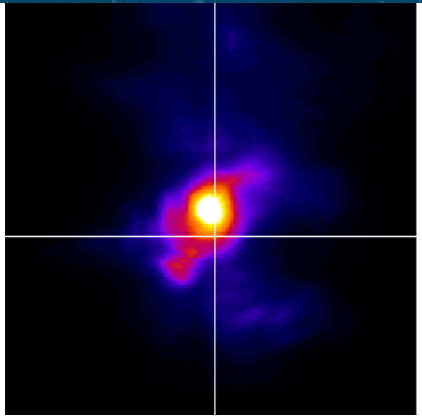
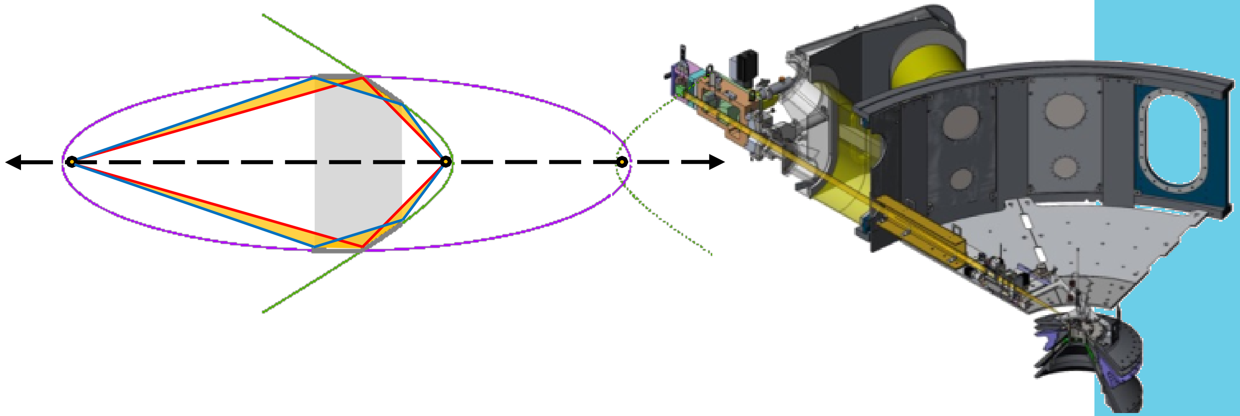
SAND2020-13289C

High-resolution imaging of warm x-ray sources with a Wolter optic on the Z Machine





PRESENTED BY

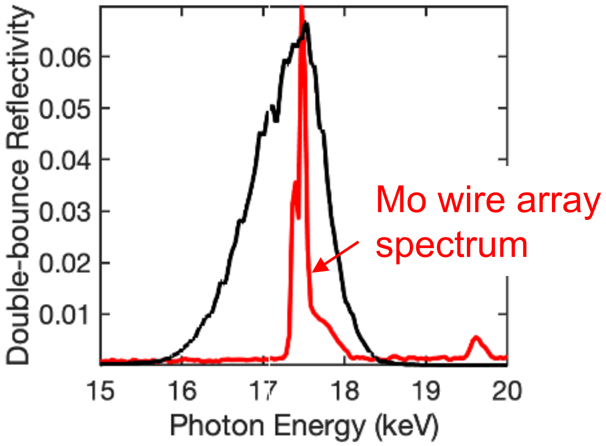
Jeff Fein (SNL), on behalf of the Wolter team

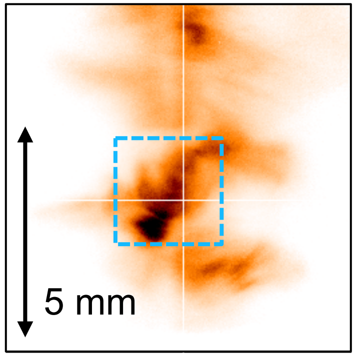
High Temperature Plasma Diagnostics Conference 2020

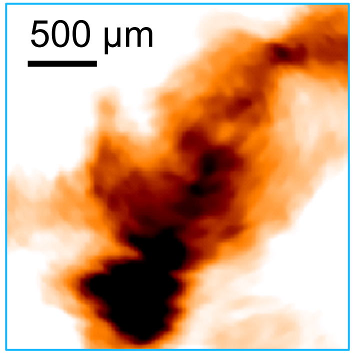
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Multilayer Wolter optics are pushing the limits of imaging large (>5 mm), warm (>15-keV) x-ray sources with high resolution

- **We have used a Wolter optic to successfully image ~17.5-keV K-shell emission distributions from large (>5 mm) Mo wire arrays on the Z Machine**
- **The Wolter images reveal unprecedented structure in these sources that will enable a better understanding of x-ray generation mechanisms**
- **Deblurring techniques show potential to recover sub-resolution hot-spot structures in recorded images**
- **New fabrication techniques and multilayer design have been developed, capable of producing even better-performing optics for higher energy sources**







Collaborators

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Lawrence Livermore National Laboratory, Livermore, CA

S. Romaine, L. Sethares, R. Bruni

Harvard-Smithsonian Center for Astrophysics

K. Kilaru, O.J. Roberts

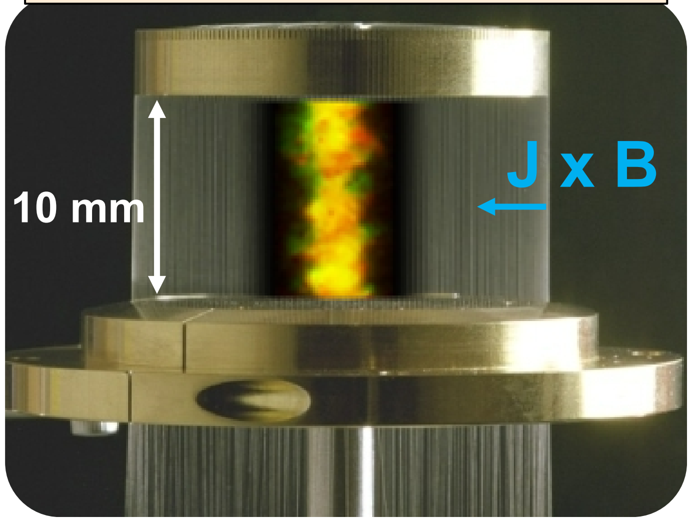
Universities Space Research Association

B. Ramsey

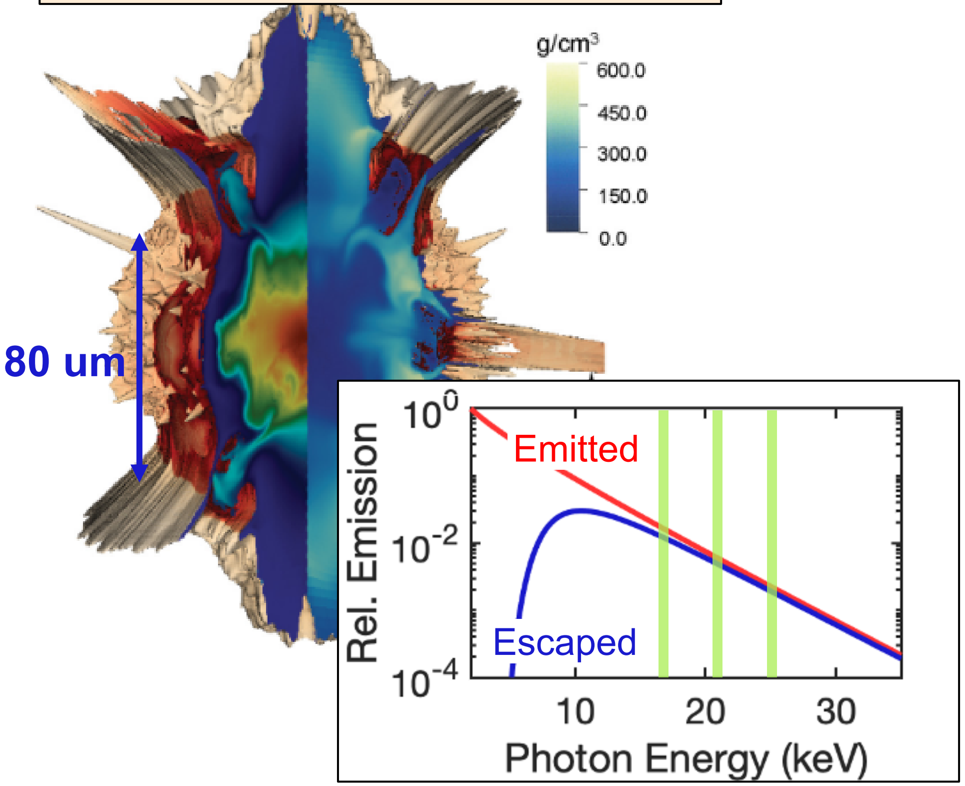
NASA Marshall Space Flight Center

Hi-resolution, narrowband imaging of >15 keV x-rays is desirable in many HED applications

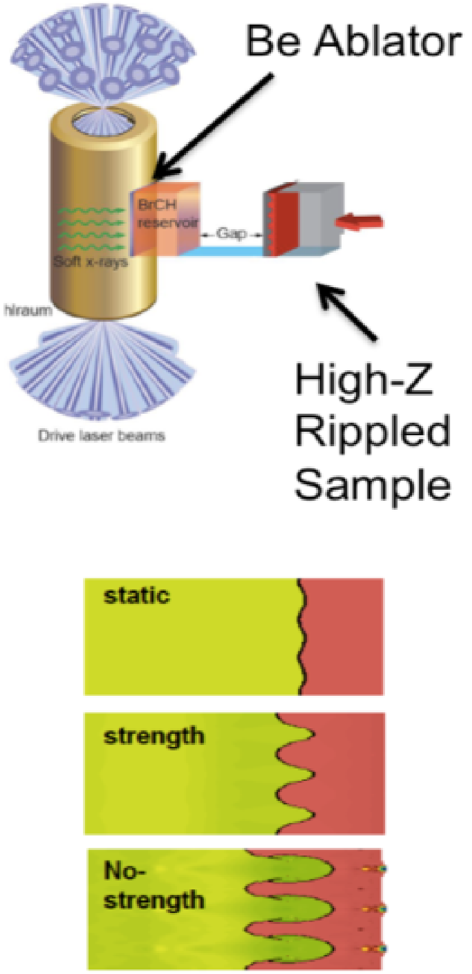
K-shell x-ray sources on Z[1,2]



ICF capsule hot spot[3] imaging



Strength of hi-Z materials[4]



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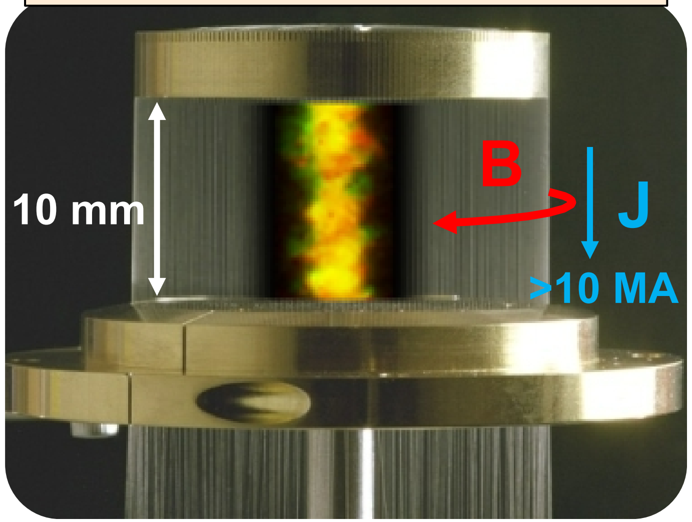
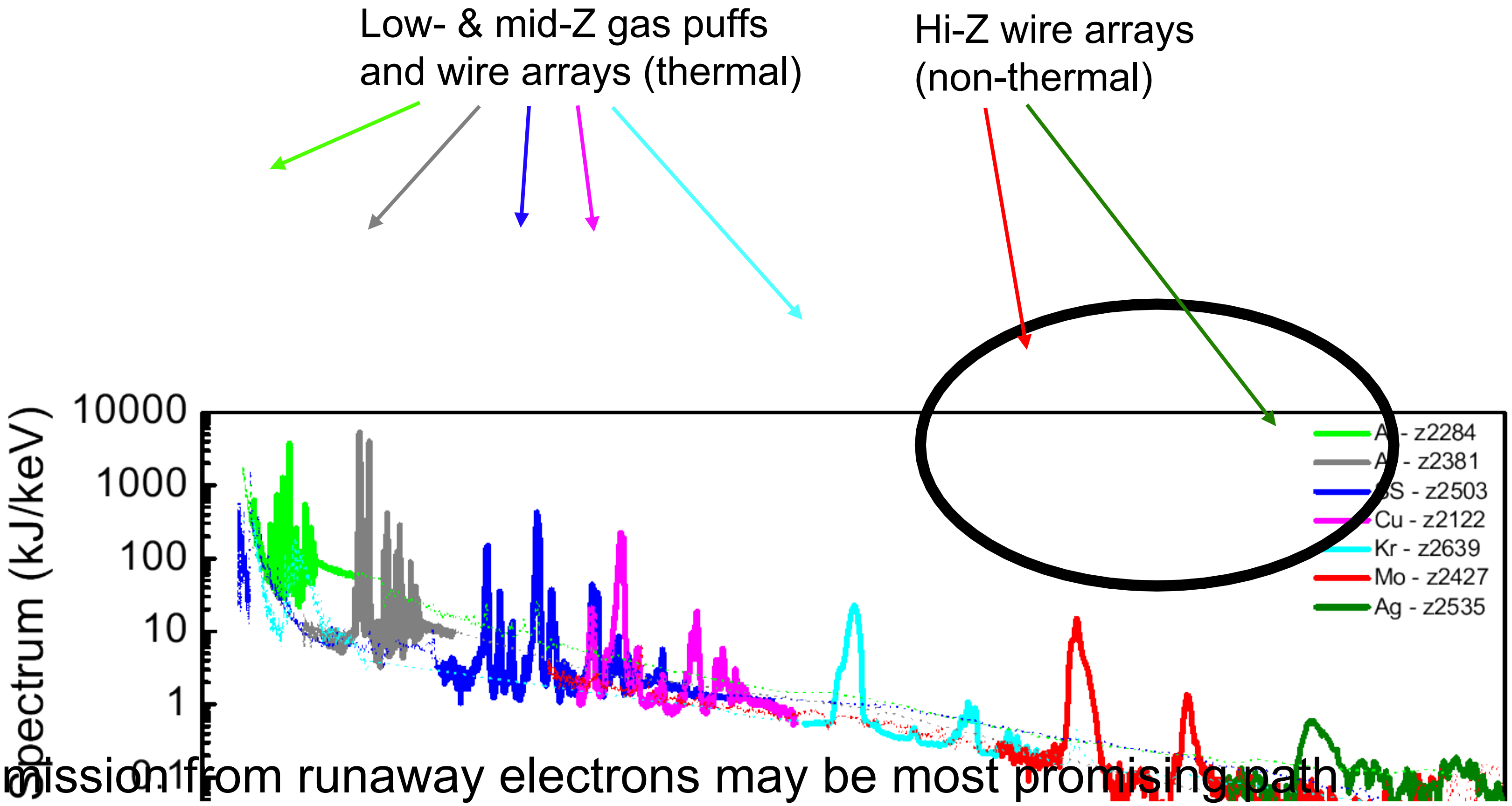
1. Jones, B., et al. RSI (2008), 2. Ampleford, D. J. POP (2014),
3. Clark, D. S., et al. (2016). *Physics of Plasmas*, *23*(5), 4. Park, H. -S., et al. PRL (2015)

HED = High Energy Density

Sandia is developing warm (>15 keV) K-shell x-ray sources for radiation effects science on the Z Machine

K-shell x-ray sources on Z[1,2]




Low- & mid-Z gas puffs and wire arrays (thermal)

Hi-Z wire arrays (non-thermal)

- Cold K-shell (non-thermal) emission from runaway electrons may be most promising path to higher energies[1]
- *Imaging* of K-shell emission from non-thermal wire array z-pinches can aid understanding of primary x-ray generation mechanisms (disruption, beams, etc.) to later ***optimize output***

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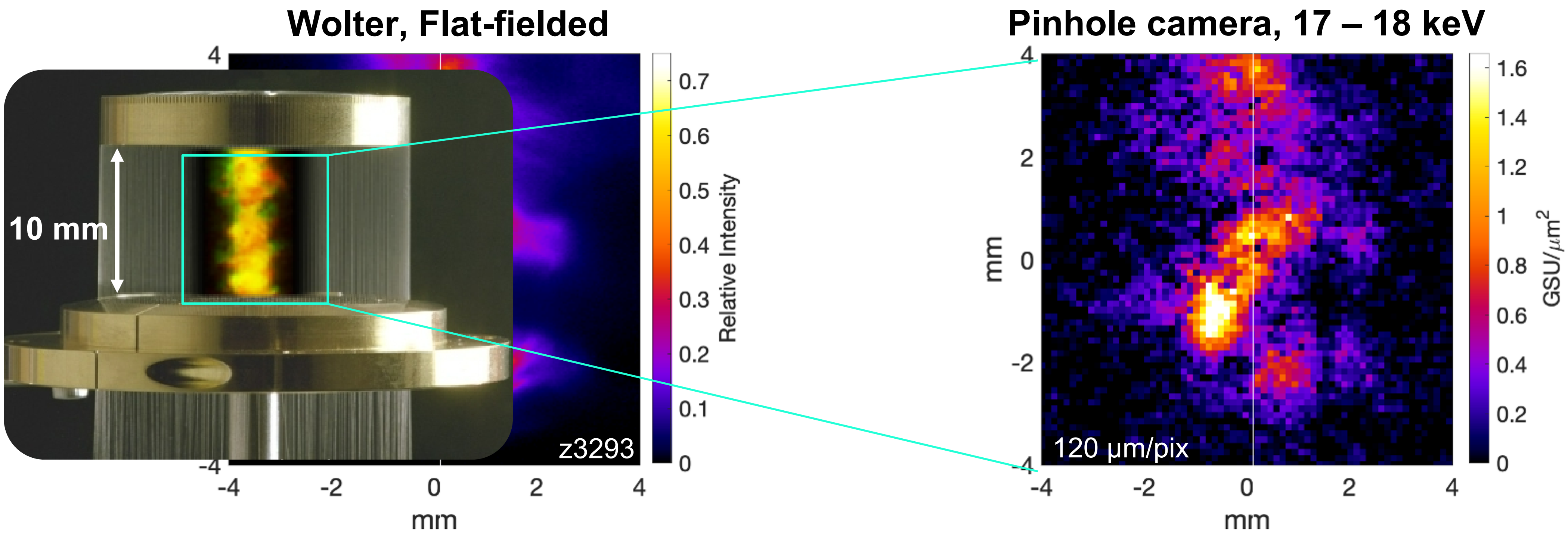
1. D.J. Ampleford, POP (2014), 2. B Jones, RSI (2008)

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



Wolter, Flat-fielded

Pinhole camera, 17 – 18 keV

Previous limitations:

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

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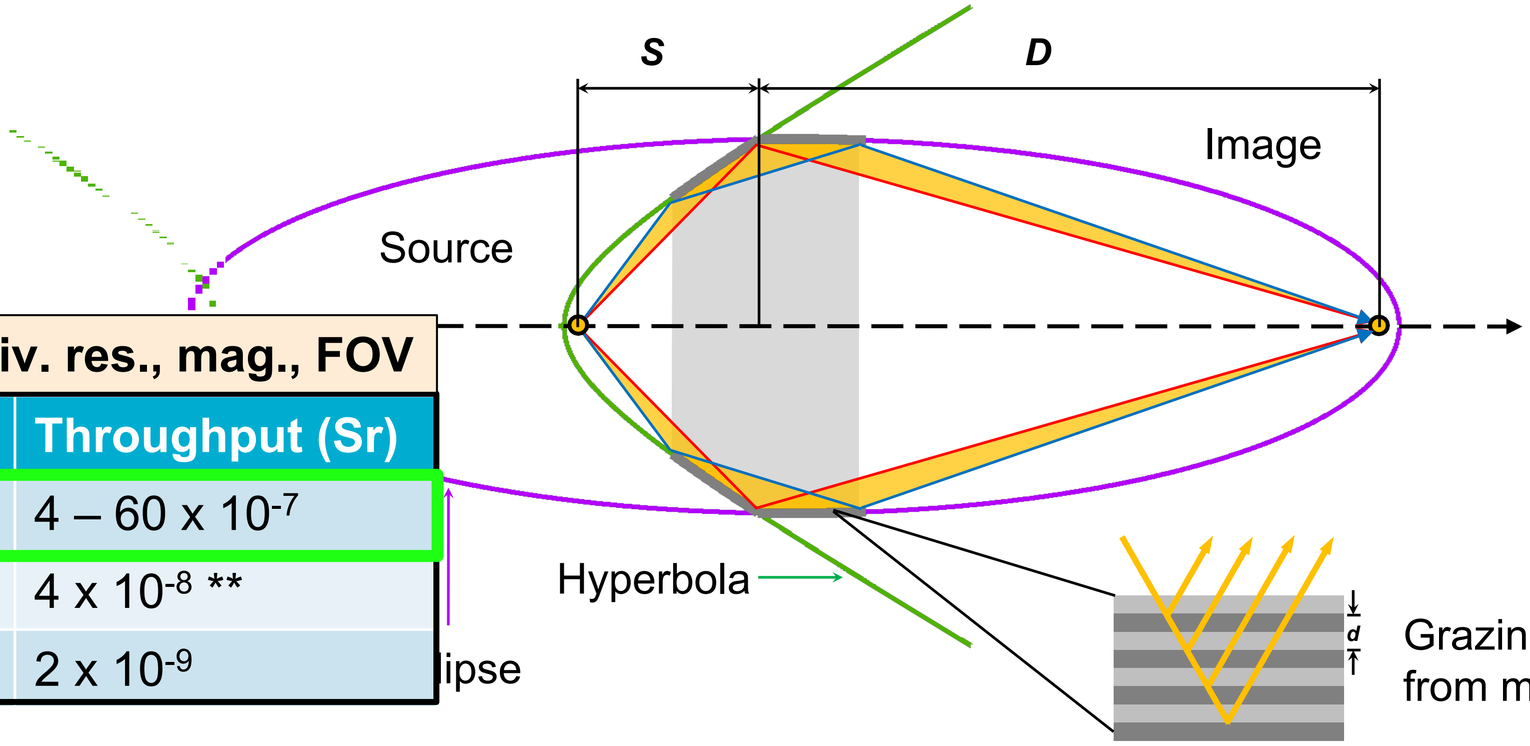
1. L. A. McPherson, RSI (2016), 2. J.R. Fein, RSI (2018)

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

Wolter type-I microscope:



Grazing incidence reflection from multilayer mirrors

Optic behaves like lens:

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

Imagers w/equiv. res., mag., FOV

Optic	Throughput (Sr)
Wolter	$4 – 60 \times 10^{-7}$
Crystal Imager	4×10^{-8} **
Pinhole Imager	2×10^{-9}

Advantages:

- **Can image over large FOV while maintaining <150-µm resolution**
- **High collection efficiency from geometry and multilayer ($\Omega_{optic} = 10^{-4}$ Sr, R > 1%)**

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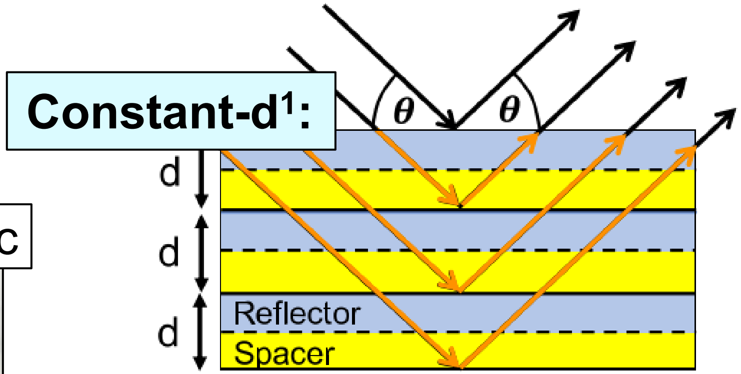
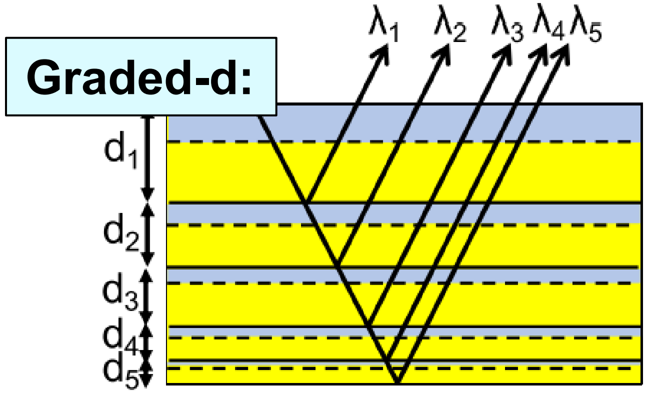
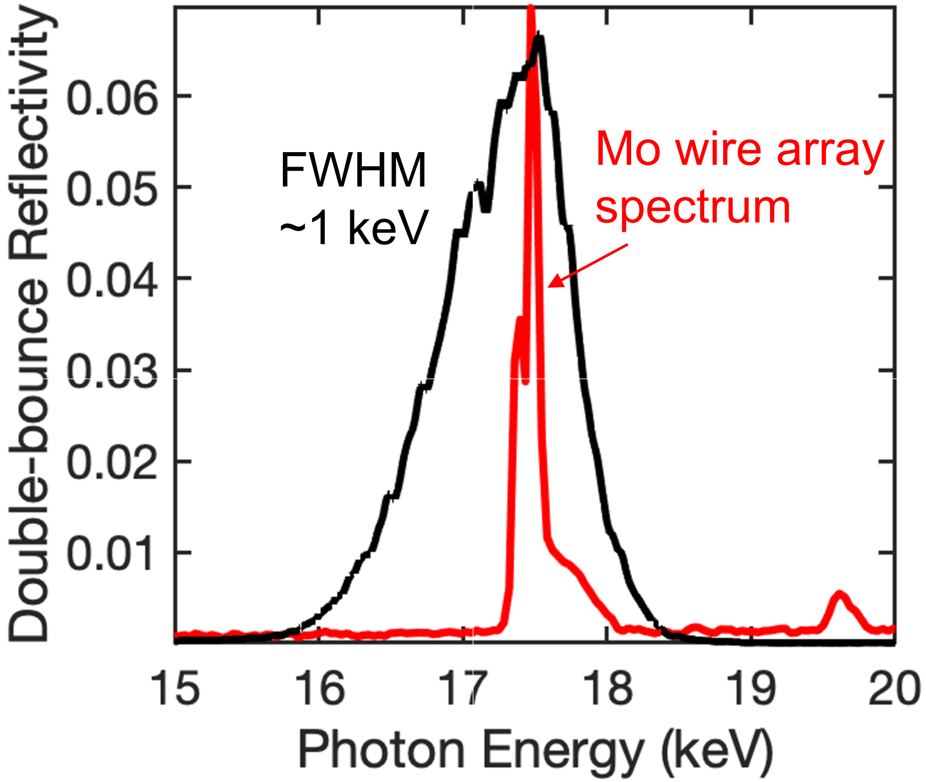
1. H. Wolter, Ann. Phys. (1952), 2. J. K. Vogel et al., Rev. Sci Instrum (2018), **Schollmeier, et al., RSI (2016)

Novel small-diameter multilayer optics enable high-efficiency imaging of >15 keV sources w/tunable band-pass[1,2]

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







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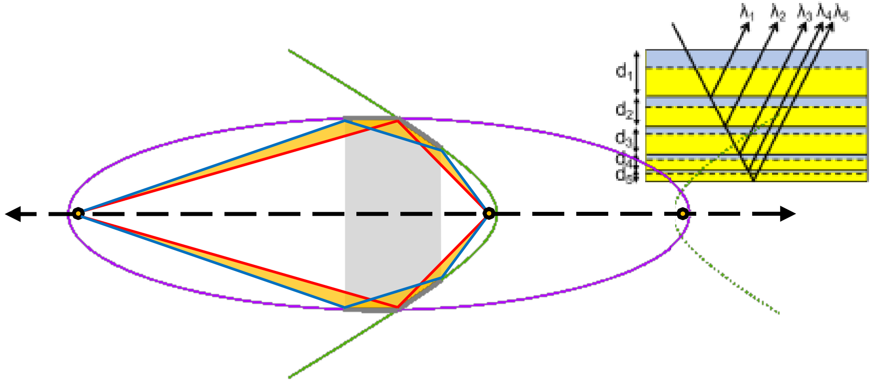
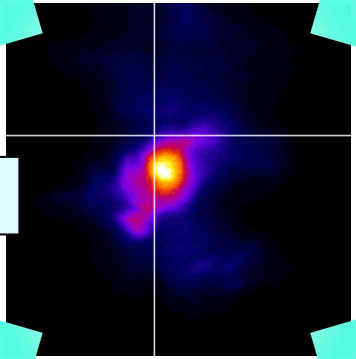
1. J. K. Vogel et al., Rev. Sci Instrum (2018), 2. S. Romaine et al. Proc. SPIE (2013)

Development of the Wolter imager for Z has been a multi-institutional effort between NNSA labs and academic partners

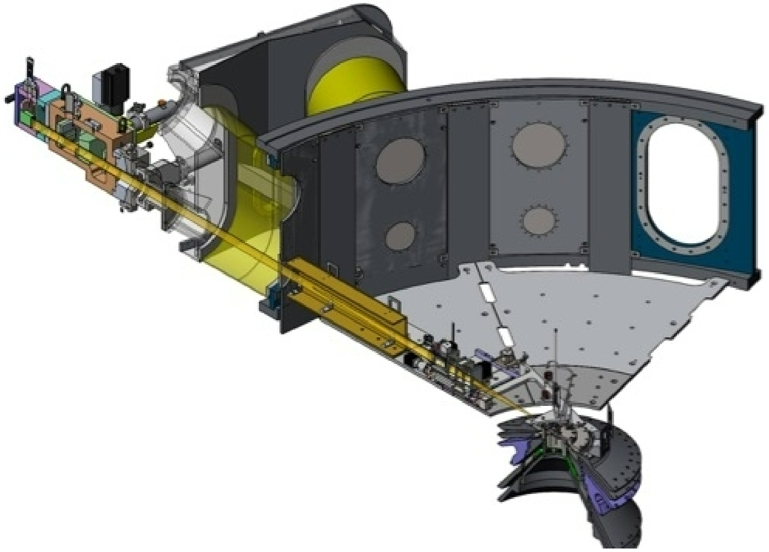
Optic and Multilayer Design (LLNL)



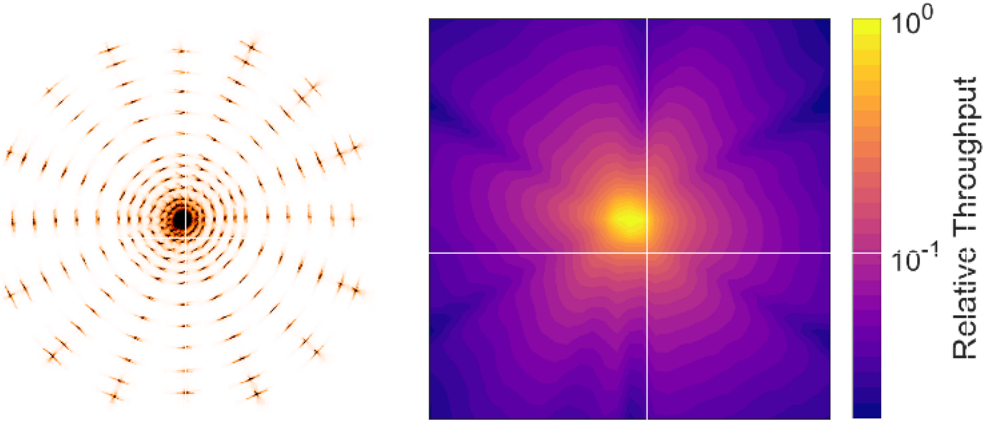
Mandrel/multilayer Fabrication (NASA MSFC + Harvard CfA)



Mechanical Design/Controls/Fielding (SNL)

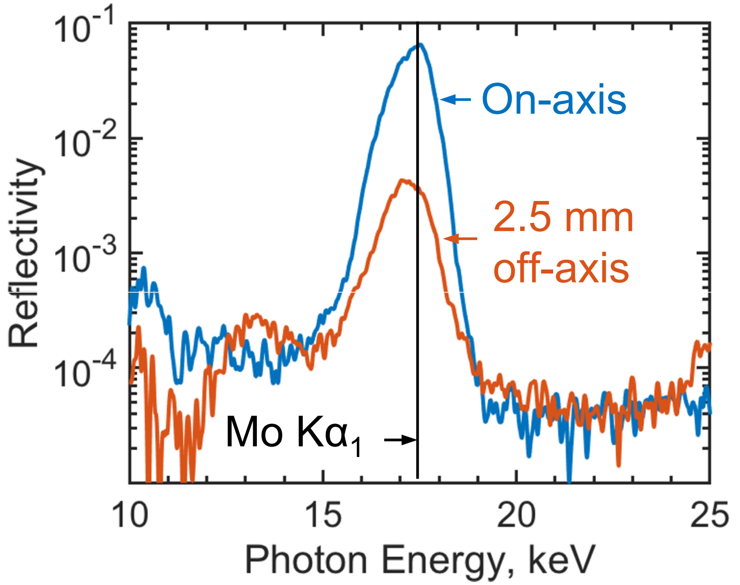


Calibration & Image Processing (LLNL + SNL)

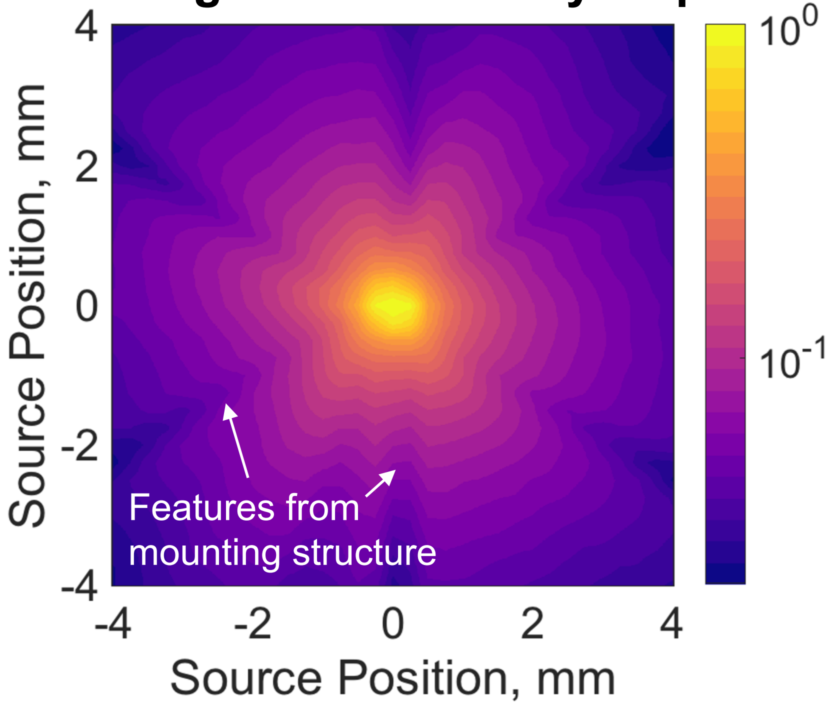


Extensive calibration measurements[1,2] are used to qualify optics and to conduct detailed image-postprocessing

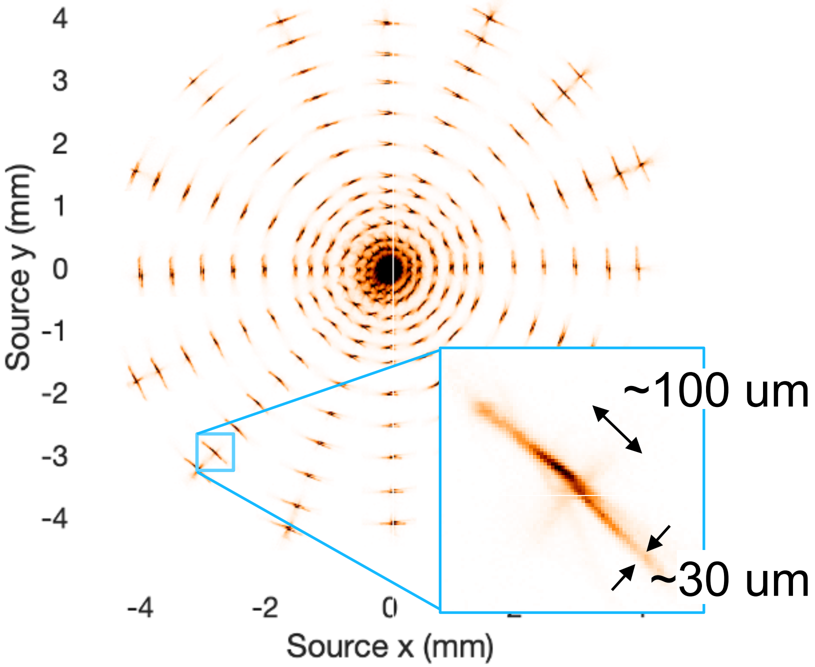
Spectrally-resolved reflectivity



Integrated reflectivity map



Point-spread function (PSF) map



- Characterize optics' reflectivity, bandpass and spatial resolution in x, y and z
- Optics demonstrate significant (expected) variation in throughput and resolution over >5 mm FOV

Optics' resolution in microns:

Optic	17.5 keV	22-keV
On-axis	70 x 75	40 x 70
2.5 mm off-axis	50 x 115	20 x 90

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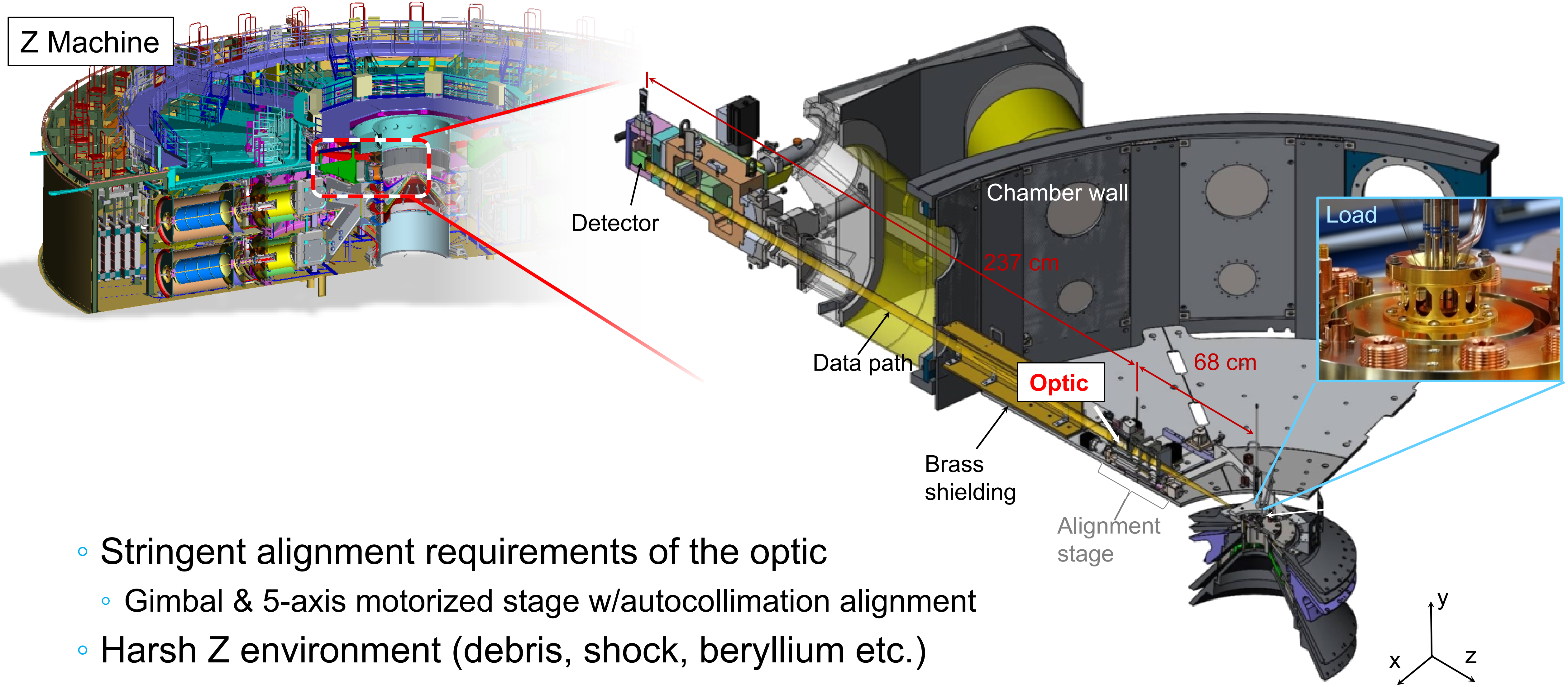
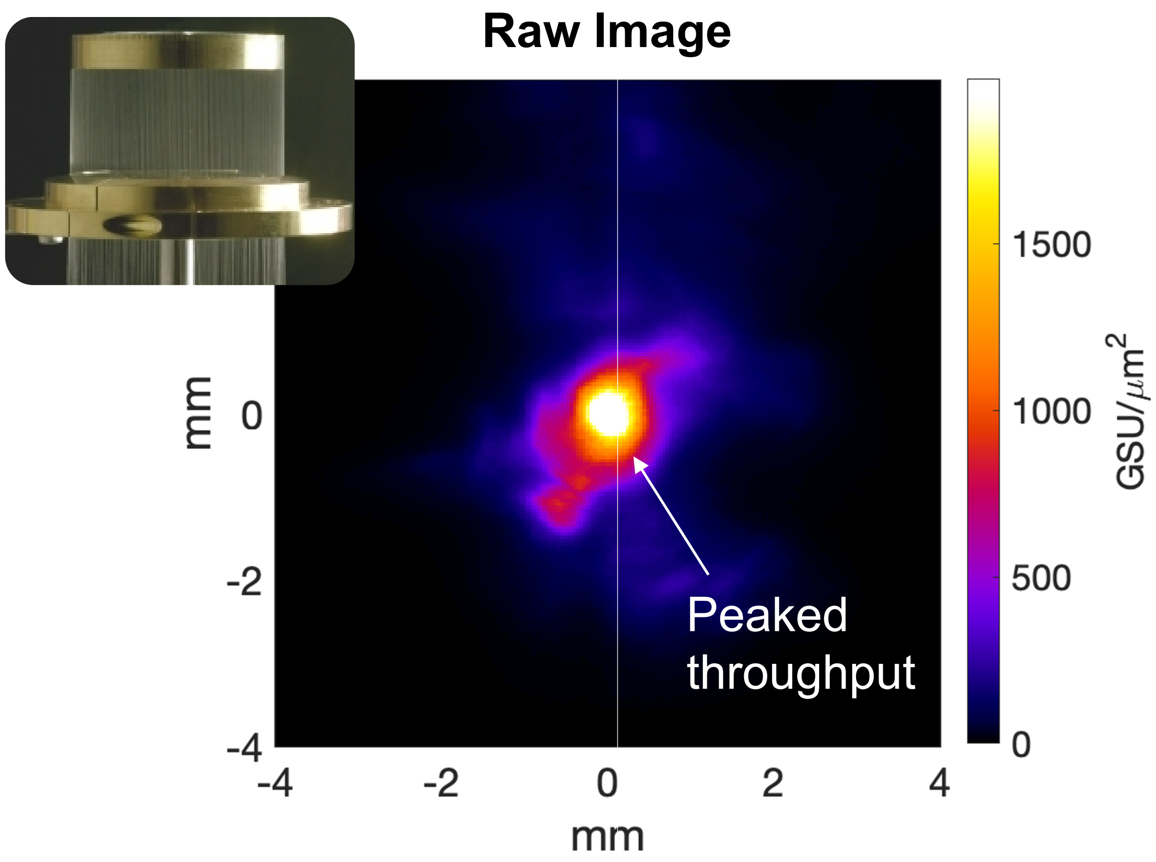
1. M. Wu, et al. Rev. Sci Instrum (2018), 2. B. Kozioziemski, et al. Rev. Sci Instrum (2018)

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



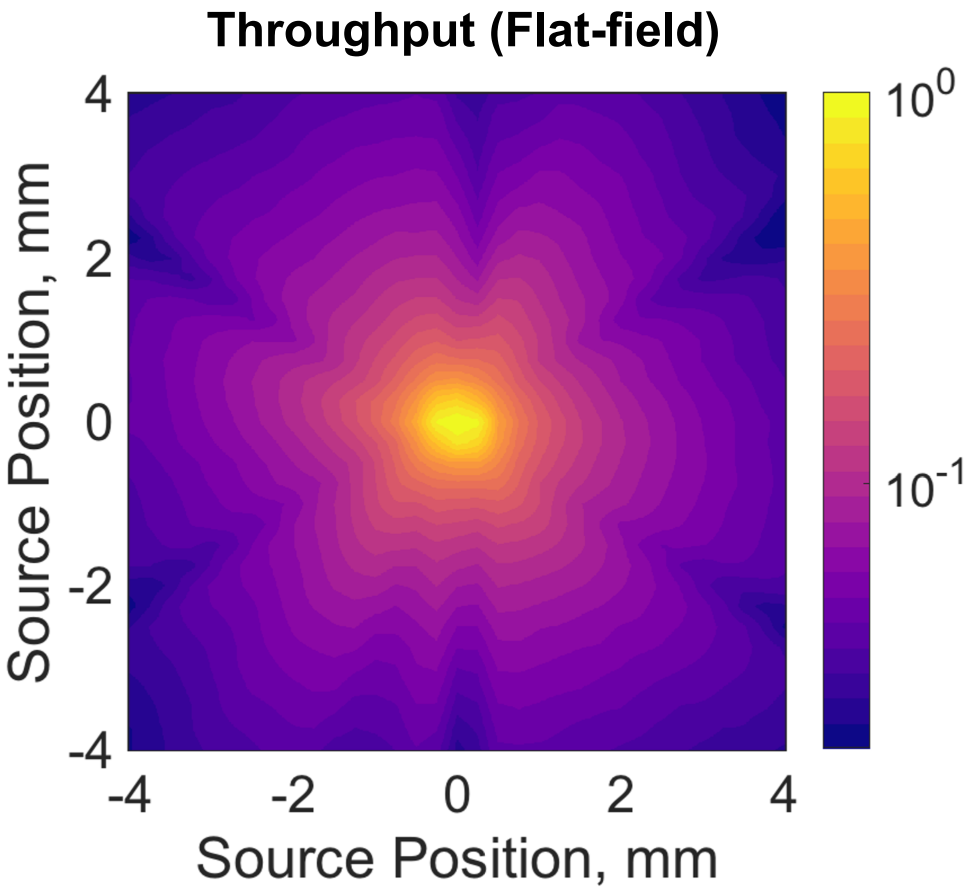
- Stringent alignment requirements of the optic
  - Gimbal & 5-axis motorized stage w/autocollimation alignment
- Harsh Z environment (debris, shock, beryllium etc.)
  - Robust shielding…the optic survives!

We successfully imaged Mo non-thermal wire arrays on the Z Machine with the Wolter optic



Raw Image

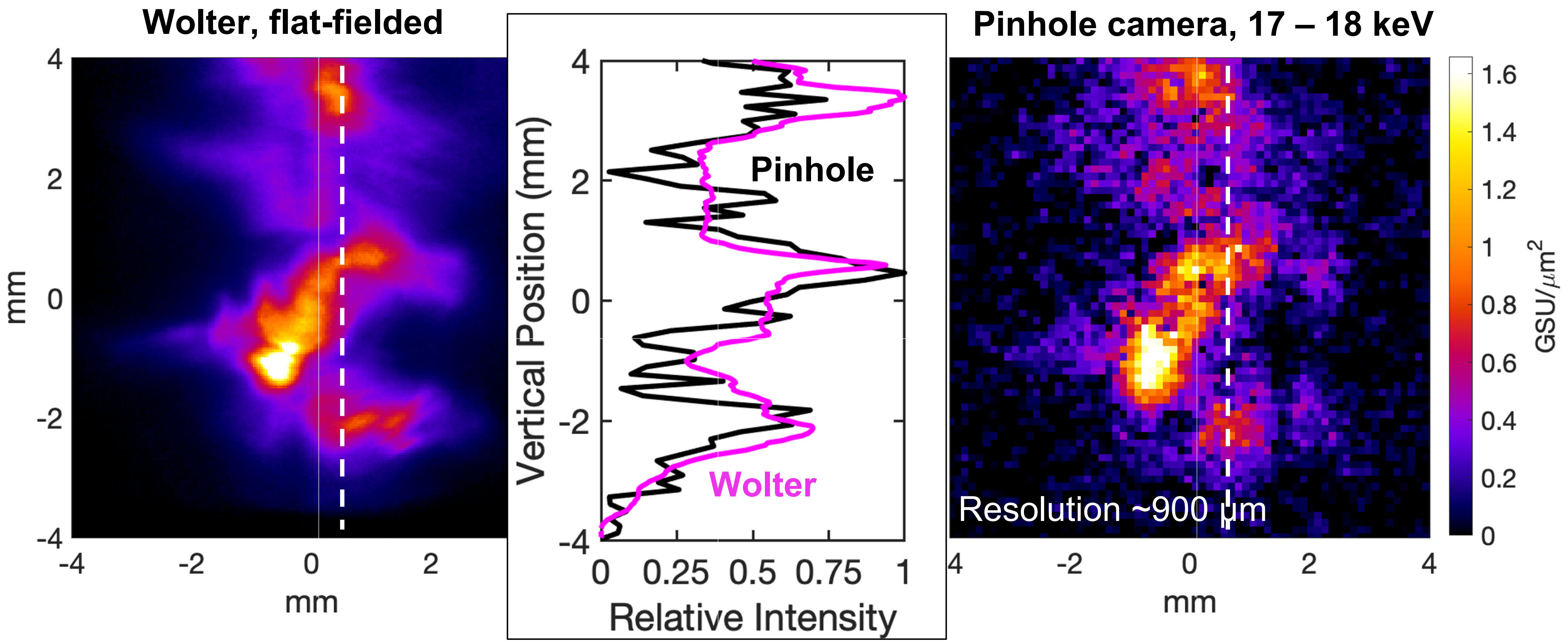
Peaked throughput



Throughput (Flat-field)

- Need to flat-field images to remove effect of highly varying throughput over FOV

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



Wolter, flat-fielded

Pinhole camera, 17 – 18 keV

- Wolter image has >100 – 1000x more signal than bandpass pinhole camera image at higher magnification and spatial resolution
- Wolter image shows features smaller than 200 microns in size

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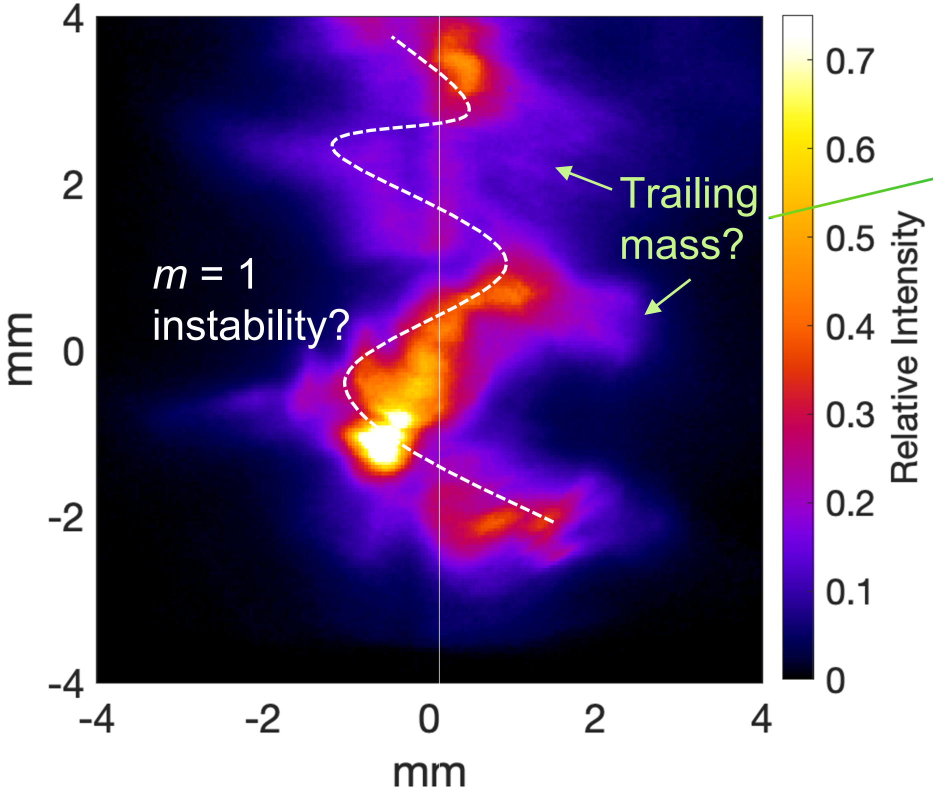
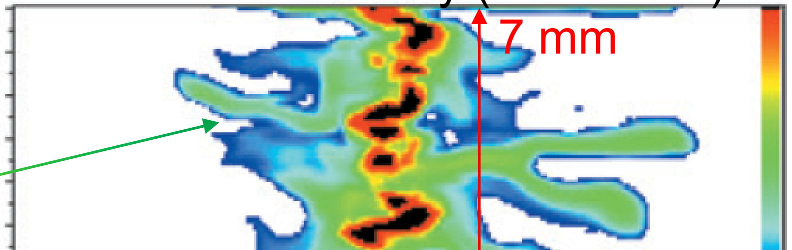
1. J.R. Fein, RSI (2018), 2. L. A. McPherson, RSI (2016)

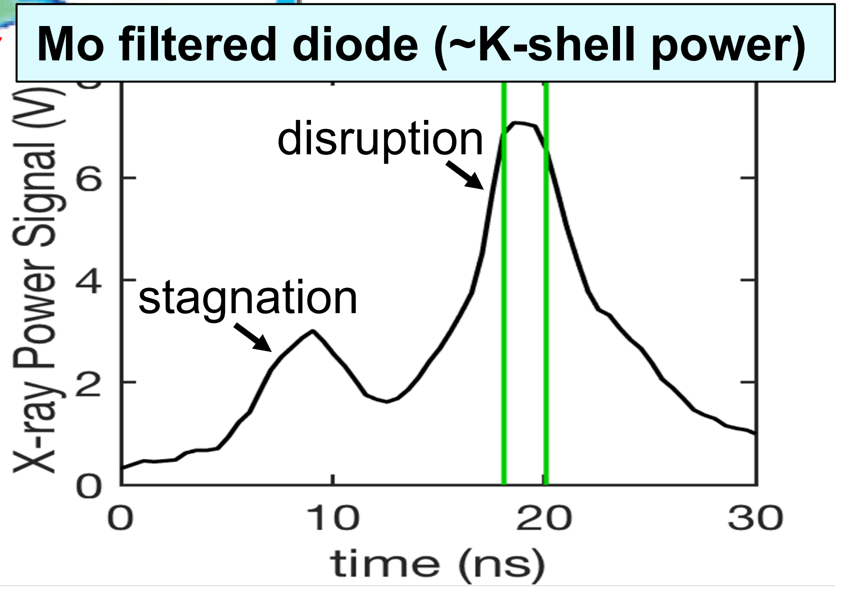
Wolter image shows key signatures of a disrupting plasma column with additional structure



Post-stagnation density profile of simulated wire array (GORGON)[1]



Mo filtered diode (~K-shell power)



- Emission is concentrated in helical structure, consistent with beams impacting still-compressed dense plasma being ripped apart by m = 1 instability
- Significant smaller-scale structure within disrupted column and emission at > 2 mm radius

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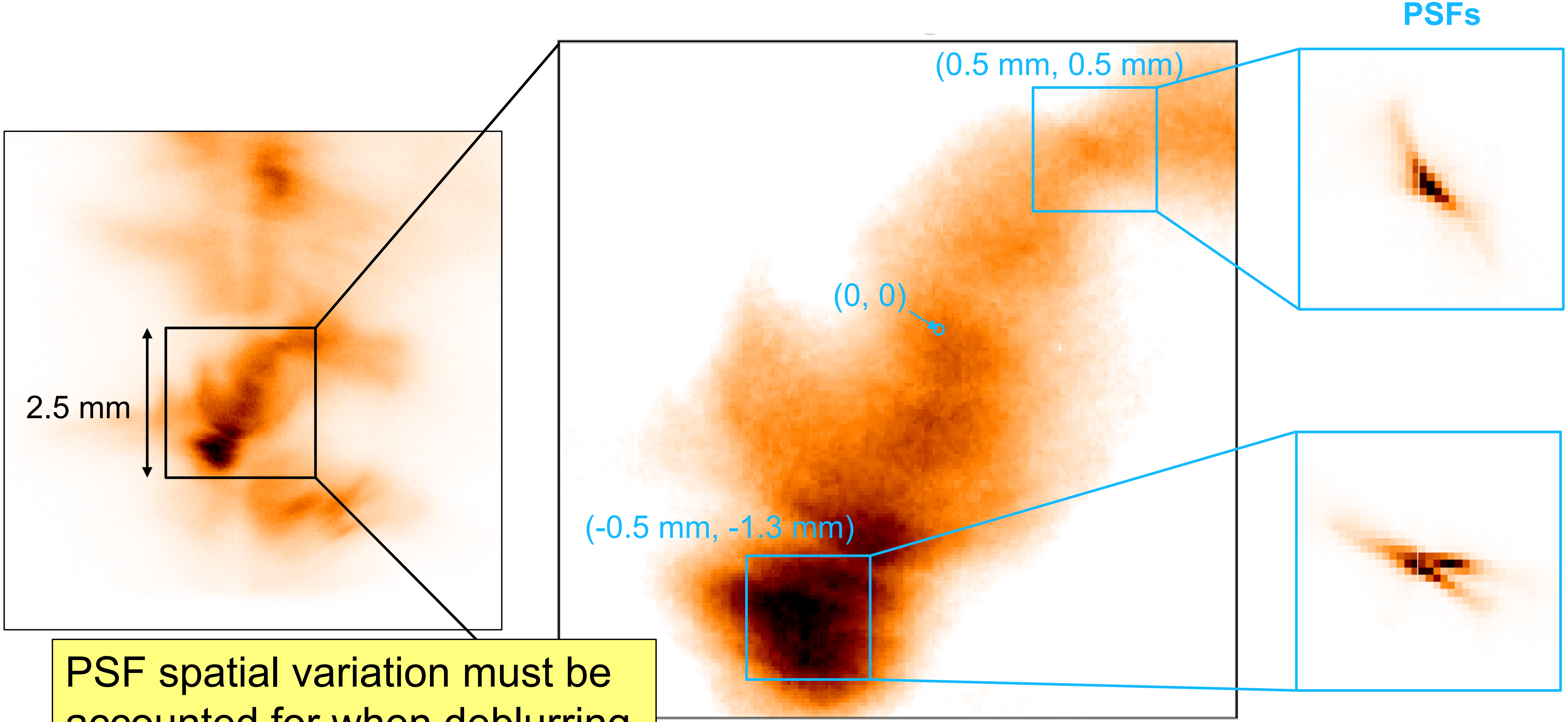
[1] Chittenden, et al., PPCF (2004)

We can make further attempts to resolve detailed structures by leveraging our understanding of the optic's PSF



PSF spatial variation must be accounted for when deblurring

Modal decomposition of shift-variant PSF using measured PSF data enables conventional deblurring

- Model shift-variant PSF as sum of shift-invariant PSF modes constructed from data:[1]

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

Shift-variant PSF

coefficients

shift-invariant PSF modes

- Image is sum of weighted convolutions:

$$\boldsymbol{g} = \sum_{p} \boldsymbol{c}_p * (\boldsymbol{a}_p \cdot \boldsymbol{f})$$

Image

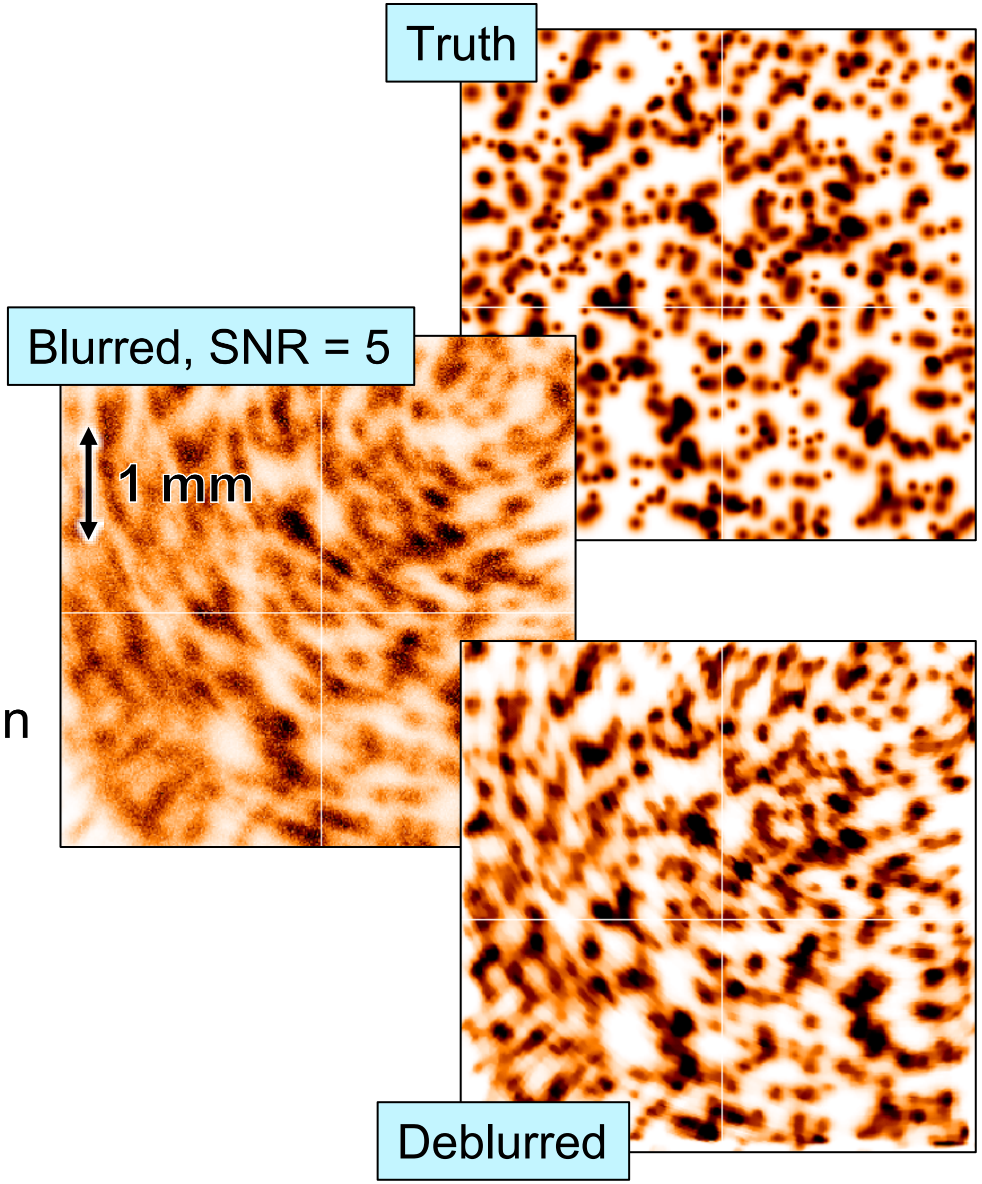
Source

- Deblur iteratively using Expectation-Maximization (Lucy-Richardson) or gradient descent methods w/regularization

$$\hat{\mathrm{f}} = \mathrm{argmin}_{\mathbf{f}}\ \mathcal{L}(\mathrm{f}) + \sum_{i} \beta_i \mathcal{P}_i(\mathrm{f})$$

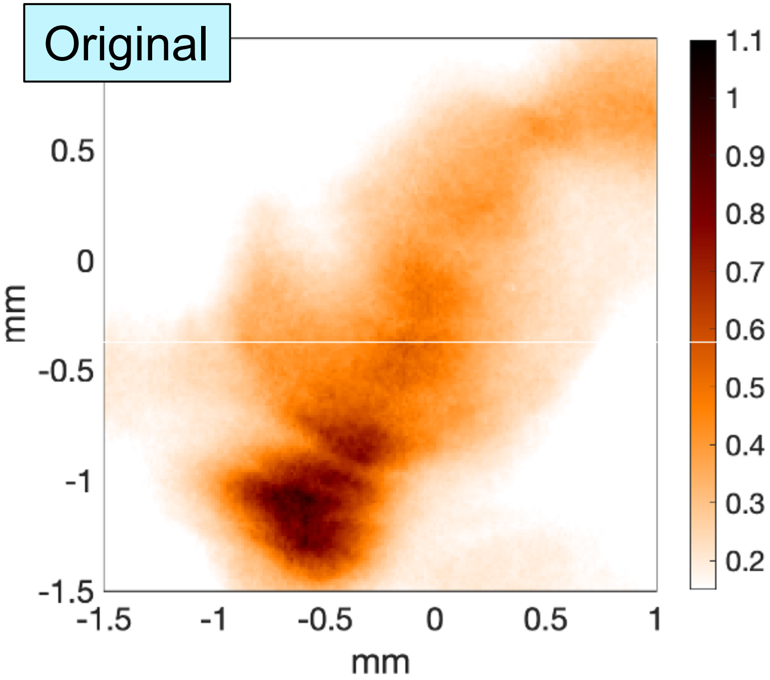
Likelihood/ data fit term

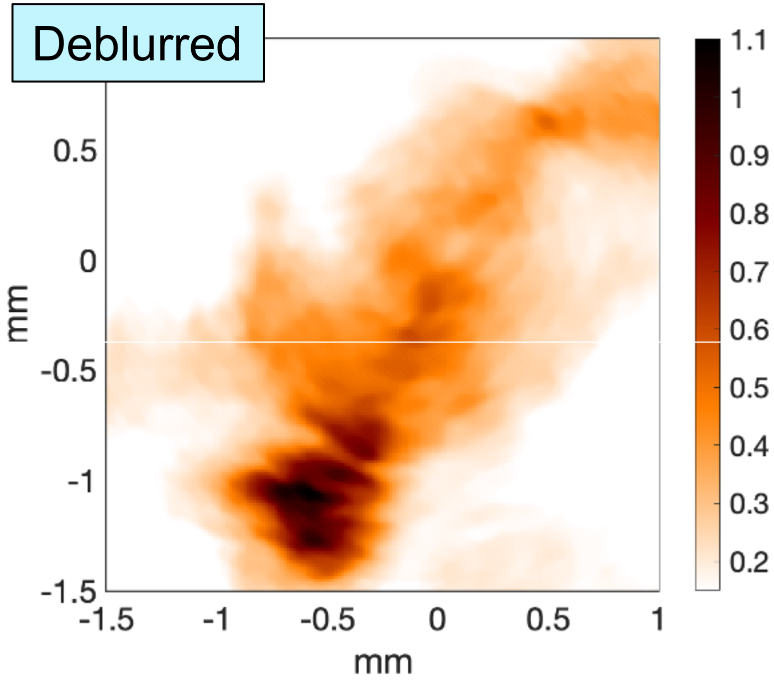
e.g. Total Variation[2] and/or Tikhonov regularization



1. Denis, et al., Int. J. Comput. Vision (2015), 2. Rudin, et al., Physica D (1992)

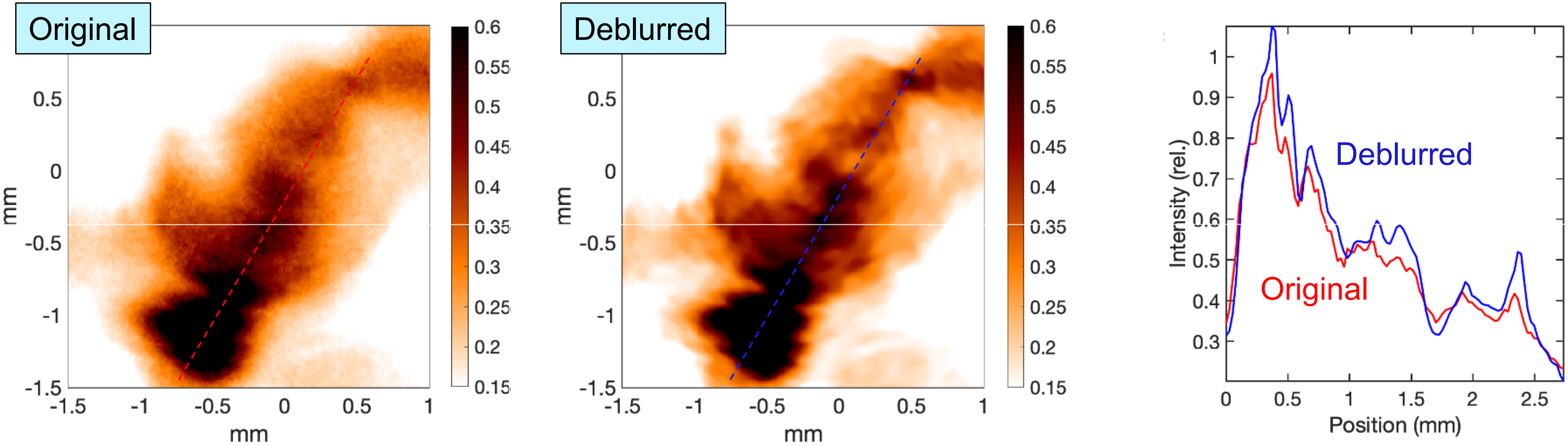
Deblurring of Wolter images uncovers hot-spot like structures below the resolution limit





- ~100 micron hot spots exist within larger-scale disrupted stagnation column
- Hot spots could be evidence of micro-pinches creating high density regions

Deblurring of Wolter images uncovers hot-spot like structures below the resolution limit



- ~100 micron hot spots exist within larger-scale disrupted stagnation column
- Hot spots could be evidence of micro-pinches creating high density regions

Integration of hCMOS for time-gated imaging will enable study of hot spots' temporal behavior[1]

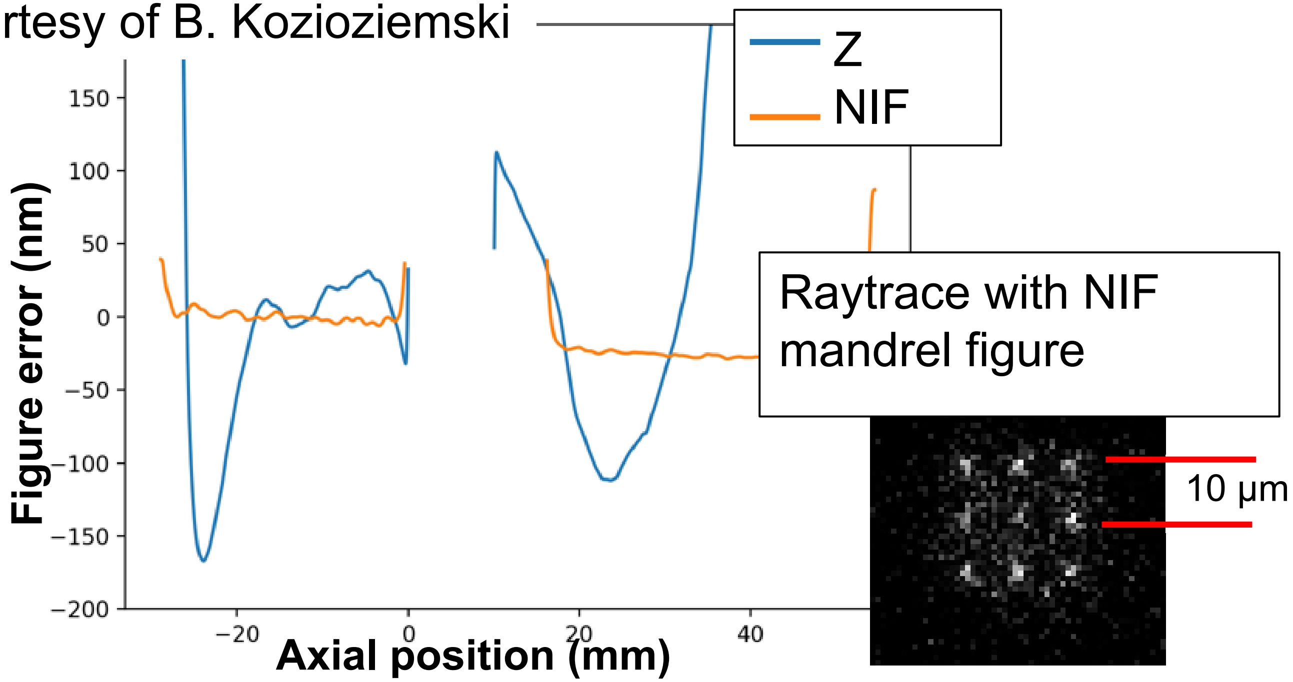
Tony Colombo's and Quinn Looker's talks

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

Even higher resolution is possible with improvements in polishing and optic shape

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

Courtesy of B. Koziozemski



Raytrace with NIF mandrel figure

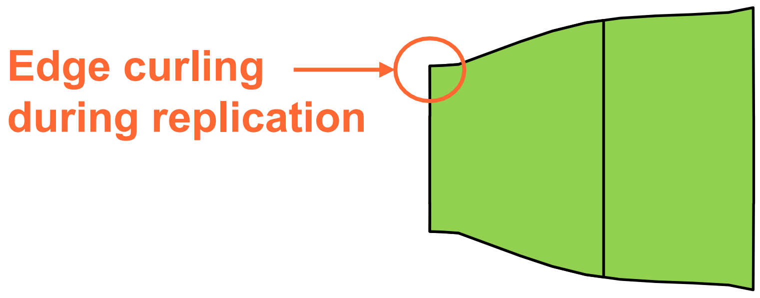
~10x reduction in figure error, expect < 10-µm resolution:

- Lap polishing improvements, slurry, alignment for Zeeko

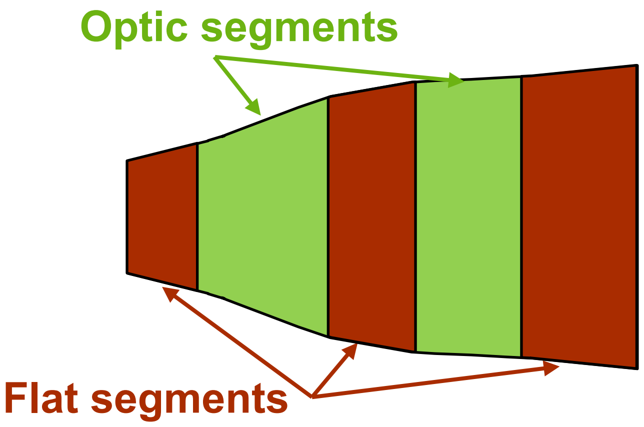
Poster by Julia Vogel

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

Z optic shape:



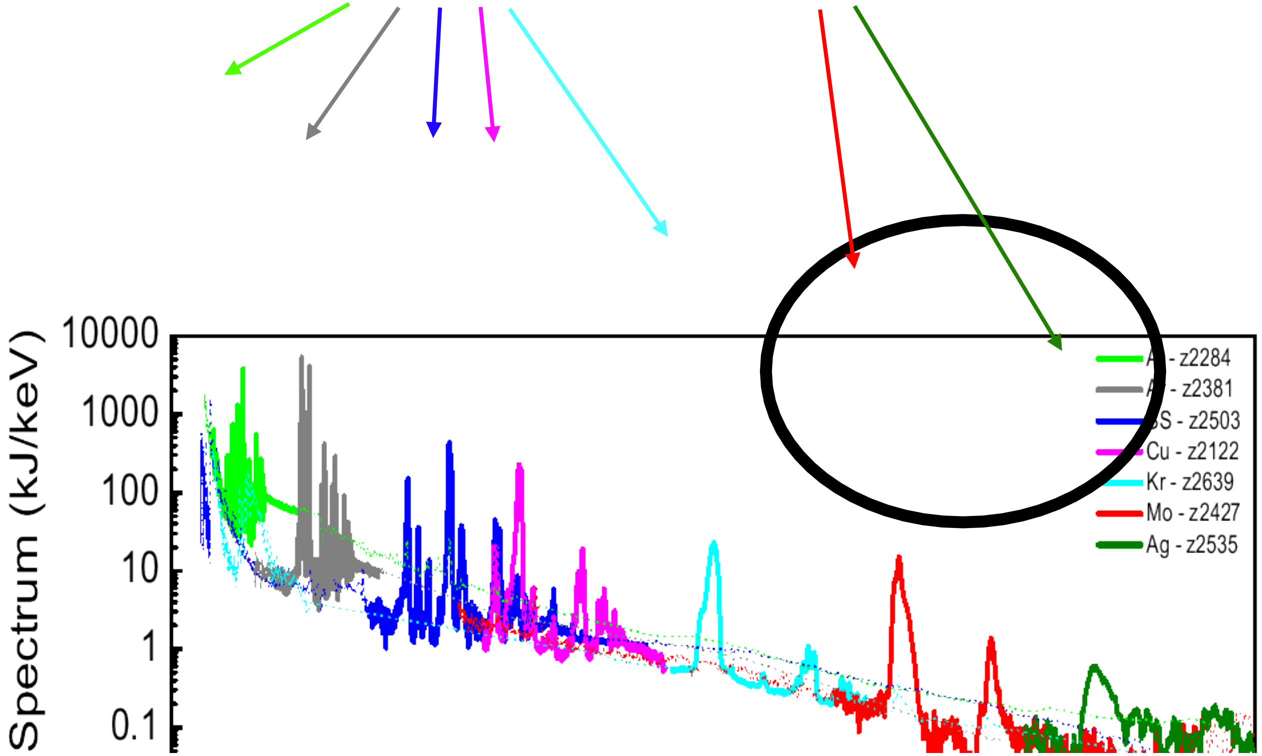
New mandrel shape:

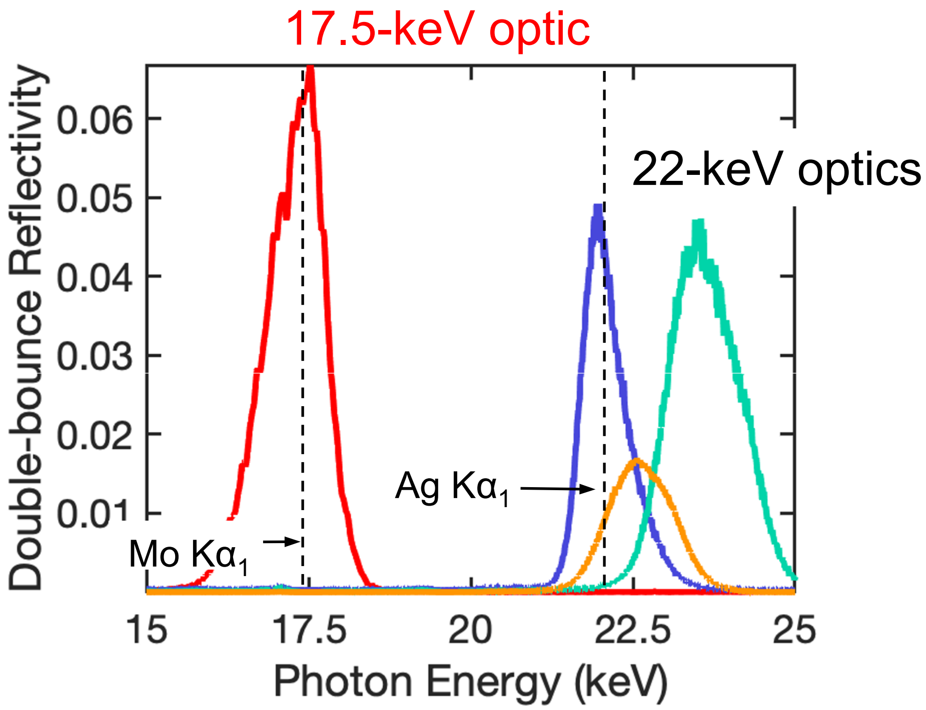


Significant effort has gone into development of 22-keV optics, looking towards even higher-energy sources

Low- & mid-Z gas puffs and wire arrays (thermal)

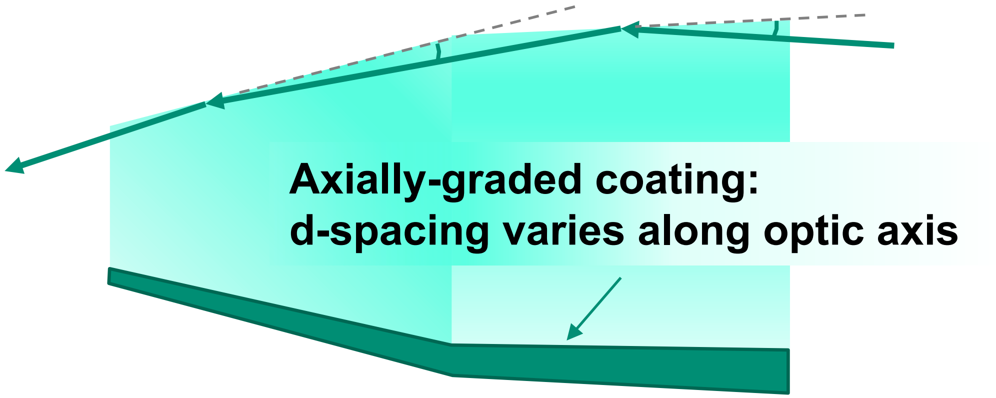
Hi-Z wire arrays (non-thermal)

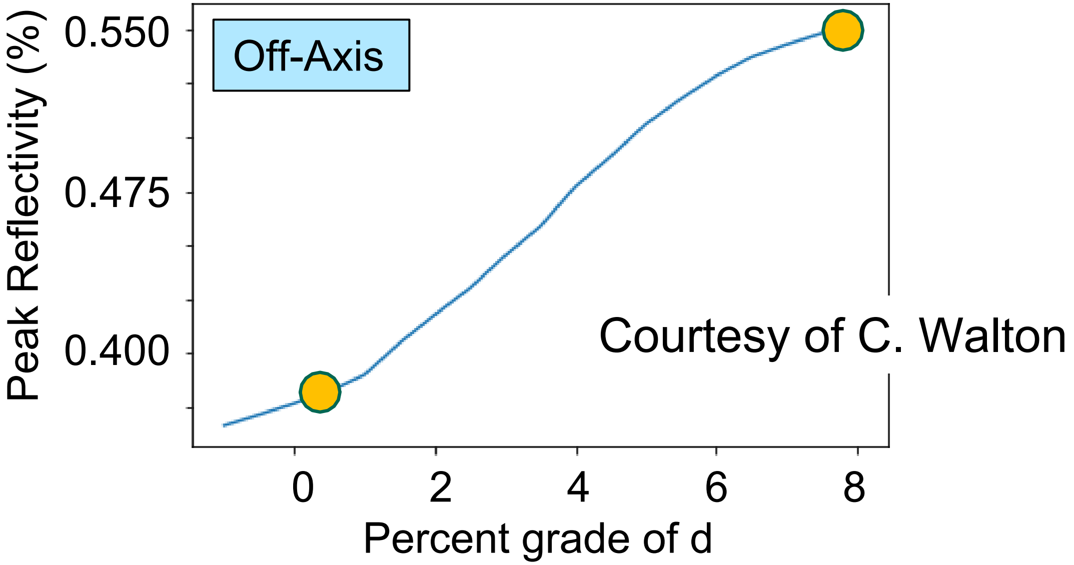




- These sources become increasingly dim at higher energies
- Reflectivity also decreases at higher energies
- The problem is worsened when adding time-gating!

New multilayer recipe studies show potential for optics w/improved performance for non-thermal x-ray sources and other applications



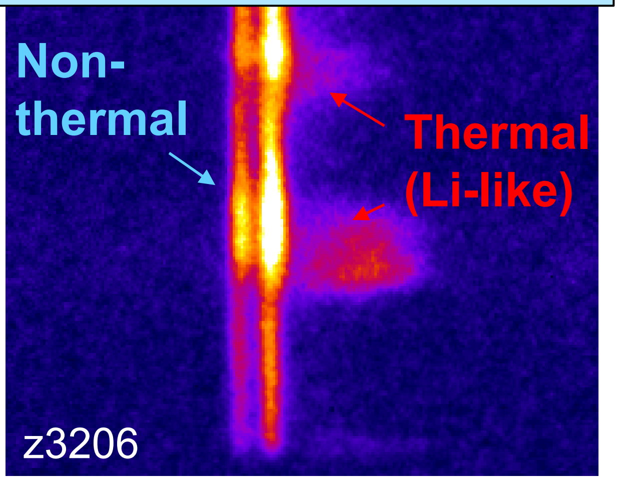


Courtesy of C. Walton

- Improving fabrication techniques to increase # of bi-layers, scoping alternative multilayer materials (CfA)
- Optimization framework is being developed to find multilayer recipes with higher reflectivities, higher ratios of **non-thermal**:**thermal**, uniformity of response, etc. (LLNL)
  - Optimize over d-spacing, # of bi-layers in multiple stacks, axial grading, etc.

Poster by Julia Vogel

Axially-resolved K-shell spectrum of Mo wire array



Multilayer Wolter optics are pushing the limits of imaging large (>5 mm), warm (>15-keV) x-ray sources with high resolution

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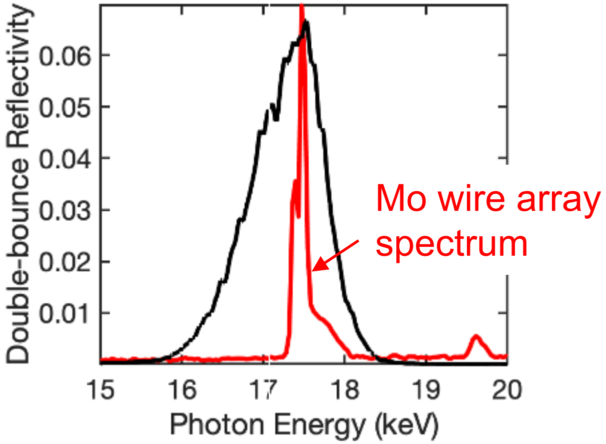
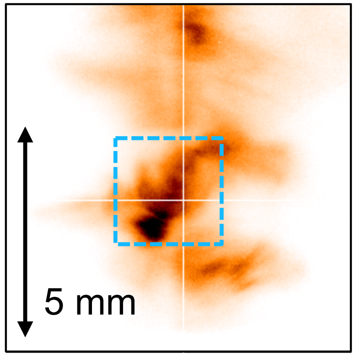
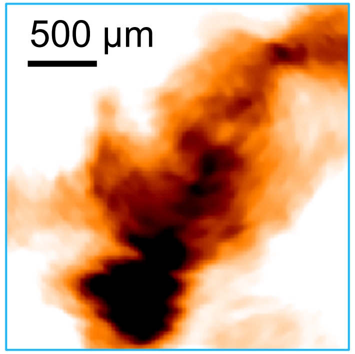
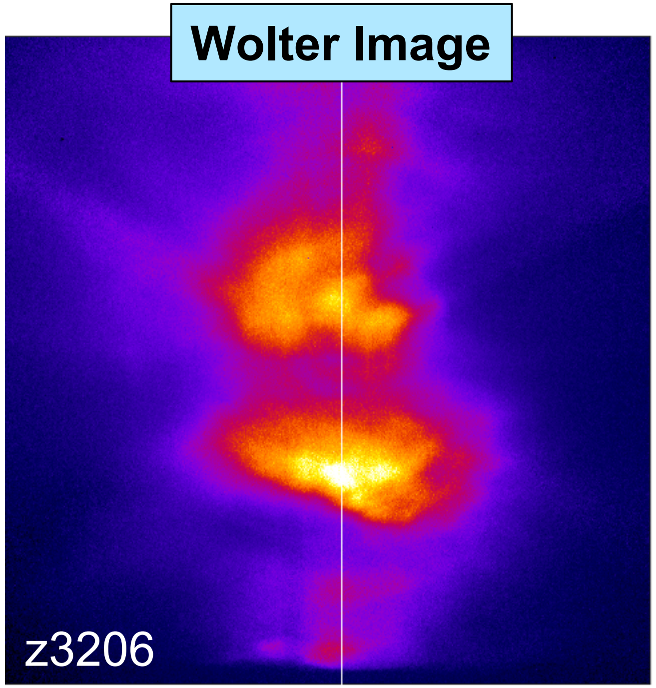
- **The Wolter images reveal unprecedented structure in these sources that will enable a better understanding of x-ray generation mechanisms**
- **Deblurring techniques show potential to recover sub-resolution hot-spot structures in recorded images**
- **New fabrication techniques and multilayer design have been developed, capable of producing even better-performing optics for higher energy sources**



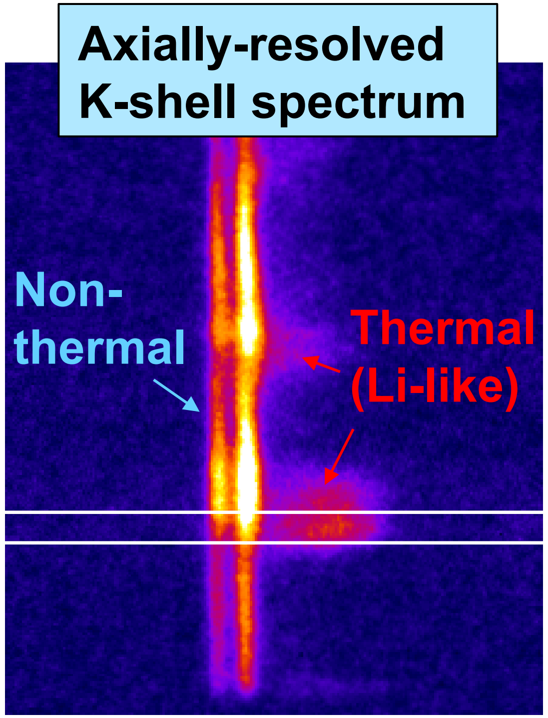




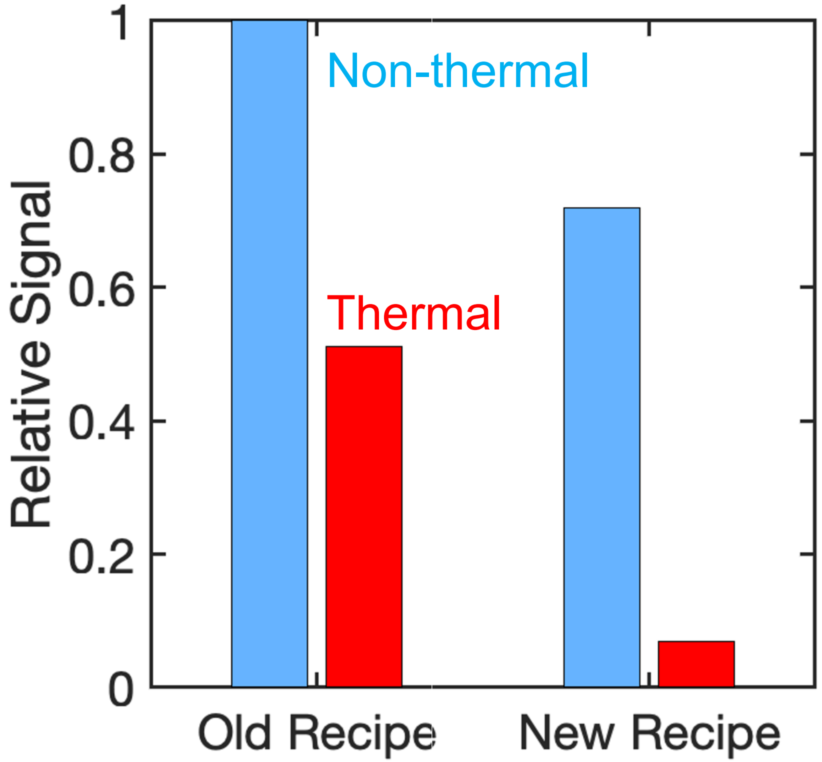
New multilayer recipe optimization efforts can lead to optics with improved performance for non-thermal x-ray sources



Wolter Image



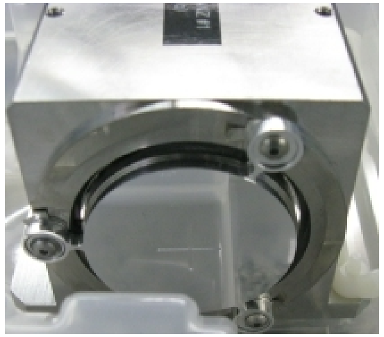
Axially-resolved K-shell spectrum

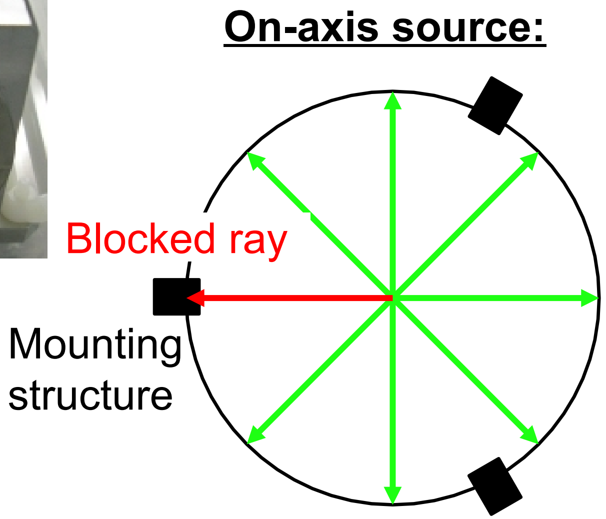


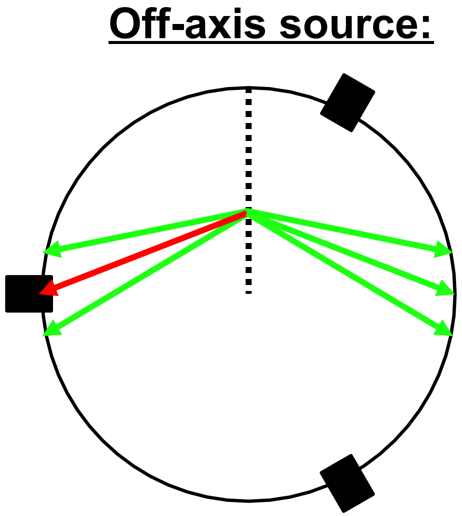
- Significant thermal emission can contribute to image, contaminating interpretation of non-thermal emission distribution
- Techniques are being developed to optimize multilayer recipes for higher reflectivities and higher ratios of non-thermal:thermal
  - Optimize over d-spacing, # of bi-layers in multiple stacks, axial grading, etc.

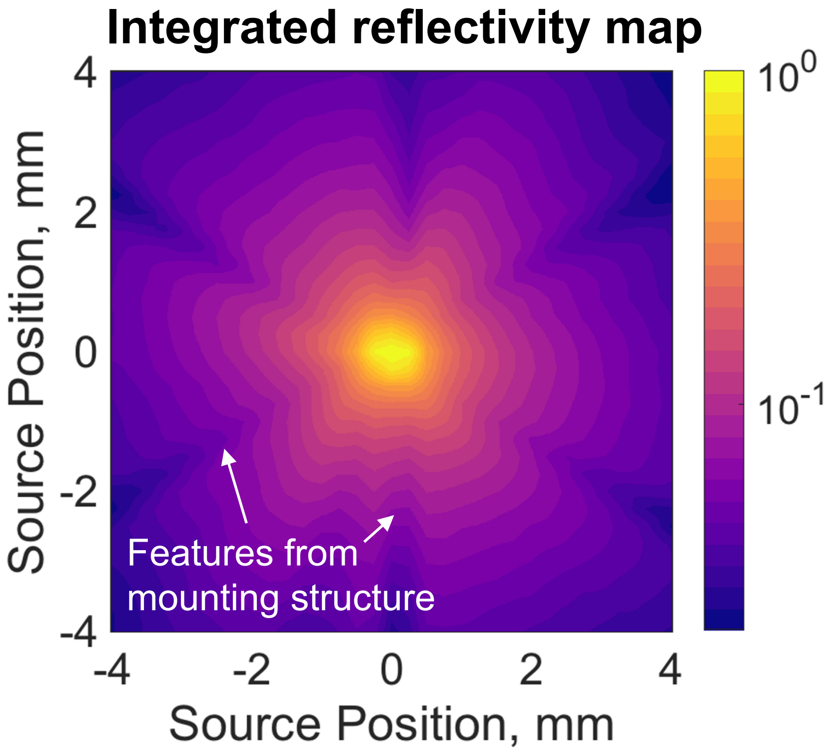
Led by Chris Walton,
Poster by Julia Vogel

Optic mounting structure creates additional features in throughput map









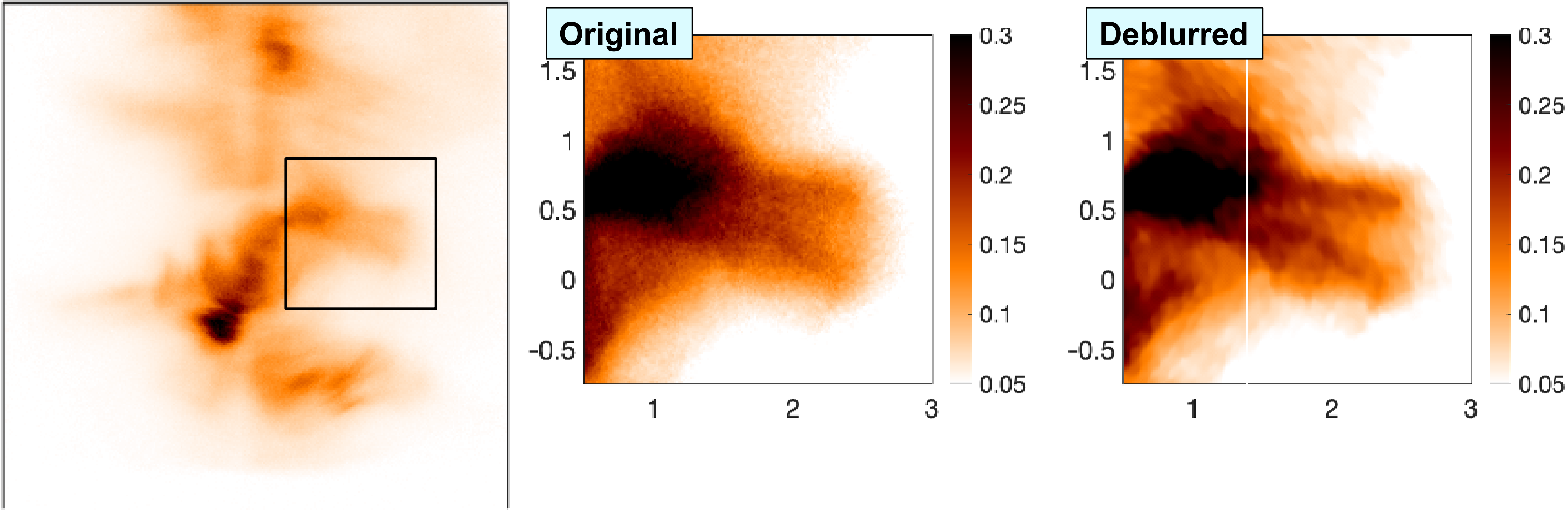
Source on-axis:

- Rays reflected from whole optic surface

Source off-axis:

- Rays reflected from only narrow region in plane ~orthogonal to source position

Deblurred image shows additional structure at large radius



- Fingers may be left-over spikes from MRT in trailing mass

Large solid angle and multilayer give Wolter superior throughput compared to other imaging modalities

Imagers w/equiv. res., mag., FOV, <1 keV BW

Optic	Solid Angle (Sr)	Efficiency (%)	Throughput (Sr)
Wolter	$1\text{x}10^{-4}$	0.4 – 6	$4 – 60 \text{ x } 10^{-7}$
Crystal Imager	$1\text{x}10^{-3}$	$4 \text{ x } 10^{-3}$	$4 \text{ x } 10^{-8}$
Pinhole Imager	$2\text{x}10^{-8}$	10	$2 \text{ x } 10^{-9}$

- Assumes large crystal (2 cm x 3 cm), uses Mo K-alpha$_2$ (17.34 keV)