FROM X-RAY TELESCOPES TO NEUTRON SCATTERING: USING WOLTER MIRRORS TO FOCUS A NEUTRON BEAM.

PART I: Misha

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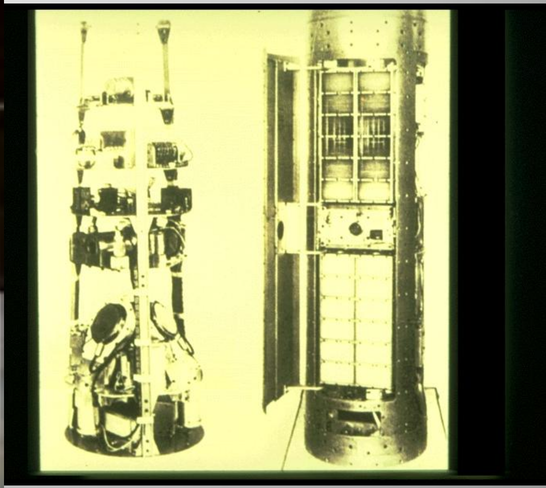
X-ray Astronomy

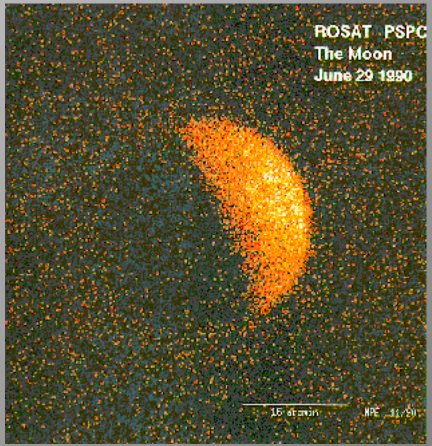
Birth of X-Ray Astronomy

- In 1962, Riccardo Giacconi and colleagues at AS&E flew sounding rocket to look at x-ray fluorescence from the moon
- Lunar signal was overshadowed by very strong emission from the Scorpious region
- Discovered the first extra-solar x-ray source, Sco X-1, and pervasive x-ray background
- This was the effective birth of x-ray astronomy



Early observations

•From these early observations a picture emerged of a typical x-ray source:
•A compact object (neutron star, black hole, white dwarf) orbiting around a normal star
•Matter streams down on to the compact object forming an accretion disk
•As the matter spirals down and is compressed it gets very hot and emits x rays



X-Ray Optics

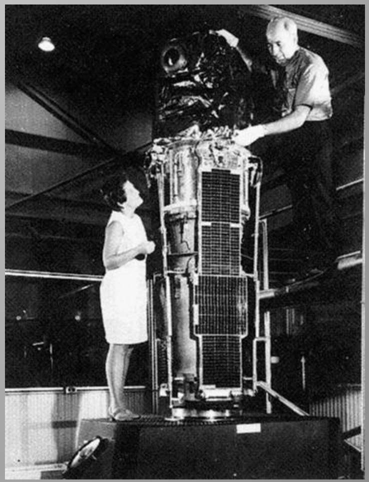
Why focus x rays ?

1) Imaging - obvious
2) Background reduction
   - Signal from cosmic sources very faint, observed against a large background
   - Background depends on size of detector and amount of sky viewed
     - Concentrate flux from small area of sky on to small detector

$\Rightarrow$ *enormous increase in sensitivity*

First dedicated x-ray astronomy satellite – UHURU →

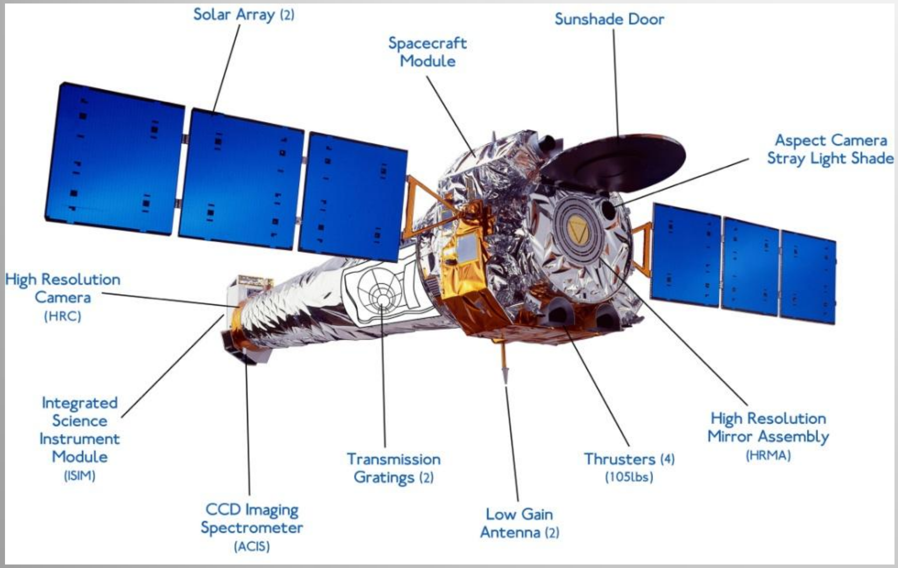
mapped 340 sources with large area detector (no optics)

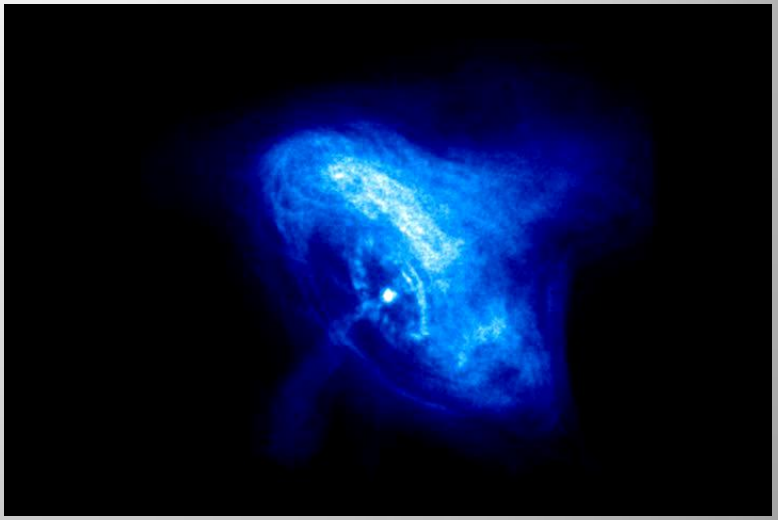


Chandra observatory - ~ same collecting area as UHURU

- *5 orders of mag more sensitivity --- 1,000 sources / sq degree in deep fields*
- *1 background count / keV year !*

Chandra Observatory





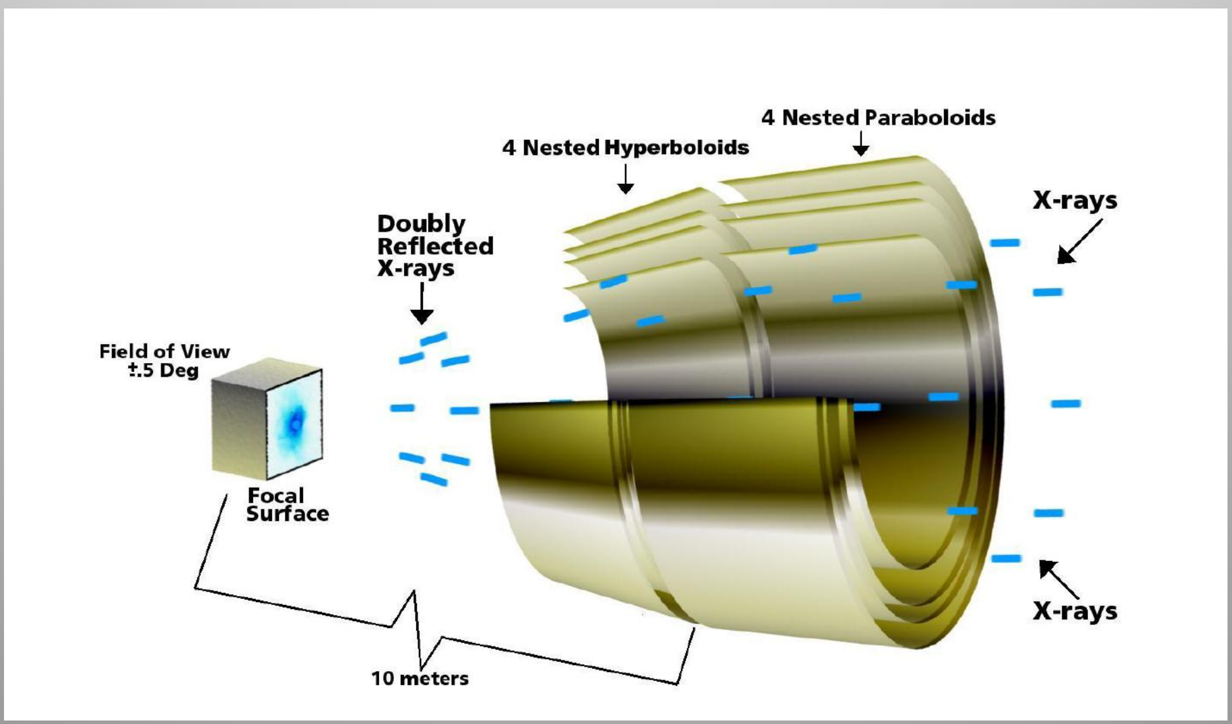
The Crab Nebula and its Pulsar

Center of our Galaxy

Approaches to Fabrication

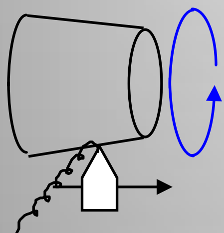
• **X-ray optics are very challenging to fabricate. Because of very short wavelength of x-rays the mirror surface must be smooth to ~ 0.5 nm rms.**

• **Also, for good angular resolution, the figure must be accurate to < 1 micron.**

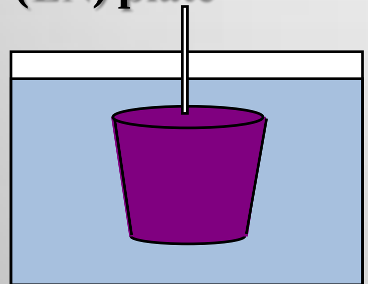


Mandrel Preparation

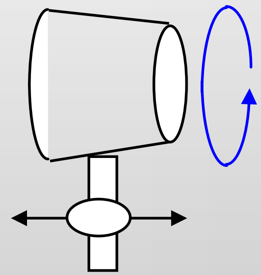
1. CNC machine, mandrel formation from Al Bar



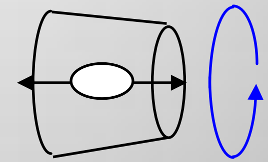
2. Chemical clean and activation & Electroless Nickel (EN) plate



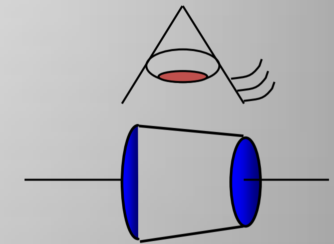
3. Precision turn to sub-micron figure accuracy



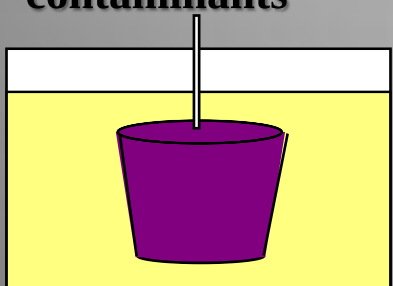
4. Polish and superpolish to 3 - 4Å rms finish



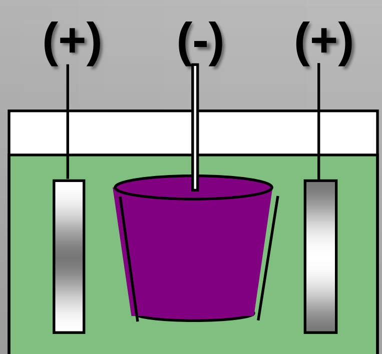
5. Metrology On mandrel



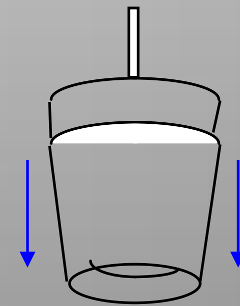
6. Ultrasonic clean and passivation to remove surface contaminants



7. Electroform nickel shell onto mandrel



8. Separate optic from mandrel in cold water bath

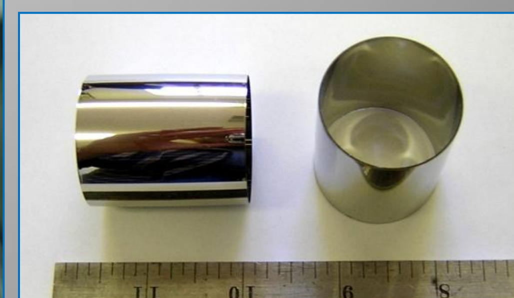


Different types of X-ray shells fabricated at MSFC

60 cm length – 5 cm diameter - 250 μm thick

Down to 50 μm thick

Up to 50 cm diameter



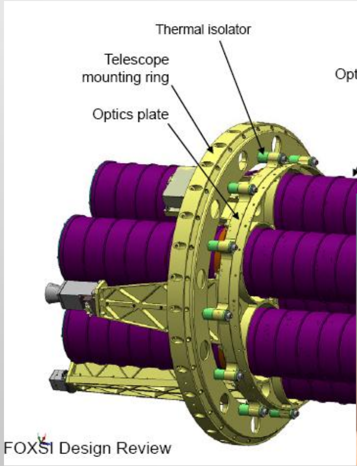
Down to 2.5 cm diameter

X-ray Mirror Application

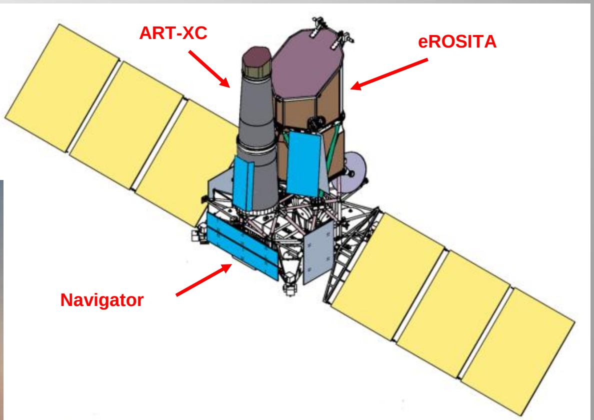
Astronomical applications

Hero

Foxsi



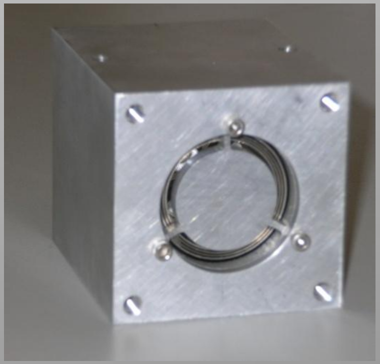
ART

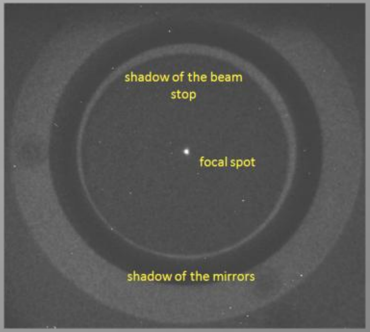


Non-astronomical applications

Medical imaging

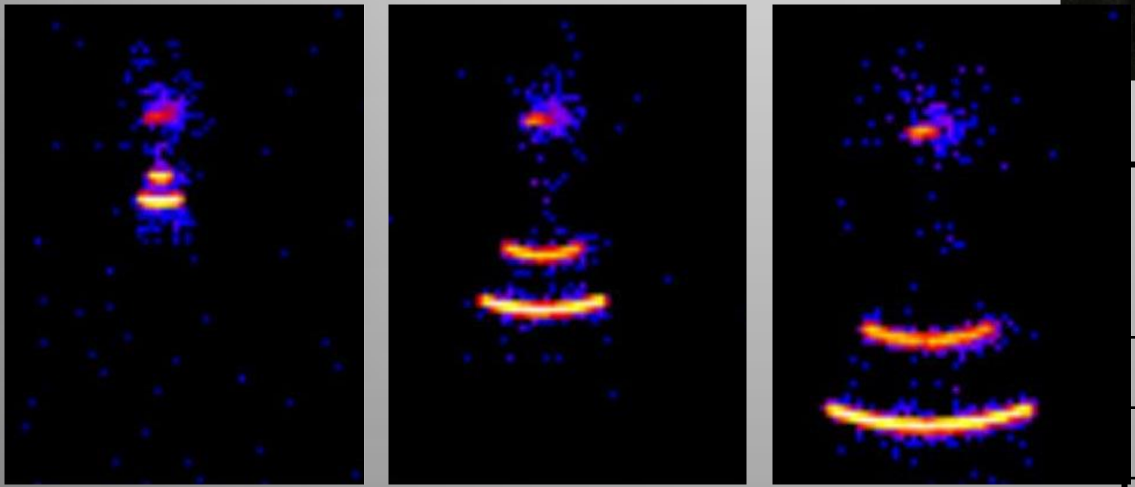
Neutron imaging





NIST experiment

- ✓ The refraction index is less than unity for most of materials for neutrons and x-rays. The highest reflectivities for thermal and cold neutrons would be obtained with a pure nickel surface.



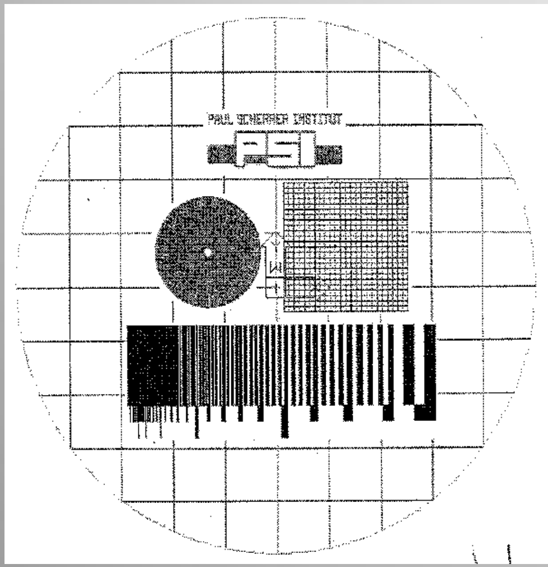
0.67 m 2.67 m 4.67 m

Distance from the focal spot to the detector

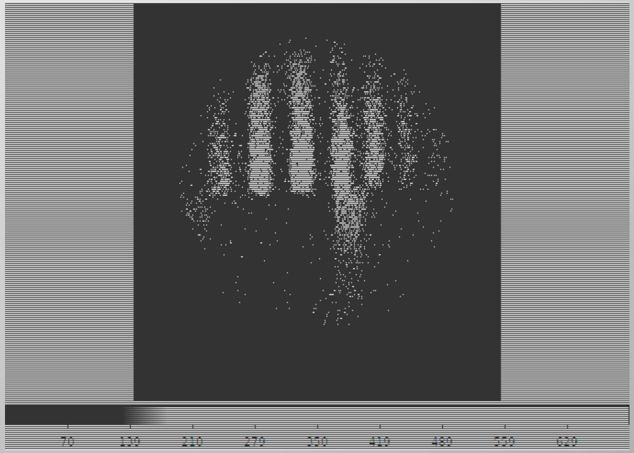
Neutron wavelength, Å	Effective area, mm^2	Gain
6	17.9±0.4	8.5
10	17.1±0.2	8.2
20	15.8±1.6	7.6

Imaging with Neutron optics

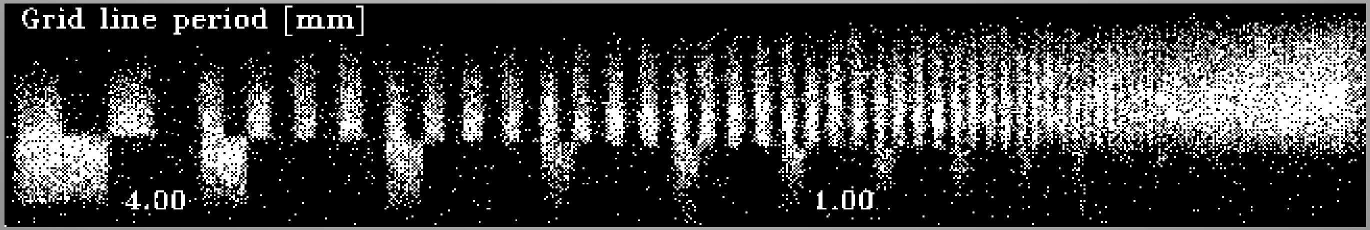
The imaging properties of the microscope has been tested at the instrument development beamline at HFIR (CG1-D).



The schematic of the GD test object.

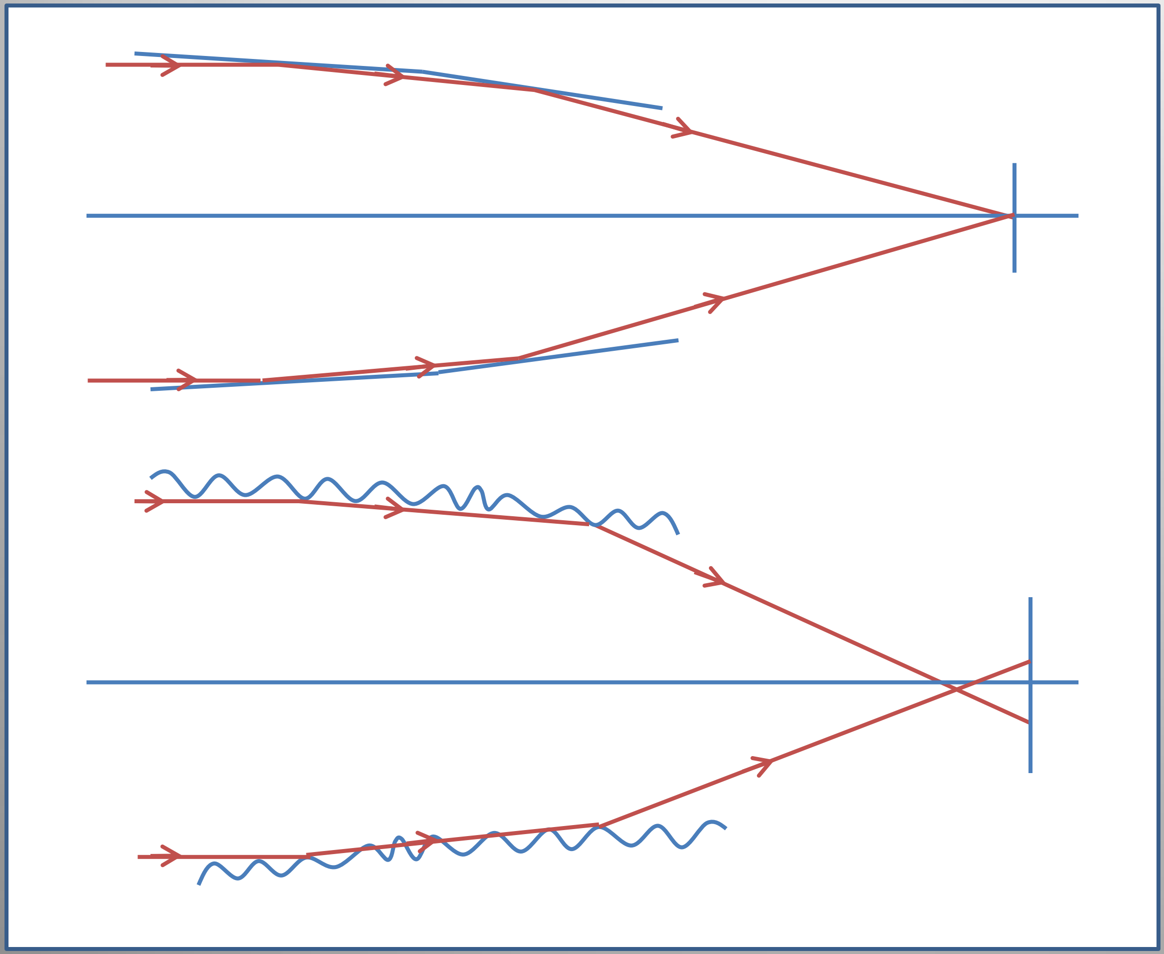


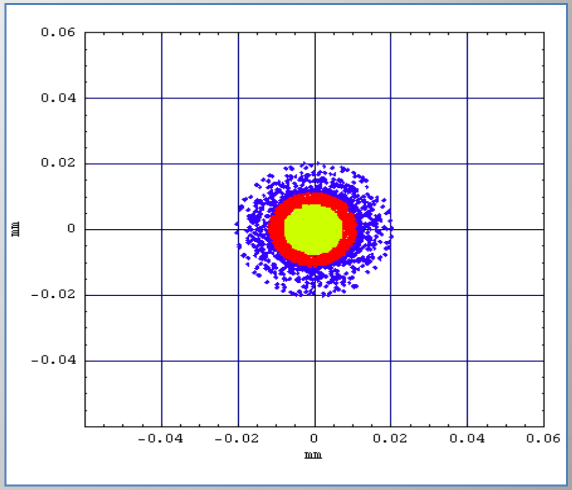
Sample of the neutron image collected using the grazing incidence microscope. Two line periods are presented on the image. Three left periods are 1.43 mm, that correspond to 0.715 mm wide lines. Three right periods are 1.18 mm, that corresponds to 0.69 mm wide lines.



The microscope is capable to resolve the period of 0.290 mm (0.145 mm spatial resolution)

Figure Deviations





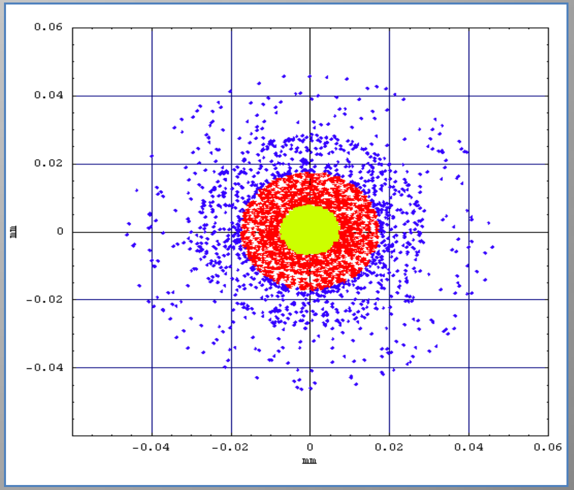
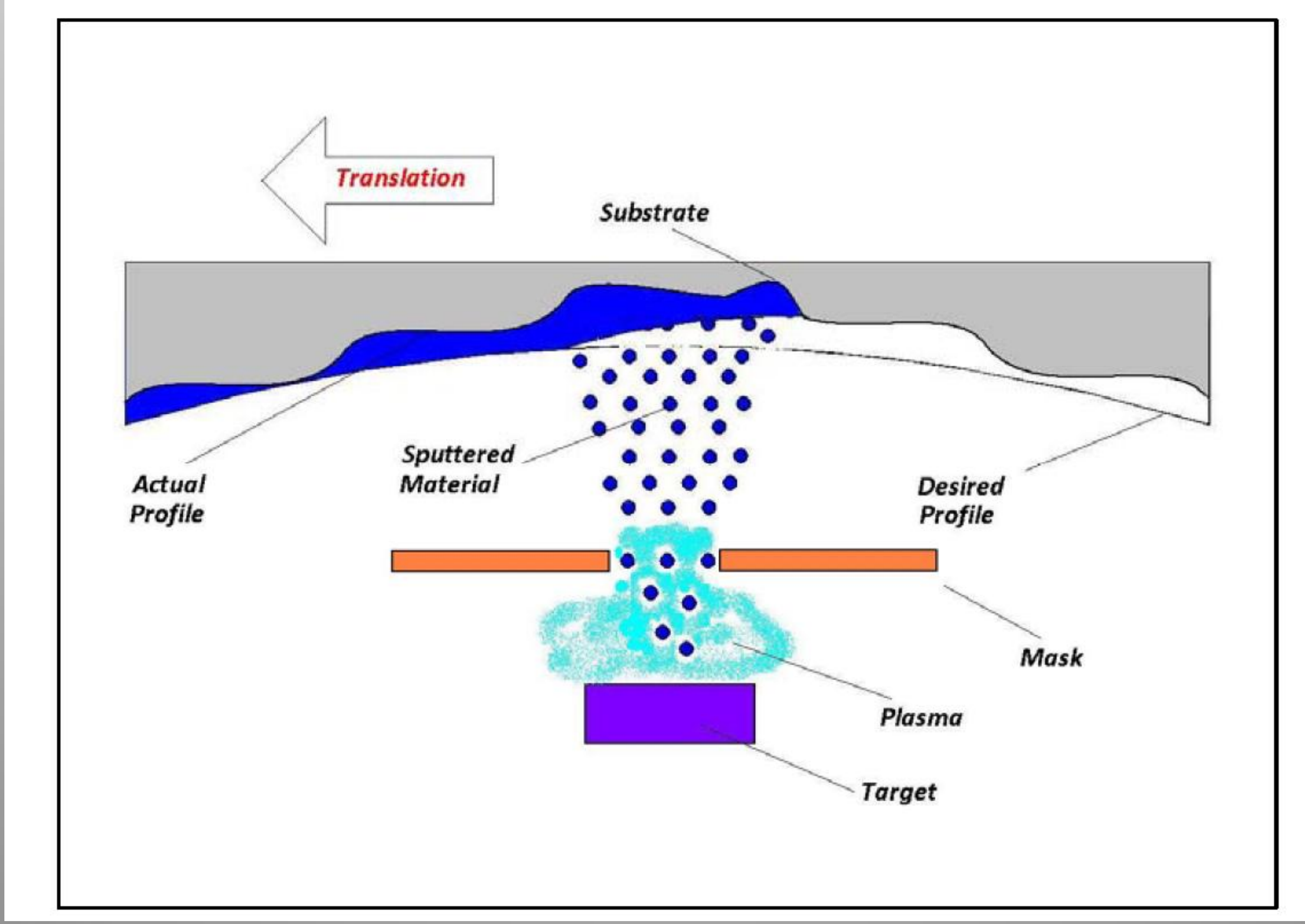


Figure deviations degrade imaging quality

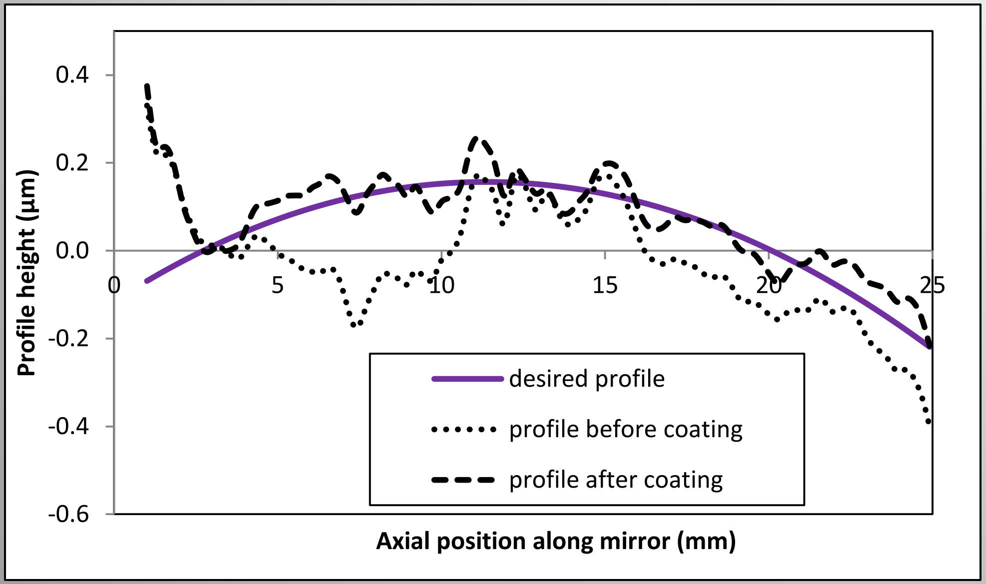
Mirrors for Future – Differential Deposition

Vacuum deposit a filler material to compensate for figure imperfections

Proof of concept work underway at MSFC



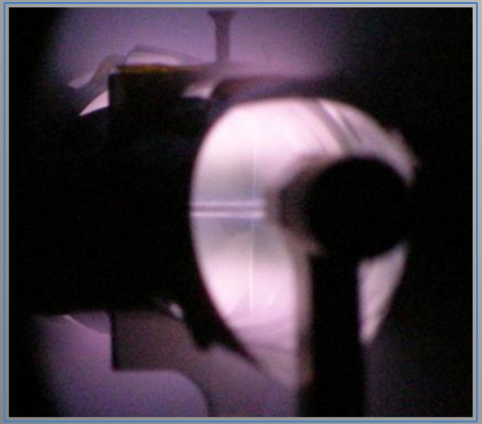
Proof of concept

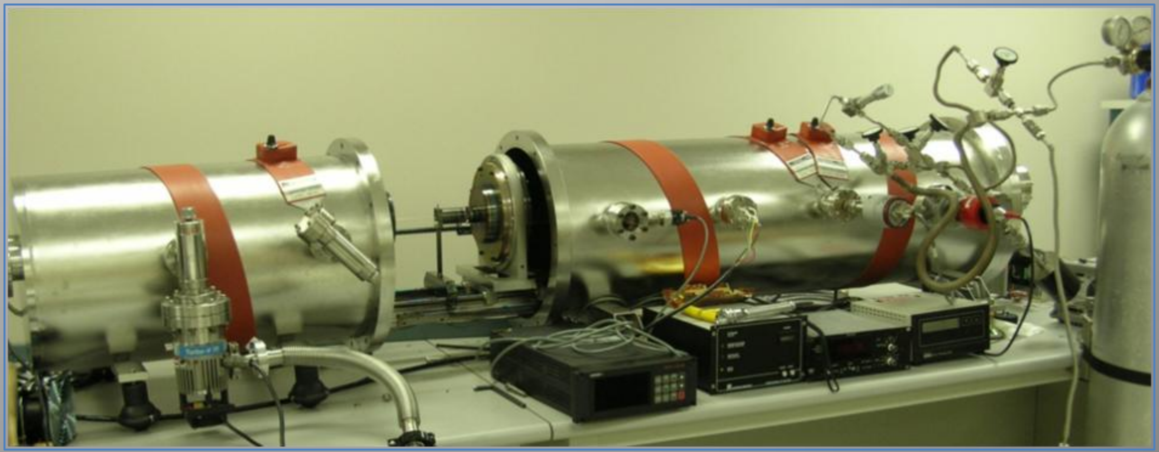


RMS difference improvement from 0.11 µm to 0.058µm

RMS slope error improvement from 12 arc sec to 7 arc sec

The shell mirror was replicated from the mandrel used for neutron optics fabrication.





Theoretical performance improvement

Correction stage	Average deposition amplitude (nm)	Slit-size (mm)	Metrology uncertainty (nm)	Angular resolution (arc secs)
1	300	5	± 0	3.6
			± 10	3.6
			± 50	7.3
2	40	2	± 0	0.6
			± 1	1
			± 5	2
			± 10	3.5
3	4	1	± 0	0.2
			± 0.5	0.2
			± 1	0.5
			± 2	0.8

- Simulations performed on X-ray shell that has 8 arc sec HPD
- Potential for ~arc-second-level resolution – with MSFC's metrology equipment
- Sub-arc sec resolution can be achieved with the state-of-art metrology equipment

Multilayer coatings

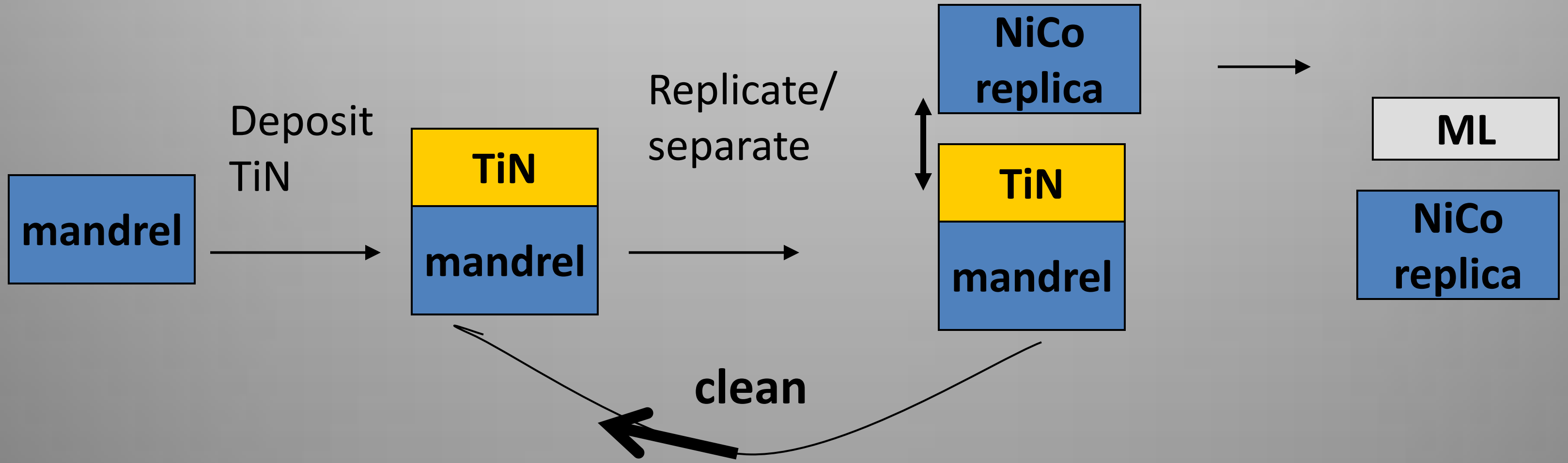
Typical release layers for nickel electroforming:
Gold (ebeam)
Nickel oxide

Ideal Properties for release layer

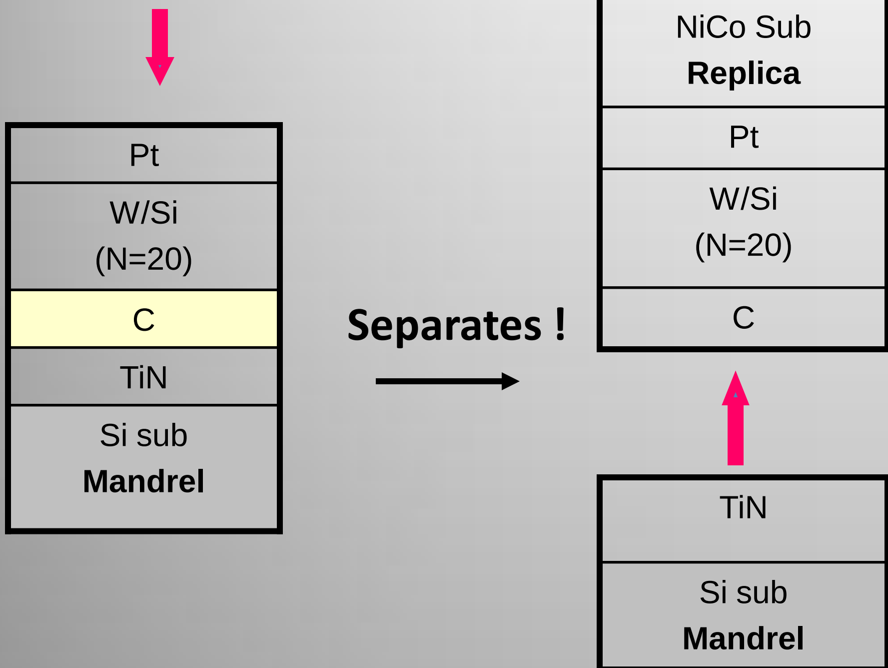
- Smooth (< 4 A microroughness for ML)
- 'Non-sticky'
- High Vickers hardness
- Low stress

Titanium Nitride: conductor, extreme hardness

Material	**Vickers Hardness**	**Density** (g/cm^3)
Ni	~700	8.9
TiN	~2200	5.3
SiC	~2500	3.2



X-ray multilayer coatings

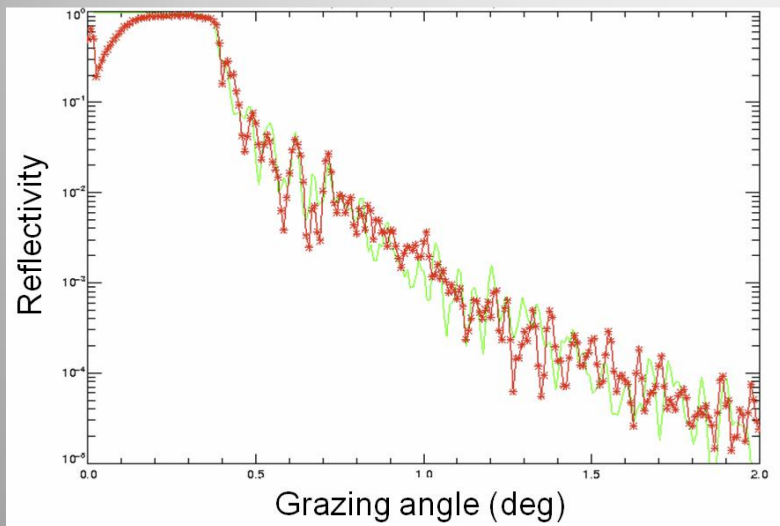


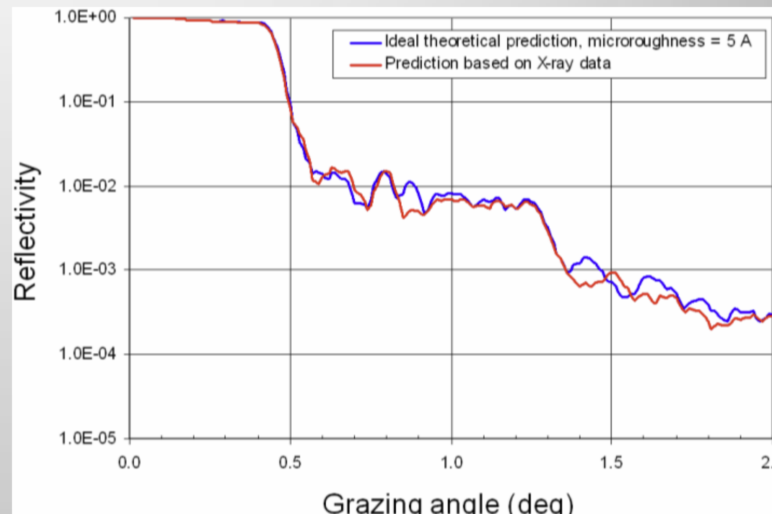
TiN coated mandrel (left in figure) and 150 µm thick NiCo replicated shell. Mandrel is 25mm diameter x 45mm height

- Deposited thick TiN coatings polished to 3Å µr
- Replicated > 20 times (NiCo from TiN); good surface
- Deposited thin TiN coatings (4 Å µr /AFM no polishing)
- Replicated W/Si MLusing carbon release and ‘no’ degradation of ML structure
- Replicated NiCo shell from TiN coated conical mandrel

Neutron multilayers

NiC/Ti continuously graded film with m=2.0, R=90%, N=19 on SPFS





X-ray reflectivity (red) and a model fit (green), taken using λ = 1.54 Å. Layer thicknesses are: 85 Å< NiC < 390 Å; 71 Å < Ti < 141 Å.

Simulated data for neutron reflectivity *at wavelength of 2.35 A*vs. graze angle of the NiC/Ti continuously graded film. Red is predicted response based on 1.54 Å X-ray data; Blue is ideal prediction based on interface microroughness of 5 Å.

SAO DC magnetron sputtering chamber has 22 inch diameter x 14 inch height.

- Neutron reflectivity measurements
- Transfer the coating process to nickel flats
- Replication from the flats
- Replication from curved mandrels

Part II

Boris