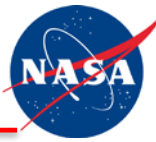


SCIENCE RESEARCH & PROJECTS DIVISION/ST10



X-Ray Optics at MSFC

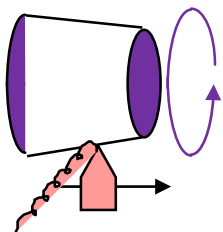
Brian Ramsey, Steve Bongiorno, Dave Broadway



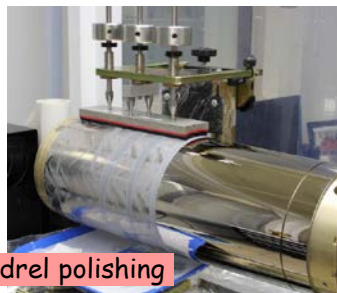
1. Electroformed nickel replication (ENR)– Brian Ramsey
2. Computer-controlled polishing – Steve Bongiorno
3. Full shell optics by direct fabrication – Steve Bongiorno
4. Differential deposition – Brian Ramsey
5. Low-stress coatings – Dave Broadway
6. X-ray optics process flow / Conclusion – Steve Bongiorno

Electroformed Nickel Replication (ENR)

Mandrel - machining Al bar, electroless nickel coating, diamond turning and polishing

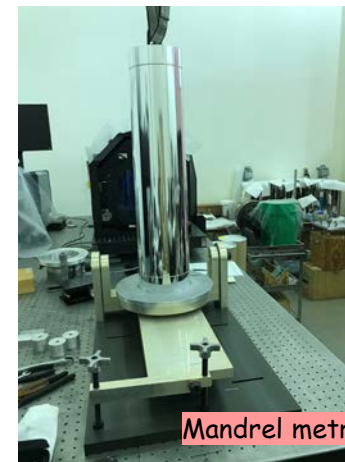
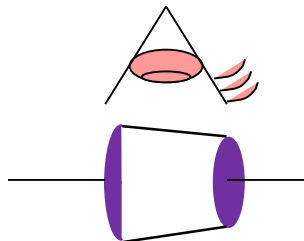


Mandrel diamond turning



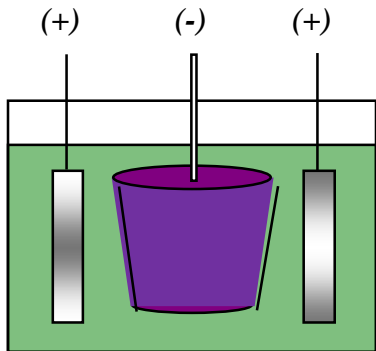
Mandrel polishing

Metrology on mandrel



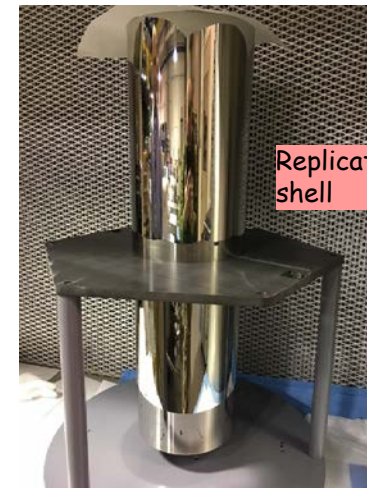
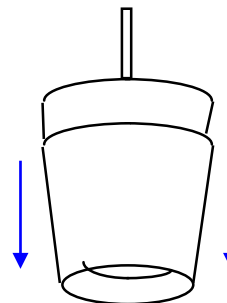
Mandrel metrology

Electroform Ni/Co shell onto mandrel



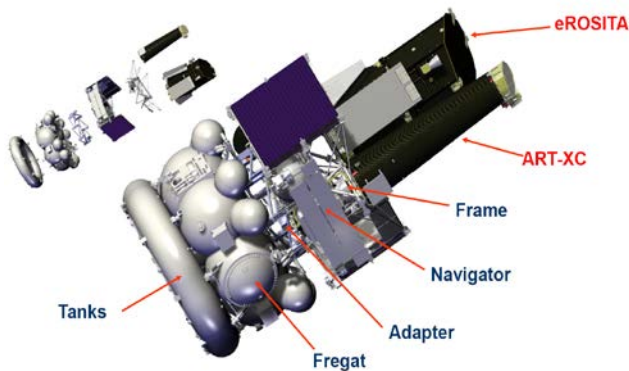
X-ray shell electroforming

Separate optic from mandrel in cold water bath

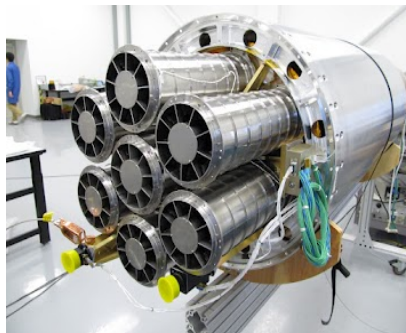


Replicated X-ray shell

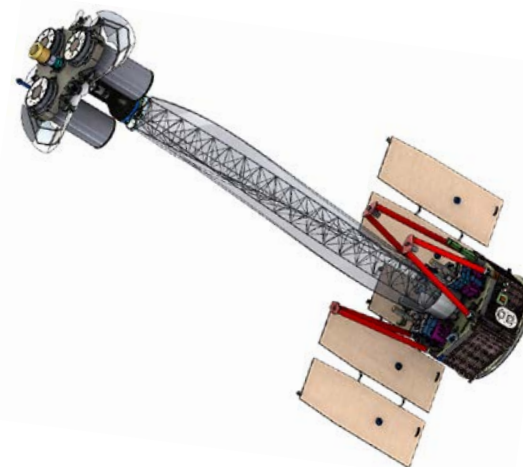
ART-XC instrument on Spectrum Rontgen Gamma Mission



FOXSI (Rocket)



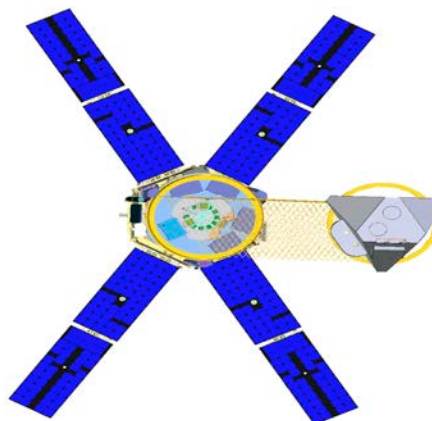
IXPE Small Explorer



HERO

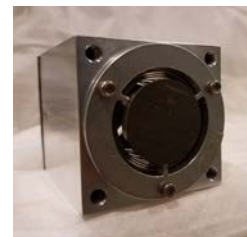


FOXSI Small Explorer (Phase A study)

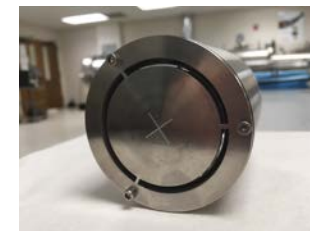


Non-Astronomical Applications

Neutron Imaging



Plasma Diagnostics



New Developments

Challenge

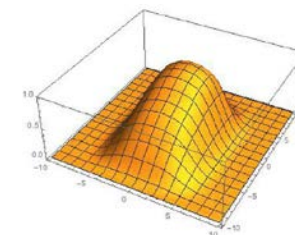
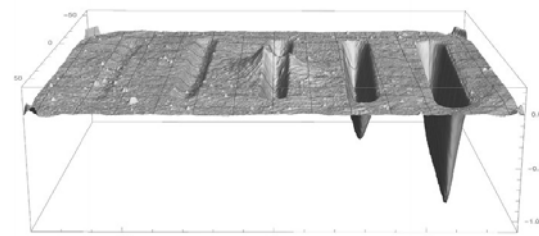
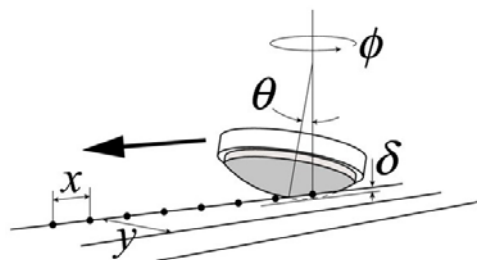
- The optical figure of mandrels used to produce replicated nickel cobalt grazing incidence optics directly impacts performance of the optic.

Objective

- Reach sub-arcsecond half-power diameter (HPD) mandrel figure error to enable future missions.

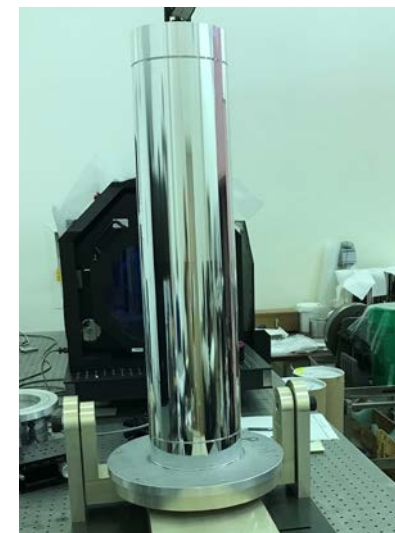
Approach:

- Test methods for aligning Zeeko CC polishing machine coordinates with mandrel coordinates with mandrel fiducials.
- Continue improving surface roughness and polishing wear function stability by adjusting abrasive slurry parameters.
- Polish mandrels with Zeeko machine for shape correction and super polish with large laps to achieve final surface roughness.
- Estimate finished mandrel performance with mandrel metrology on Zygo interferometer at MSFC.

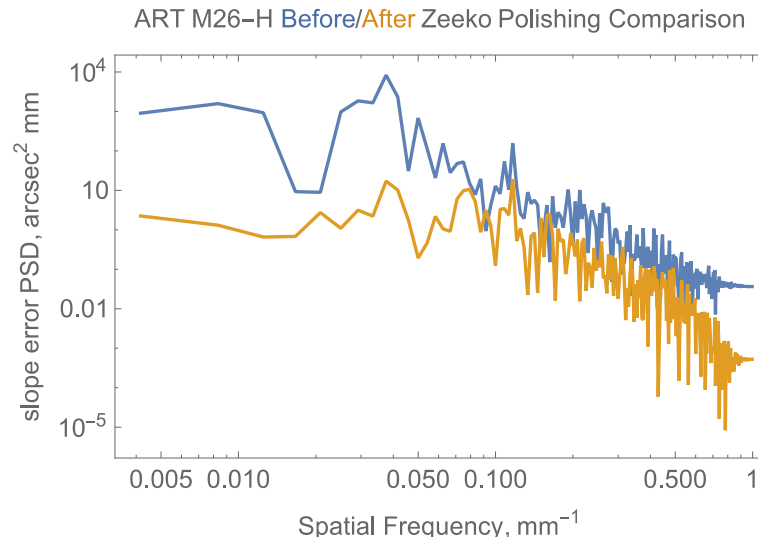
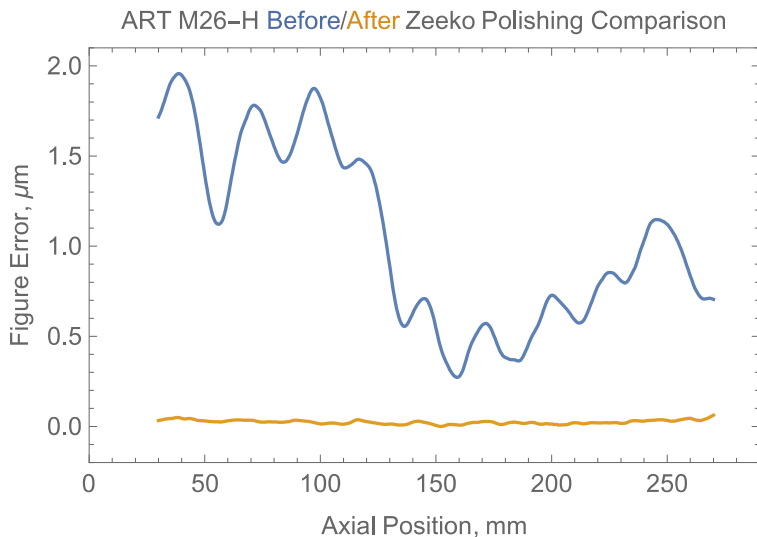


CC polishing process loop

1. Characterize machine/bonnet wear
2. Map optic/mandrel surface error
3. Deconvolve surface error map with wear function to generate toolpath
4. Polish optic
5. Iterate



Cylindrical Correction Complete, azimuthal average, Polishing time: 71.5 hours



	before	after
Figure error (St. Dev.)	500 nm	10.7 nm
Slope error (> 2 cm) (RMS)	6.32 arcsec	0.30 arcsec
Low frequency (> 7 cm) slope error (RMS)	2.66 arcsec	0.09 arcsec
Mid frequency (2-7 cm) slope error (RMS)	5.73 arcsec	0.29 arcsec

Full width at half max $\approx 6.66 * \text{RMS slope error} = 2.00 \text{ arcsec}$

TRL Level

Currently at ~ 3

Challenges and future work

- Complete test mandrel polishing and quantify surface quality improvement.

Applicable to Athena

Yes, for direct polishing of full-shell optics.

Challenge

- Future X-ray missions require large effective area, lightweight, high angular resolution grazing incidence optics.

Objective

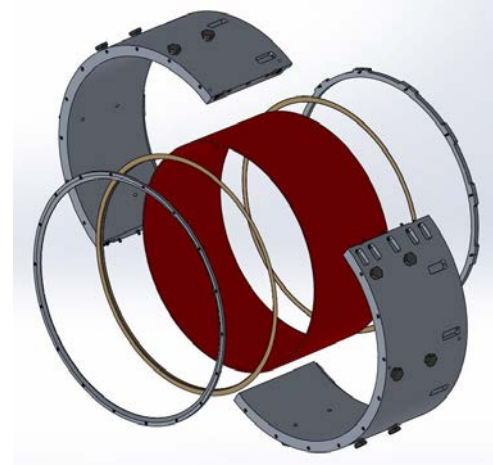
- Using high specific stiffness metal materials (Be, AlSi, AlBe), produce sub-arcsecond grazing incidence full-shell optics approximately 3 mm thick.

Approach:

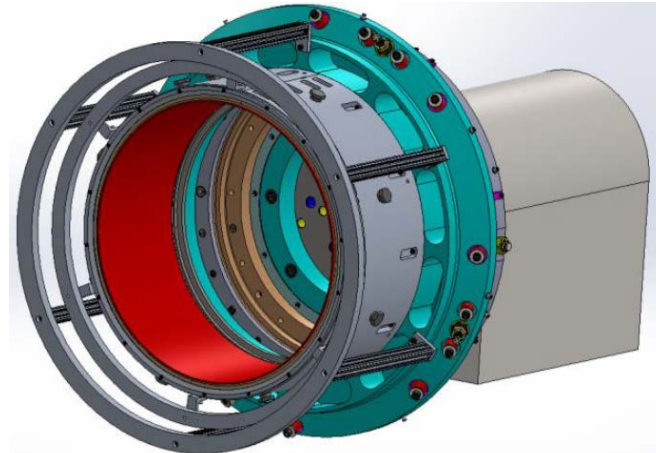
- Diamond turn inner and outer surface of as-purchased metal/metal-composite shells.
- Implement in-situ metrology to measure the shape of the shell while mounted in the polishing machine.
- Directly polish shells in the Zeeko machine at MSFC.
- If needed, apply differential deposition in chamber at MSFC to improve mid-spatial frequency shape error.



Aluminum surrogate shell



Shell support structure



Shell support structure
mounted to diamond
turning machine

TRL Level

Currently at ~ 2

Challenges and future work

- Delivery of 3 mm thick figured and polished NiP plated aluminum shell
- Design of X-ray test support fixture, and cross-calibrated verification of in-situ metrology system. Delivery of X-ray test support fixture and verification of the 3 mm and 1.5 mm thick mirrors via X-ray testing.

Applicable to Athena

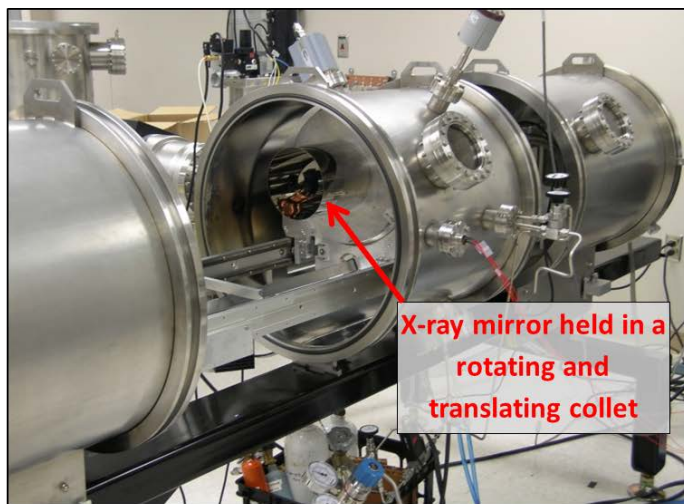
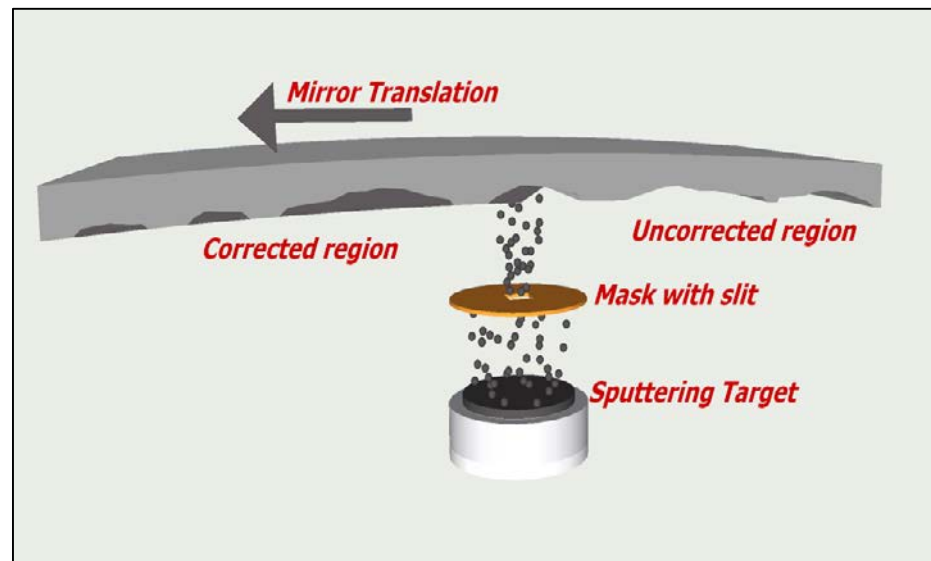
Yes, for direct polishing of full-shell optics.

Objective

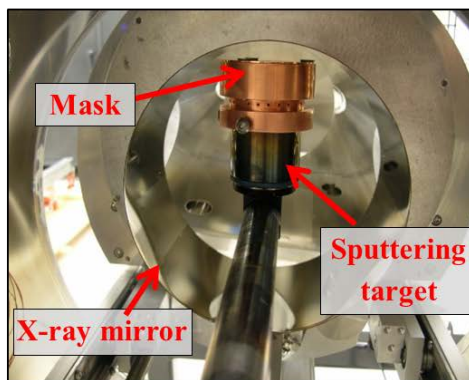
Develop a process to provide post-fabrication improvement to x-ray optics

Approach

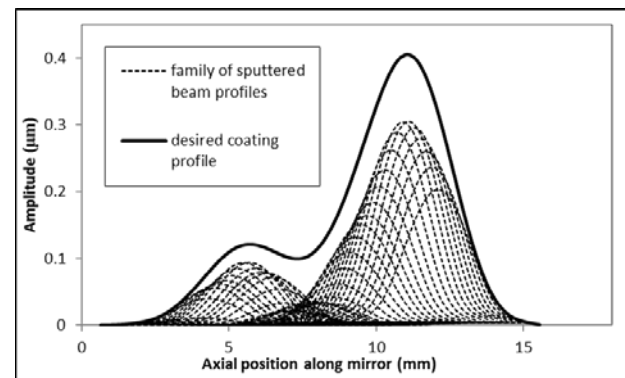
Use physical vapor deposition to selectively deposit material on mirror surface to reduce figure errors



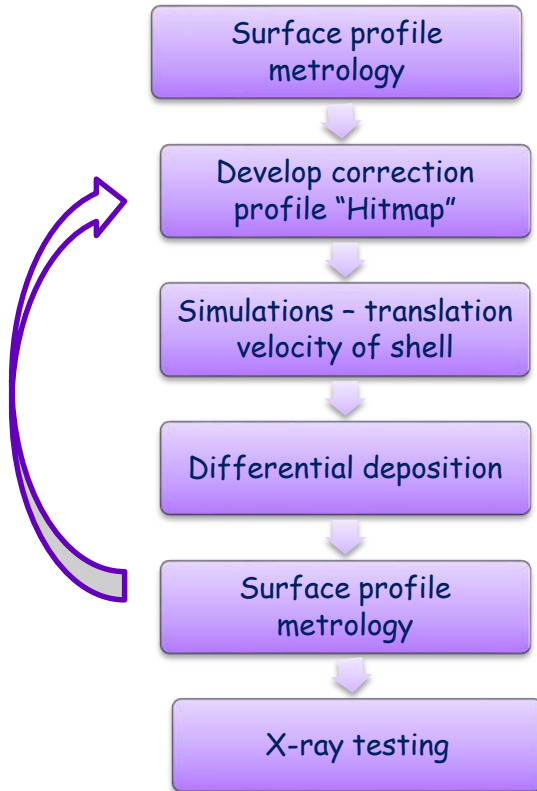
Horizontal differential-deposition chamber



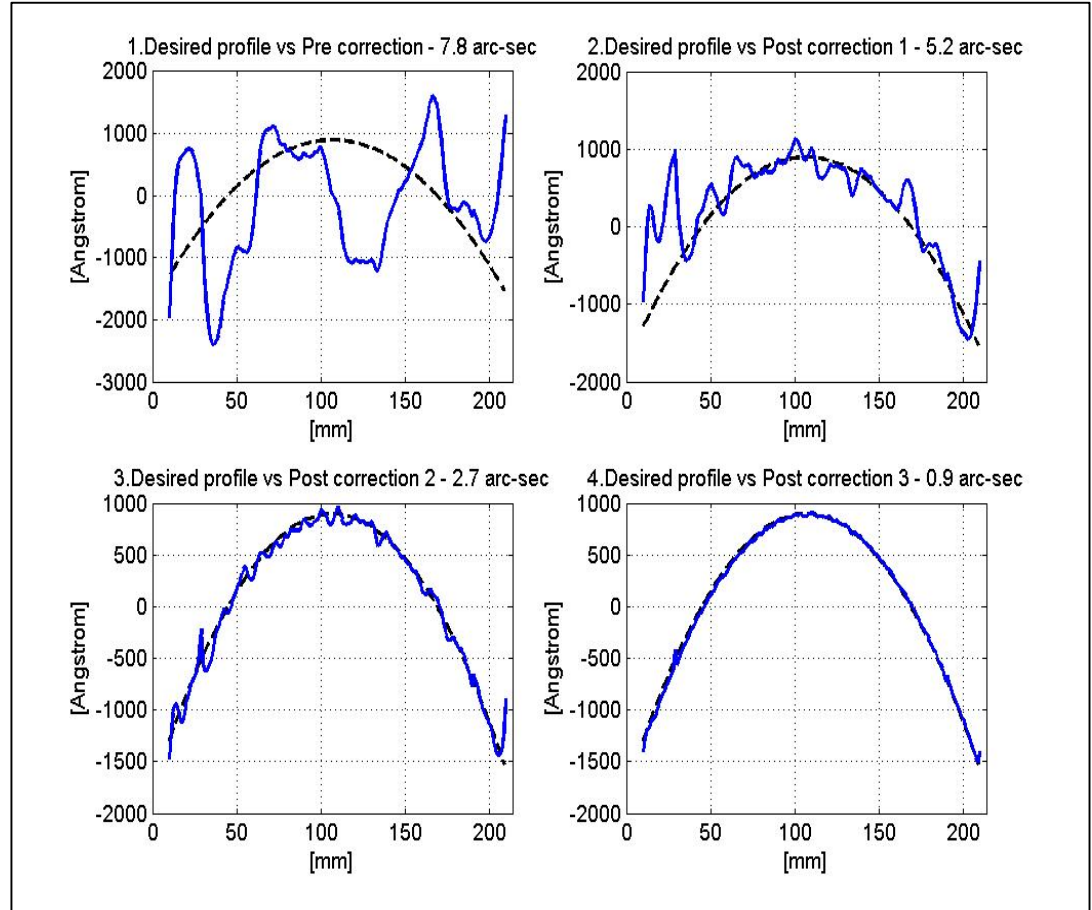
Sputtering head with copper mask positioned inside shell



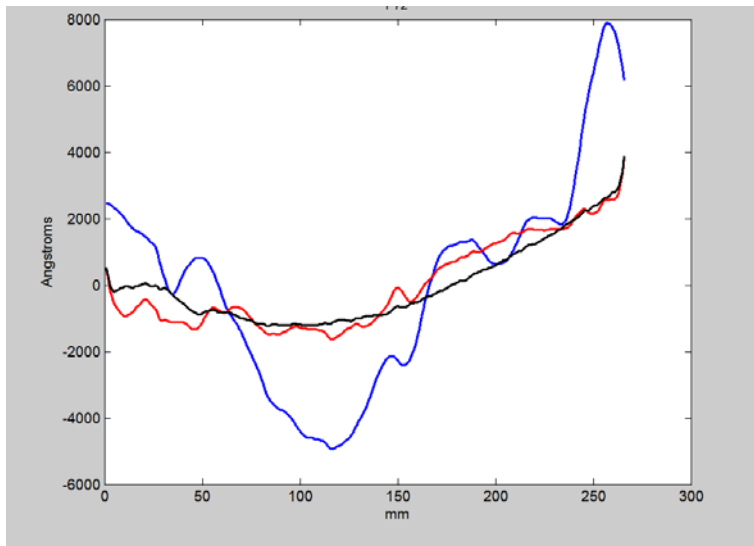
Differential deposition process flow



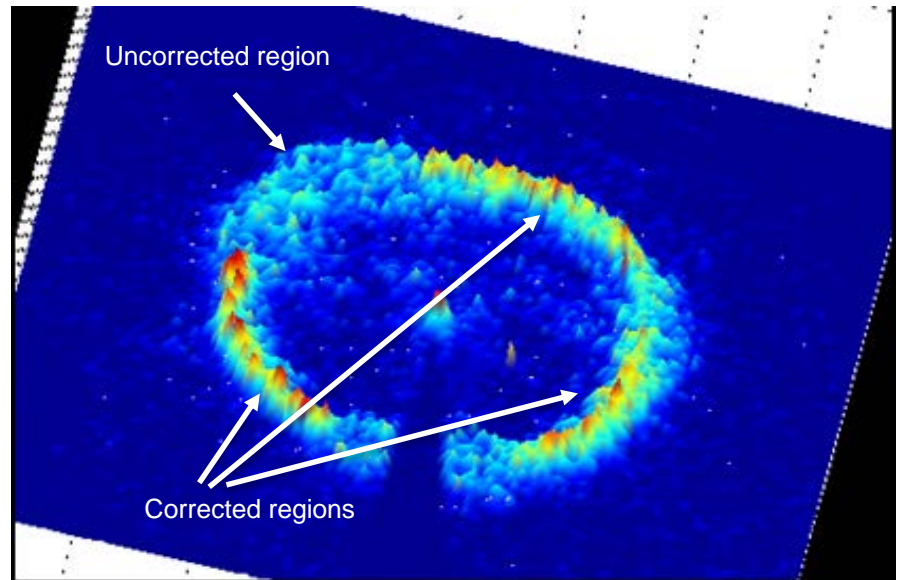
Simulation of successive corrections with finer slits



Axial figure profiles: Initial (blue), after 1 correction pass (red), after 2 correction passes (black)



Intra-focus x-ray image showing uncorrected and corrected mirror quadrants



- Using ART-XC mirror shells , have obtained a factor of > 2 improvement in angular resolution for a single stage of correction from 17 arcsec to 7.2 arcsec HPD.
- Metrology on mirror shell with 2 stages of correction shows factor of 3 improvement from 17 arcsec to 5 arcsec HPD.

TRL Level

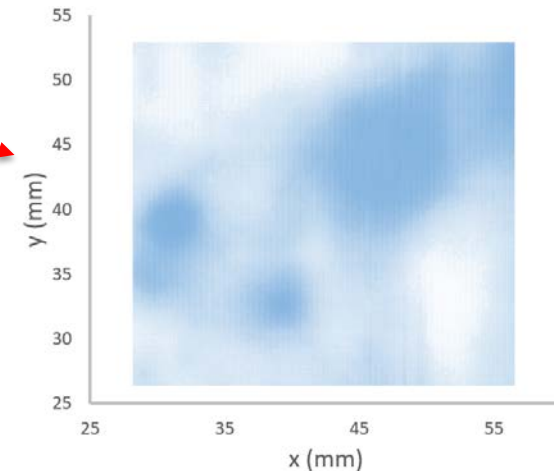
Currently at ~ 3

Challenges and future work

- Assess coating-stress effects.
- Implement active slits to compensate for change of internal diameter of shell with length (less of a challenge for large-diameter optics)
- Develop in-situ metrology
- Develop custom masks for rapid correction

Applicable to Athena

Yes, for figure control of full shell (or segmented) optics.



Challenge

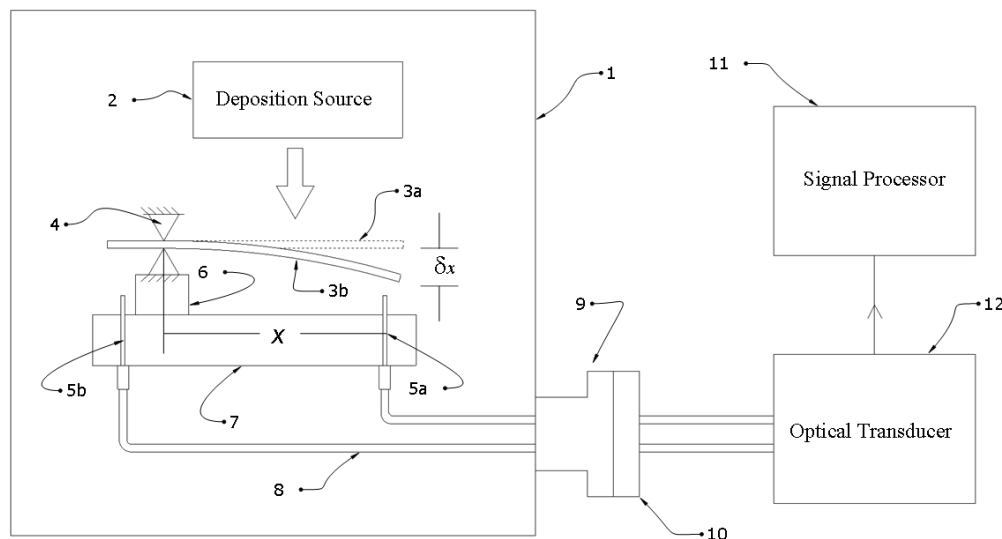
- Small amounts of coating stress can significantly distort a large thin-shell optic.
 - Preservation of substrate figure after deposition of x-ray reflective coatings is a leading technological challenge.

Objective

- Develop advanced low stress x-ray optical coatings (single-layer and multi-layer) that will enable future missions.

Approach:

- The use of a proven novel highly-sensitive method of in-situ stress measurement that will be adapted to curved substrates.
 - Investigate stress growth in films and methods for its reduction.
- The design and implementation of a novel single and multilayer coating scheme for achieving inherently uniform coatings on flat and curved segments.

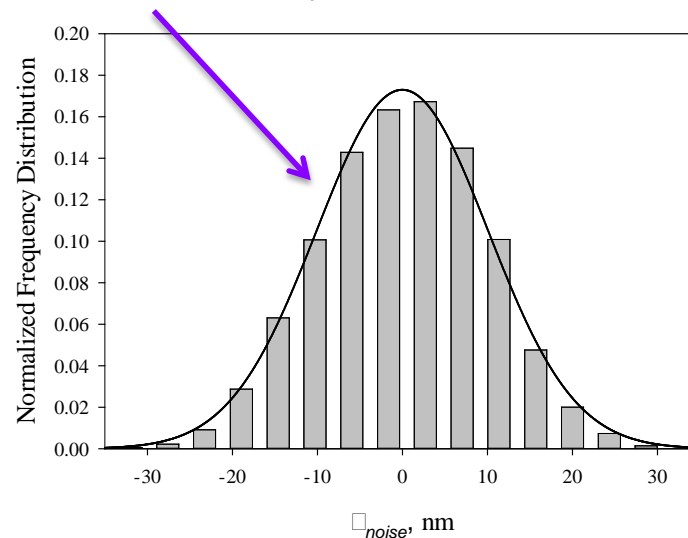


- Film stress deforms figured substrates and degrades imaging resolution.
- We measure stress in-situ using a high resolution (i.e. 5 nm) fiber optic displacement sensor.
- The sensor measures the cantilever tip deflection caused by the film stress which is calculated using the Stoney Eqn:

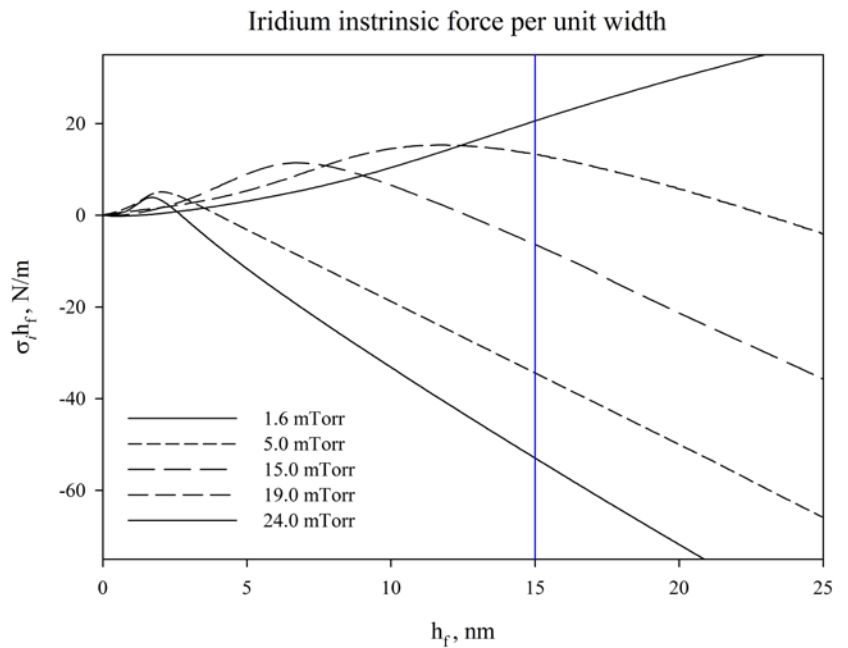
$$\sigma h_f = \frac{E_s h_s^2 \delta_x}{3(1 - \nu_s) x^2}$$



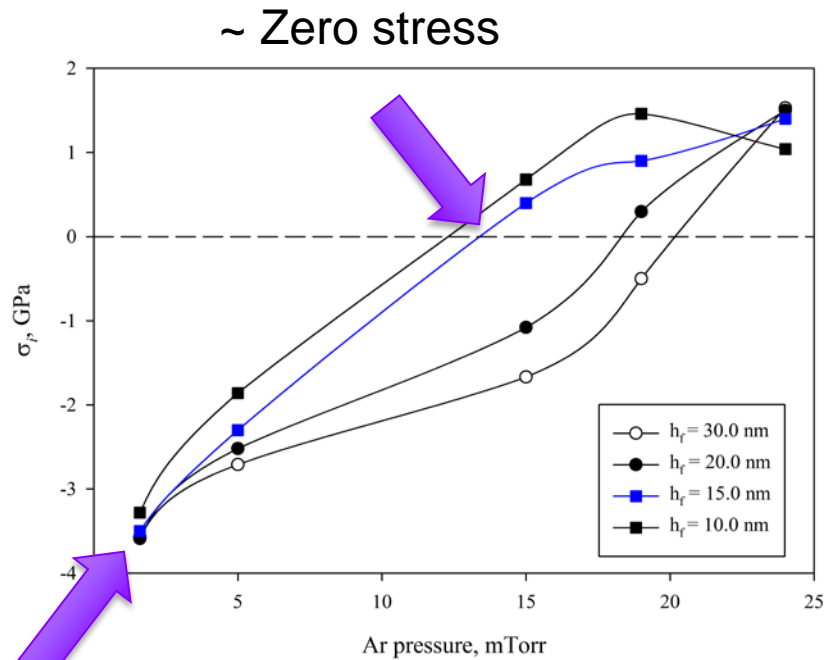
25 MPa*nm sensitivity



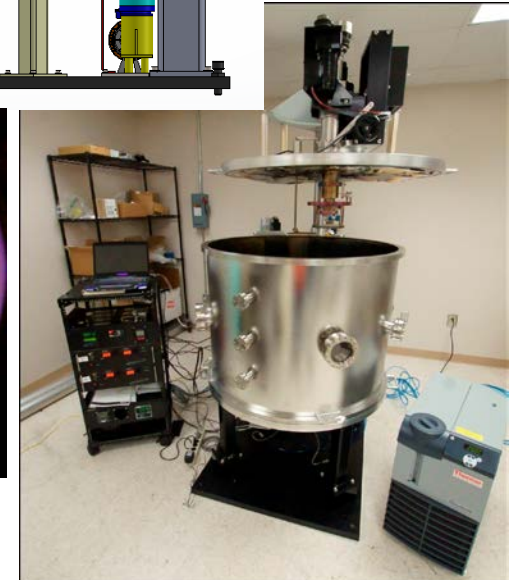
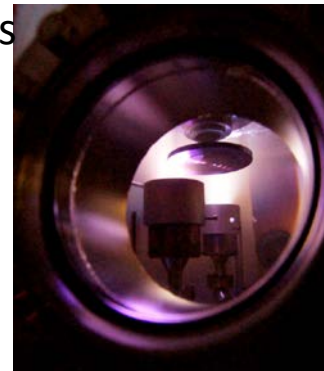
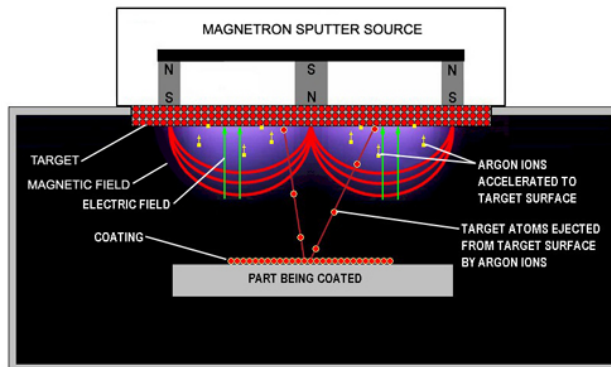
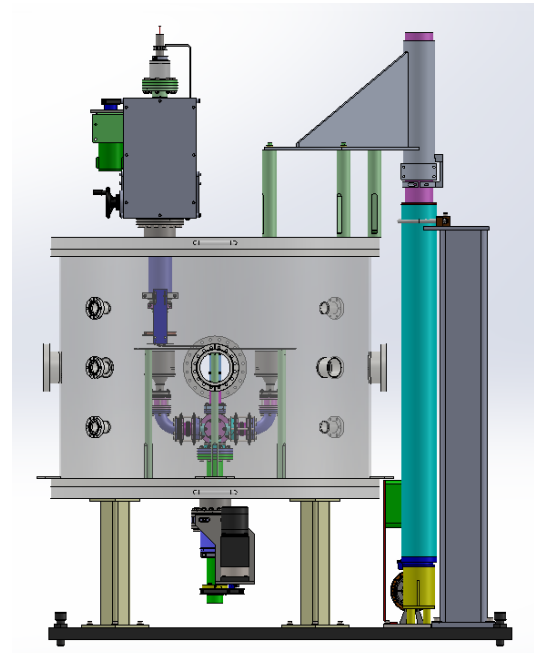
- The requirements for missions are typically satisfied with 10-20 nm of Ir
- Through Ar pressure optimization we can reduce the stress to near zero (measured 3 orders of magnitude decrease)
- Surface roughness increases from 3 to 4.5Å

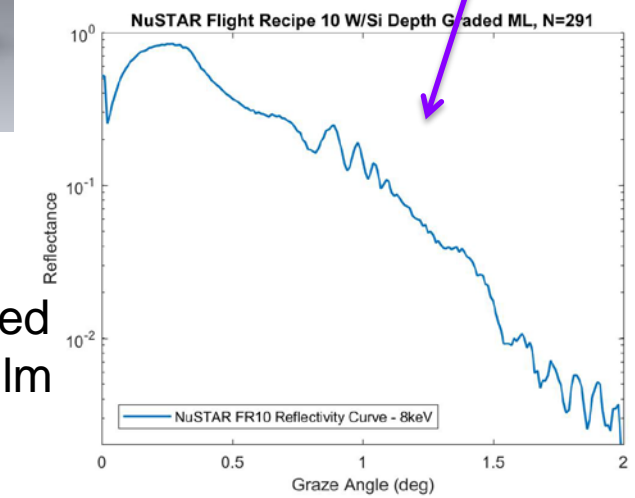
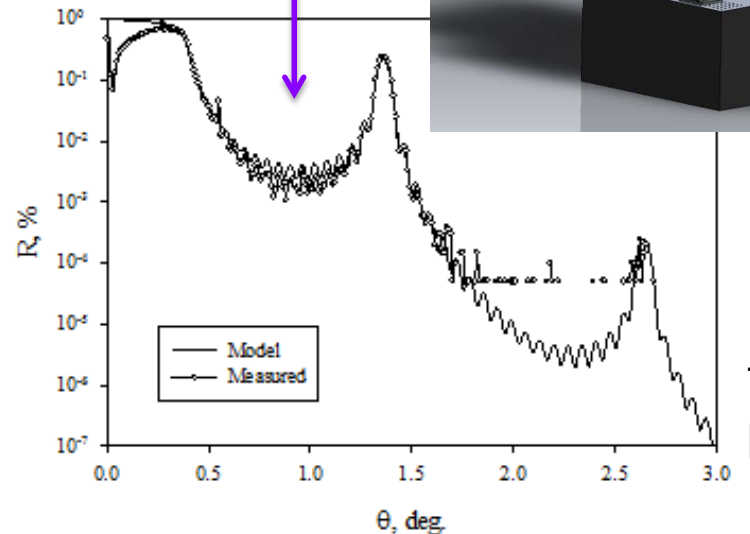
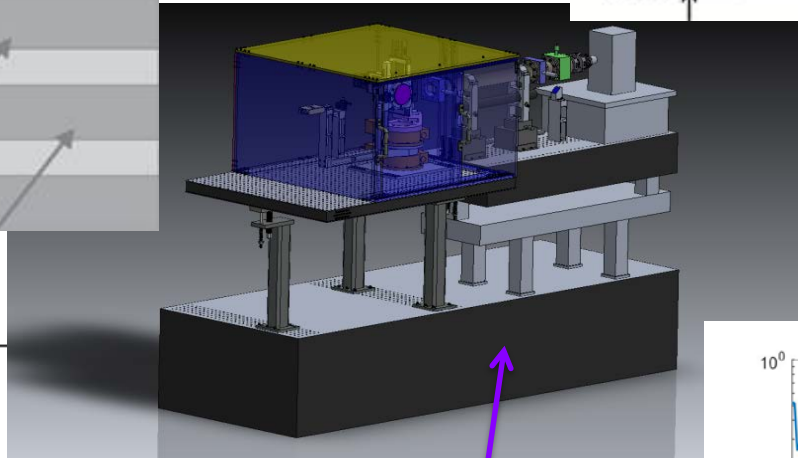
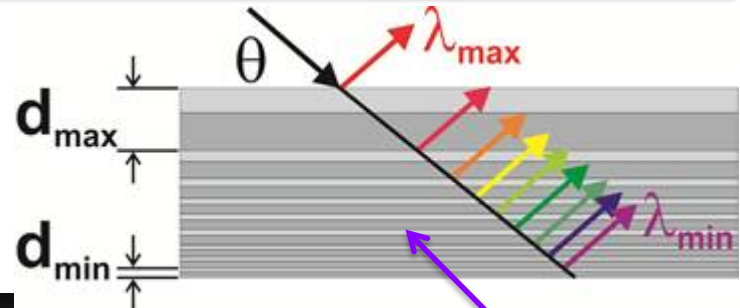
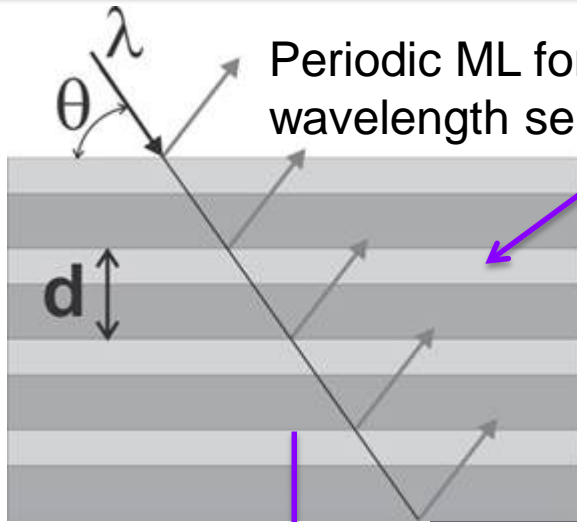


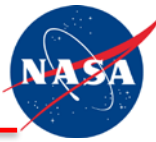
-3.7 GPa



- Procured with MSFC innovation funding (CIF) award
- For development of depth graded ML's
Designed for flexibility in deposition geometry
- Currently utilizes up to four 2 in. dia. circular cathode positions
- Ion milling capability
- Spinning substrate holder
 - Holds up to 4 inch dia. substrates
 - Bias can be applied
- Future work includes system upgrade to expand capability to coat segmented substrates







TRL Level

Currently at ~ 3

Accomplishments

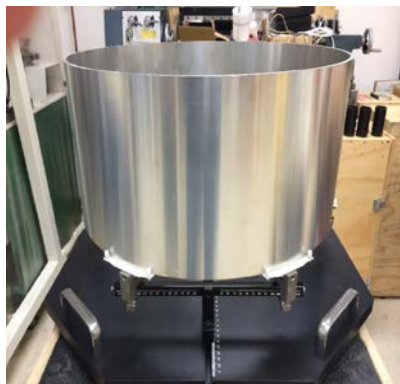
- Reduced iridium coating stress by three orders of magnitude by exploiting the film's growth mechanism that was revealed by in-situ stress measurement capability.
- Demonstrated approach for achieving targeted reflectivity response of the depth graded multilayer coatings.

Challenges and future work

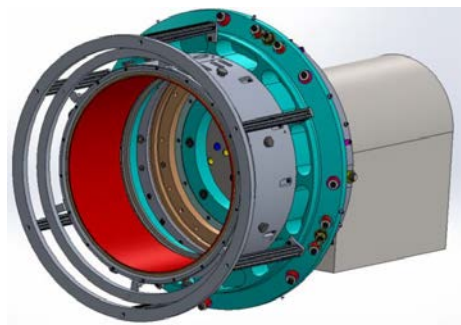
- Completion of new deposition system design to enable the coating and in-situ stress measurement of curved optical segments
- Development of in-situ stress measurement during thermal annealing processes

Applicable to Athena :

Yes, to maintain figure of full shell (or segmented) optics.



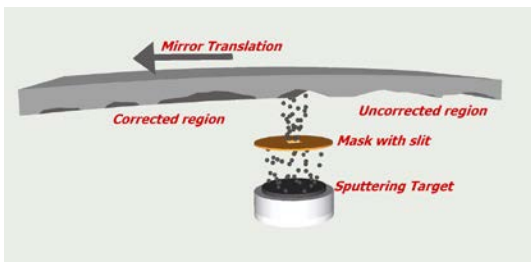
Machined mirror blanks



Diamond turning
TRL~2



Computer controlled polishing
TRL~3



Differential deposition
TRL~3



Low-stress reflective coatings
TRL~3



Alignment and module integration
TRL~3