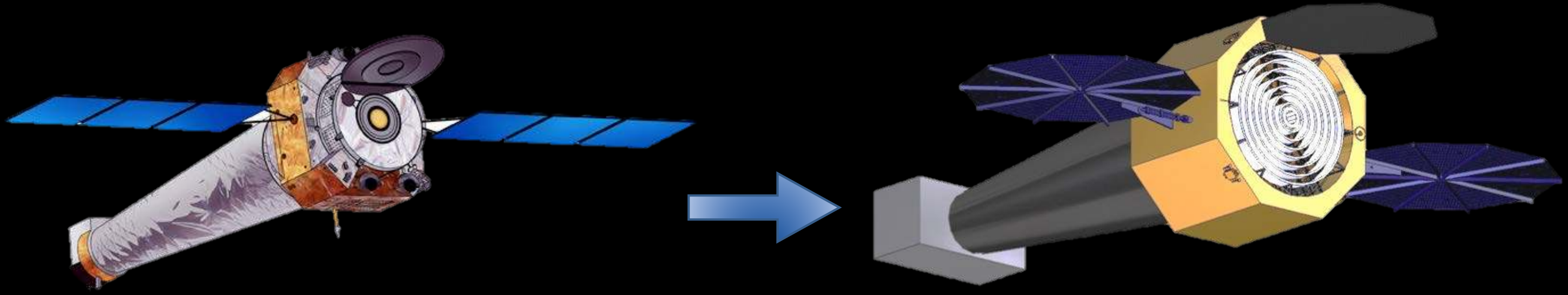
Adaptive X-ray Optics IV (SPIE 9965)
2016 August 28; San Diego, CA (USA)

Toward large-area sub-arcsecond x-ray telescopes II



Chandra X-ray Observatory (1999-?)

X-Ray Surveyor concept (~2035?)

Steve O’Dell
NASA Marshall Space Flight Center
and co-authors

Authors represent most of the US effort toward sub-arcsecond x-ray telescopes.

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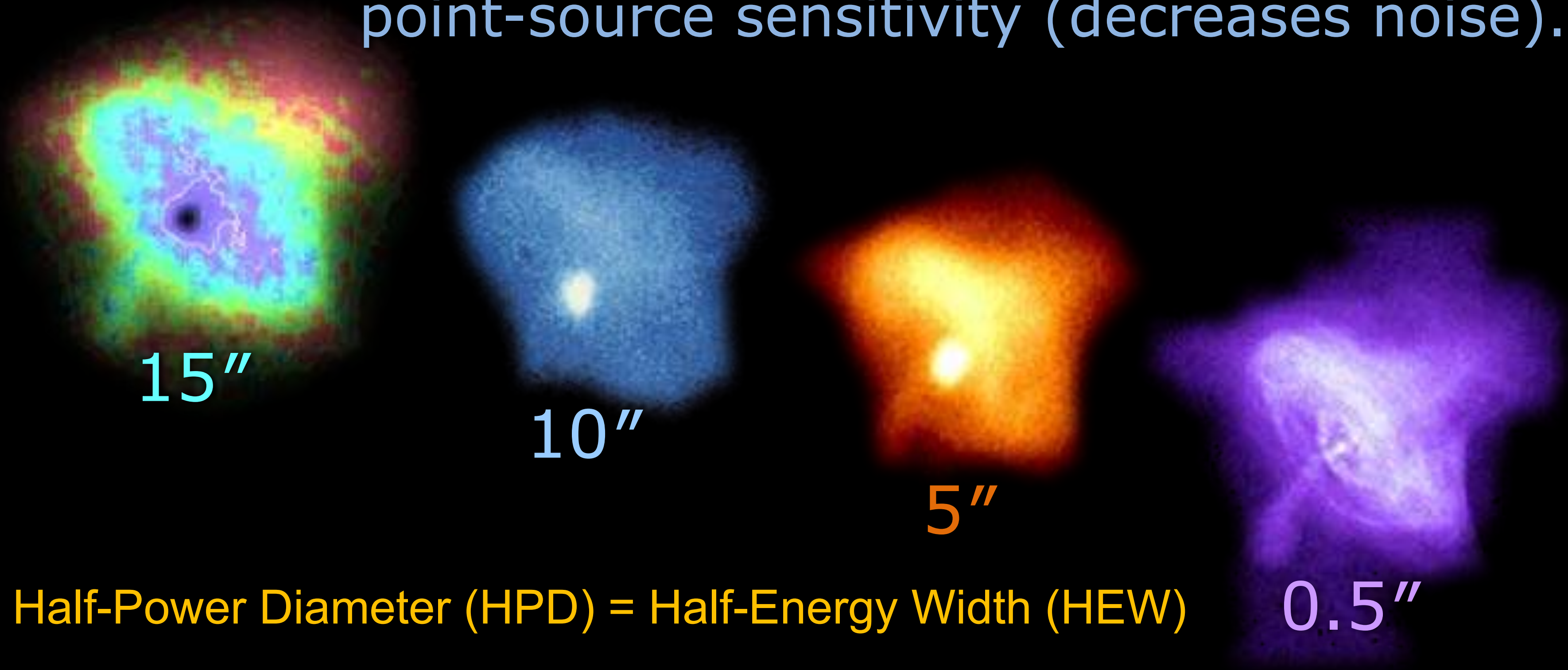
Key science metrics of an x-ray telescope are angular resolution and aperture area.

Finer angular resolution improves imaging quality and point-source sensitivity (decreases noise).



Half-Power Diameter (HPD) = Half-Energy Width (HEW)

Larger aperture area improves sensitivity (increases signal), down to angular-resolution confusion limit.

Outline

- Motivation and issues
- Categories of potential solutions
- Post-fabrication corrections

Outline

- Motivation and issues
  - ☐ Seek *Chandra* resolution with 30 × *Chandra* area.
  - ☐ Must resolve both technologic and programmatic challenges.
    - ○ Achieve aperture area and imaging performance within constraints of mass, envelope, cost, and schedule.
- Categories of potential solutions
- Post-fabrication corrections

2020 Decadal Survey in Astronomy and Astrophysics sets priorities for decade.

- National Research Council (NRC) conducts Survey for relevant Government agencies (NASA & NSF).
  - Addresses space-based and ground-based astronomy.
  - NASA typically adopts Decadal Survey’s priorities.
  - NASA will suggest space-based astronomy missions.
    - Four Science and Technology Definition Teams (STDT) are developing facility-class mission concepts for NASA.
      - X-Ray Surveyor
      - Far-IR Surveyor
      - LUVOIR Surveyor
      - Habitable Exoplanet Imaging (HabEx)
    - Only one of these is likely to start in the 2020s.
      - Expected launch date would be mid-to-late 2030s.

STDT is defining science-driven requirements for X-Ray Surveyor.

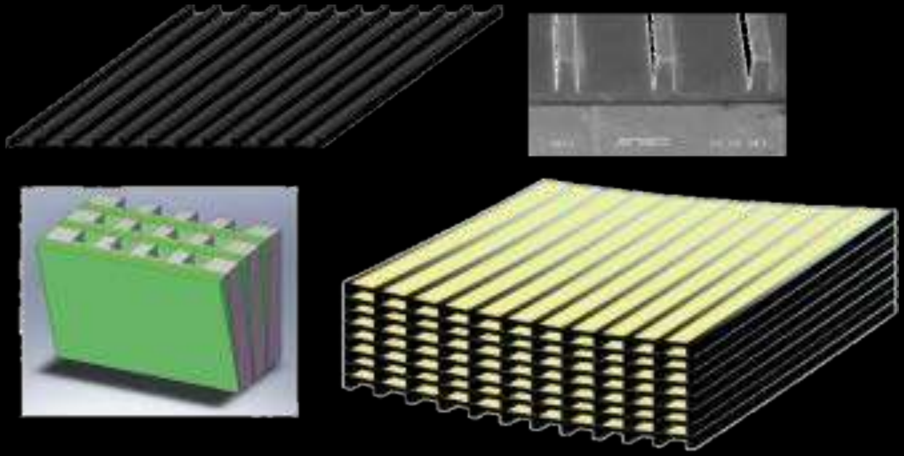
- Anticipate scientific need for an x-ray telescope with *Chandra*’s 0.5″ resolution and 30 × its area.
- There is general agreement on the top-level technologic and programmatic challenges.
  - Preserve *Chandra*’s angular resolution ≈ 0.5″ HPD.
  - Reduce mirror areal mass to *Chandra*/30 ≈ 1.5 kg/m^2.
  - Reduce mirror areal cost to *Chandra*/30 ≈ 1 M$/m^2.
- There is not general agreement on how to solve these challenges.
  - Stiff optics (rigidly supported over-constrained mirrors)
  - Static optics (fixed, moderately constrained mirrors)
  - Active optics (adjustable alignment | figure correction)

Outline

- Motivation and issues
- Categories of potential solutions
  - ☐ Stiff optics
  - ☐ Static optics
  - ☐ Active optics
- Post-fabrication corrections

ESA selected ATHENA as its 2nd large-class (L2) mission, for launch in 2028.

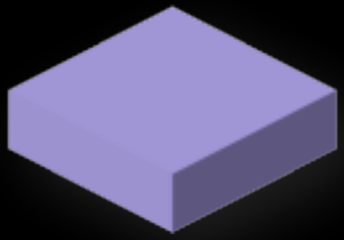
- X-ray mission is in study Phase A, working toward adoption around 2020.
  - Require HEW ≈ 5″.
- ATHENA will use stiff, silicon-pore optics (SPO).
  - Cosine Measurement Systems [NL] leads SPO technology development.
    - Processing and stacking of silicon wafers are highly automated.
    - Resulting rigid x-ray optics units are to be co-aligned.



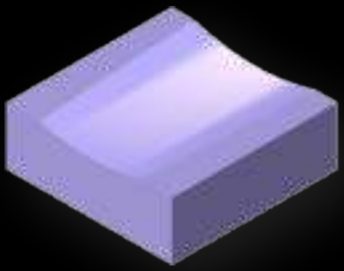
www.the-athena-x-ray-observatory.eu

ESA/ Marcos Bavdaz

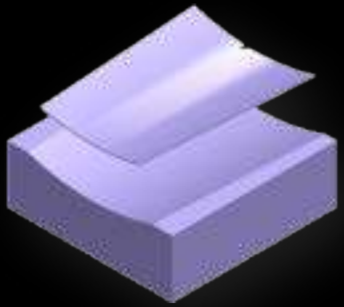
GSFC uses a novel process for light x-ray mirrors of monocrystalline silicon.



1. Procure single crystalline silicon.
2. Heat and chemically etch to remove all surface/subsurface damage.



1. Wire-EDM machine conical shape.
2. Heat and chemically etch to remove damage.
3. Polish to achieve excellent figure and micro-roughness.



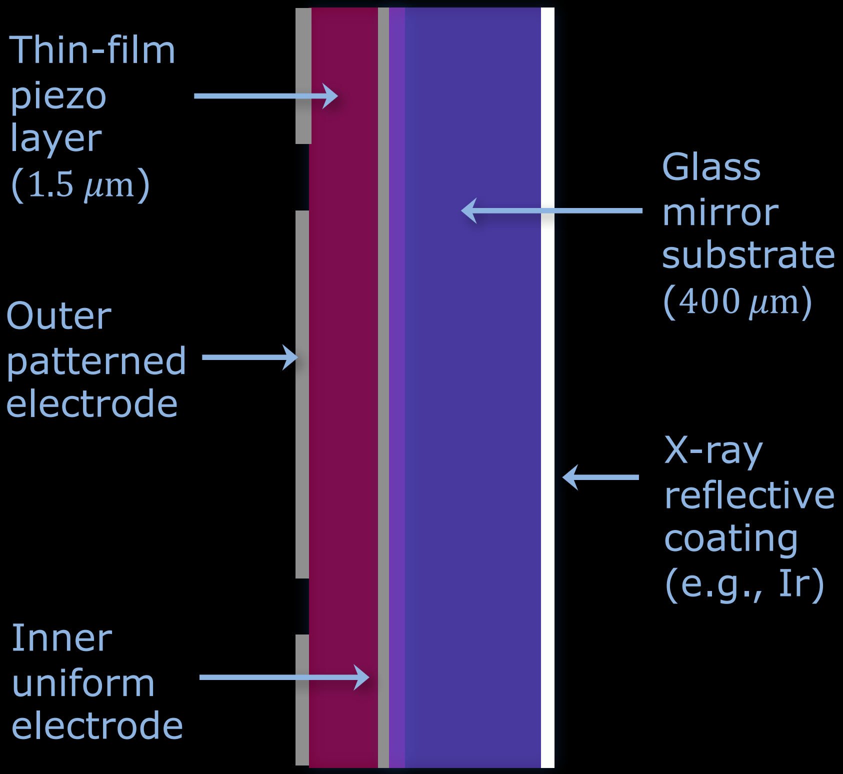
1. Use Wire-EDM to slice off the thin mirror segment.
2. Heat and chemically etch to remove all damage from back and edges.

- Advantages over glass
  - ❑ No internal stress
    - Distortion-free material removal after etching
  - ❑ Ideal material properties
    - High thermal conductivity
    - Low thermal expansion
    - High elastic modulus
  - ❑ Better performance
    - Made mirrors < 3″ HEW$_2$
    - Aim to build ~ 1″ mirror stack by end 2017
    - Aim to build ~ ≥.;1″ meta-shell by end 2019.

GSFC/ Will Zhang

SAO is developing lightweight active x-ray optics with thin-film piezo arrays.

- Piezoelectric array corrects figure through surface-parallel actuation

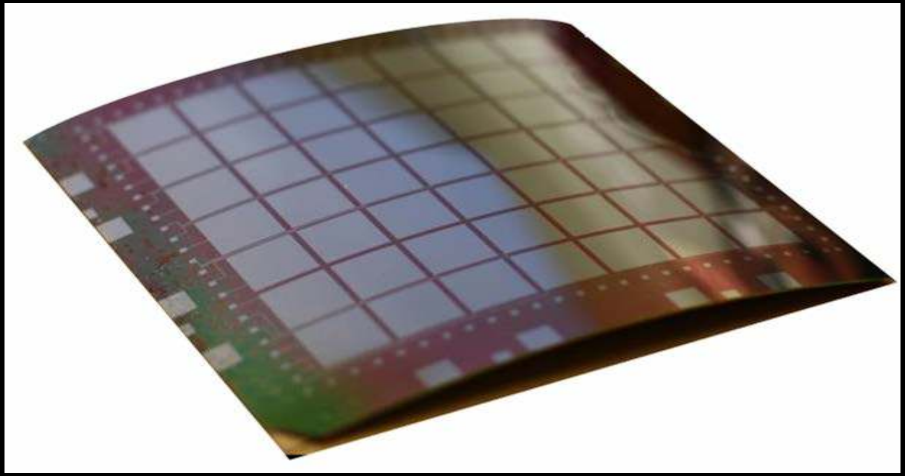


- PSU is fabricating thin-film piezoelectric arrays.
  - ❑ Slumped-glass mirrors from SAO (OAB)
  - ❑ Piezoelectric (PZT) on conductive film, high-T crystallized and annealed
  - ❑ Patterned electrode array with ZnO TFTs
    - ○ Row-column addressing
    - ○ Anisotropic Conductive Film (ACF) connections
  - ❑ Integral T-compensated strain gauges

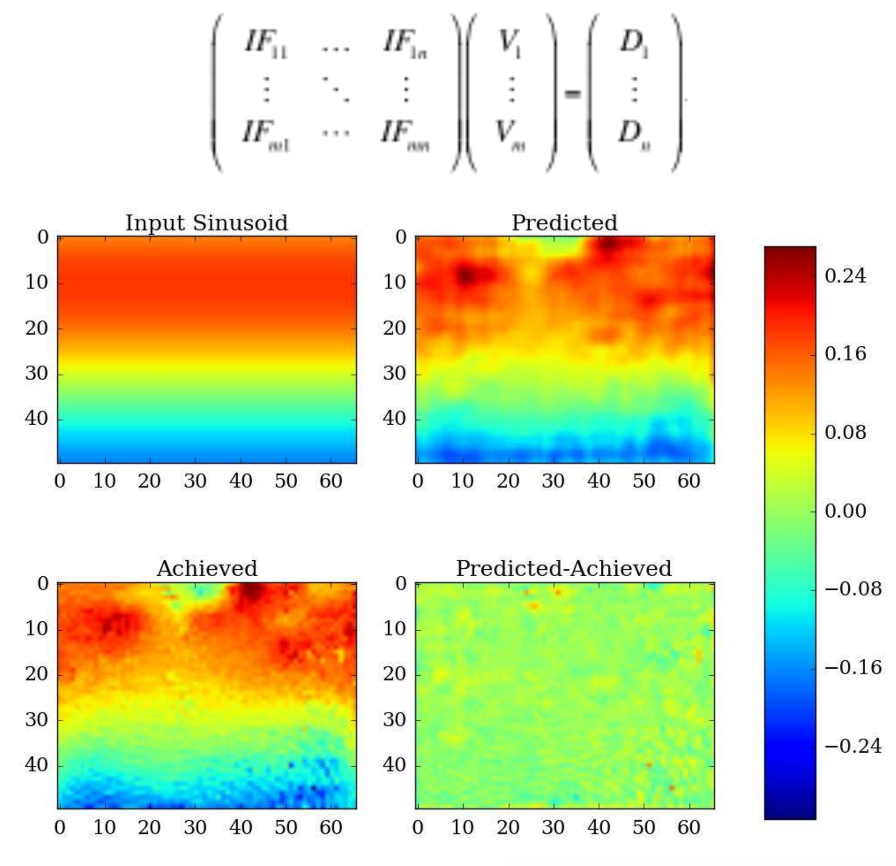
SAO/ Paul Reid

Correction uses calibrated influence functions to determine array voltages.

- Adjustment methodology
  - ☐ Shack-Hartman wavefront sensor metrology
    - ○ Calibrate influence function
    - ○ Measure mirror figure
  - ☐ Calculate and apply voltages for correction



- Correction matrix

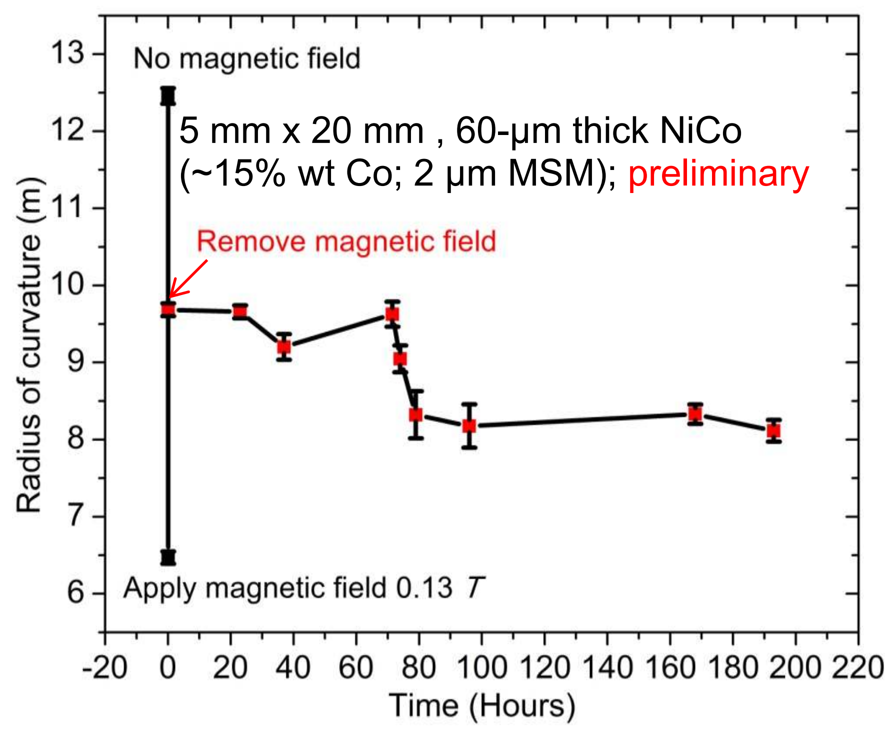


$$\begin{pmatrix} IF_{11} & \cdots & IF_{1n} \\ \vdots & \ddots & \vdots \\ IF_{m1} & \cdots & IF_{mn} \end{pmatrix} \begin{pmatrix} V_1 \\ \vdots \\ V_m \end{pmatrix} = \begin{pmatrix} D_1 \\ \vdots \\ D_n \end{pmatrix}$$

SAO/ Ryan Allured

A magnetic smart material MSM provides writable surface-parallel actuation.

- Use a magnetically hard substrate or coated layer.
- Deposit magnetostrictive (MSM) thin film on back.



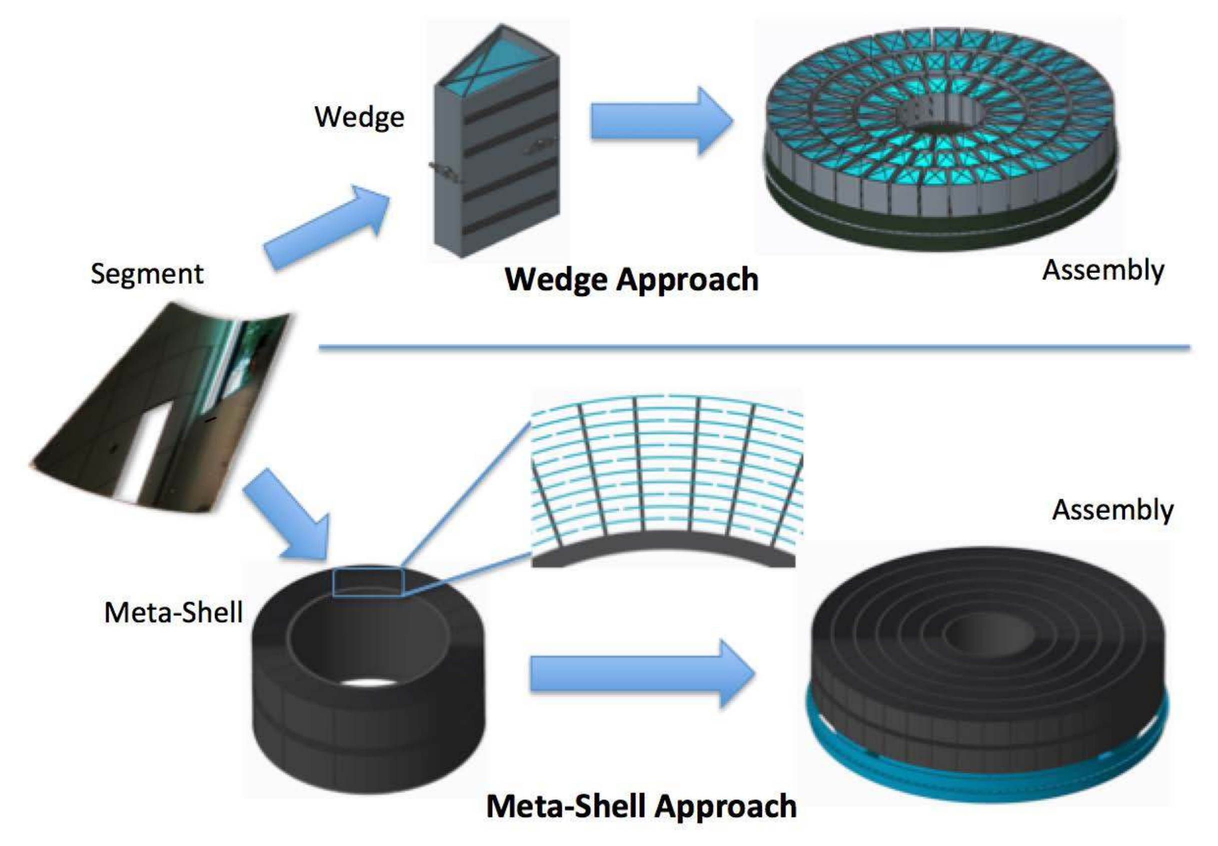
- Northwestern Univ. is developing MSM actuators for x-ray optics.
  - ❑ Demonstrated that concept may work.
  - ❑ Must speed up relaxation and stabilization.
  - ❑ Are building models to compare to experiments.
- Can also control coating stress to provide some static figure correction.

NWU/ Mel Ulmer

NWU/ Xiaoli Wang

Synthesize large-area nested Wolter-1-like telescope with aligned segments.

- Few-100-m^2 surface area in several 1000 segments



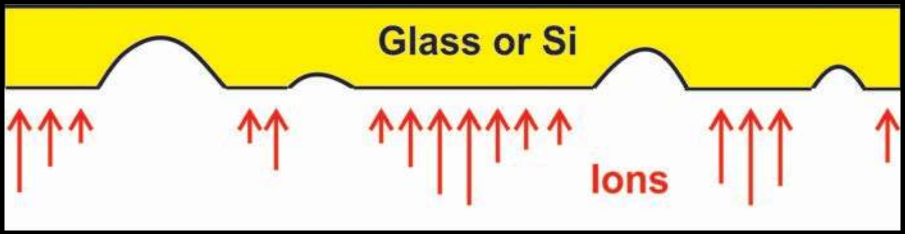
GSFC/ Will Zhang

Outline

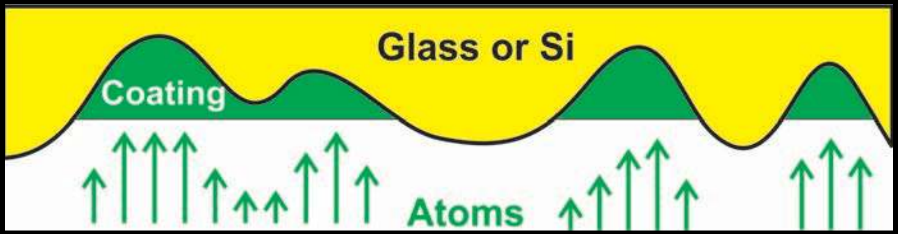
- Motivation and issues
- Categories of potential solutions
- Post-fabrication corrections
  - ☐ Differential erosion or deposition
  - ☐ Coating stress manipulation
  - ☐ Ion implantation

Low-pressure subtractive or additive machining corrects residual figure errors.

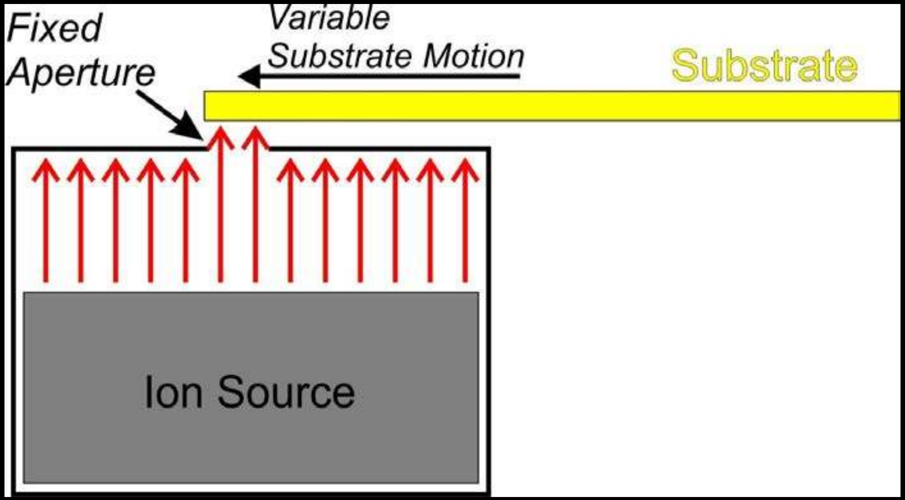
Differential Erosion



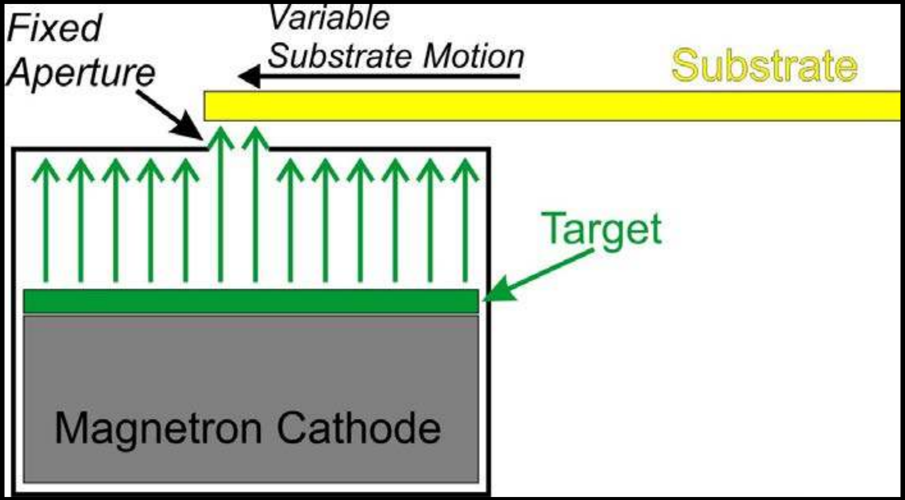
Differential Deposition



Ion-Beam Figuring

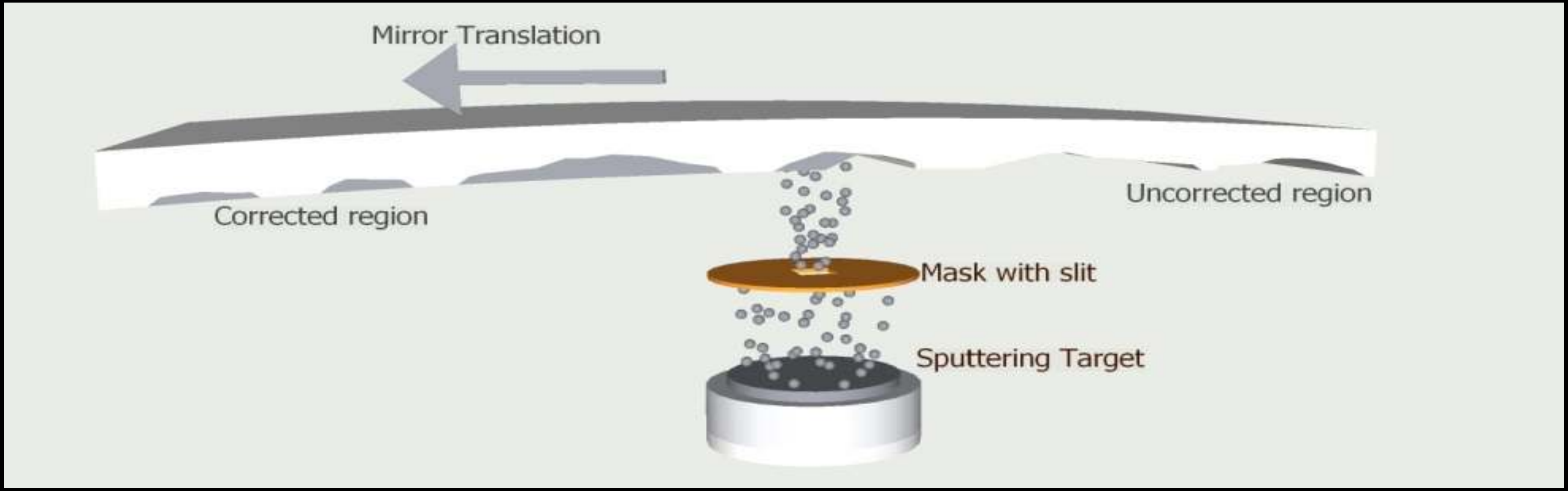


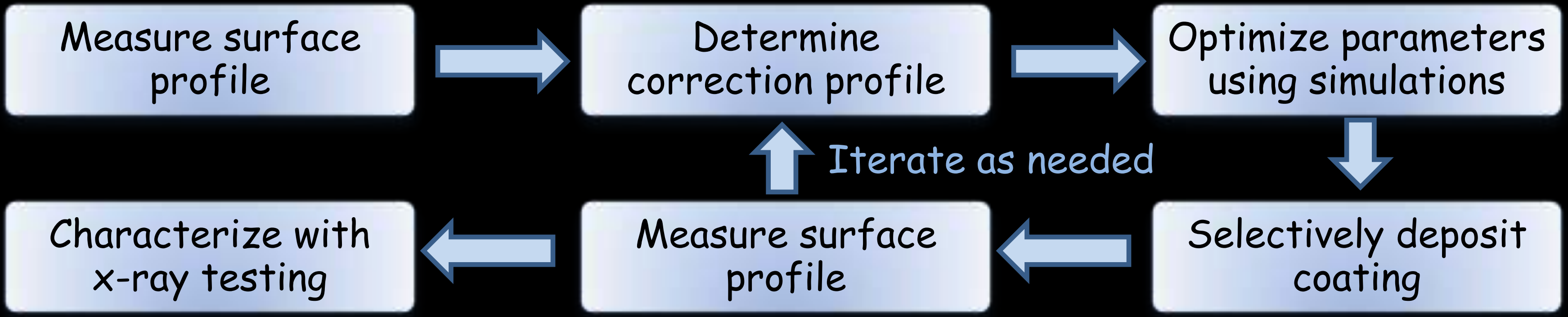
Selective Deposition



RXO/ David Windt

Differential deposition allows correction of mid-frequency figure errors.



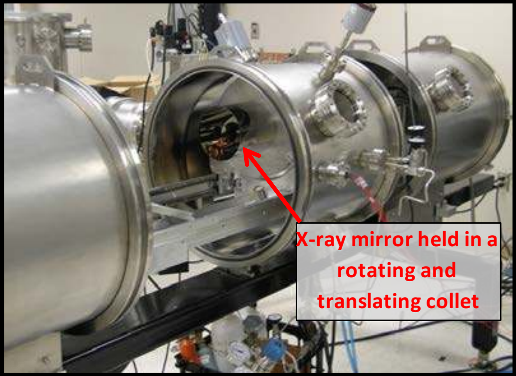


Measure surface profile → Determine correction profile → Optimize parameters using simulations → Selectively deposit coating → Measure surface profile → Characterize with x-ray testing

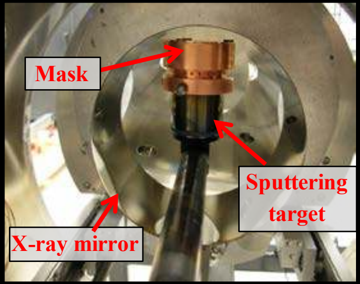
Iterate as needed

MSFC/USRA/ Kiran Kilaru

MSFC is applying differential deposition to correct thin-walled x-ray mirrors.

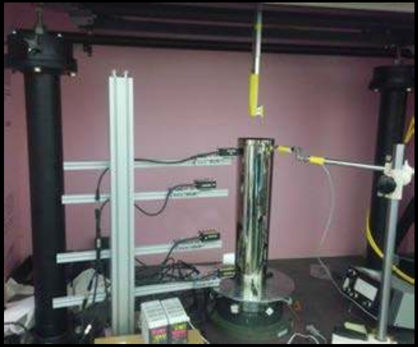


Horizontal differential-deposition chamber

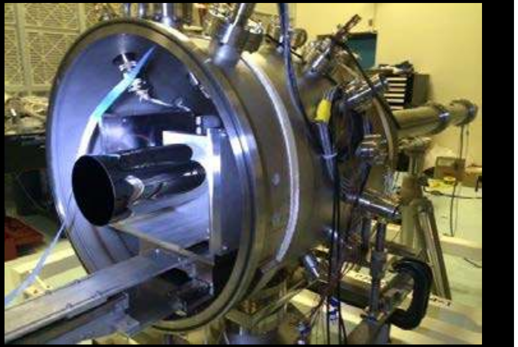


Sputtering head with copper mask positioned inside shell

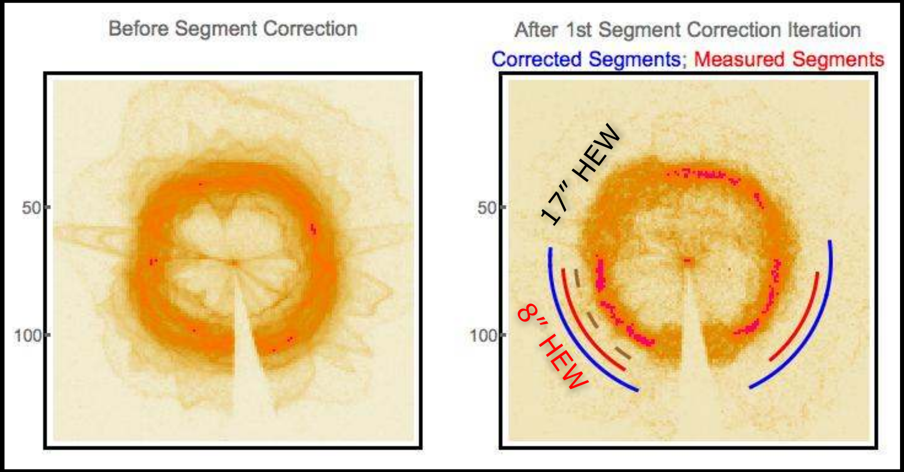
- Results are promising.
  - ❑ 2-pass correction of HEW by factor of 3 (metrology)
  - ❑ 1-pass correction of HEW by factor of 2 (x-ray test)
    - ○ 3 corrected azimuthal sections in intrafocal image



Metrology of shell with MSFC VLTP and circularity test stand

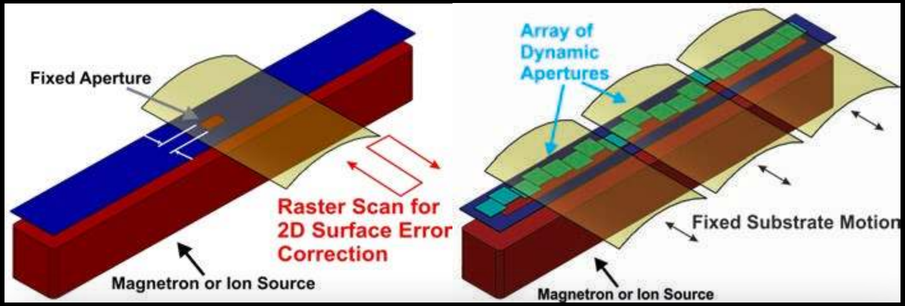


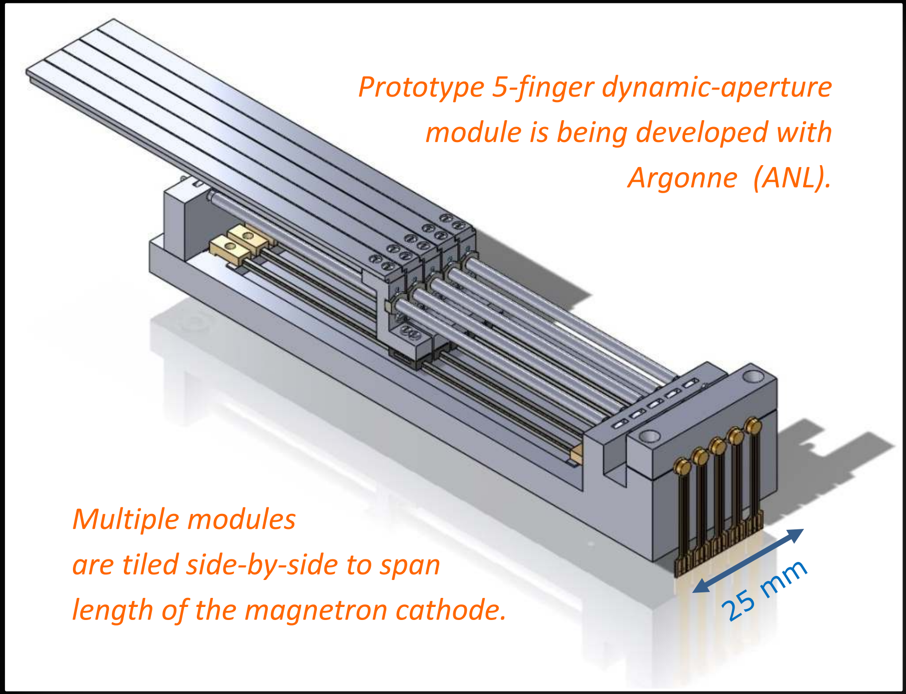
Corrected shell installed in bell housing for x-ray testing at MSFC 100-m beam



MSFC/USRA/ Kiran Kilaru

RXO is developing dynamic apertures for 2D differential erosion or deposition.

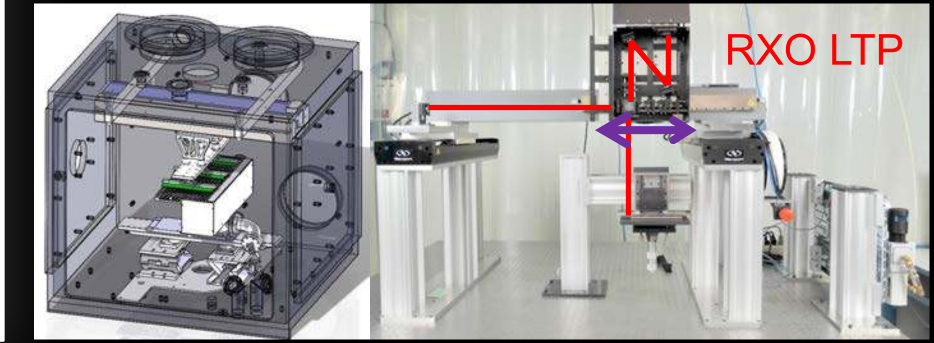




Prototype 5-finger dynamic-aperture module is being developed with Argonne (ANL).

Multiple modules are tiled side-by-side to span length of the magnetron cathode.

- Dynamic aperture array
  - ❑ Simultaneously corrects multiple azimuths
    - Constant axial speed
    - Modulated aperture widths
  - ❑ Applications
    - Differential erosion
    - Differential deposition
    - Laterally graded multilayer



RXO/ David Windt

Coating stress is an issue for sub-arcsecond imaging with thin mirrors.

- Astronomical x-ray mirrors use thin-film coatings.
  - High-density coating or multilayers for x-ray reflectivity
  - For active optics, piezoelectric array
- Distortion depends upon film stress σ_f and thickness h_f and upon substrate thickness h_s.
  - E.g., Stoney formula: $\kappa = 6(1-\nu_s)\sigma_f h_f/(E_s h_s^2)$
    - Dependence upon substrate thickness h_s is quadratic.
    - Key coating parameter is the integrated stress $\sigma_f h_f$.
  - Both intrinsic coating stress and temperature-dependent strain (CTE differences) cause distortion.
    - Separating these two effects can be challenging.
    - Annealing or other relaxation may play a role.

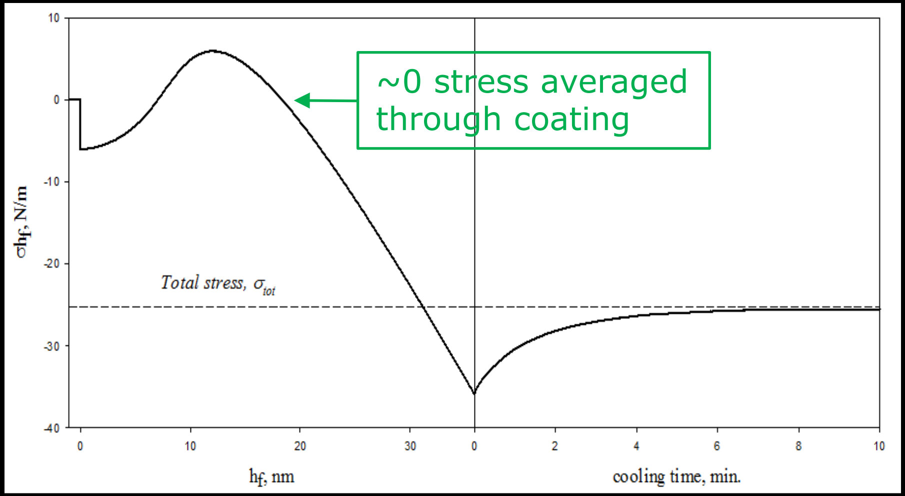
Several groups are investigating various methods for controlling coating stress.

- Monitor integrated stress in situ during sputtering, to take advantage of dynamics of thin-film growth.
  - MSFC/ David Broadway
- Deposit bilayer to tune the net integrated stress of compressive and tensile thin films.
  - RXO/ David Windt; SAO/ Suzanne Romaine
- Deposit coating on front and on back to balance integrated stress.
  - GSFC/ Kai-Wing Chan
- Anneal coating at elevated temperature to relieve stress.
  - GSFC/ Kai-Wing Chan

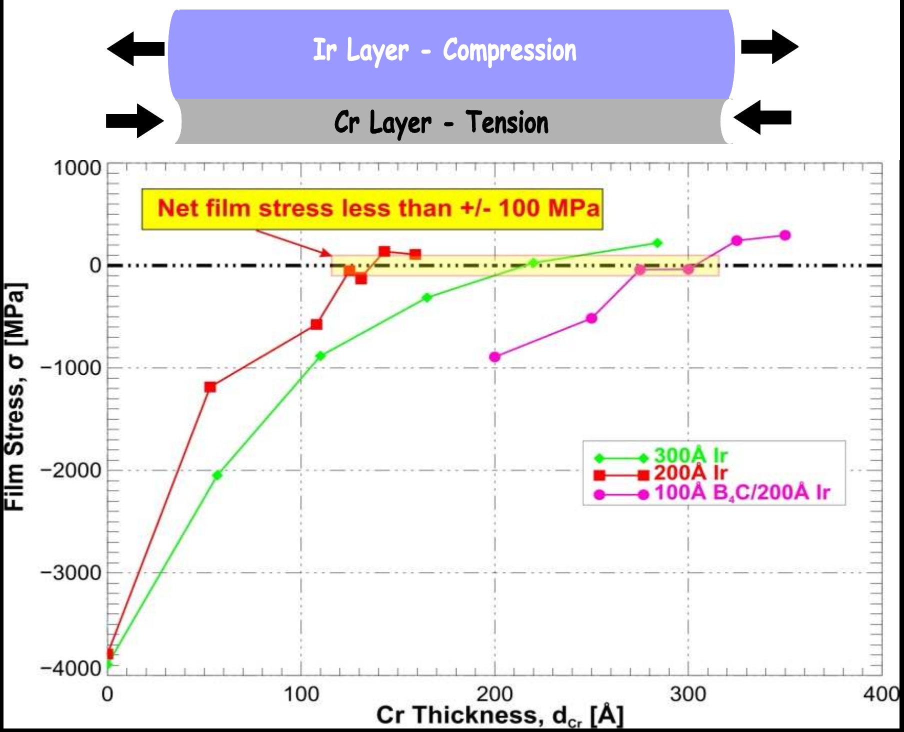
Methods for controlling deposition stress of thin films (continued)

- Iridium film growth
  - Tensile through coalescence stage
  - Very compressive after
- Tune mean stress of film
  - -3 MPa, 0.5-nm rough

- Bilayer cancelation
  - Ir compressive stress
  - Cr tensile stress



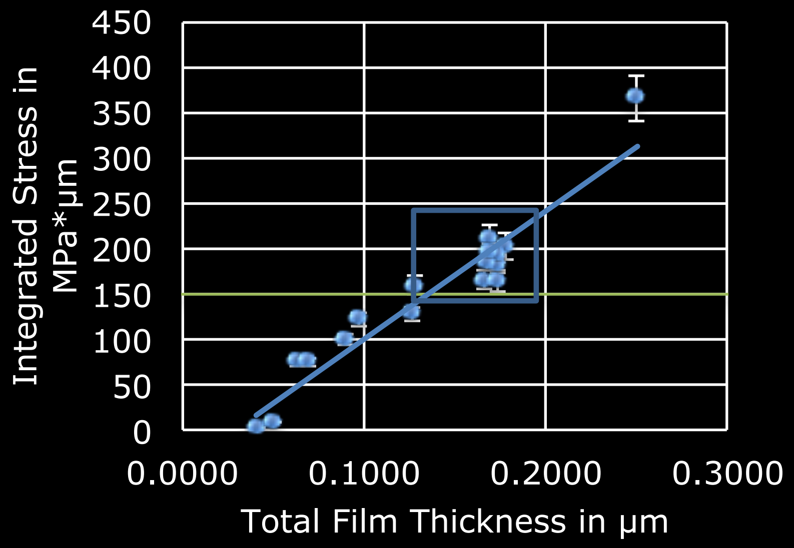
MSFC/ David Broadway



RXO/ David Windt

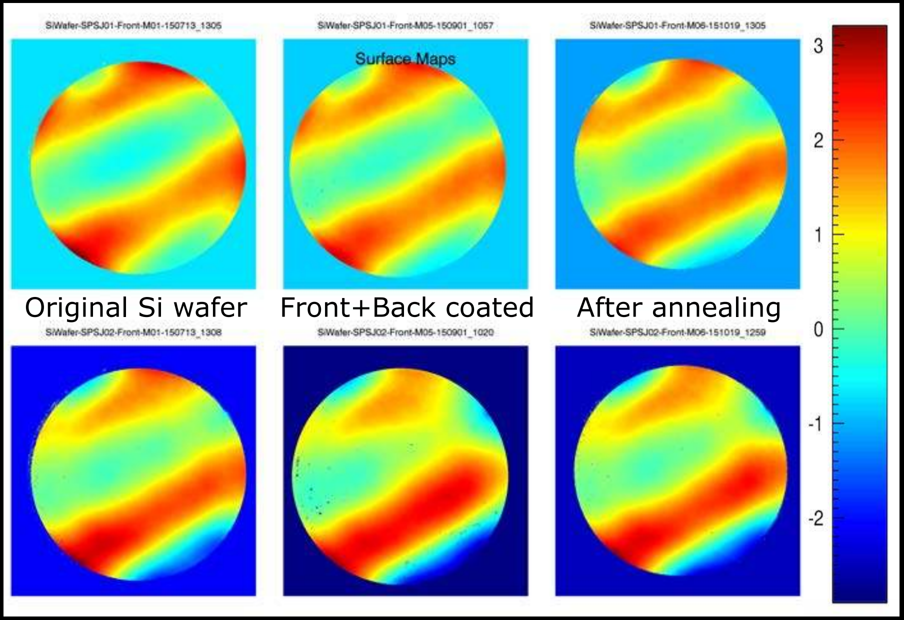
Methods for controlling deposition stress of thin films (continued)

- PZT compensation
  - PZT tensile stress on back
  - Ir/Cr bilayer on front
- Tune net integrated stress
  - 10-nm Ir + 160 nm Cr



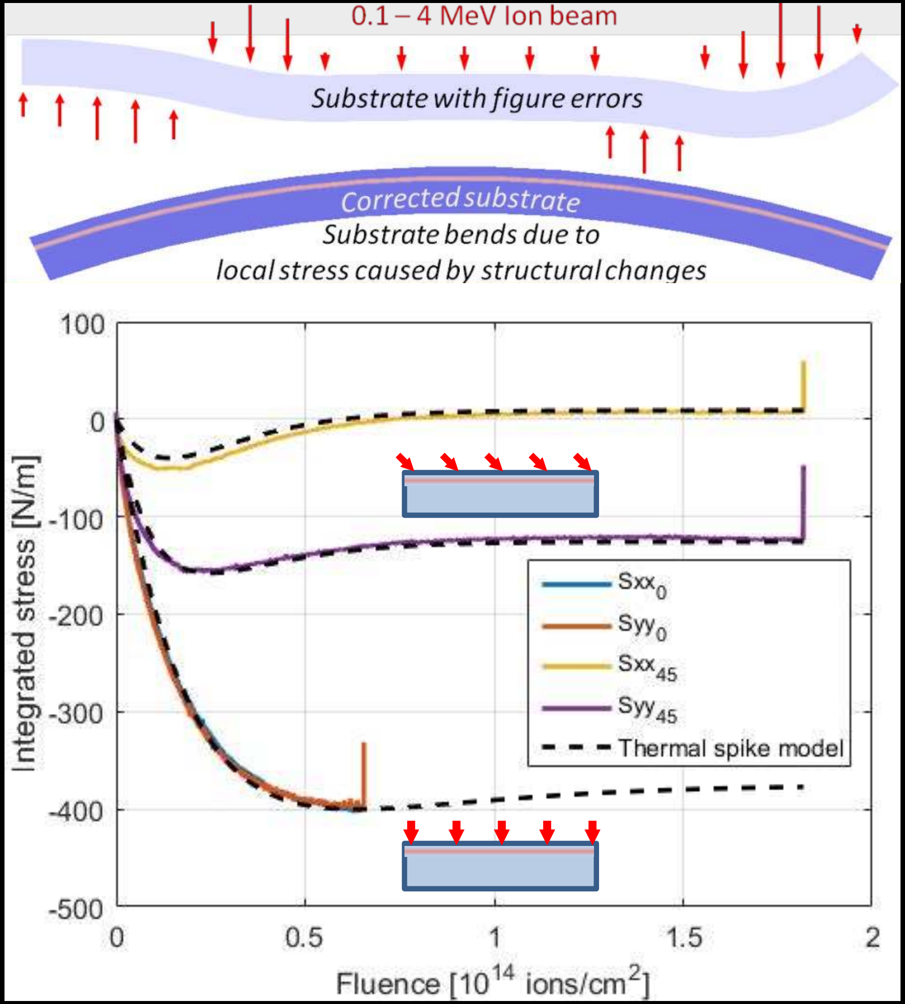
SAO/ Suzanne Romaine

- Multiple approaches
  - Front and back coating
    - Sputtering
    - Atomic Layer Deposition
  - Annealing at 320℃

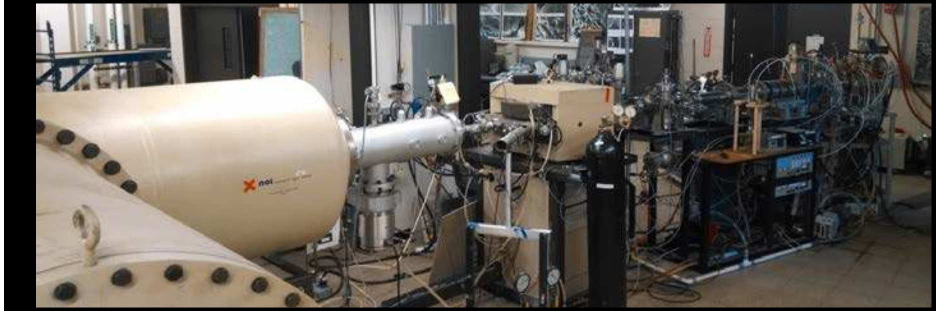


GSFC/ Kai-Wing Chan

Differential stress from ion implantation allows static correction of figure errors.



- MIT is using its ion beam to develop this approach.
  - Operates at 1-6 MeV.
    - Implant depth $1 - 4\ \mu m$
  - Low surface degradation
  - Integrated stress measure
    - Thermal spike model
    - Anisotropic ($\parallel$ vs $\perp$) stress
    - Dose-dependent relaxation



MIT/ Brandon Chalifoux

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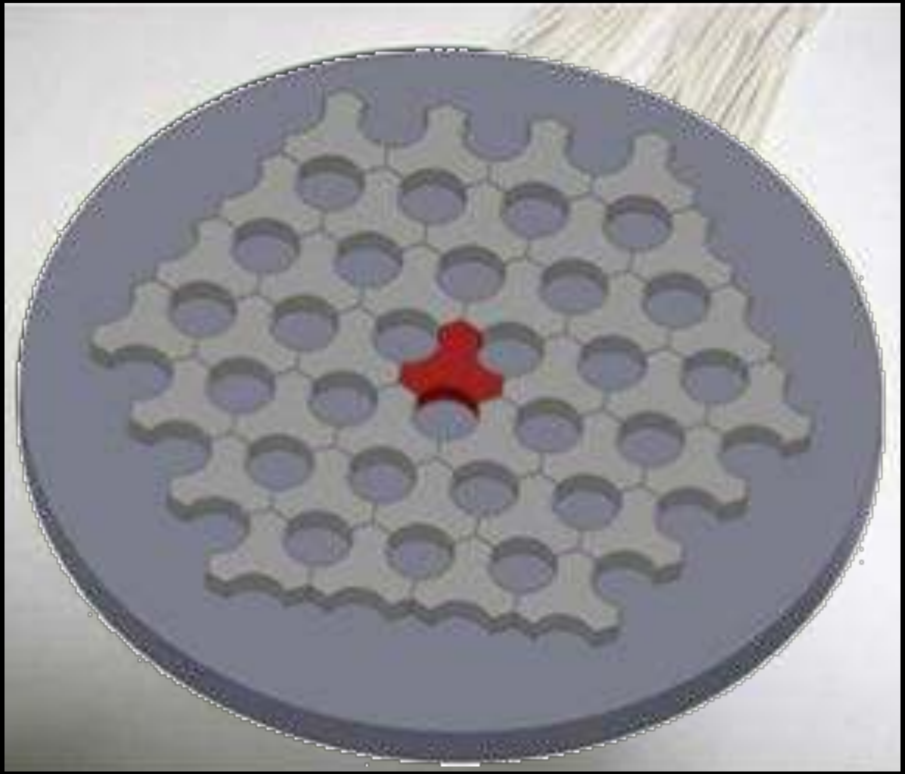
Back-up slides

An array of electroactive pads provides surface-tangential actuation (STA).

Xinetics deformable mirror (DM) uses 4×27 array of electrostrictive (PMN) pads bonded to mirror.

Xinetics and ANL characterized DM.



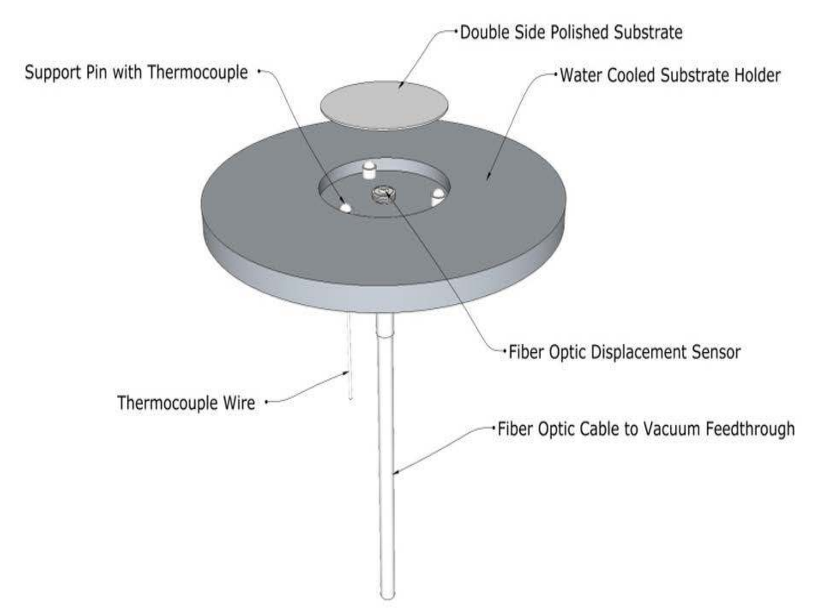
Xinetics prototype uses PMN array bonded to a silicon mirror.

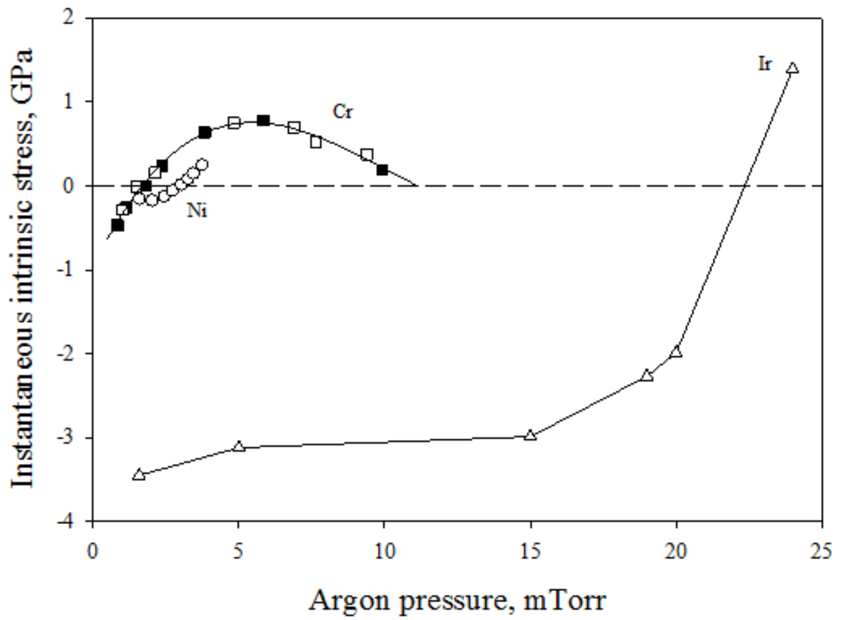
Each node is addressable for STA.

NGC/ AOA Xinetics

MSFC has developed thin-film-stress monitor for in situ measurements.

- In-situ measurement helped identify a mechanism for reducing the stress in sputtered iridium by 3 orders of magnitude





MSFC/ David Broadway