The NIST Wolter optic neutron microscope

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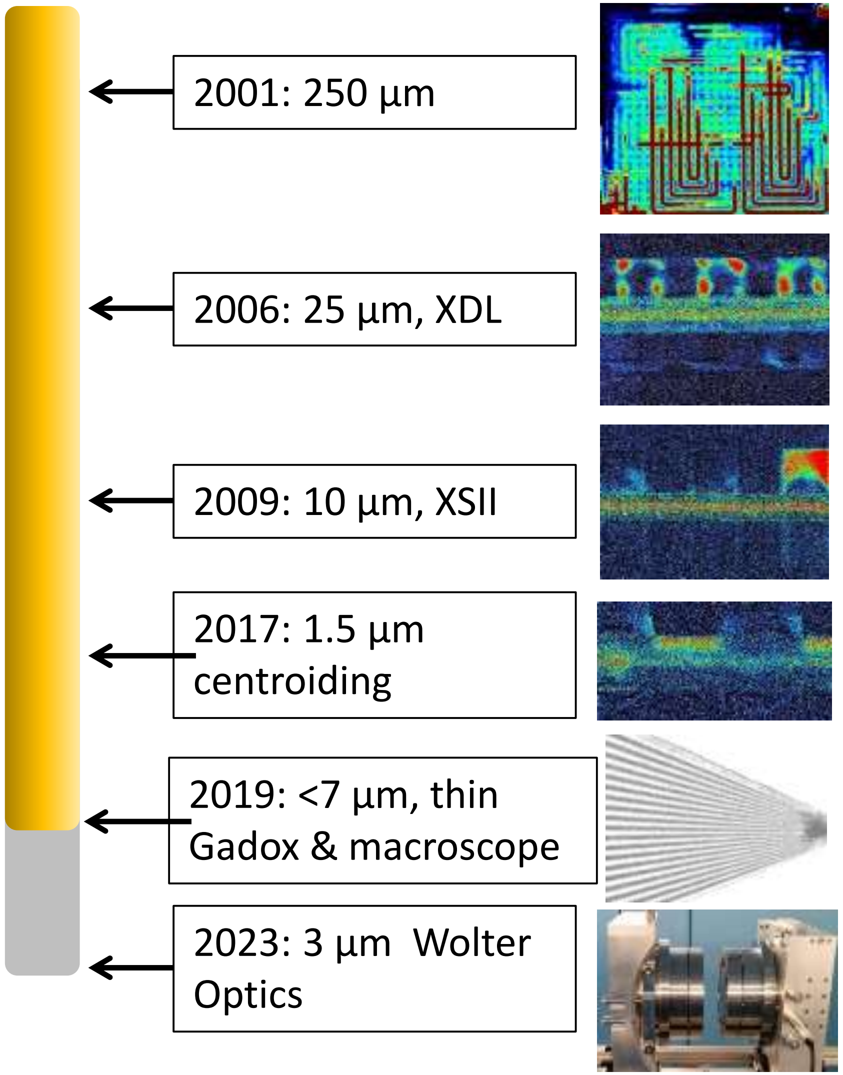

2001: 250 µm

2006: 25 µm, XDL

2009: 10 µm, XSII

2017: 1.5 µm centroiding

2019: <7 µm, thin Gadox & macroscope

2023: 3 µm Wolter Optics

Limbo photo credit: By Endlisnis - Street limbo 3, CC BY 2.0,
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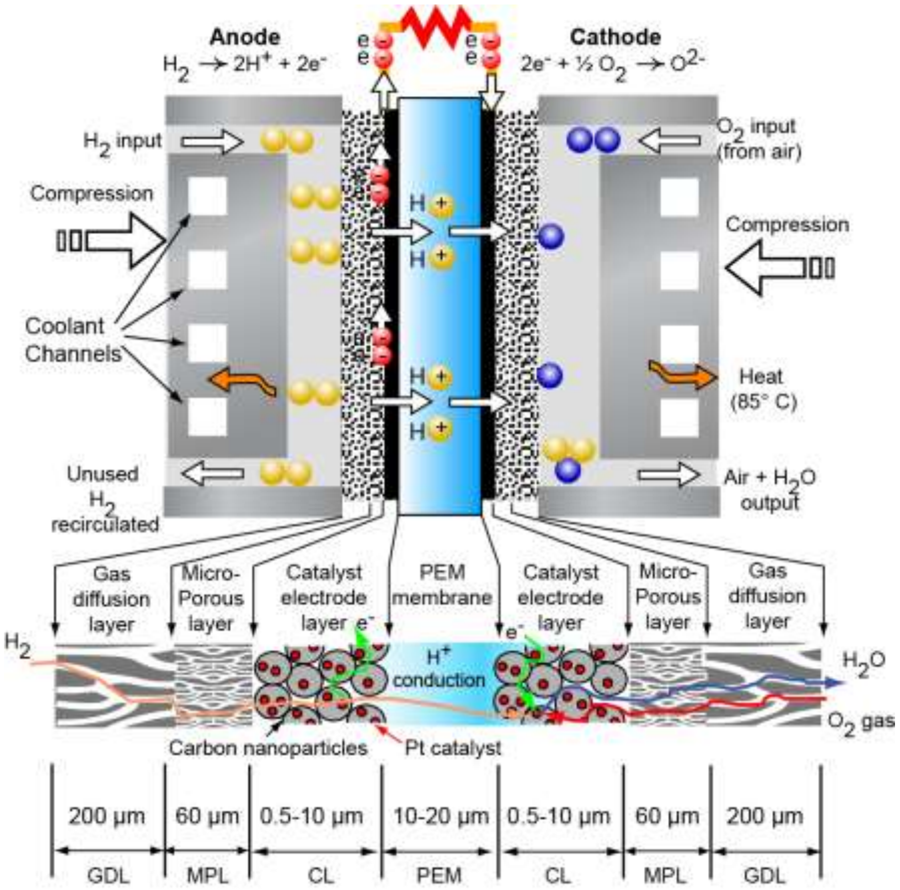
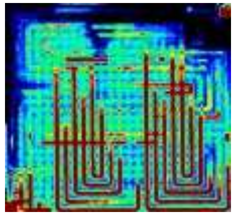
Timeline Spatial Resolution Development at NIST

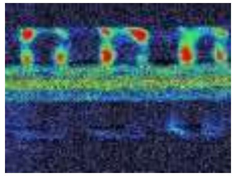


The real limbo competition has been to try and see water inside the catalyst layers of PEMFC during operation

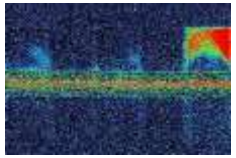
2001: 250 µm



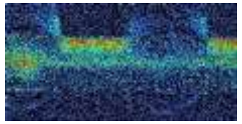
2006: 25 µm, XDL



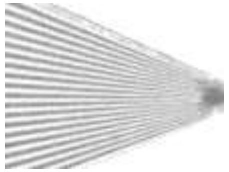
2009: 10 µm, XSII



2017: 1.5 µm centroiding



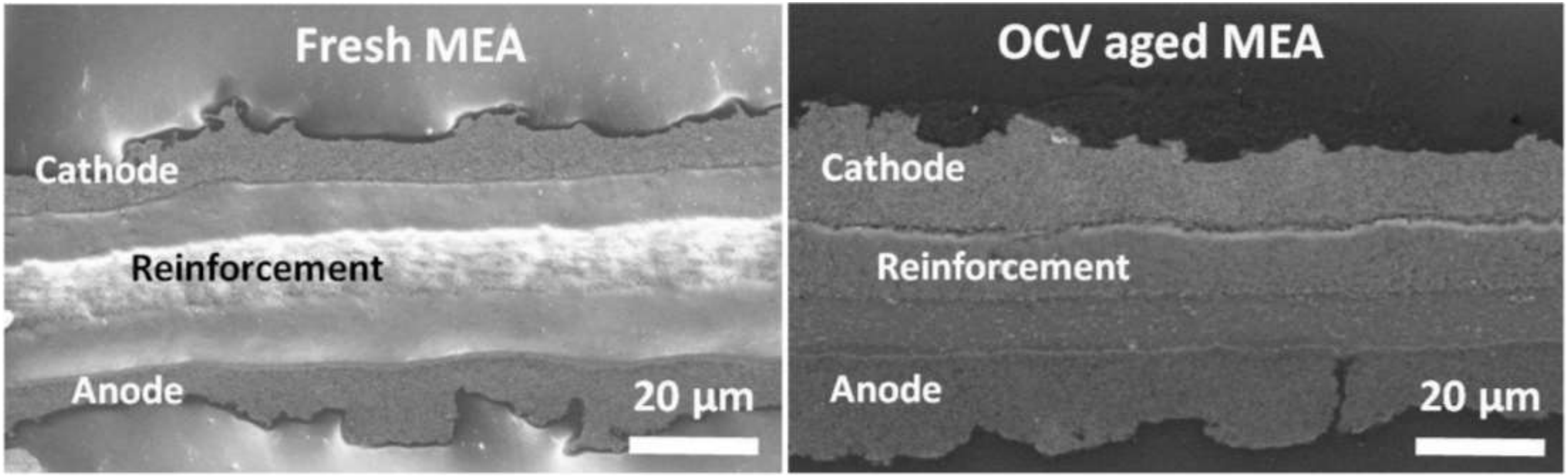
2019: <7 µm, thin Gadox & macroscope



2023: 3 µm Wolter Optics

- 250 µm **(1-30 Hz frame rate)**: In-plane studies of total water content and manifold.
- 25 µm (**20 minut**e): Through plane water distribution to begin GDL transport studies.
- 10 µm (**20 minut**e): More accurate measurement of diffusion media as well as temperature driven phase change flow and thermal osmosis, studies of PGM-free catalyst layers.
- 1.5 µm (**2 hours**): GadOx centroiding improves resolution but requires long exposure times.
- Thinner granular scintillators yield resolution on order of thickness, Gd-157 enables few microns
- **Wolter Optics 3 µm (1 s):** A neutron lens will improve ***both*** spatial and time resolution; spatial resolution is easier with magnification; time resolution improves with focusing

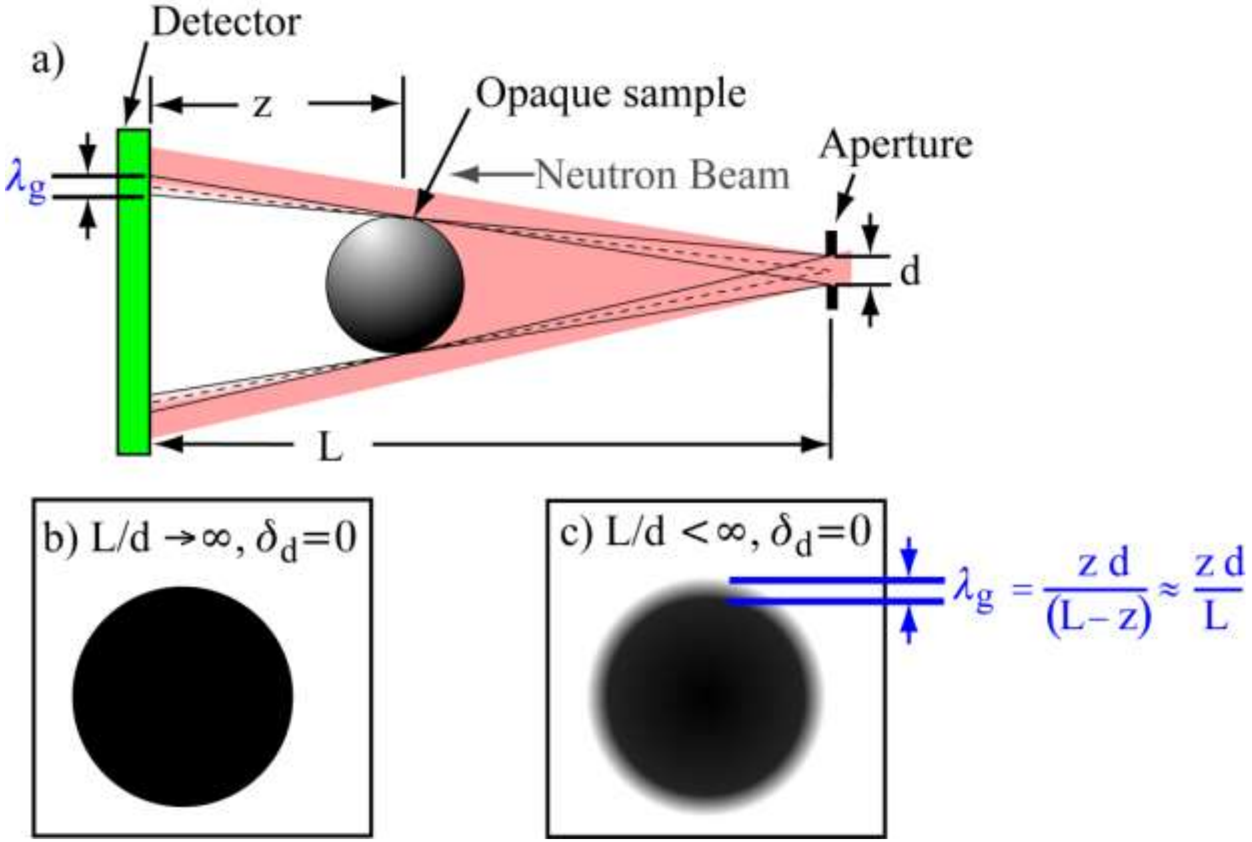
Real MEA's aren't flat -> ***need 3D***



The Limits of Pinhole Optics and Conventional Neutron Imaging

- Poke hole in reactor wall, form image of core at detector
- Best resolution when object ***contacts*** detector due to ~cm sized apertures
  - No geometric magnification
- Resolution derived from collimation, producing geometric blur:

  $\lambda_g \approx z\, d \,/\, L$
- Flux goes as $(d/L)^2$, Small d and/or large L → small Flux → ☹
- Even with better detectors, in a 1 μm pixel with flux 10^6 $\text{cm}^{-2}\ \text{s}^{-1}$, there's only 1 neutron every 100 s. ☹☹

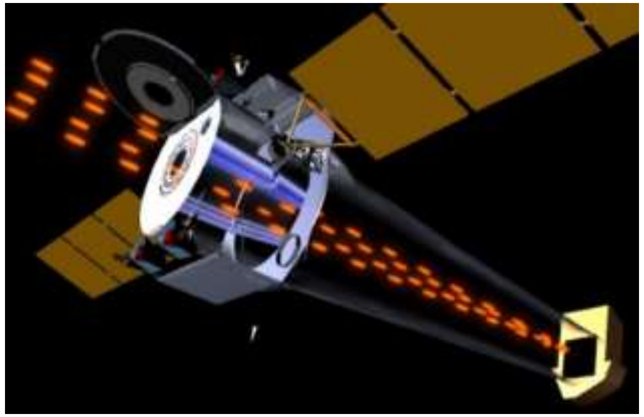


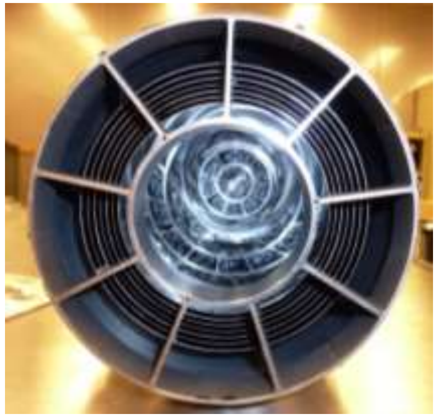
If only we had a neutron imaging lens …

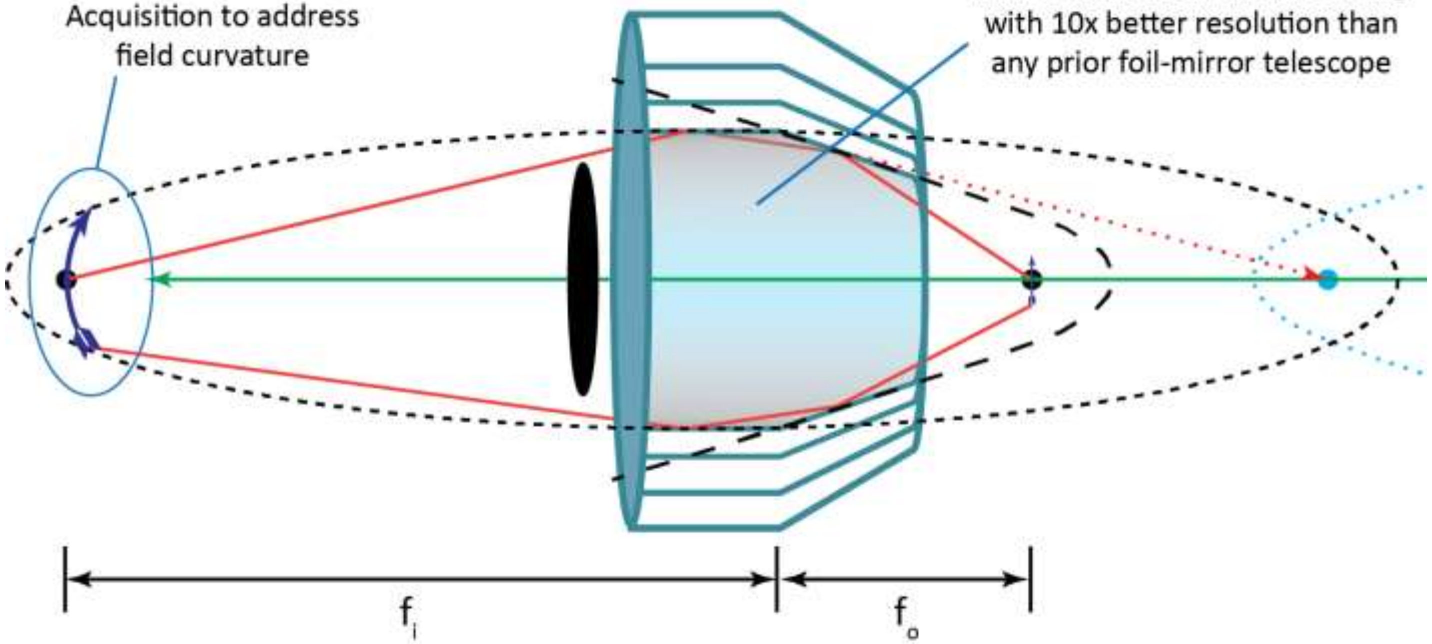
But:

- $n \sim 1 - 10^{-6} \lambda^2$ (similar to x-rays)
- Neutrons are neutral and neutron beams are large, not points, many electron and x-ray tricks don’t translate

Transforming x-ray telescopes into neutron microscopes


Wolter Optics power CHANDRA


NiCo-foil Focused
X-ray Solar Imager


Lens Design and Image Acquisition to address field curvature

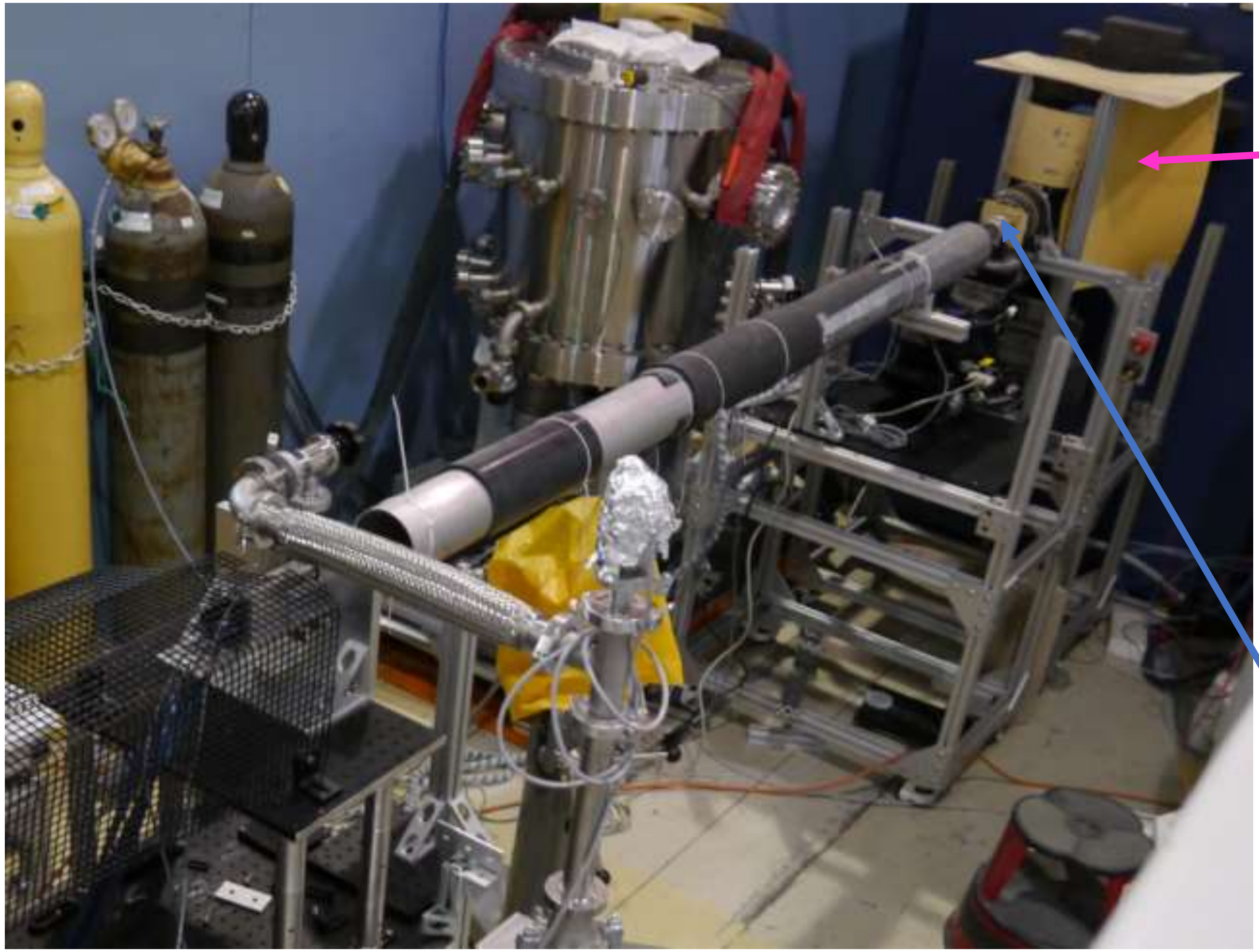
Mirror fabrication and mounting with 10x better resolution than any prior foil-mirror telescope

The neutron lens is based on mirror foil Wolter Optics:

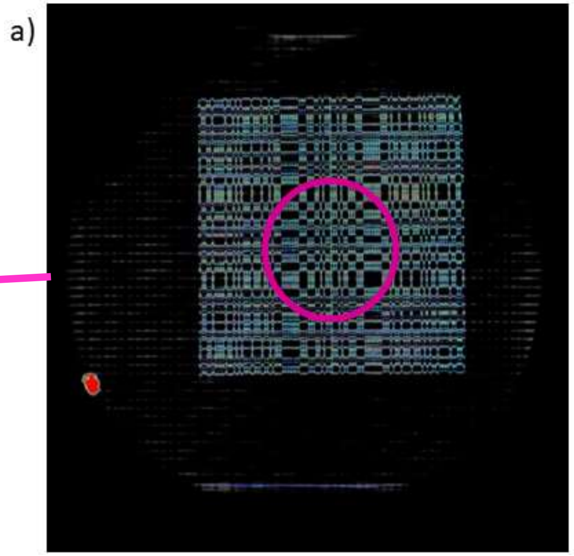
- Need to realize 1 arcsec angular resolution
- ***X1000+ flux***
- Image magnification for ***spatial resolution of 3 μm***
- Achromatic lens
- ~1 m separation between lens, object, and detector

Win-win over pinhole cameras: boosts ***time*** ***and*** ***spatial*** resolution

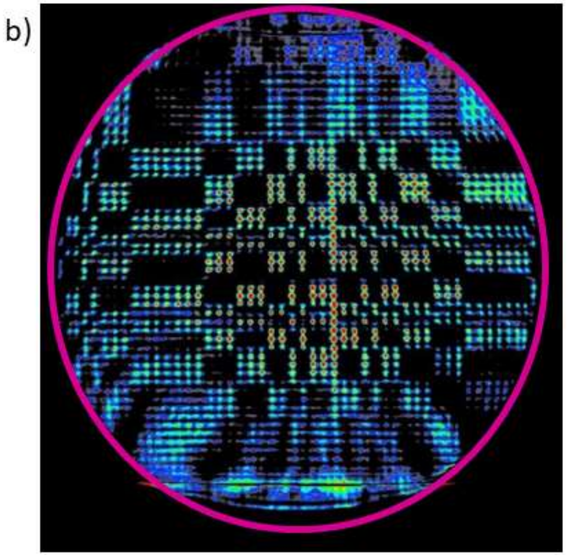
The First Neutron Microscope images



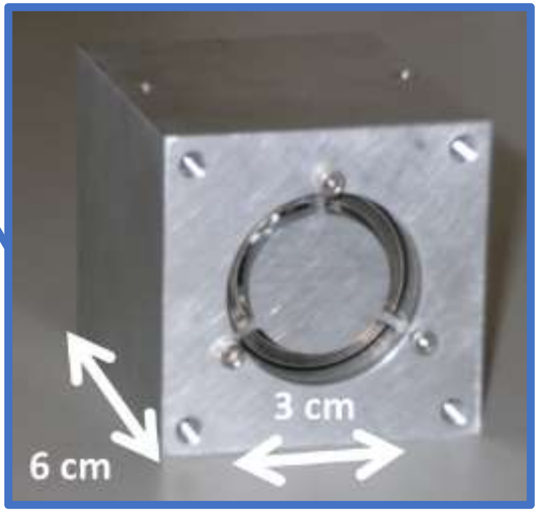
Detector, 2.6 m from
Optic, 3.2 m from sample



Pinhole Grid
Conventional Image



Pinhole Grid
Microscope Image

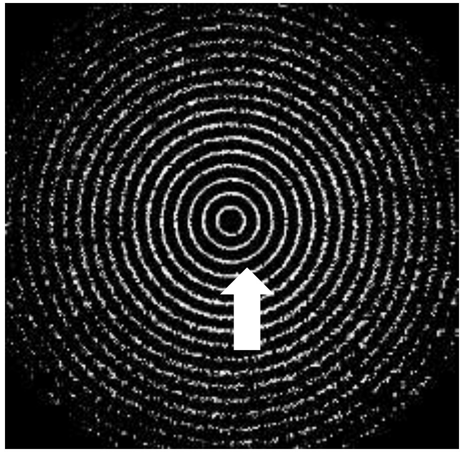


Prototype optic

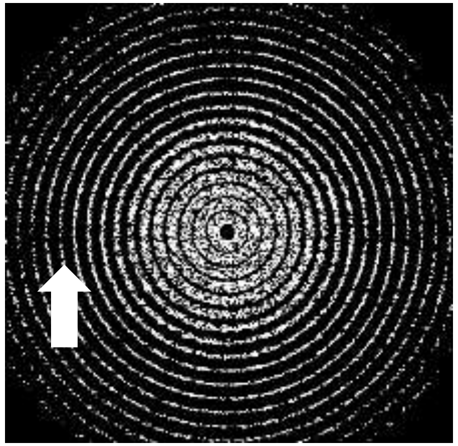
D. Liu et al, Appl. Phys. Lett. 102, 183508 (2013); doi: 10.1063/1.4804178

Field curvature

- Ray-tracing results of concentric rings for a parabolic-parabolic lens with M=1x, 8m focal length, 6 cm diameter
- The best focal surface is not planar but has curvature
- Resolution degrades with increasing offset from the center

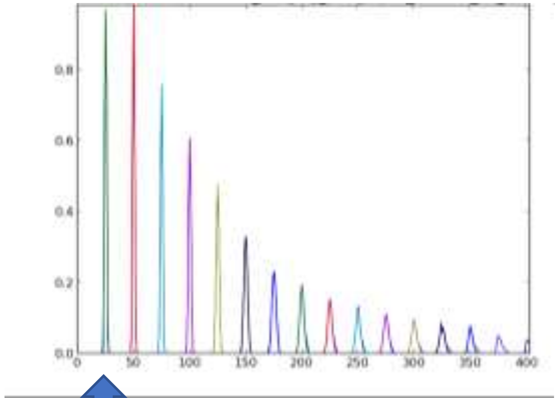


Detector at focus

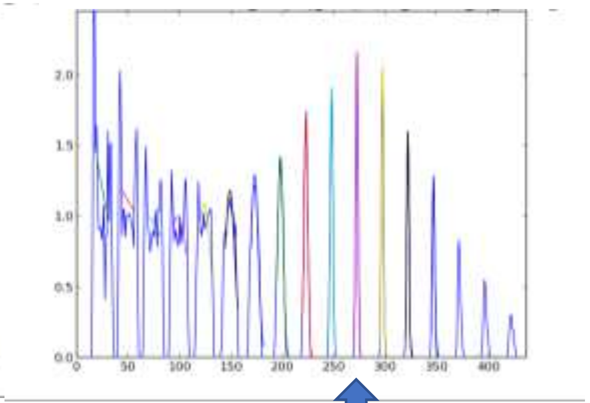


Off focus (4cm upstream)

Image on detector



Sharp image

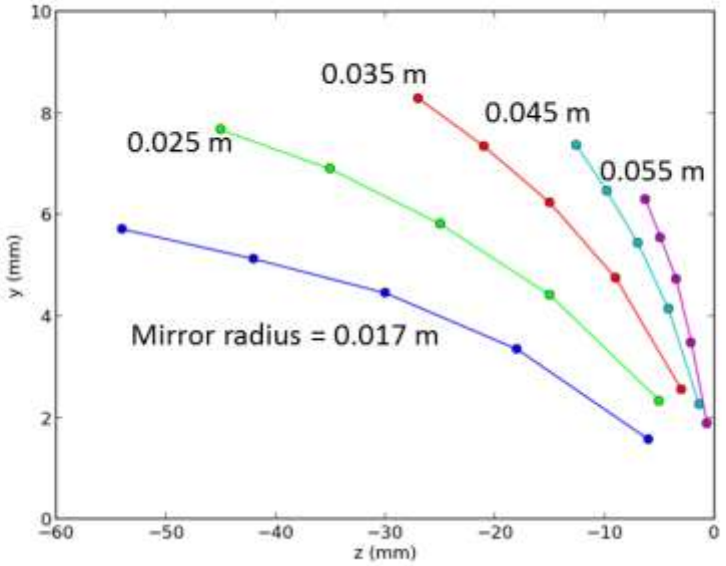


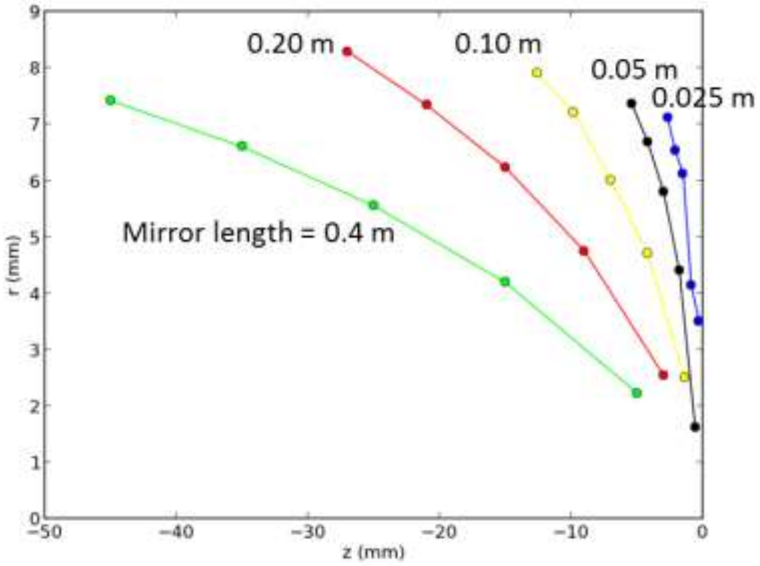
Sharp image

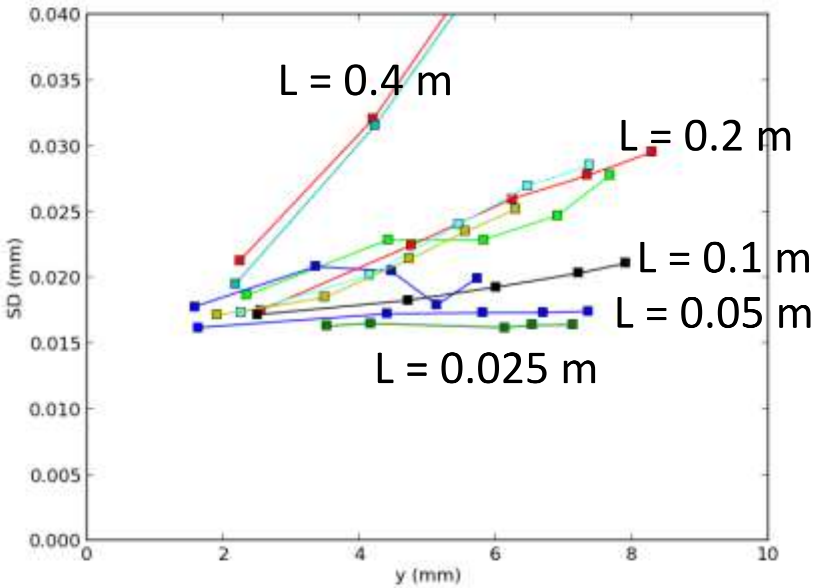
Radial Profile

Field Curvature

- vs. Mirror Radius (L = 20 cm)
- vs. Mirror Length (R = 3.5 cm)



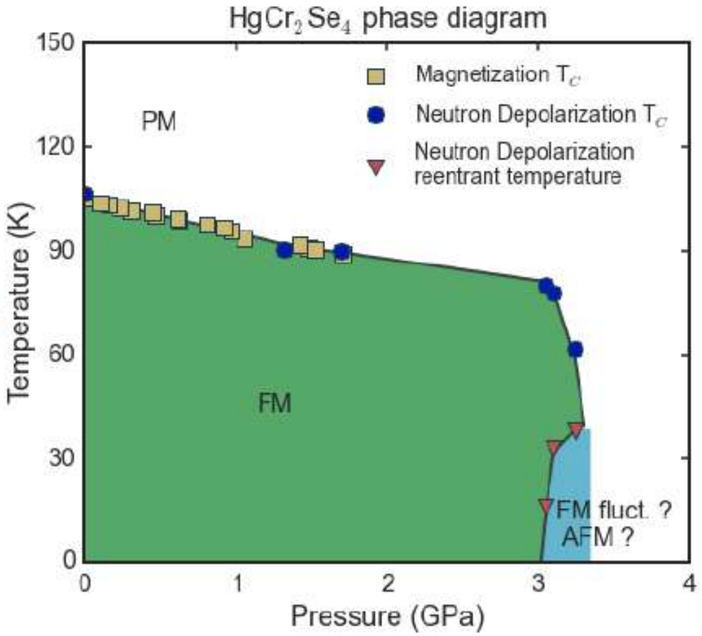




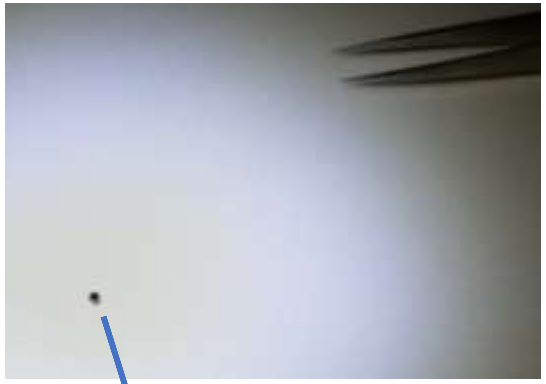
- Paraboloid-Paraboloid configuration, M = 1, 8 m focal length
- Field curvature is determined by quadratic fit
- Curvature ~ L / √R
- ***Solution: Many short mirrors as radius is optimized for flux collection***

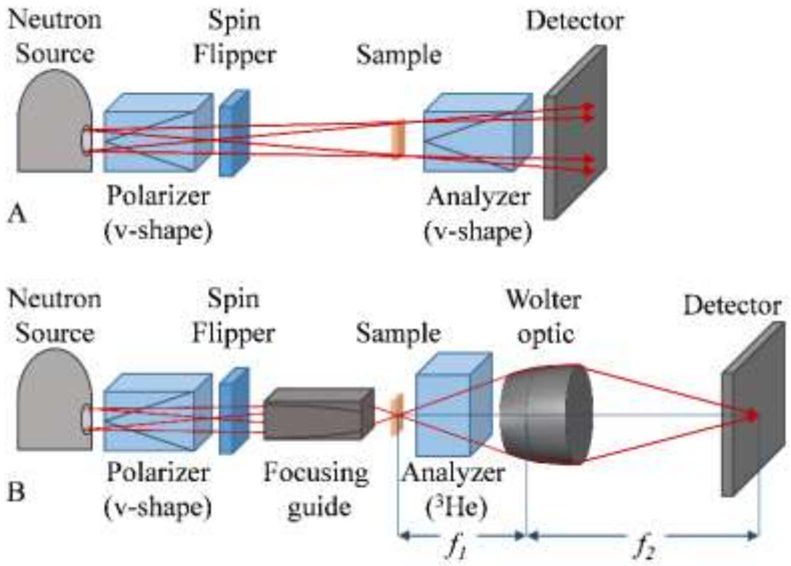
- Plot of the standard deviations along the best focus lines (field curves)
- The decay rate of resolution is seen to depend mostly on radius rather than mirror length

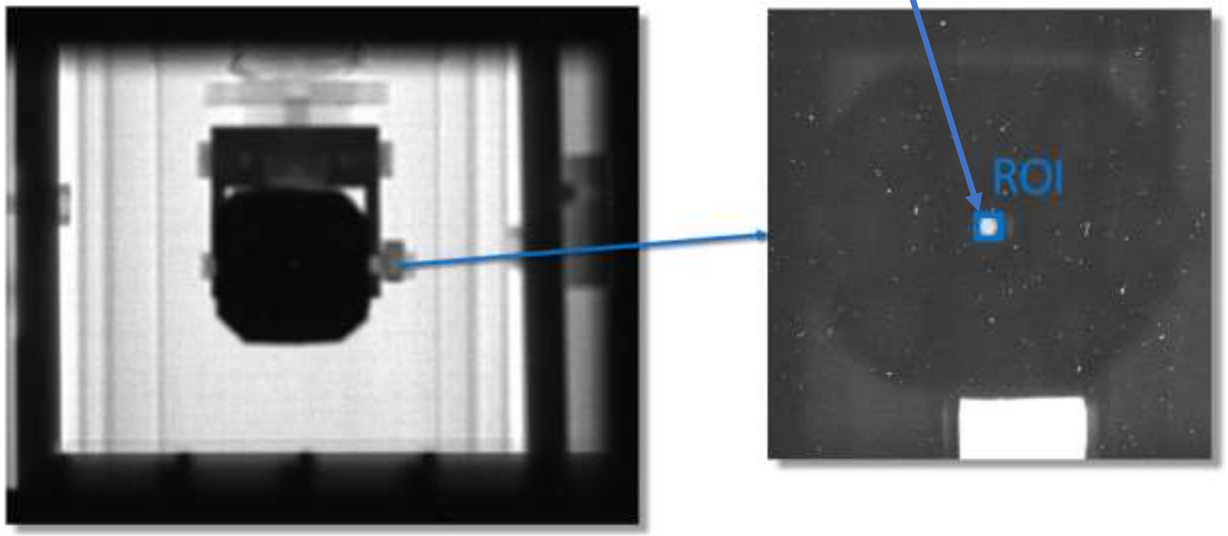
Wolter Optics: Mapping Inhomogenities in Quantum Magnets



- Quantum magnet T_C can depend on composition and on pressure
- T_C measures of samples in clamp cells in cryostats can suffer from poor SNR
- Neutron depolarization imaging is a robust probe, but poor image resolution
- Wolter optics are a neutron image-forming lens
- A lens preserves resolution even with:
  - ➢ Bulky environments
  - ➢ Spin polarization

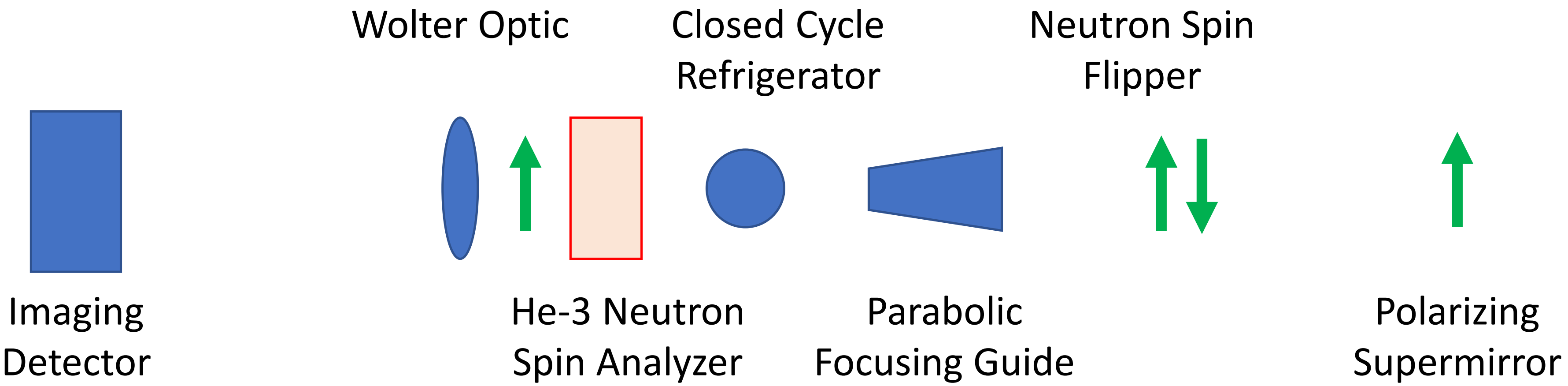






P. Jorba et al. JMMM 2019

Neutron Depolarization Imaging with a Wolter Optic



Wolter Optic

Closed Cycle Refrigerator

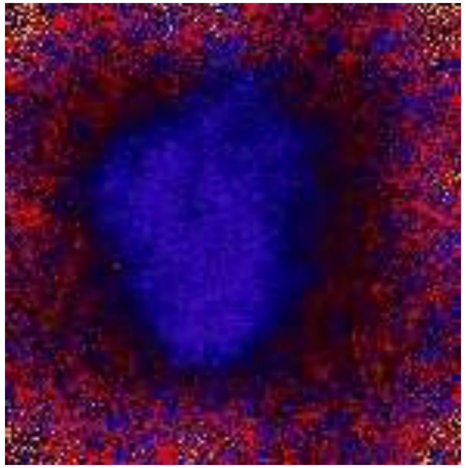
Neutron Spin Flipper

Imaging Detector

He-3 Neutron Spin Analyzer

Parabolic Focusing Guide

Polarizing Supermirror

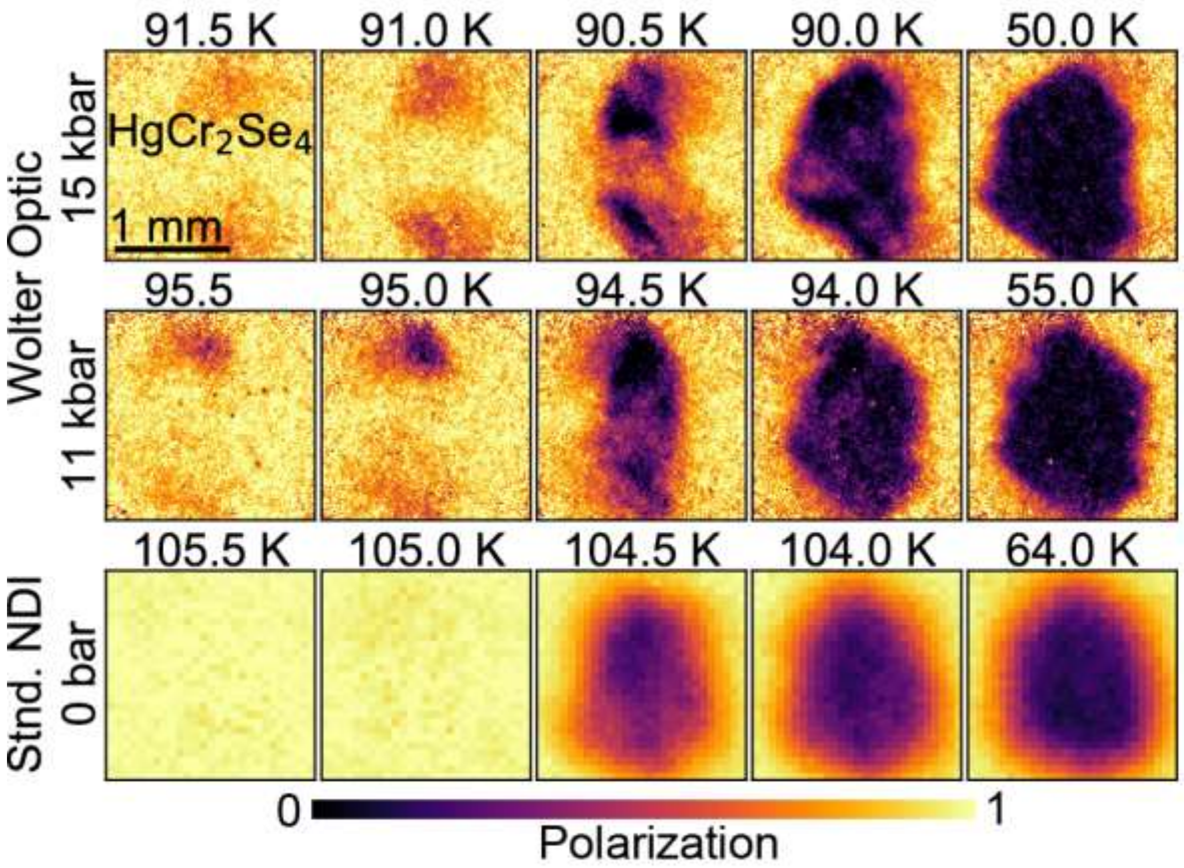


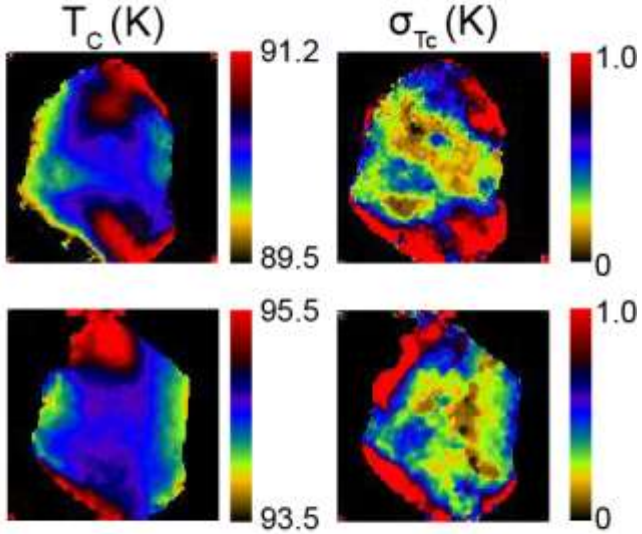
Depolarization vs temperature

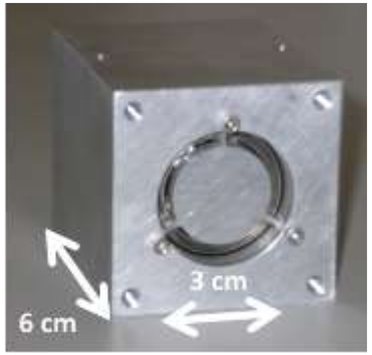
10 FEB 2017: Photo at ANTARES beam, He-3 holding field not shown

P. Jorba et al. JMMM 2019

Mapping Inhomogenities in Quantum Magnets





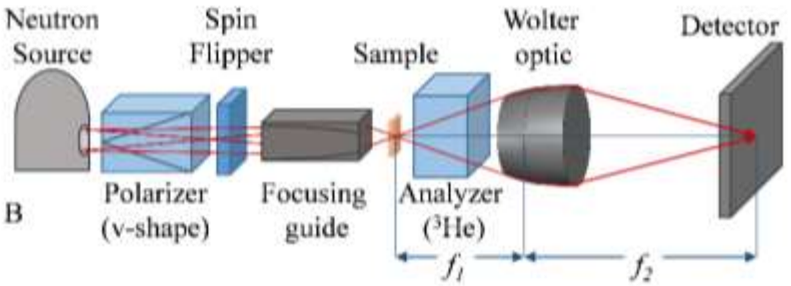


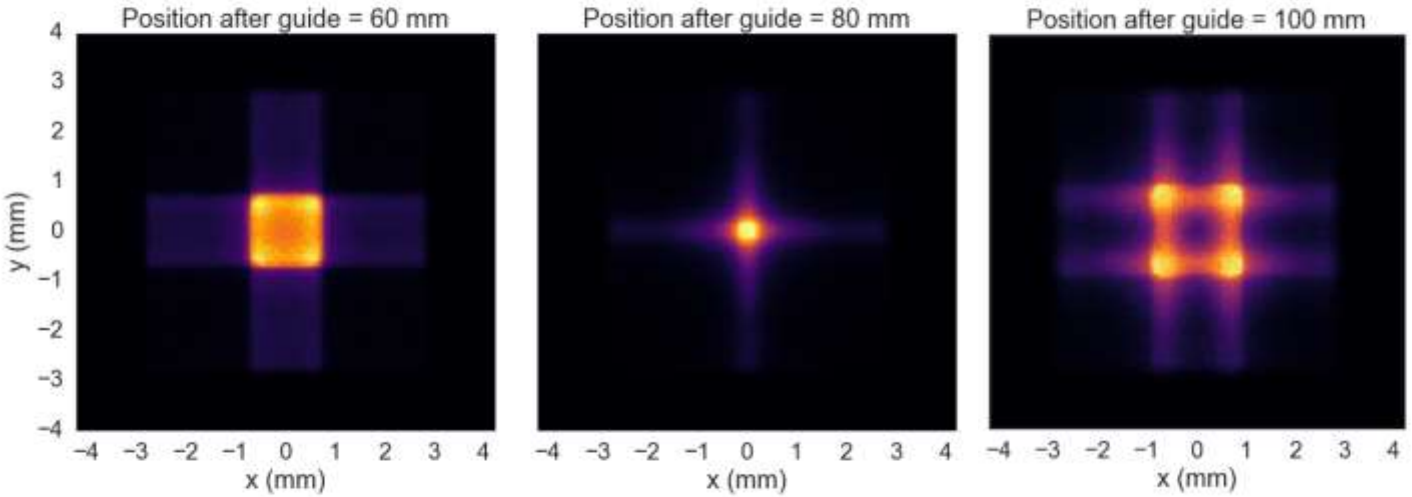
Prototype optic used for measurements at ANTARES at FRM2

- Factor of 10 improvement in spatial resolution over standard (100 µm vs 1 mm)
- Factor of 2 improvement in time resolution over standard (3 min. vs 6 min.)
- Distribution in T_C likely due to freezing of pressure medium

P. Jorba et al. JMMM 2019

The mirrors image the intensity pattern at the focal plane





Ray-tracing

Focus – 20 mm

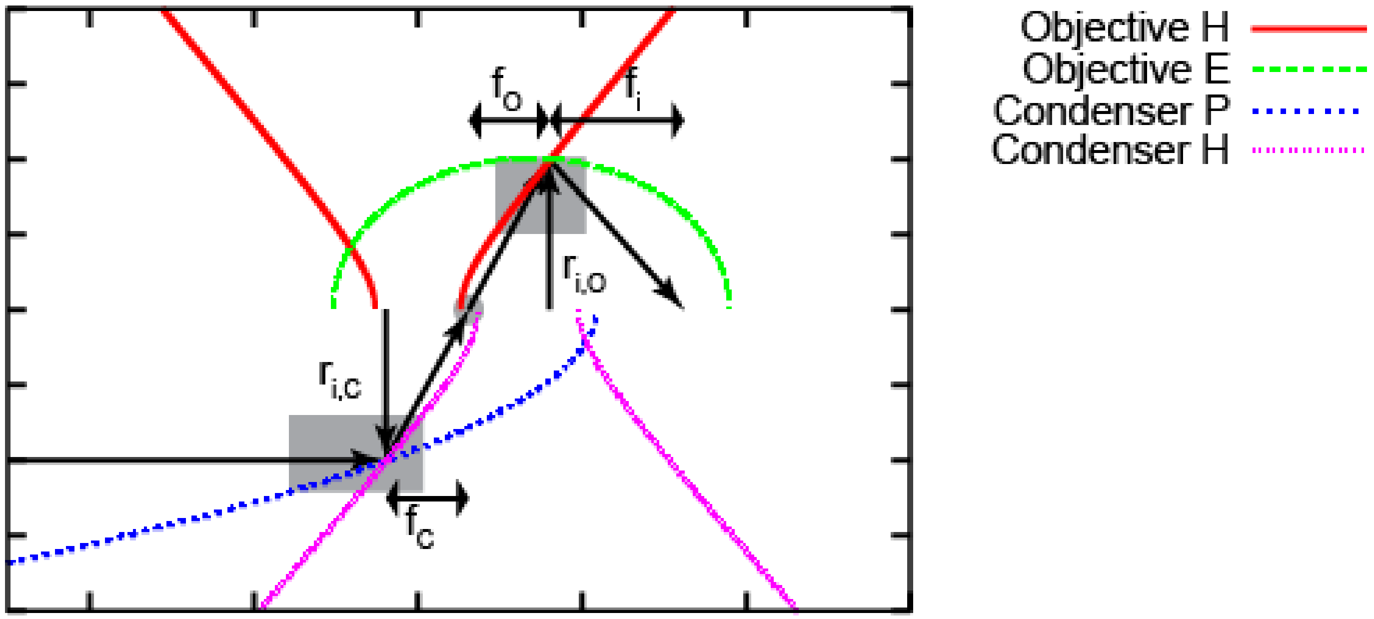
Focus

Focus + 20 mm

Images with Wolter mirrors

P. Jorba et al. JMMM 2019

We intend to create the first neutron analog of Hooke’s microscope



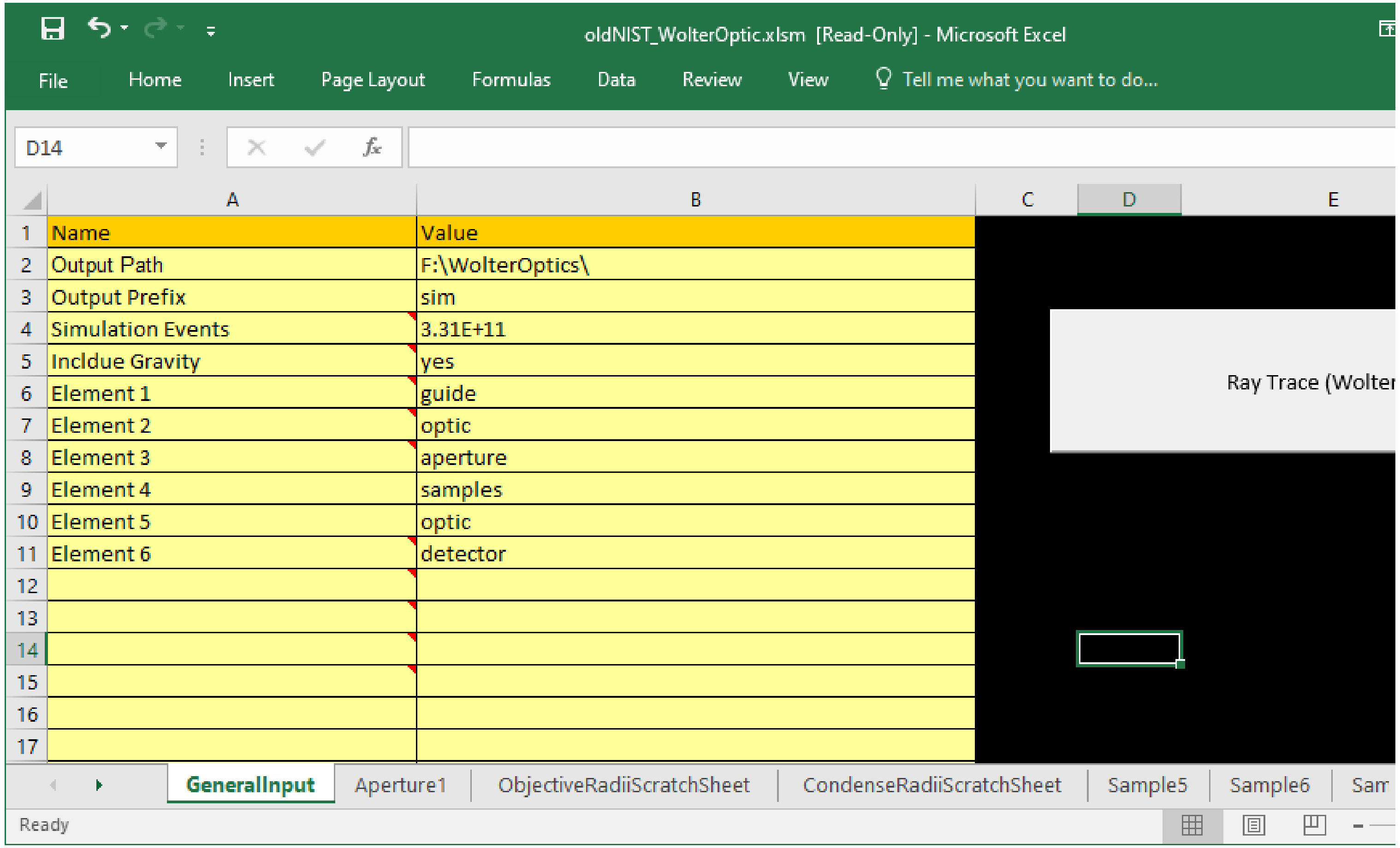
Sketch of parameters optimized through ray tracing with the constraints:

- minimum ri = 2 cm
- figure error is 10 µrad, so maximum object focal length is 75 cm to have 3 µm resolution
- Objective optic length limited to 20 cm to reduce field curvature
- See:
  - M Abir et al, J. Imaging (2020), *6*(10), 100; doi: 10.3390/jimaging6100100
  - DS Hussey et al NIMA (2021) 987, 164813, doi: 10.1016/j.nima.2020.164813.

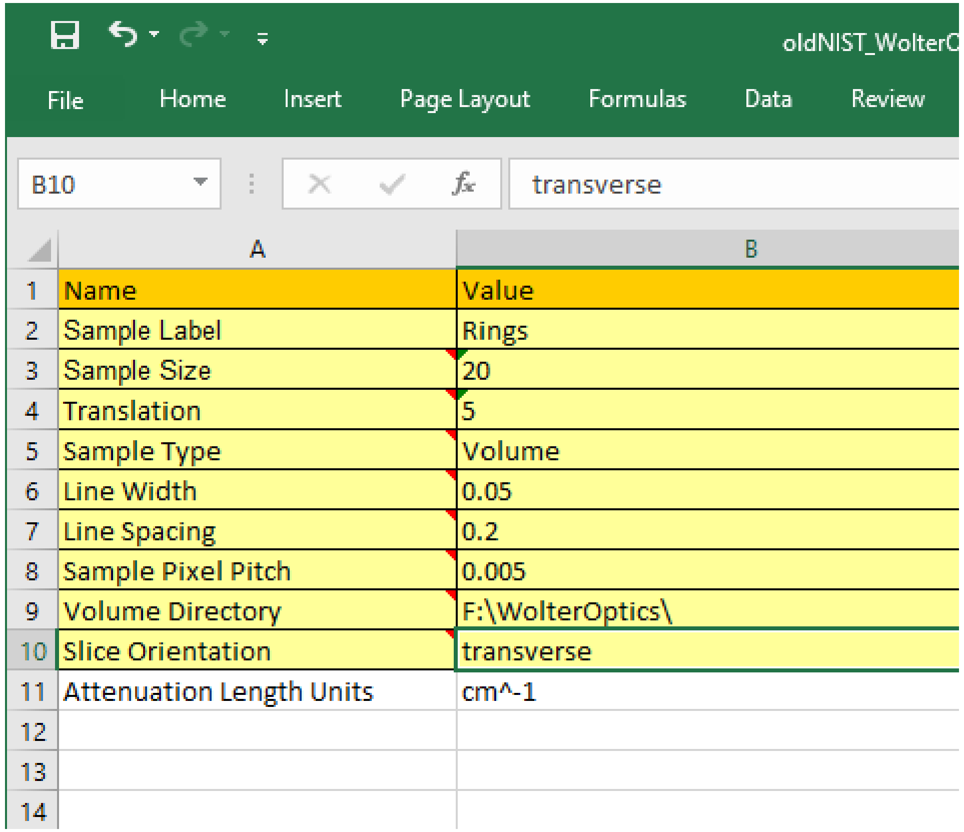
Some comments on NIST ray tracing – Monte Carlo

- Written in MATLAB to take advantage of CUDA capabilities (arrayfun is fast)
  - Also independent of the effort at MIT using McSTAS
  - Random particle generation using neutron guide spectrum and divergence
  - Includes roughness, expected mirror figure error, gravity
  - Not particularly well documented …
- Main code about 850 lines, plus definitions of guide, optics, sample(s), aperture(s), detector(s)
- Instrument “designed” using an Excel spreadsheet, specifying order and geometry of each optical component
- With no sample, two Wolter optics, 1 s exposure (10^11 neutrons) requires 1 h on an nVIDIA TI-1085 GPU
- With a sample, a fair bit longer (depends on # slices, etc.), waiting on an A100 to arrive to load sample volume into GRAM

Defining an “Instrument”

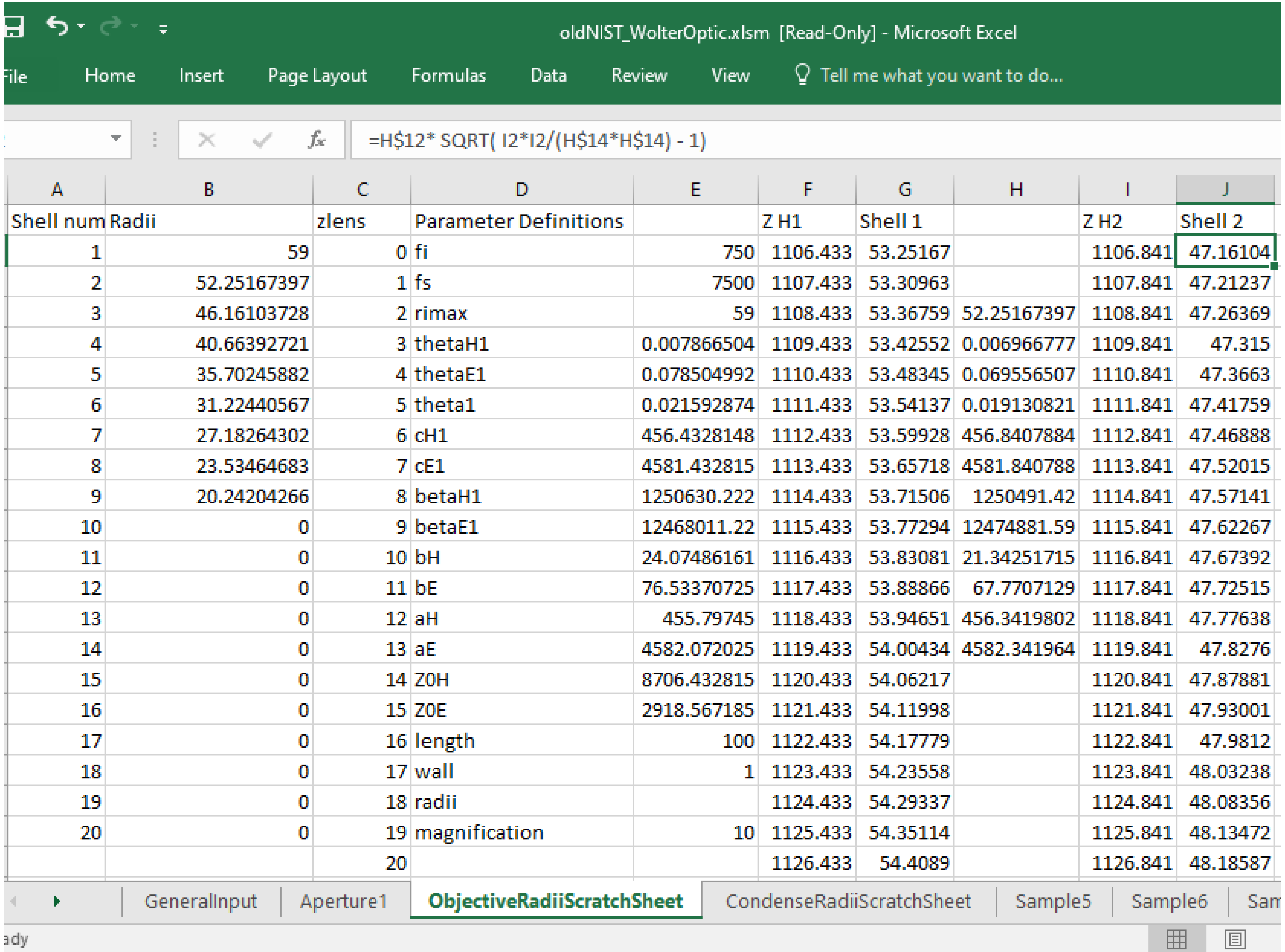


	A	B
1	Name	Value
2	Output Path	F:\WolterOptics\
3	Output Prefix	sim
4	Simulation Events	3.31E+11
5	Incldue Gravity	yes
6	Element 1	guide
7	Element 2	optic
8	Element 3	aperture
9	Element 4	samples
10	Element 5	optic
11	Element 6	detector
12		
13		
14		
15		
16		
17		



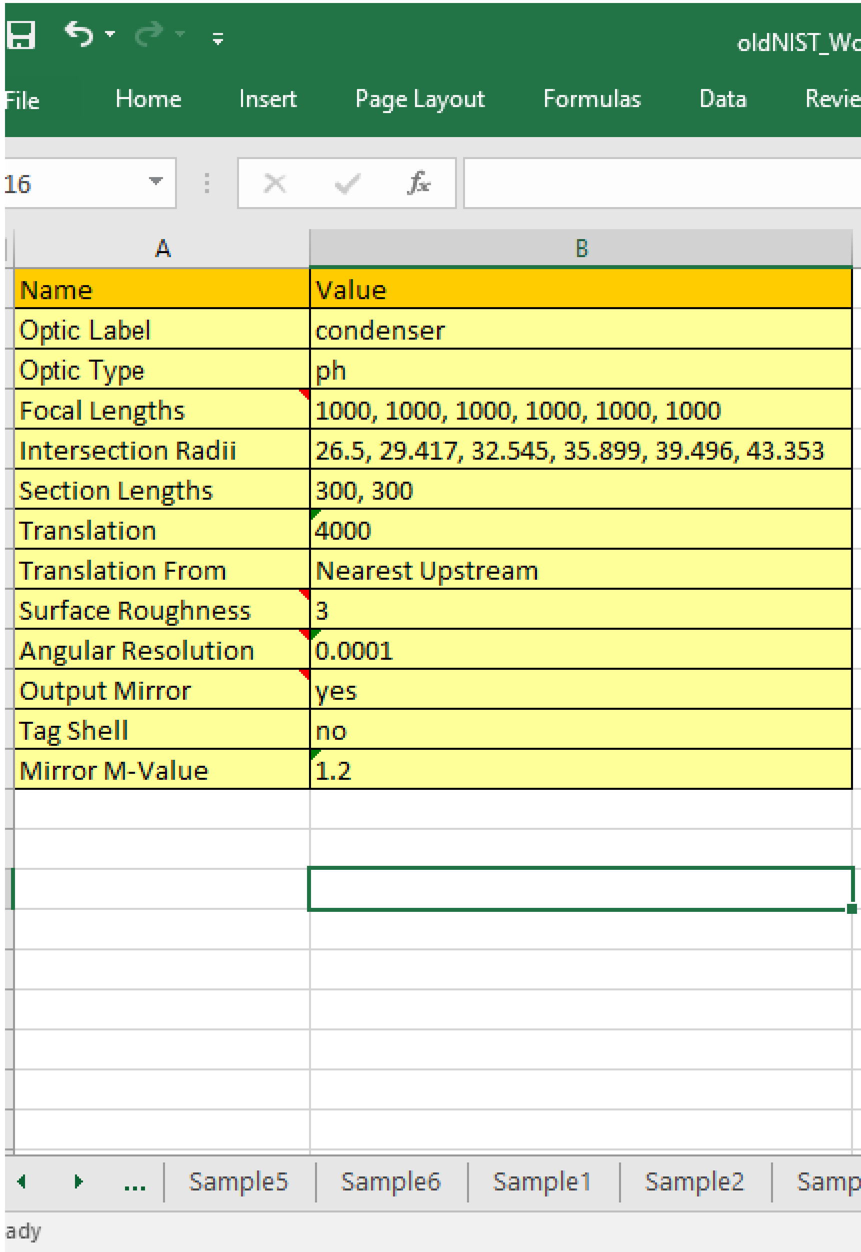
	A	B
1	Name	Value
2	Sample Label	Rings
3	Sample Size	20
4	Translation	5
5	Sample Type	Volume
6	Line Width	0.05
7	Line Spacing	0.2
8	Sample Pixel Pitch	0.005
9	Volume Directory	F:\WolterOptics\
10	Slice Orientation	transverse
11	Attenuation Length Units	cm^-1
12		
13		
14		

Defining an optic



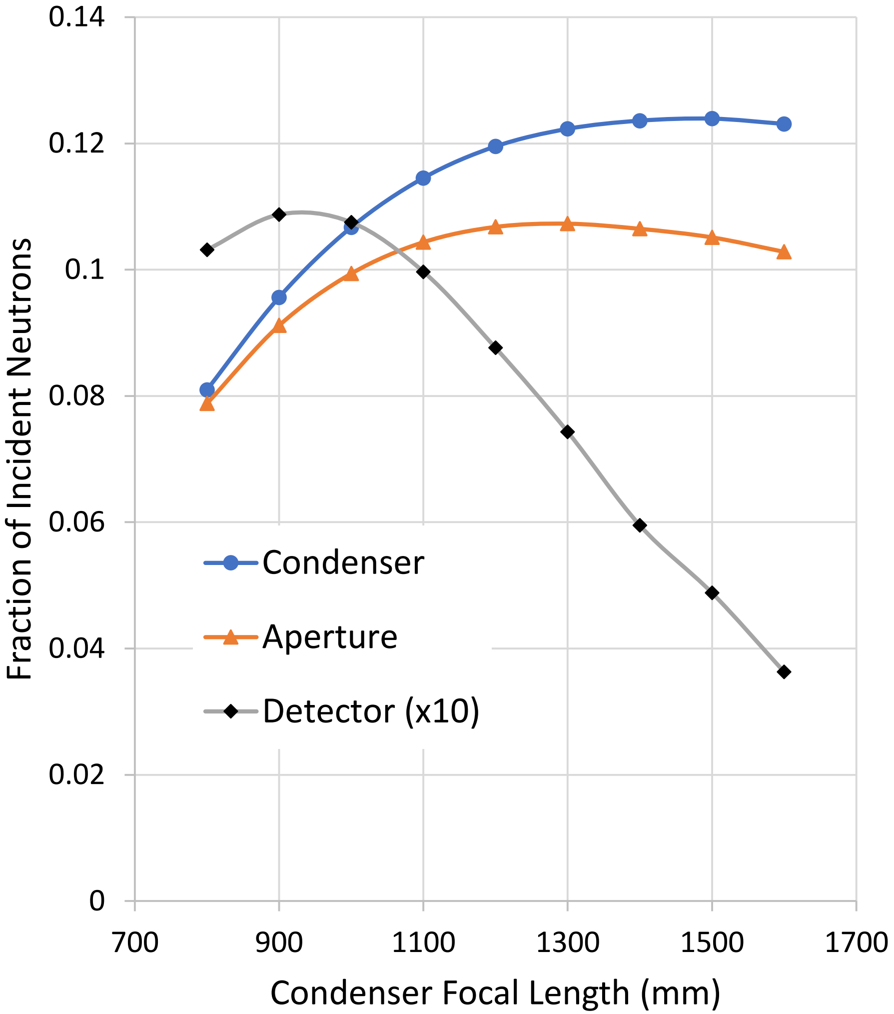
=H$12* SQRT(I2*I2/(H$14*H$14) - 1)

A	B	C	D	E	F	G	H	I	J
Shell num	Radii	zlens	Parameter Definitions		Z H1	Shell 1		Z H2	Shell 2
1	59	0	fi	750	1106.433	53.25167		1106.841	47.16104
2	52.25167397	1	fs	7500	1107.433	53.30963		1107.841	47.21237
3	46.16103728	2	rimax	59	1108.433	53.36759	52.25167397	1108.841	47.26369
4	40.66392721	3	thetaH1	0.007866504	1109.433	53.42552	0.006966777	1109.841	47.315
5	35.70245882	4	thetaE1	0.078504992	1110.433	53.48345	0.069556507	1110.841	47.3663
6	31.22440567	5	theta1	0.021592874	1111.433	53.54137	0.019130821	1111.841	47.41759
7	27.18264302	6	cH1	456.4328148	1112.433	53.59928	456.8407884	1112.841	47.46888
8	23.53464683	7	cE1	4581.432815	1113.433	53.65718	4581.840788	1113.841	47.52015
9	20.24204266	8	betaH1	1250630.222	1114.433	53.71506	1250491.42	1114.841	47.57141
10	0	9	betaE1	12468011.22	1115.433	53.77294	12474881.59	1115.841	47.62267
11	0	10	bH	24.07486161	1116.433	53.83081	21.34251715	1116.841	47.67392
12	0	11	bE	76.53370725	1117.433	53.88866	67.7707129	1117.841	47.72515
13	0	12	aH	455.79745	1118.433	53.94651	456.3419802	1118.841	47.77638
14	0	13	aE	4582.072025	1119.433	54.00434	4582.341964	1119.841	47.8276
15	0	14	Z0H	8706.432815	1120.433	54.06217		1120.841	47.87881
16	0	15	Z0E	2918.567185	1121.433	54.11998		1121.841	47.93001
17	0	16	length	100	1122.433	54.17779		1122.841	47.9812
18	0	17	wall	1	1123.433	54.23558		1123.841	48.03238
19	0	18	radii		1124.433	54.29337		1124.841	48.08356
20	0	19	magnification	10	1125.433	54.35114		1125.841	48.13472
		20			1126.433	54.4089		1126.841	48.18587

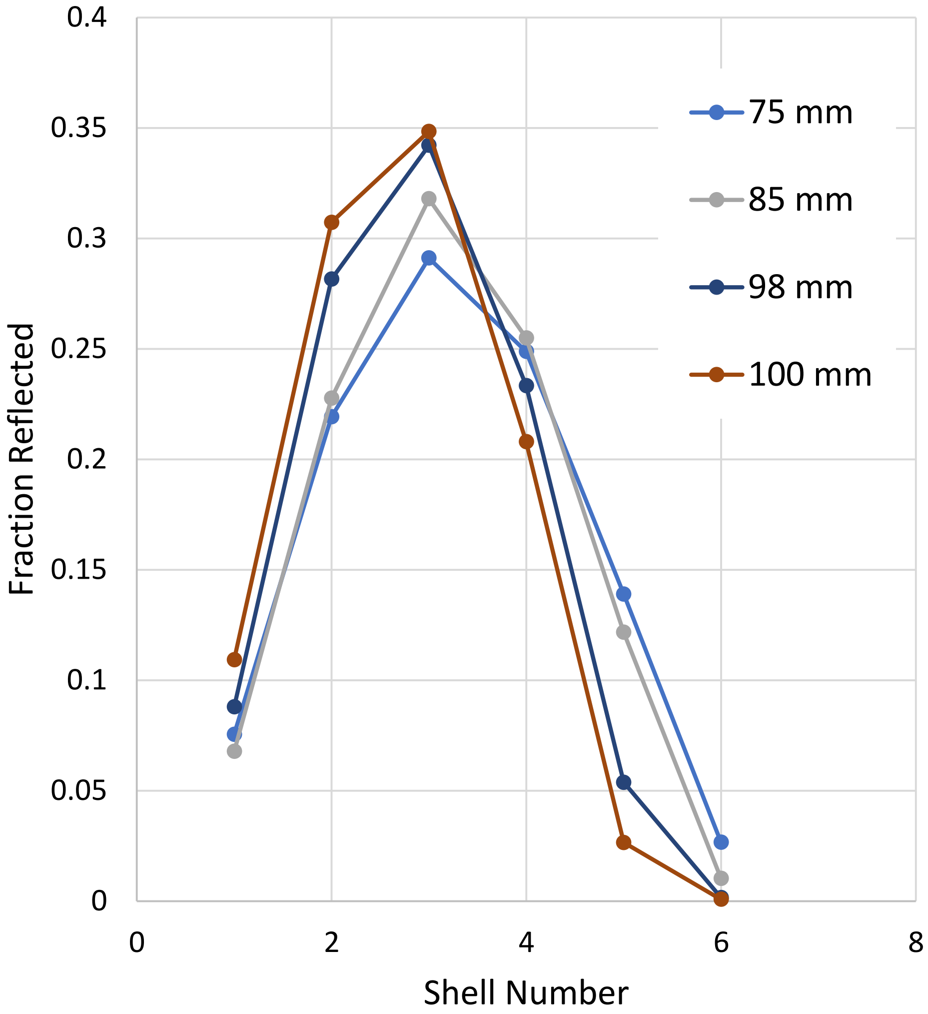


A	B
Name	Value
Optic Label	condenser
Optic Type	ph
Focal Lengths	1000, 1000, 1000, 1000, 1000, 1000
Intersection Radii	26.5, 29.417, 32.545, 35.899, 39.496, 43.353
Section Lengths	300, 300
Translation	4000
Translation From	Nearest Upstream
Surface Roughness	3
Angular Resolution	0.0001
Output Mirror	yes
Tag Shell	no
Mirror M-Value	1.2

A few of the ray tracing studies

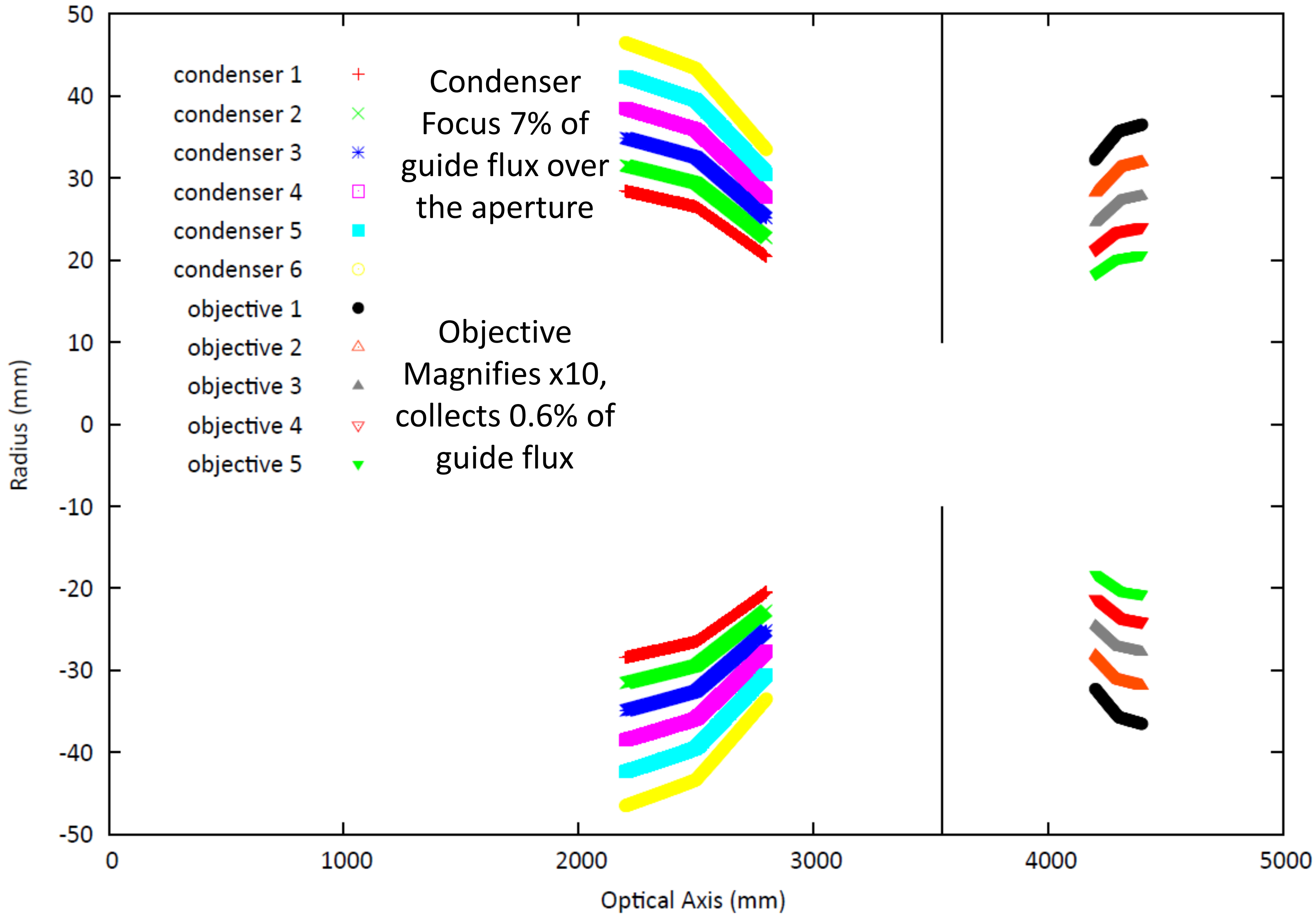


System design requires varying both lens parameters to maximize throughput



Looking at which mirrors in the Objective optic are “active”, funds support 5 shells

The Final Optics Design: Expect 1000x gain in time resolution, magnification of 10, spatial resolution of 3 μm



Condenser Focus 7% of guide flux over the aperture

Objective Magnifies x10, collects 0.6% of guide flux

Detector Position: 11800 mm

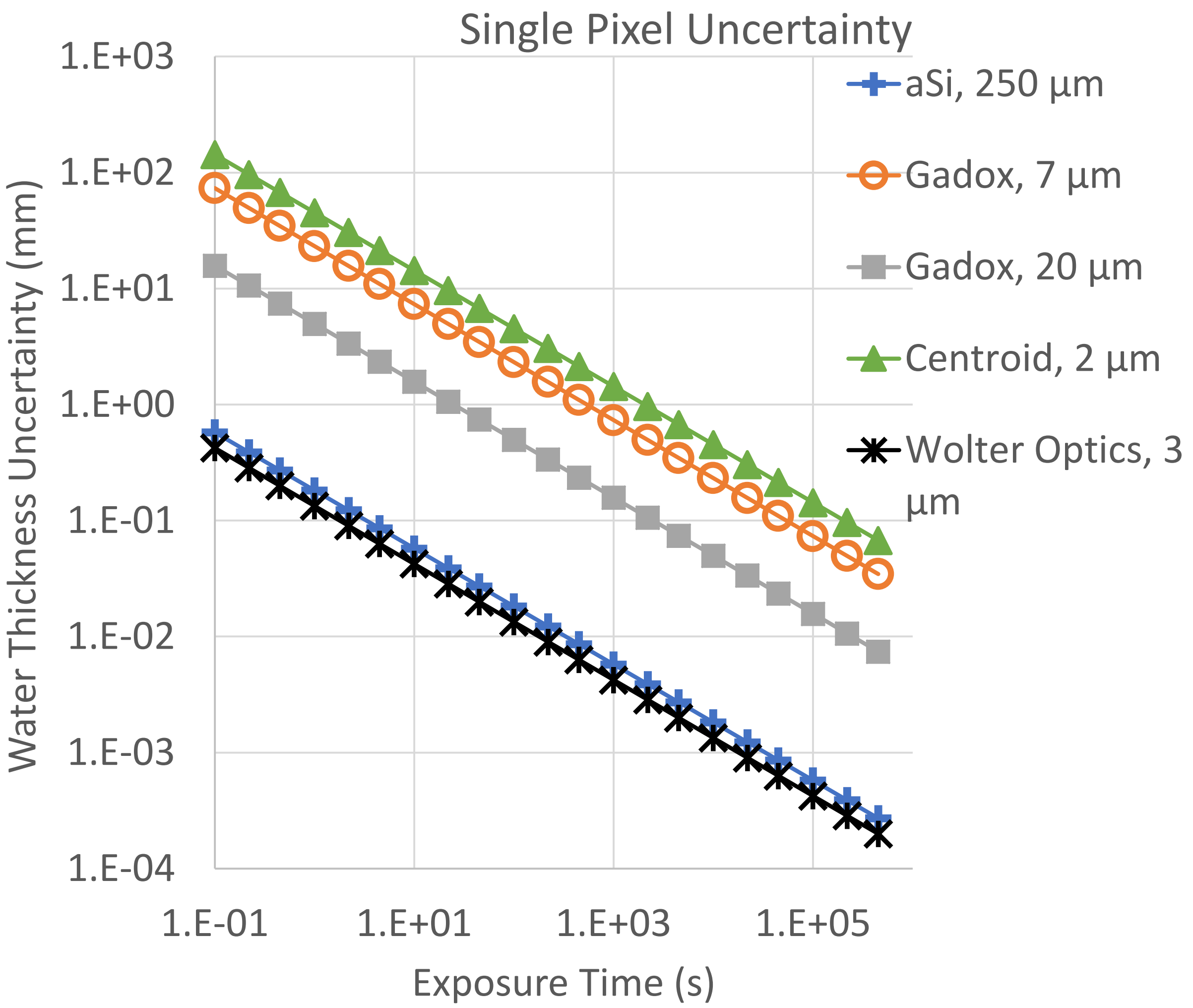
Perspective:
Conventional Pinhole would need 3.5 mm diameter, and the beam would diverge:

- **Pinhole flux: 5 × 10^5**
- **Optics flux: 1 × 10^{10}**
- ***A gain of 2x10^4!!!***

DS Hussey et al NIMA (2021) 987, 164813, doi: 10.1016/j.nima.2020.164813

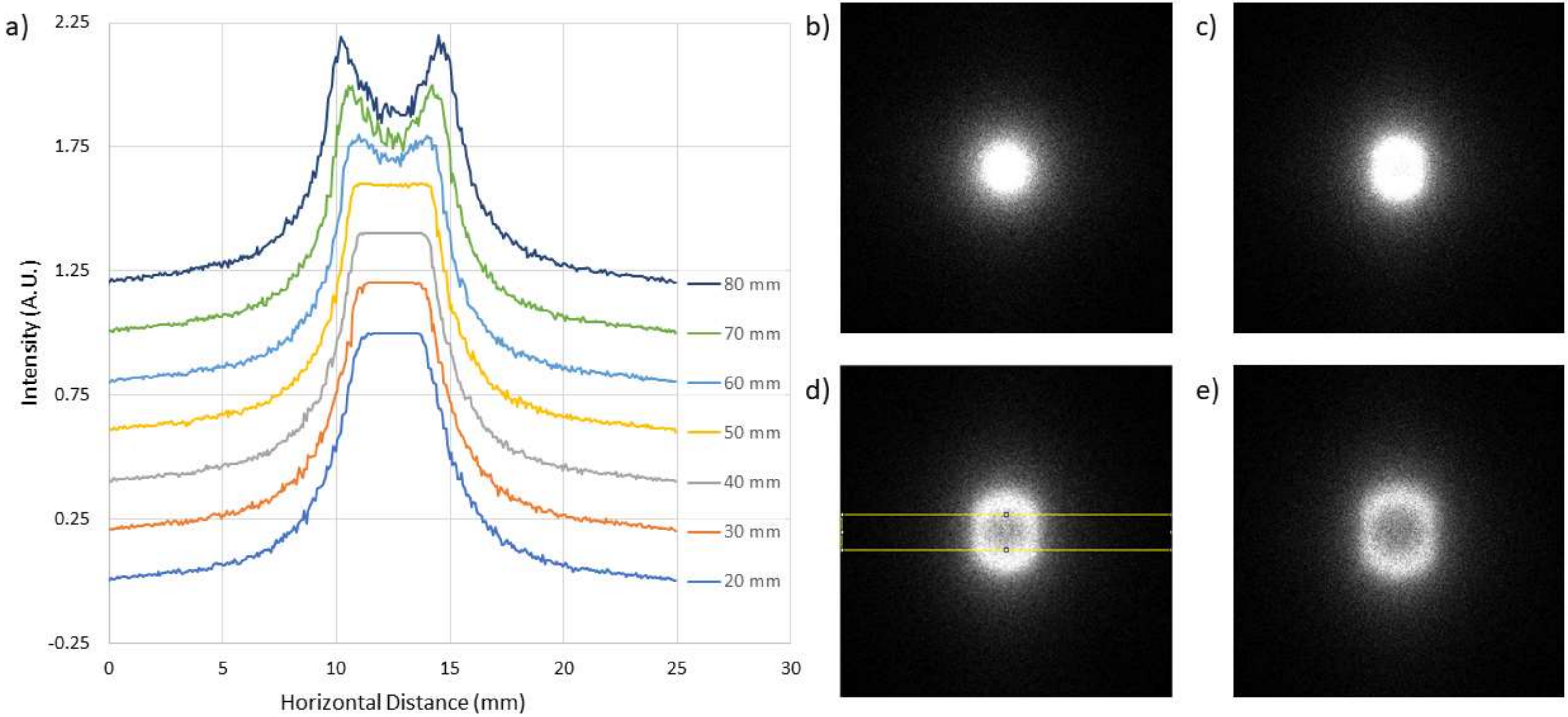
National Institute of Standards and Technology
U.S. Department of Commerce

Liquid water uncertainty for various methods/detectors



- Time and Spatial Resolution would approach a conventional synchrotron imaging beamline
- Sample environments like Furnaces, Griggs Rigs, Pressurized Fluid Flow Cells, Magnets, Cryostats,... will be straightforward to incorporate on the beamline
- Can improve quantitative analysis using a velocity selector to coarsely define the wavelength band Δλ/λ ~ 10-15%

The Condenser optic nearly forms a point source -> Tomography only



NCNR Upgrade: Source

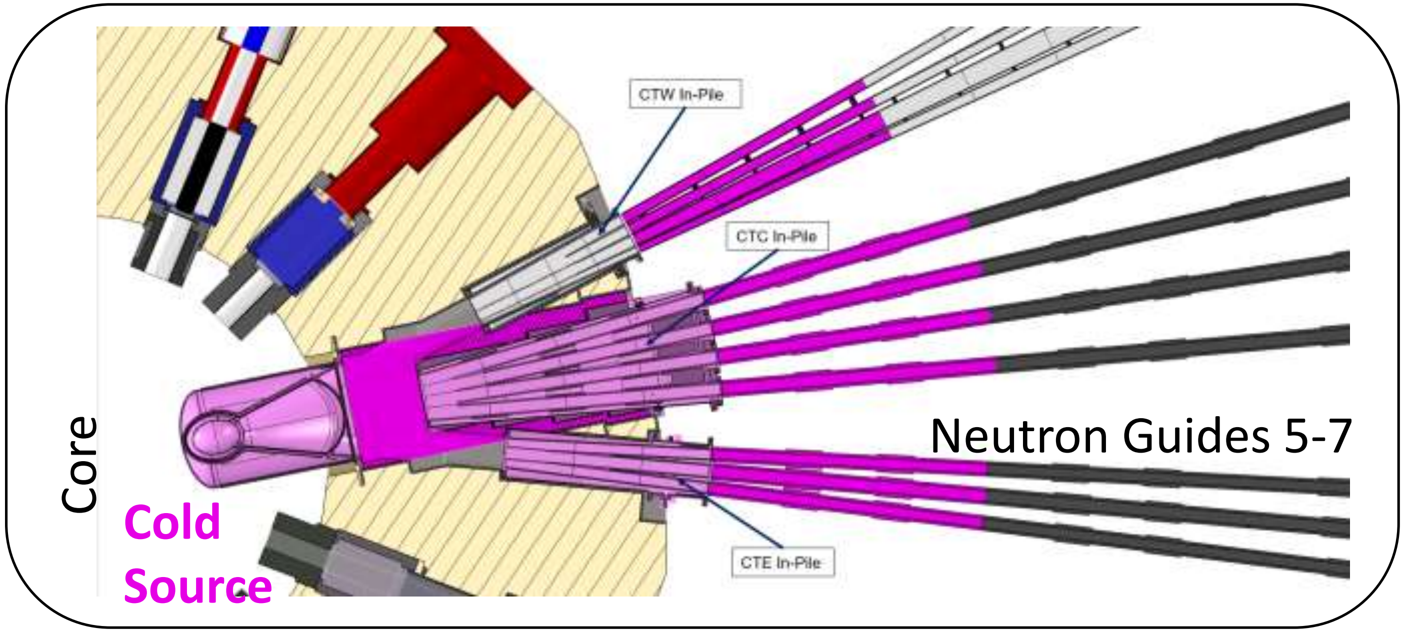
The NIST reactor is planning on a major upgrade of its cold source.

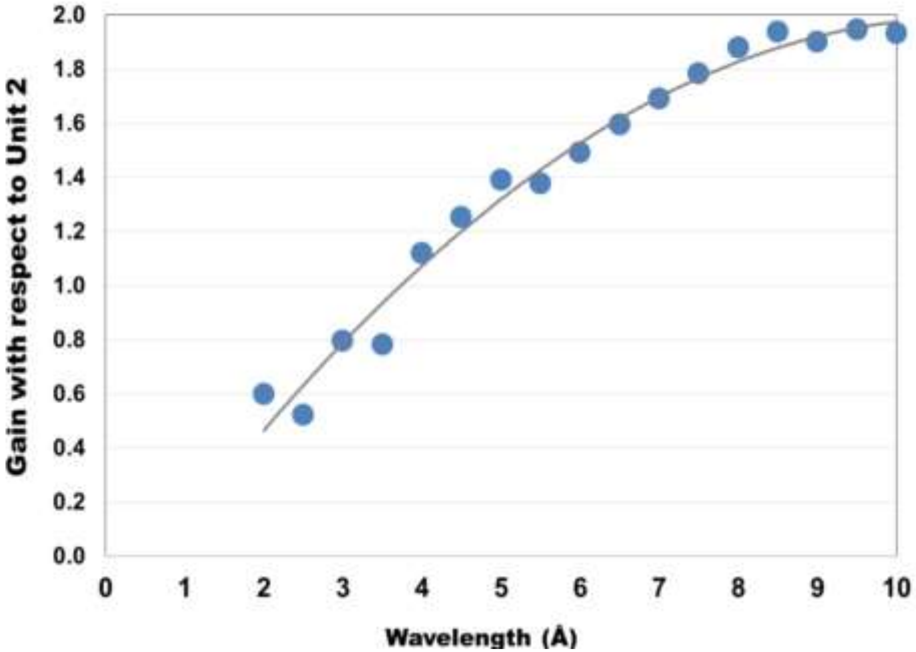
Current: Liquid Hydrogen

Future: Liquid Deuterium (lower absorption)

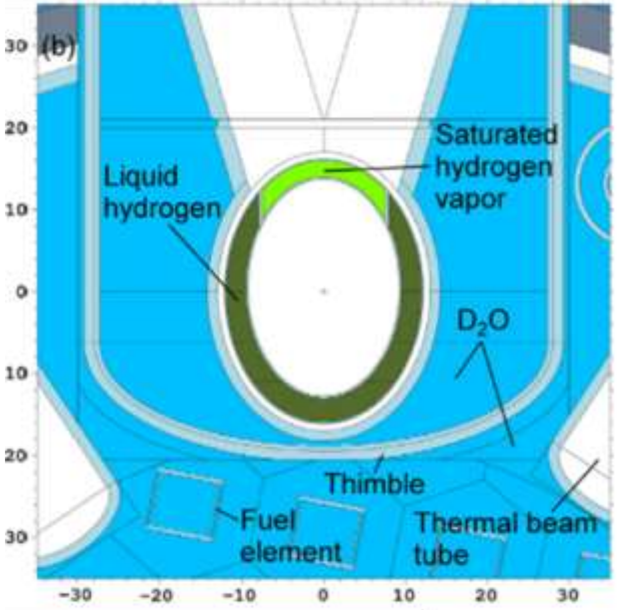
Estimate 10- 12 months for installation

Colder spectrum will benefit Wolter optics

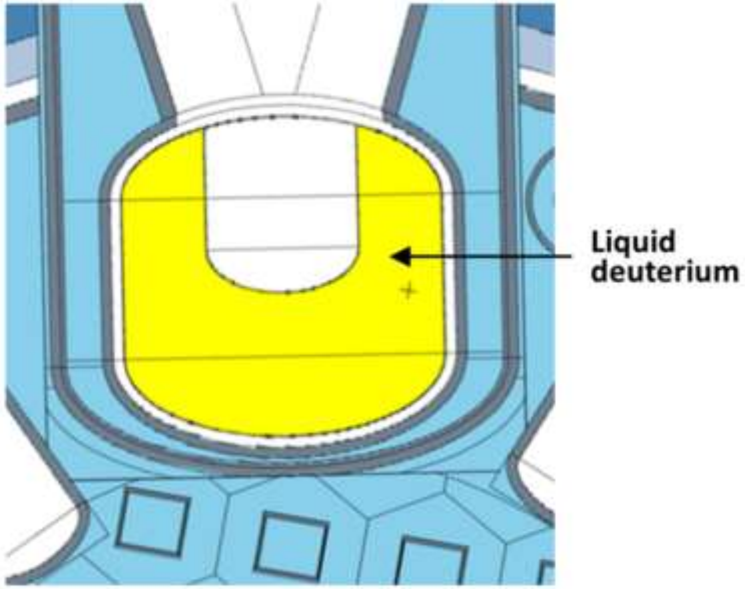




“Unit 2”



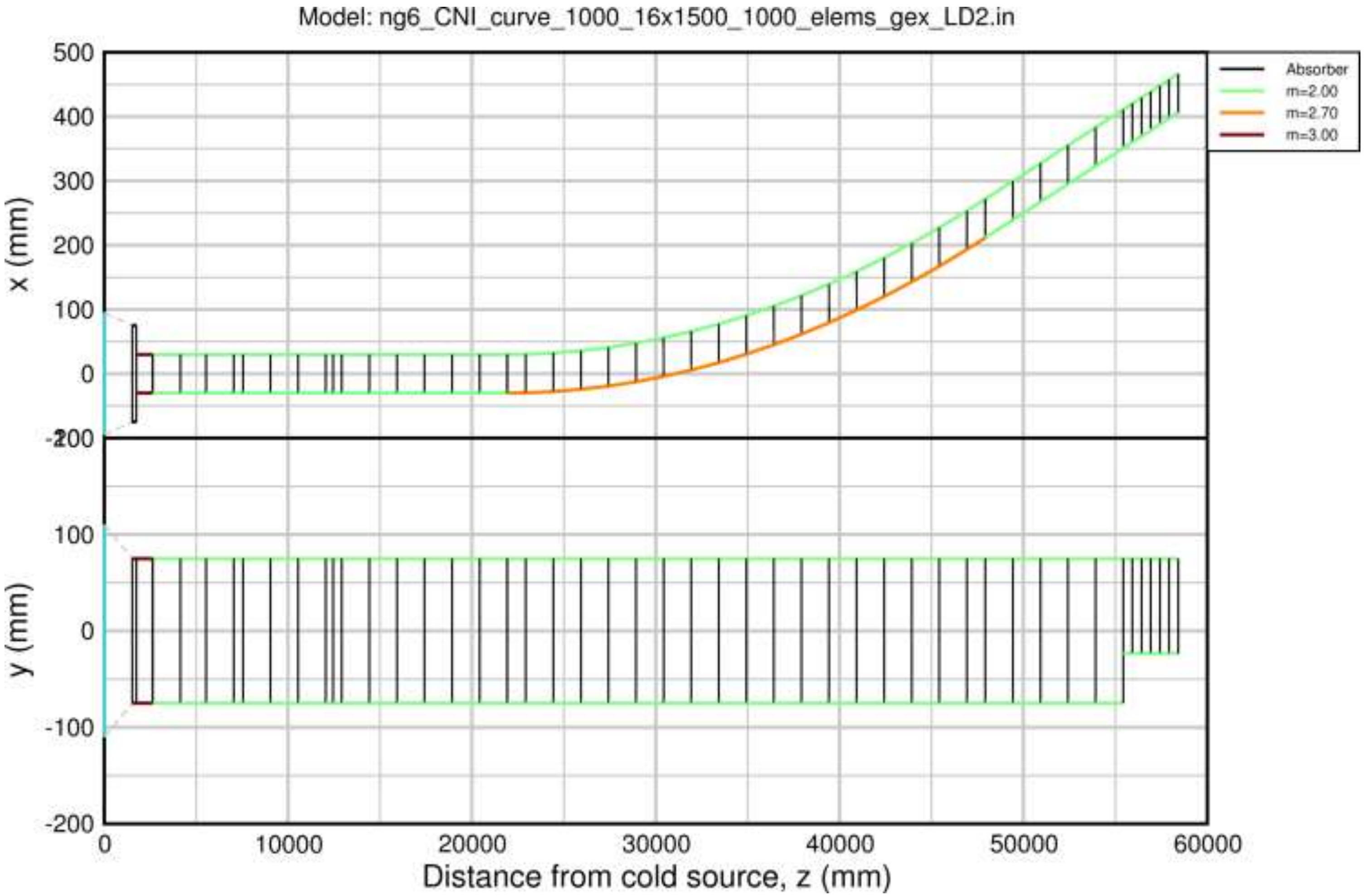
New Liquid Deuterium Cold Source



NCNR Upgrade: Guides

Straight NG-6 guide will be replaced with a new curved guide

- This reduces guide failure risks (guides are 30 years old)
- Curvature removes reactor core fast neutron and gamma ray background
- Factor 3 gain in intensity



Thanks for your attention

- Neutron imaging is a valuable tool for water management studies in PEM FC&WE systems
- The Wolter optic neutron microscope will be a huge gain in time resolution at the finest spatial resolution currently achievable
- Tomography simulations are underway, but are time consuming
- It’s hoped this new tool is ready for users in 2027 … maybe with a CLS …
- The Microscope is funded by a NIST Innovation in Measurement Science project
- *Thanks to Boris Khaykovich (MIT) for the ongoing collaboration on Wolter optics implementation and the NASA MSFC X-ray optics group*

Mandrels and hardware for diamond turning … lathe under repair currently …

Imaging Mandrel being turned at long last (02 MAR 2023)