X-ray imaging with Wolter optics in the 15-50 keV range

National ICF Diagnostics WG Meeting 2015

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Lawrence Livermore National Laboratory

Leveraging research programs to build Wolters for hard X-ray applications

Approach: multilayer-coated, replicated X-ray optics

Replicated optics

Astrophysics
- Solar astronomy
- Astrophysics

Microscopy
- Medical imaging
- Neutron scattering

Nuclear safeguards
- Spent-fuel assay

Multilayers

Leverage existing collaborations between LLNL, NASA MSFC and CfA:

Combine technologies to develop and build new diagnostics needed for NNSA facilities

How do Wolter optics work?

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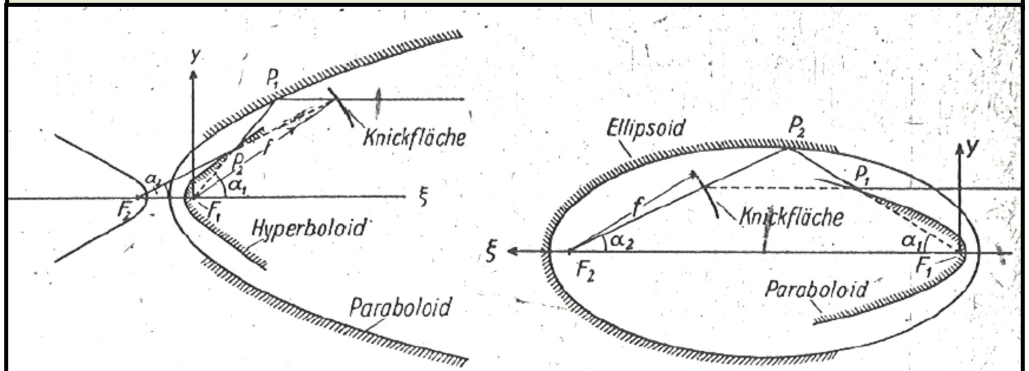


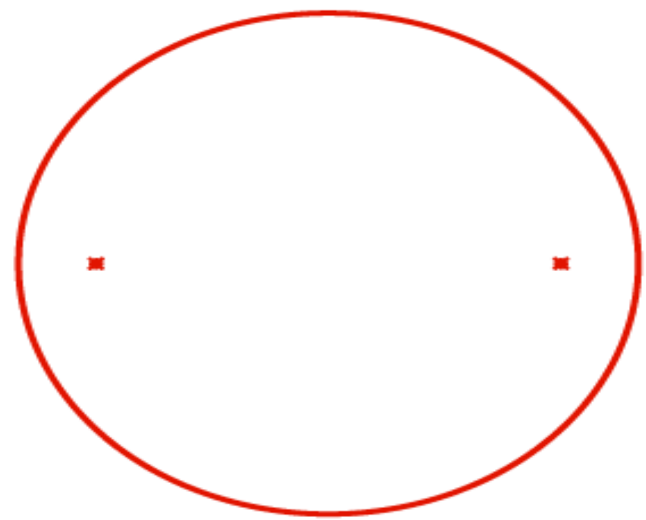
Abb. 15. Spiegelsystem 2. Art

Abb. 16. Spiegelsystem 3. Art

- Two conic surfaces of revolutions to nearly satisfy Abbe sine rule
- Three families of designs, one of which can be nested (Wolter I) and is widely used
- Wolter I has properties similar to a thin lens

→ **Advantages include:**

large solid angle and large FOV



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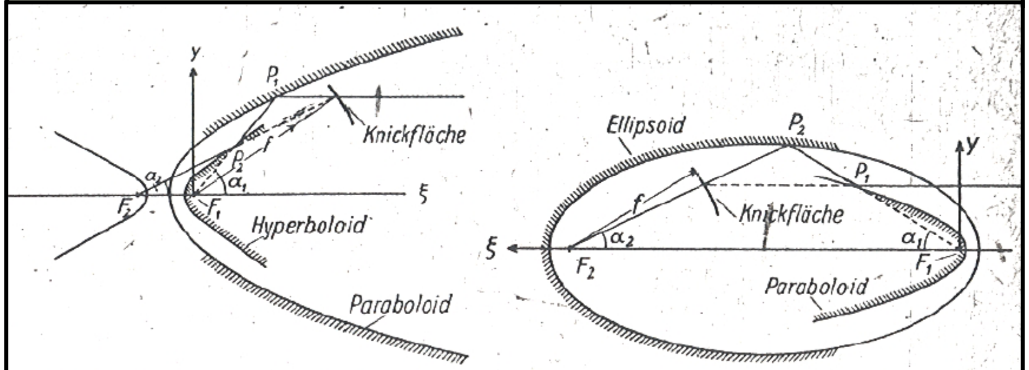

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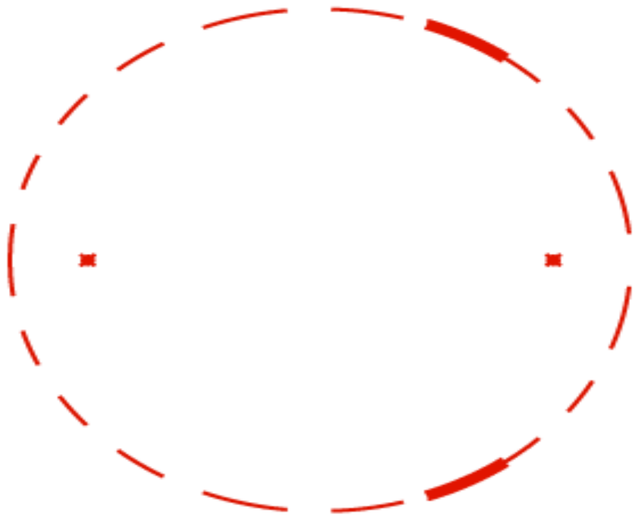

Elliptical surface

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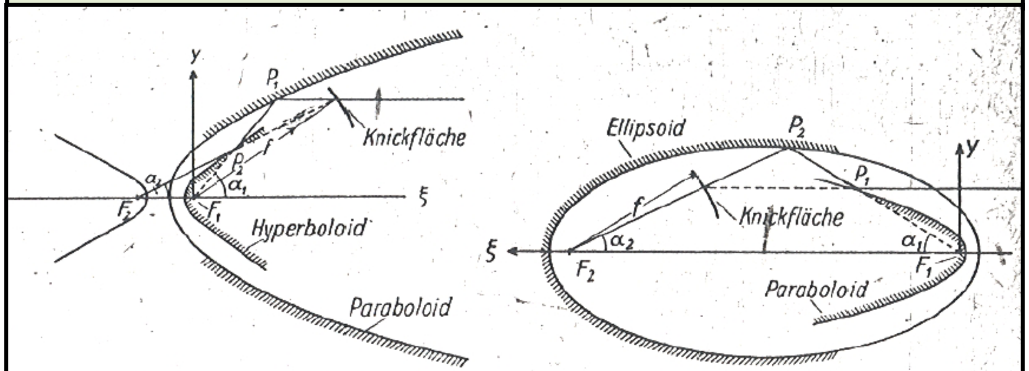

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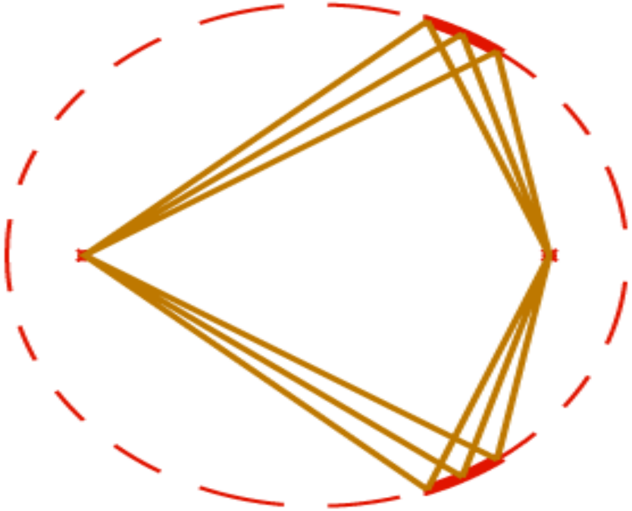

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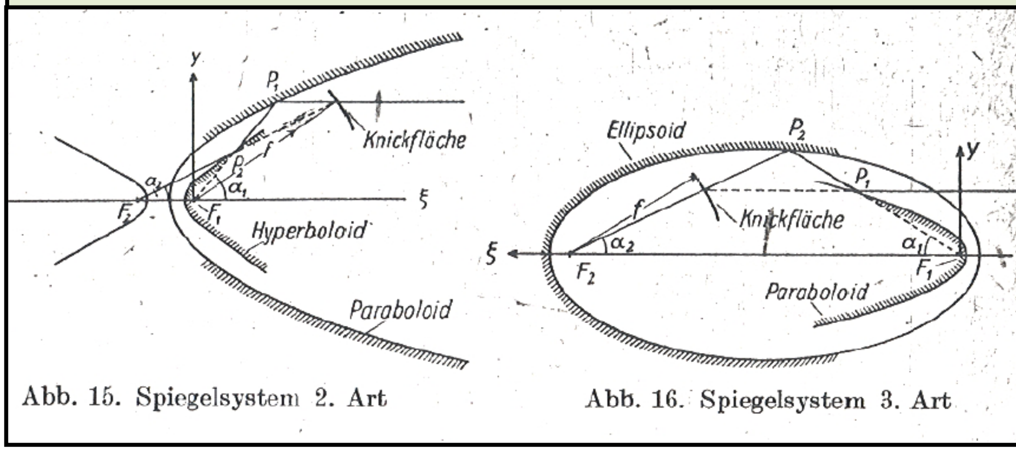

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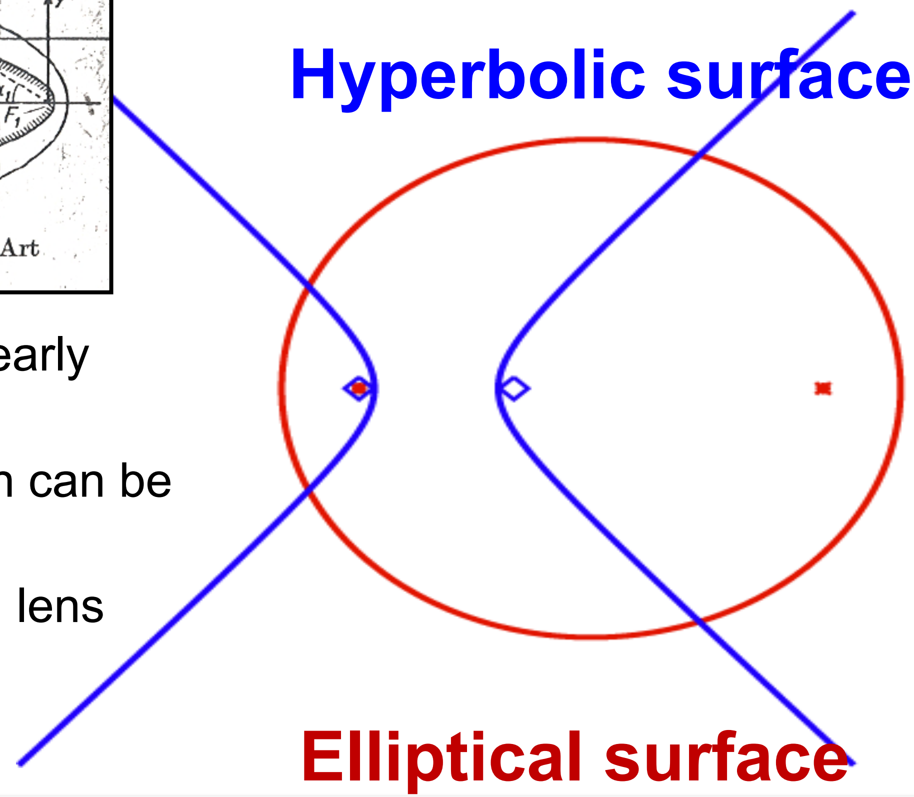

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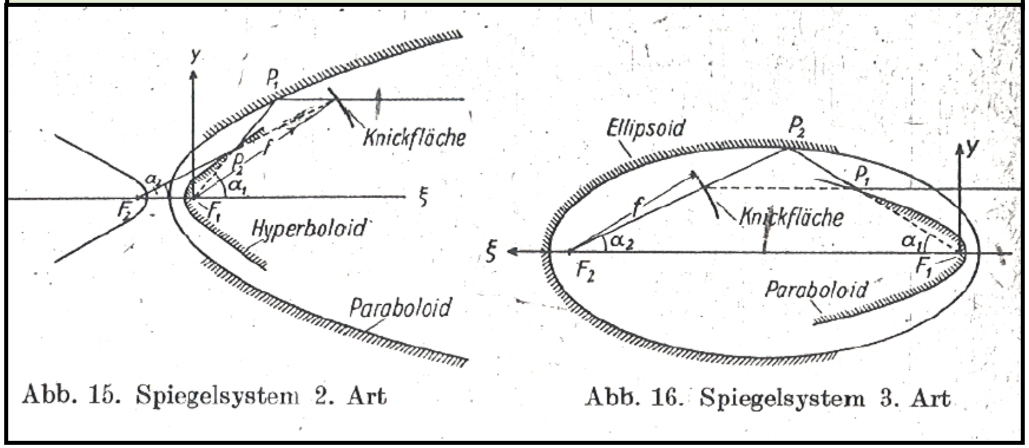

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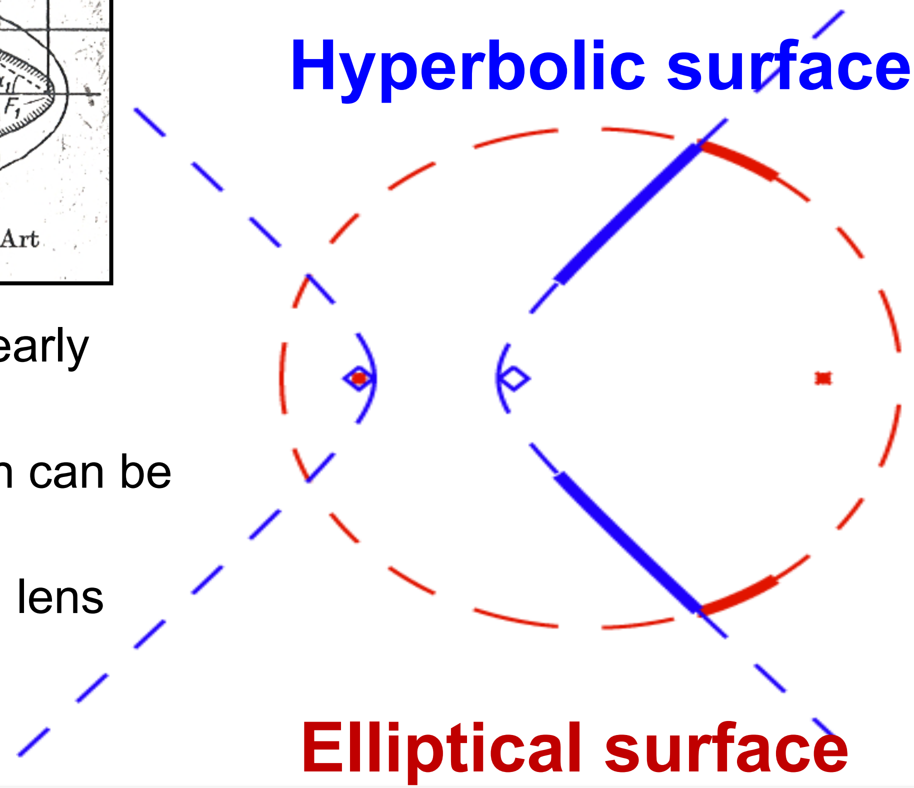

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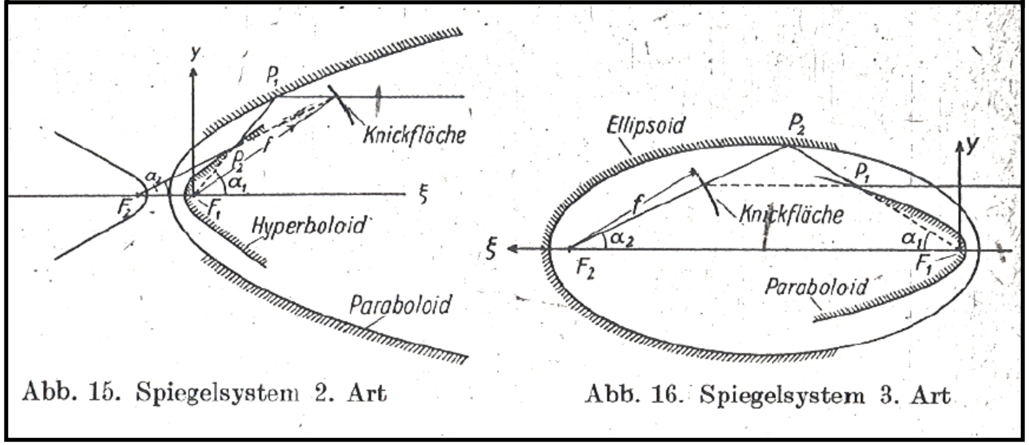

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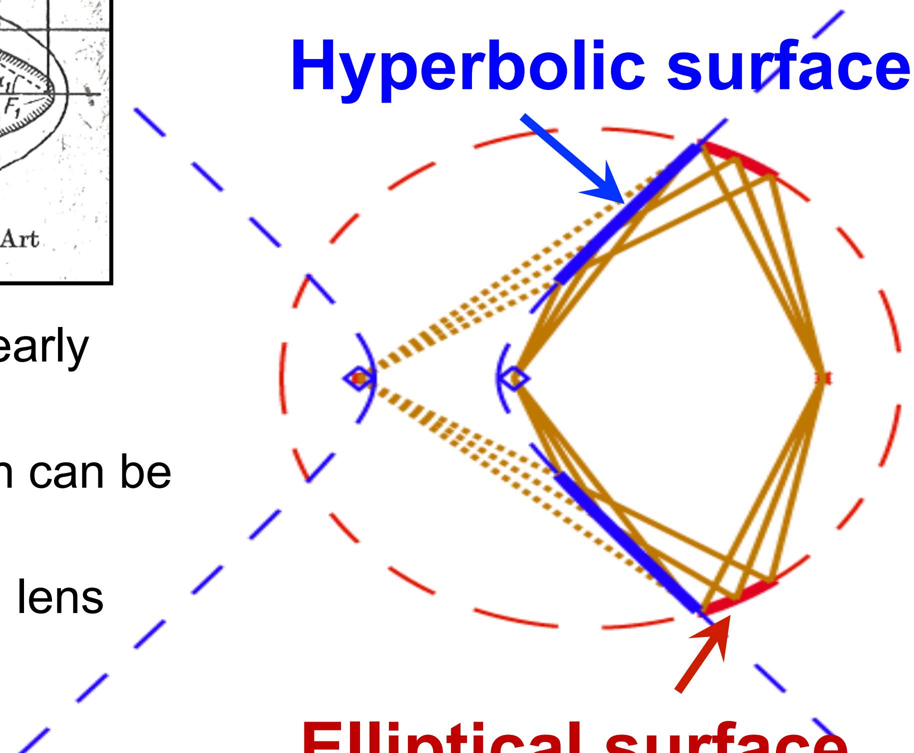
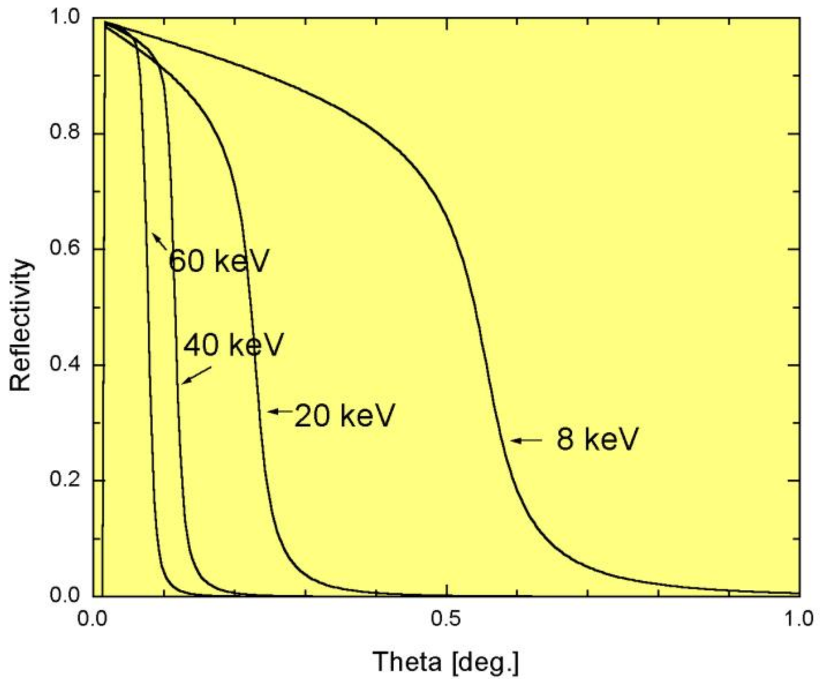


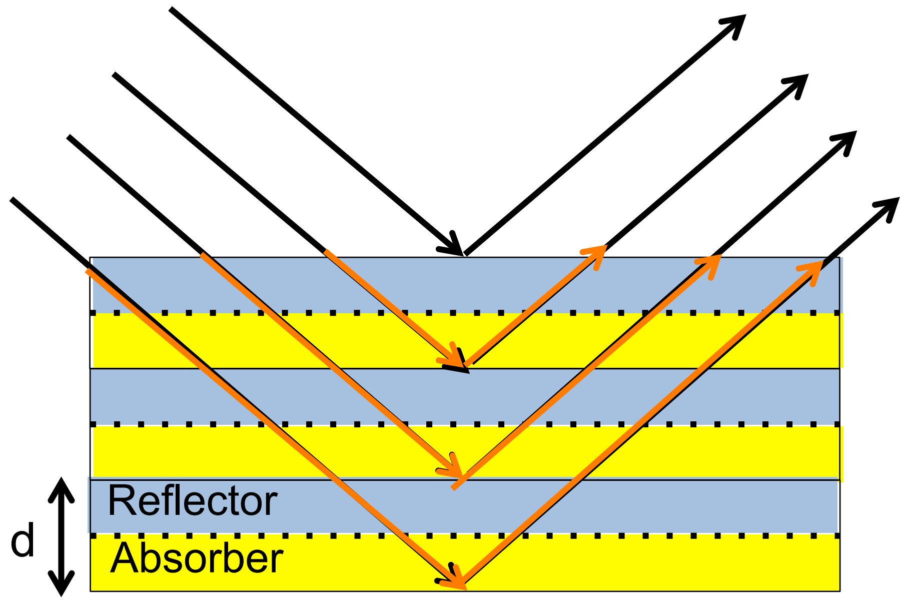
How do Multilayers optics work?

- Reflectivity for reflective (non-ML) coatings high up to critical angle (***θ_c***)
- ***θ_c*** decreases with increasing ***E***

Approach: Multilayer coatings to extend energy range
→ Makes use of Bragg's law

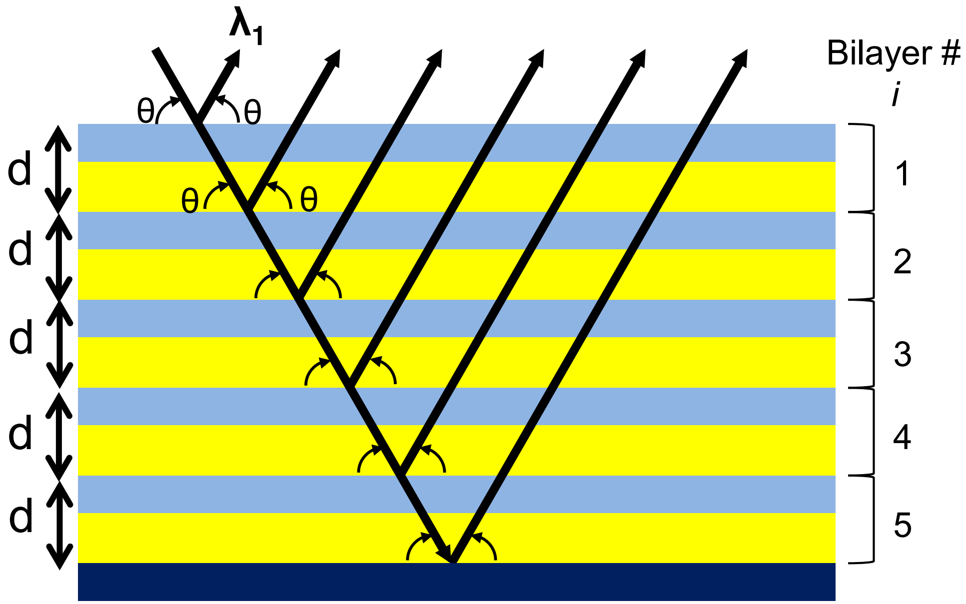
$$m\lambda = 2d\sin\theta\,[1+\chi] \approx 2d\sin\theta$$

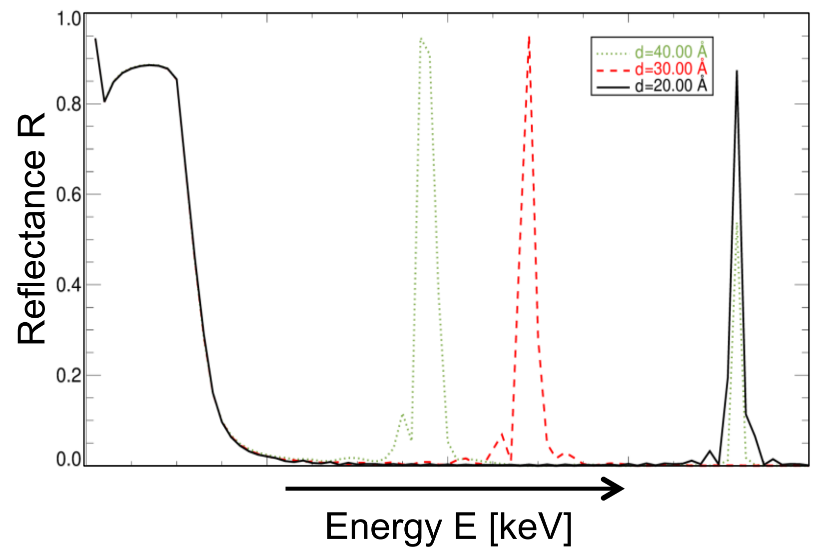




How do Multilayers optics work?

Multilayer coatings with constant period, *d*, for all bi-layers "constant d"
Multilayer acts as notch filter/ monochromator selecting a particular narrow energy range

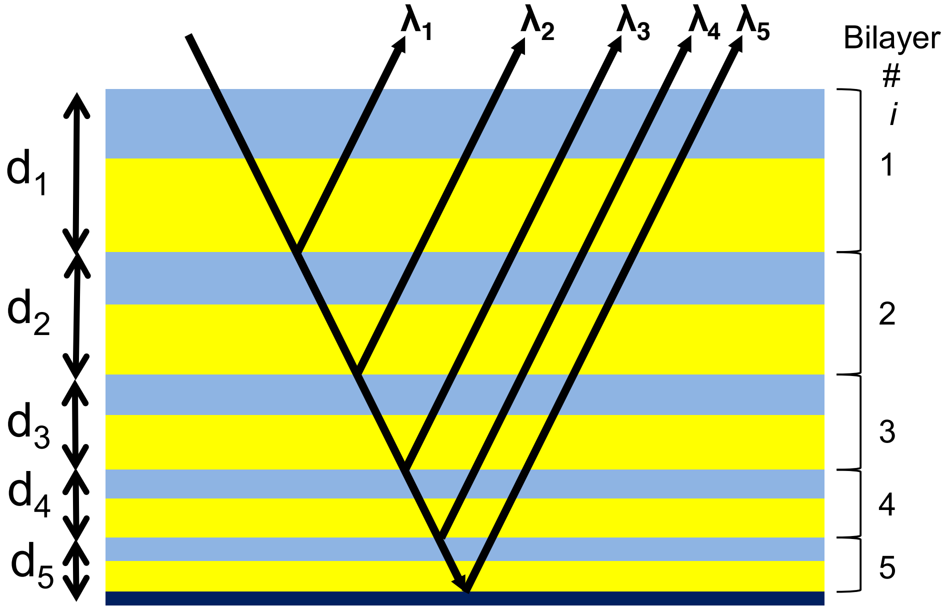


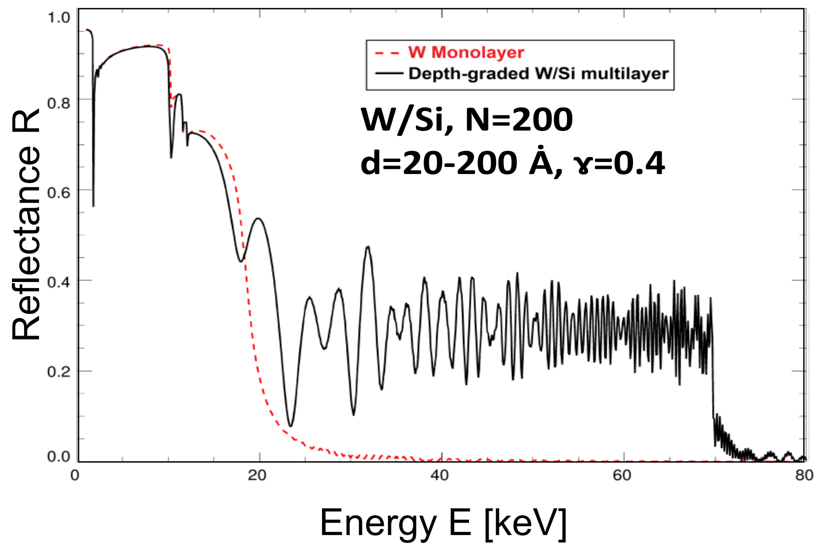


- **Tune the period (keep *d* the same throughout the stack) to maximize reflectivity at a specific *E***
- **Larger energies require smaller periods—current practical limit is *d* = 1.5 nm**

How do Multilayers optics work?

Multilayer coatings with depth-graded d-spacings:
By varying the bilayer thickness through the stack, a range of energies can be satisfied for a single incident angle.





- **Can extend energy width, at the cost of reflectivity loss**
- **The broader the energy response, the lower the overall reflectivity**
  - Must perform a mutliparameter optimization to be satisfy overall requirements

Parameters influencing optical design and ML prescription

Parameter	Optical design	Multilayer Recipe
Photon Energy ***E***	No	Yes
FOV	Yes	No
Resolution ***R***	Yes	No
Efficiency $\boldsymbol{\eta}$	No	Yes

- Optics design includes
  - physical size of optic (e.g. L_H, L_E)
  - configuration (e.g. number of shells ***N***, focal length ***f***)

$FOV \approx f \times \Delta\Theta$

(with angular view ΔΘ depending on e.g. length of mirrors, graze angle, packing fraction of nested shells)

$R \approx f \times \theta_Q$

(with angular quality θ_Q depending on the mirror quality)

- Multilayer prescription includes
  - Materials, d-spacing/depth-grading

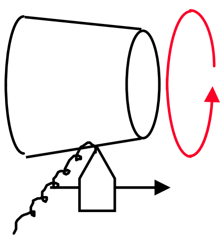
E mostly determines ML recipe, complex optimization incl. depth-grading

(can increase range of graze angles but at cost of drop in overall reflectivity, higher ***E*** have smaller graze angles)

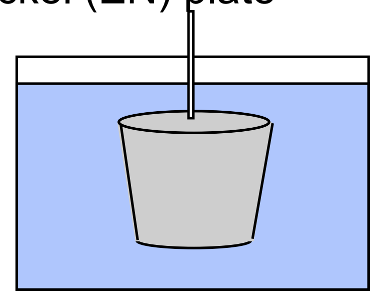
NASA MSFC Replicated Optics Process: low costs for multiple optics – one mandrel for several E optics

Preparation of Mandrel

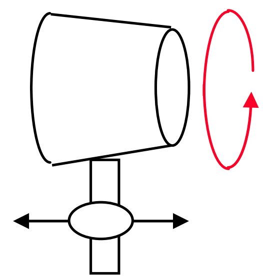
1. CNC machine mandrel from aluminum bar



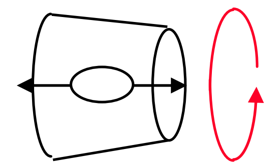
2. Chemical clean and activation & electroless nickel (EN) plate



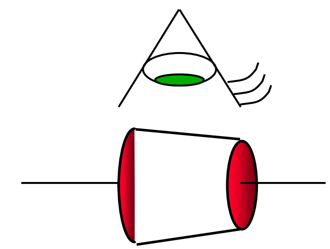
3. Precision diamond turning to 20 Å, sub-micron figure accuracy



4. Polish & superpolish to 3-4 Å rms finish

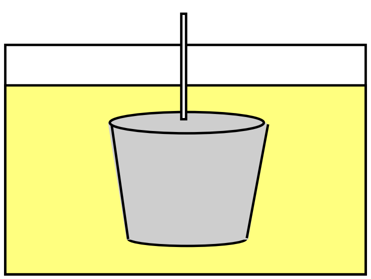


5. Metrology on mandrel



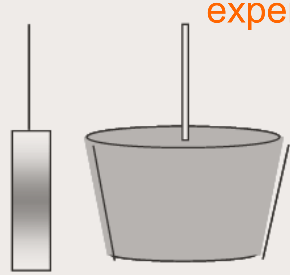
Fabrication of Shell

6. Ultrasonic clean and passivation to remove surface contaminats

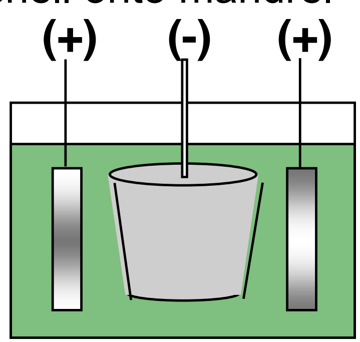


7. Deposit multilayers on mandrel

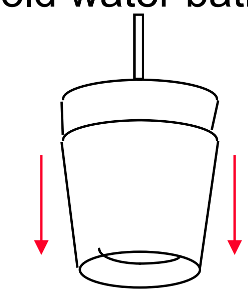
Harvard-CfA expertise



8. Electroform Ni/Co shell onto mandrel



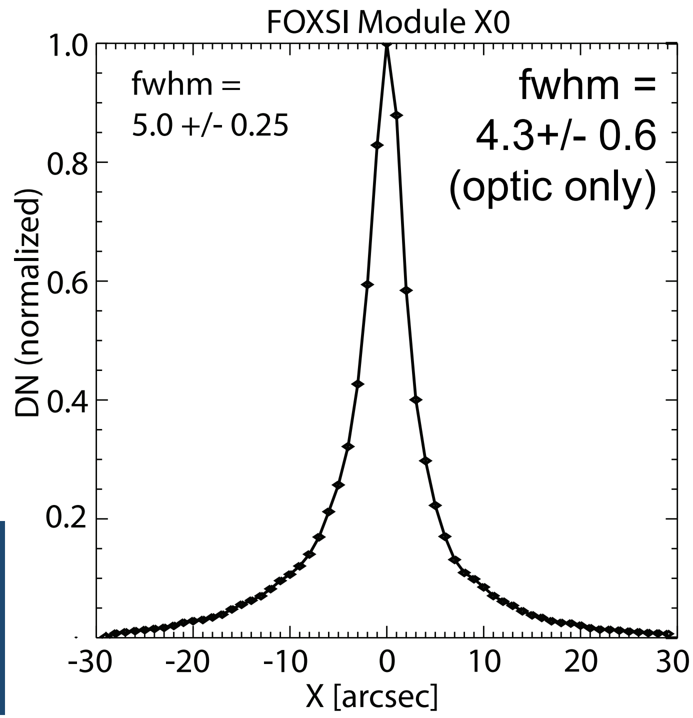
9. Separate optic from mandrel in cold water bath

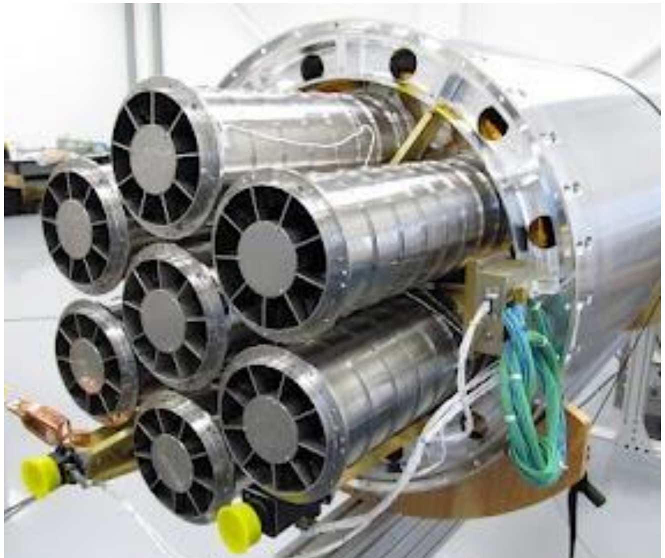


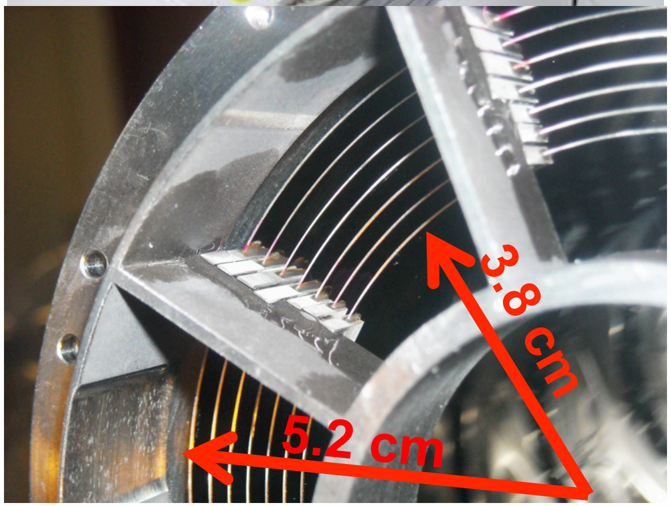
NASA MSFC's Replicated Optics Program: Astronomical applications (FOXSI, ART-XC, HEROES)

- FOXSI (Focusing Optics X-ray Solar Imager) is sounding rocket payload to study solar nanoflares
- 3× better spatial resolution and 10-100× better dynamic range than previous missions
- Total of 7 optics from only one set of mandrels
- Narrow point spread function with Gauss-like core

→ Cost reduction due to re-use of mandrels



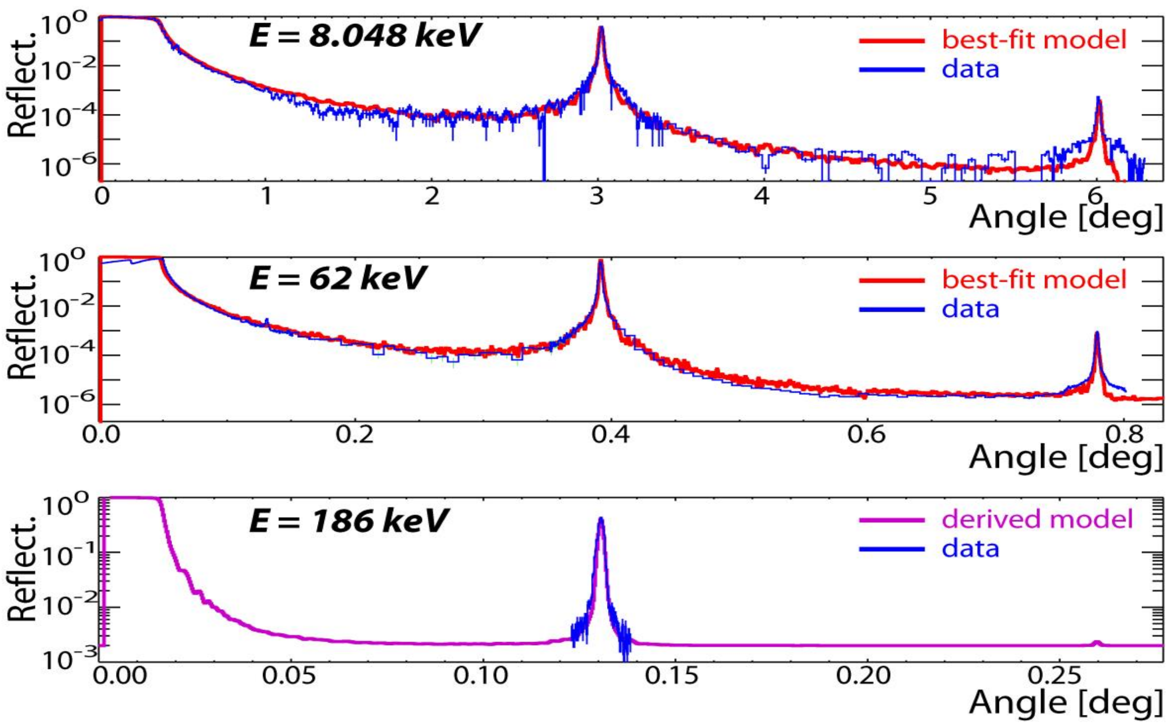


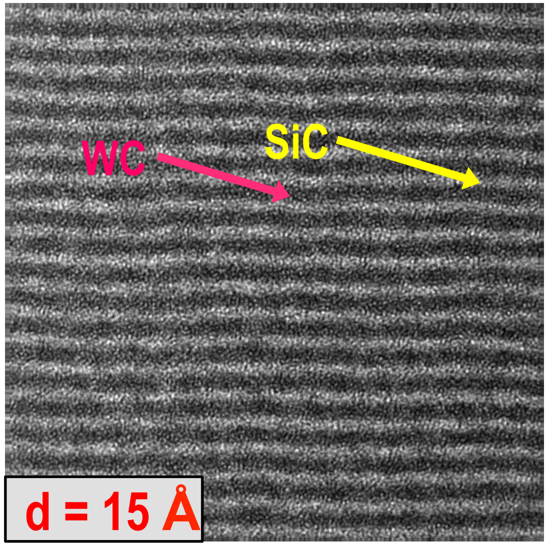


Krucker et al. *Proc SPIE* **8862** 88620R (2013)

LLNL's program for high-E, small-d multilayer program

- Use multilayers to act as a notch or pass-band filter for SNM lines from 90–400 keV
- Requires ultra short-period *d*-spacing to work at as steep angles as possible
- Calibration simplified due to possibility to use simple lab sources





TEM view through WC/SiC multilayers

Fernandez-Perea et al. *Phy Rev Lett* **111,** 027404 (2013)

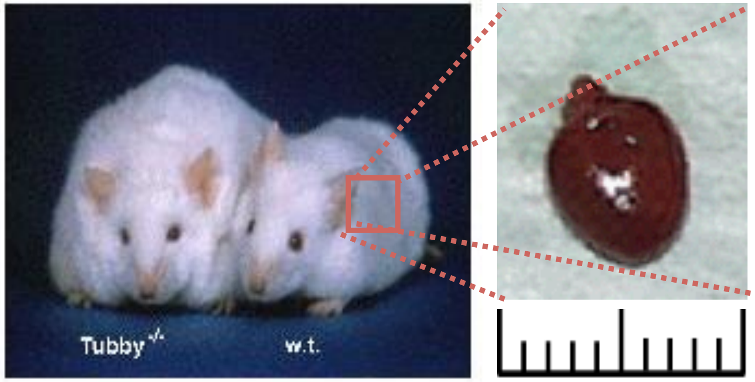
Brejnholt et al. *Opt Exp* **22**15364 (2014)

Fernandez-Perea et al. *NIM* **710,** 114 (2013)

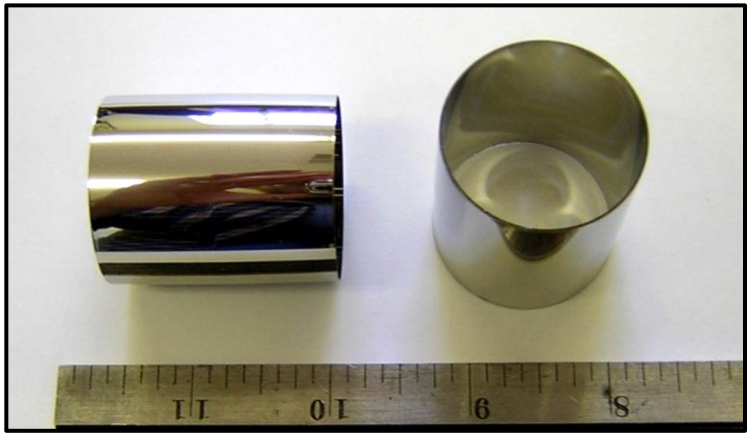
Previous microscopes demonstrate many features needed for NNSA optics

- Goal: overcome major challenge of absorptive collimation which is the coupling between efficiency and spatial resolution
- Initial efforts funded by NIH (LLNL, MSFC, CfA, UCSF) for radionuclide imaging in mice [2005-2010]
- Later efforts (MIT, MSFC) funded by DOE/SC for neutron scattering
  - Currently at 70 μm spatial resolution, consistent with ~25″ angular resolution (FWHM)
  - R&D needed to make small optics perform as well as space telescopes (5”)

Pivovaroff et al. *Proc SPIE* **5923** 59230B (2005)
Liu et al. *App Phys Lett* **102** 183508 (2013)
Liu et al. *Nat Comm* **3556** (2013)



Pre-clinical nuclear medicine requires sub-mm resolution



Replicated X-ray optics for microscopy

Putting it all together: Bring new imaging systems to Z and NIF as part of the national effort

<u>Z Applications</u>: Imaging non-thermal k-alpha emission to diagnose stagnation conditions in a Z pinch
<u>NIF Applications</u>: Self-emission imaging and radiography of ICF Implosions; Compton Radiography; Hot Spot T_e measurement

- → Organizing principal: Start with a Wolter for Z (Chris' talk on our progress), since the overall requirements are better matched to current fabrication capability (at NASA MSFC and CfA) for Wolter microscopes
- → Performance of NIF KBO and Z Wolter will drive development of Wolter optics for NIF (we are just getting started on this)
  - → We know that NIF applications will have more stringent requirements on the Wolter optic itself, and this effort will demand dedicated R&D to improve the focusing performance

Current Status

- Sandia defined requirements for measuring cold Kα emission on Z
- LLNL created possible Wolter designs and is developing detailed performance simulations
- Designs currently assumed perfect optics (100% reflectivity, no figure error) to constrain possible designs
- Next steps will include:
  - Realistic figure errors, that will impact spatial resolution
  - Realistic multilayer reflectivity, that will impact throughput (i.e., S/N)
- In parallel we are designing an X-ray optics calibration facility at LLNL and NASA MSFC/Harvard-CfA are getting ready for optics manufacturing

Initial studies show meeting Z science objectives feasible
No major obstacles expected for implementation

Preliminary "desirements" for Wolter imaging on NIF

Desirement	Specification
Field of View	At least ± 150 μm
Spatial Resolution	Detector limited or 5μm FWHM
Efficiency	At least ×100 over standard pinhole
Depth of Field	~3mm
Total throw (under study)	2m, 8m, 22m
Magnification (depends on detector)	At least ×10

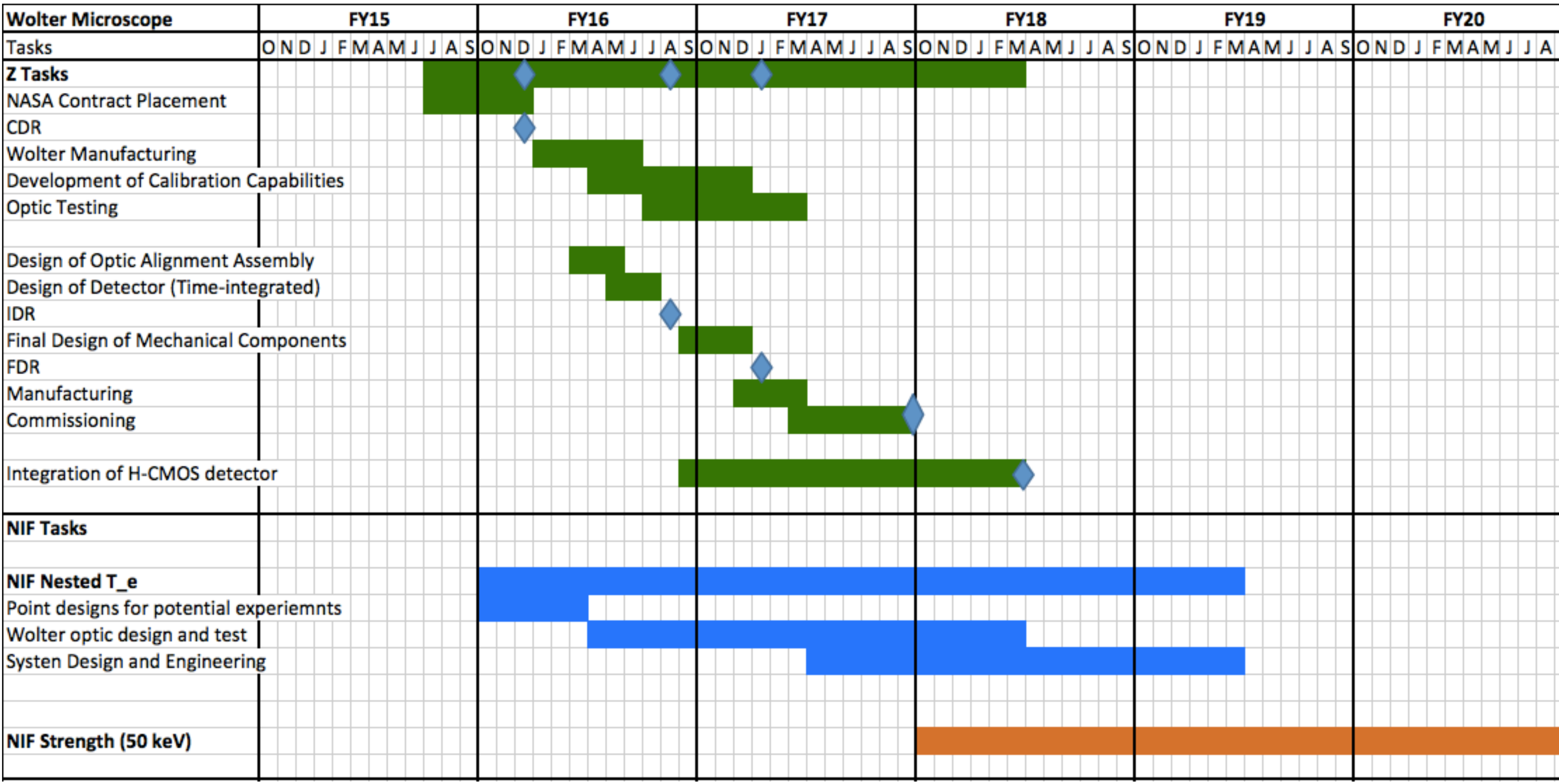
Before conducting a dedicated design effort for Wolter at NIF, we need to:

1. Conduct the broadest possible census of the NIF user community to understand their needs
2. Ingest lessons learned from X-ray imaging (using KB optics) at NIF
3. Ingest lessons learned from development and deployment of Wolters at Z

Expected challenges for NIF Wolter: navigating an interconnected multi-dimensional parameter space

- **Hard energies → smaller critical angle, more scatter**
  challenge for resolution (more off-axis blur) and efficiency
- **High resolution→ shorter mirrors, need higher substrate quality (figure worse for stubby mirrors)**
  challenge for high energy, large FOV
- **Large FOV→ large angular acceptance, need large f**
  challenge for optics radius (large α → small r) and resolution (more off-axis blur)
- **High efficiency→ Longer mirrors, small angular acceptance, nesting**
  challenge for resolution (long mirrors have worse off-axis response) and large FoV
- **Large magnification → large f**
  challenge for optics radius (large f → small r) and resolution (more off-axis blur)

Schedule



Wolter Microscope
FY15
FY16
FY17
FY18
FY19
FY20
Tasks
O N D J F M A M J J A S
Z Tasks
NASA Contract Placement
CDR
Wolter Manufacturing
Development of Calibration Capabilities
Optic Testing
Design of Optic Alignment Assembly
Design of Detector (Time-integrated)
IDR
Final Design of Mechanical Components
FDR
Manufacturing
Commissioning
Integration of H-CMOS detector
NIF Tasks
NIF Nested T_e
Point designs for potential experiemnts
Wolter optic design and test
Systen Design and Engineering
NIF Strength (50 keV)

State of the art for Wolter optics (astrophysics-driven for 50 years)

Current missions with best-of-breed optics

Mission (launch)	Angular Resolution		Mirror types	Spatial Resolution [μm]		Energy range [keV]	Telescopes × shells	Best
	HPD	FWHM		Design 1	Design 2			
Chandra (1998)	0.5”	0.1”	integral Zerodur shells	0.4–2	0.6–3	0.1–12	1 × 4	resolution
XMM-Newton (1999)	15”	5”	integral replicated Ni shells	20–61	31–92	0.1–10	3 × 56	throughput × FOV
NuSTAR (2012)	58”	25”	segmented glass	102–236	153–354	3–79	2 × 133	highest energy

Design 1: D = 2.4 m, Mag = 3
Design 2: D = 9.0 m, Mag = 9

Drivers:

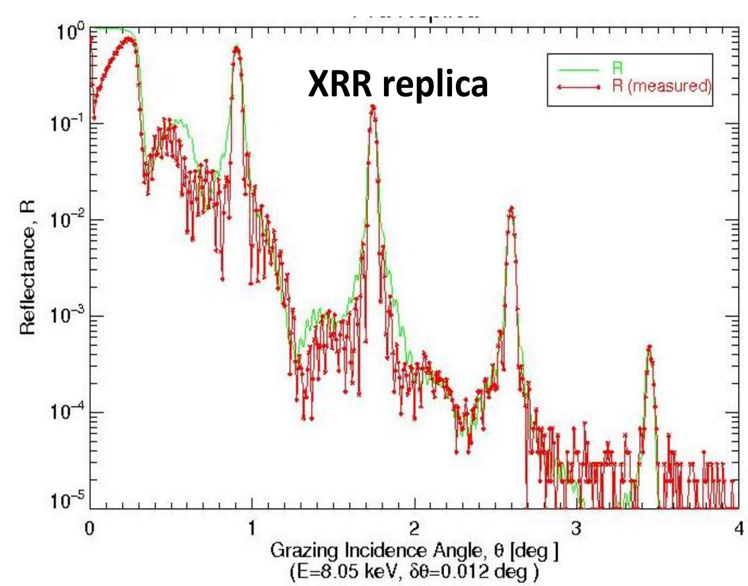
- Higher energies
- Lightweight optics
- Angular resolution
- Throughput

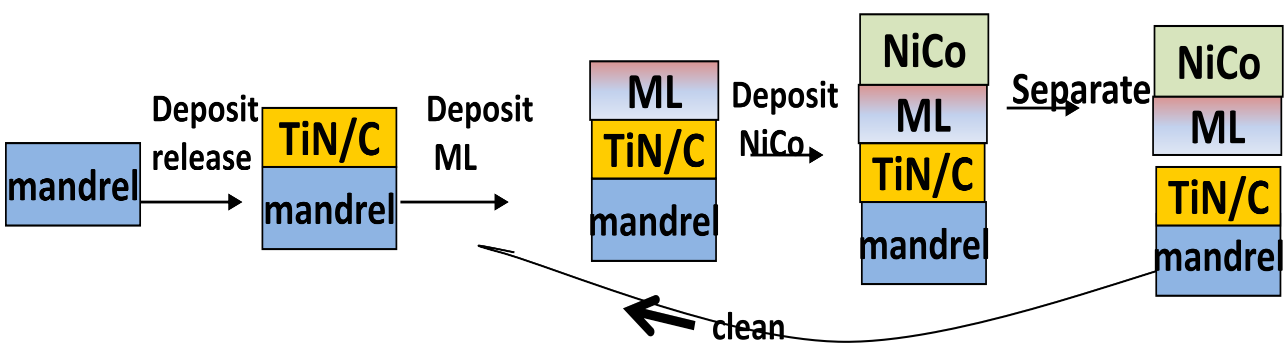
- Challenge is to simultaneously combine these attributes
- **NASA MSFC has been developing replicated X-ray optics for ~20 years to meet these requirements**

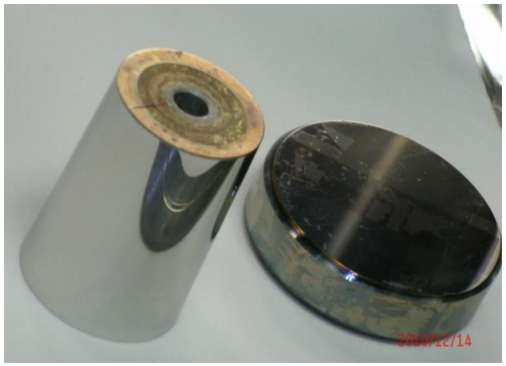
Harvard-CfA's developed novel technology for ML deposition on small diameter optics

Deposition of multilayers on mandrel

- Direct deposition of multilayers on small-radius replicated shells not feasible
- MLs deposited on mandrel using release coating, then grow shell around ML and release
- Mandrel can be cleaned and reused:
  - 22 successful replications from same (flat) mandrel without refurbishing
  - ML structure of replicated W/Si basically not degraded
  - Works also for cone-shaped mandrels







Motivations for NIF

Many experimental platforms at NIF require a narrowband, high energy (>20keV) response to improve signal to noise

- ICF hotspot self emission imaging
- ICF Compton scattering from remaining fuel mass

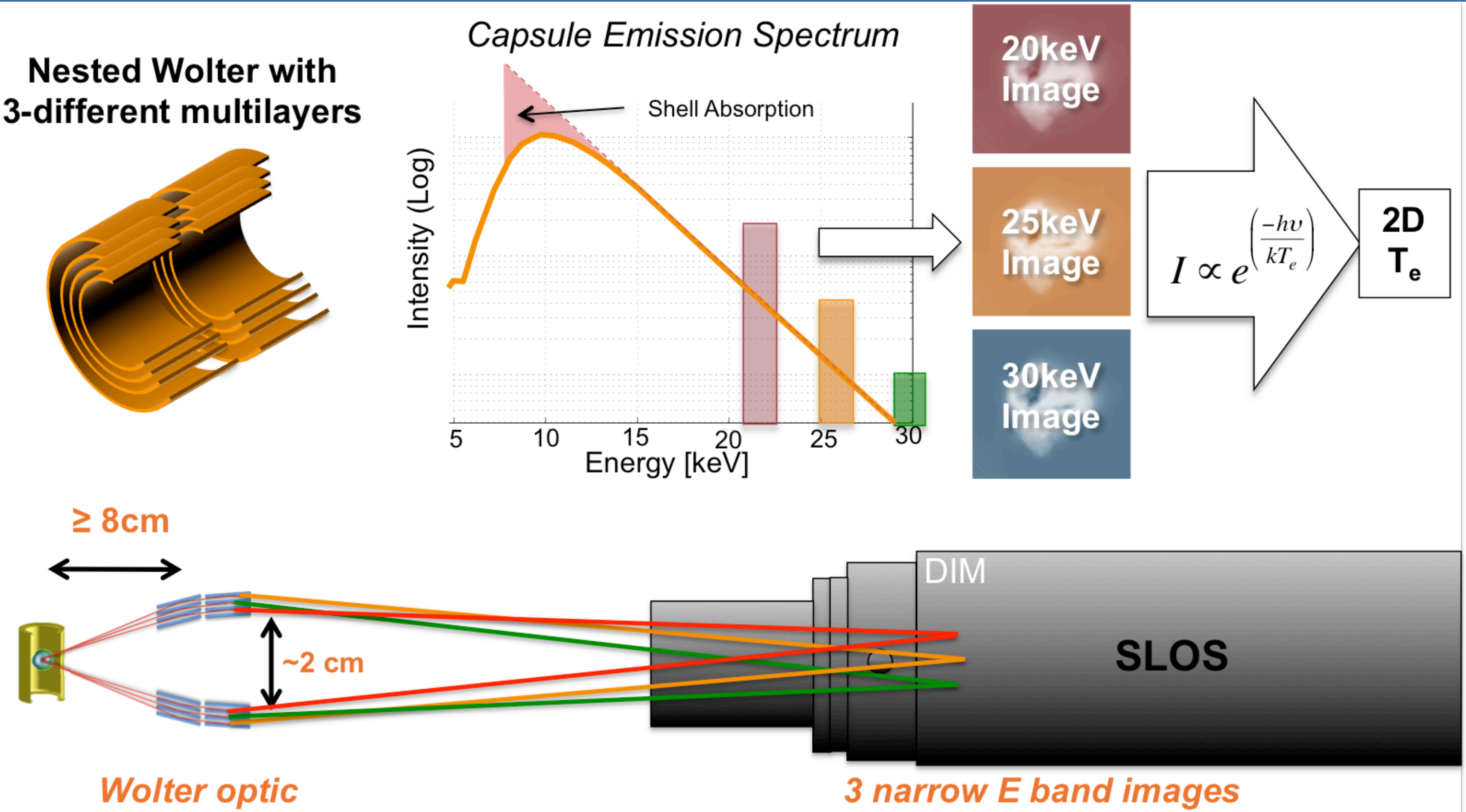
25 keV, fast

- Material strength experiments
- Complex hydrodynamics

50 keV, slow

- All experiments need significantly more flux to the detector than can be delivered by pinholes or KB systems
- **The goal is to deliver 100× more flux than the currently used pinhole systems**

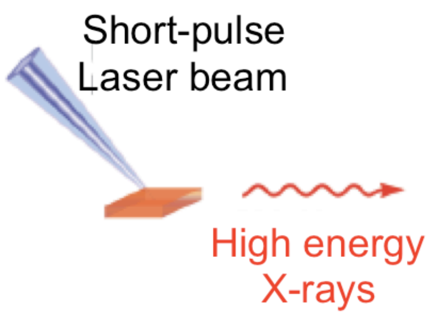
Nested multilayer Wolter optics coupled to a pulse-dilation SLOS will enable space-resolved T_e of capsule



Benefit: enables multi-monochromatic imaging (MMI) in the optically-thin regime

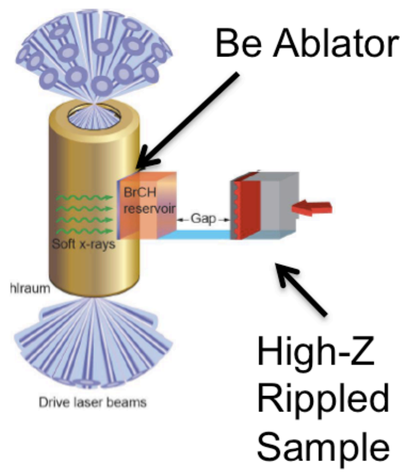
Wolter optics will enable high-contrast measurements for strength experiments on high-Z materials at NIF

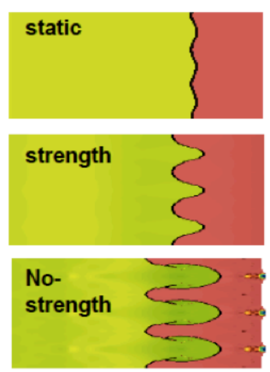
Backlighter



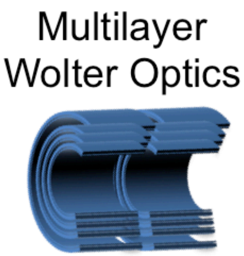
- Optimal energy depends on Z and thickness
- 40-60 keV is optimal for some important applications.

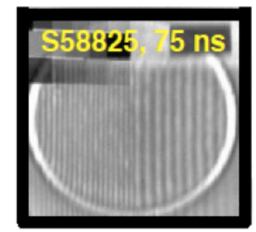
RT Strength Platform





Multilayer Wolter Imaging





Face-on radiography

- Large solid angle improves signal by ~40×
- Narrow band response improves contrast by filtering out-of-band photons
- Enables multi-frames per shot

Risks and Mitigation

Risk	How to eliminate risk	Impact	How to counteract and keep performance degradation small	Possibility
Figure errors in optics	R&D; prototyping	Limits FOV	Reduce operating distance	Medium
Deposition of small-d multilayers on mandrels	R&D; prototyping	Limits throughput	Work at shallower graze angles; nest multiple shells	Low
Mandrels require frequent refurbishment	prototyping	Higher-cost	Budget contingency; fewer number of energy-tuned optics	Low

Must also have efficient hard X-ray detectors with pixel pitch matched to optics