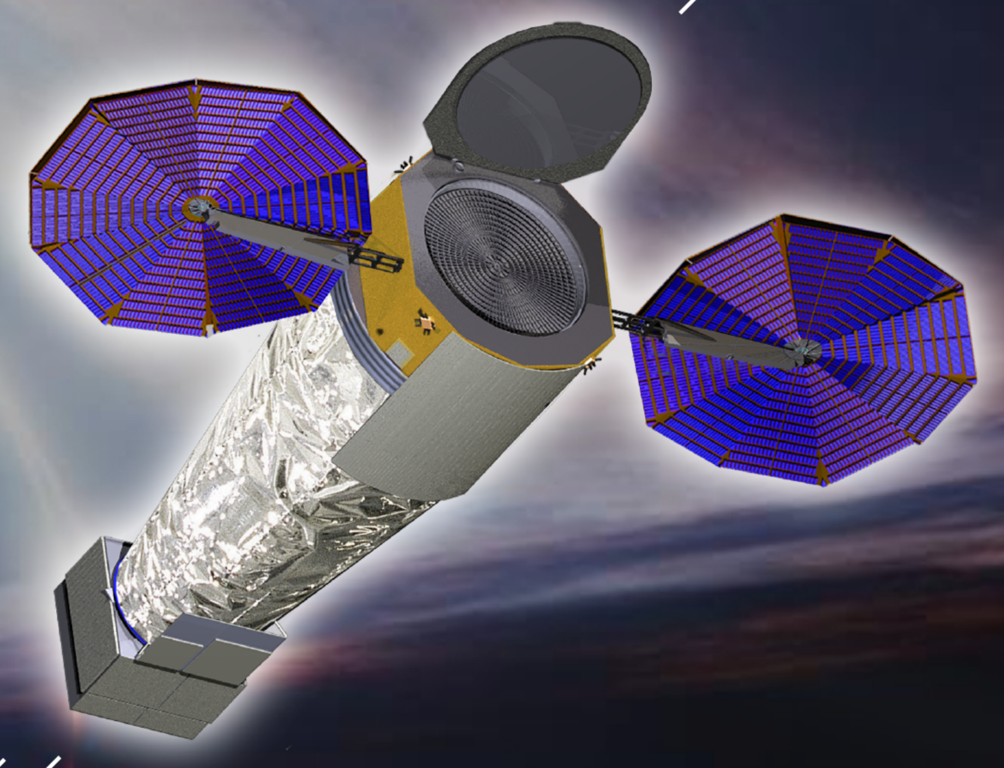
LYNX

FEASIBLITY | CONSIDERATIONS | STATUS

JESSICA GASKIN
NASA STUDY SCIENTIST

PAYLOAD & MISSION CHARACTERISTICS



LYNX MIRROR ASSEMBLY

0.5'' on-axis PSF, $2m^2$ effective area at 1 keV, sub-arcsec PSF over a 22'×22' field of view.

HIGH DEFINITION X-RAY IMAGER

An active pixel array of fine pixels covering a 22'×22' field of view with subarcsecond imaging and providing moderate spectral resolution.

LYNX X-RAY MICROCALORIMETER

An array of 1'' pixels covering a 5'×5' field of view and providing 3 eV spectral resolution. Two additional arrays are optimized for finer imaging (0.5'' pixels) and higher spectral resolution (0.3 eV in the soft band)

X-RAY GRATING SPECTROMETER

Gratings with resolving power of $R > 5000$ and ~ 4000 cm^2 of effective area across the critical X-ray emission and absorption lines of N, O, Ne, and Fe L.

THE MISSION

- Orbit: Sun-Earth L2
- Field of regard: 85% of the sky
- Consumables: sized for a 20 year mission
- Data volume: JWST comparable
- Communications: 3 times daily with DSN
- Observing Efficiency: >85%

$4.8B *to* $6.2B

40 - 70% Confidence Intervals, $FY20

Independent cost validations fall within ±5% of the Parametric Cost Estimate

Includes $350M for launch
and ~$400M for operations (after 2035)

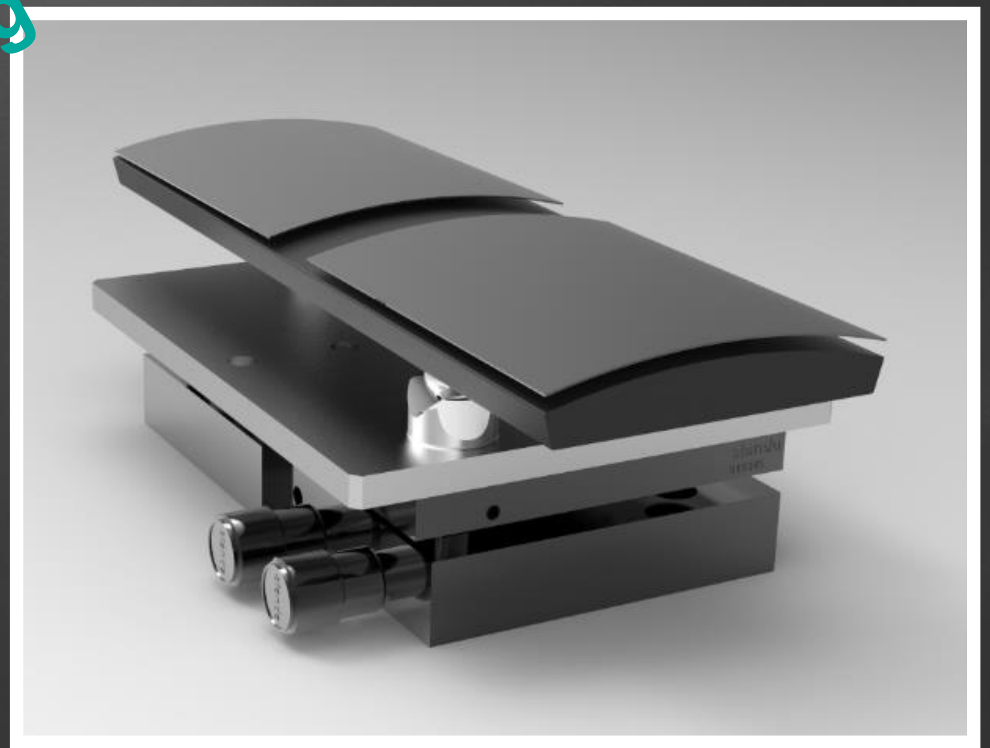
Does not include potential foreign contributions

MULTIPLE FEASIBLE MIRROR TECHNOLOGIES

REQUIREMENTS

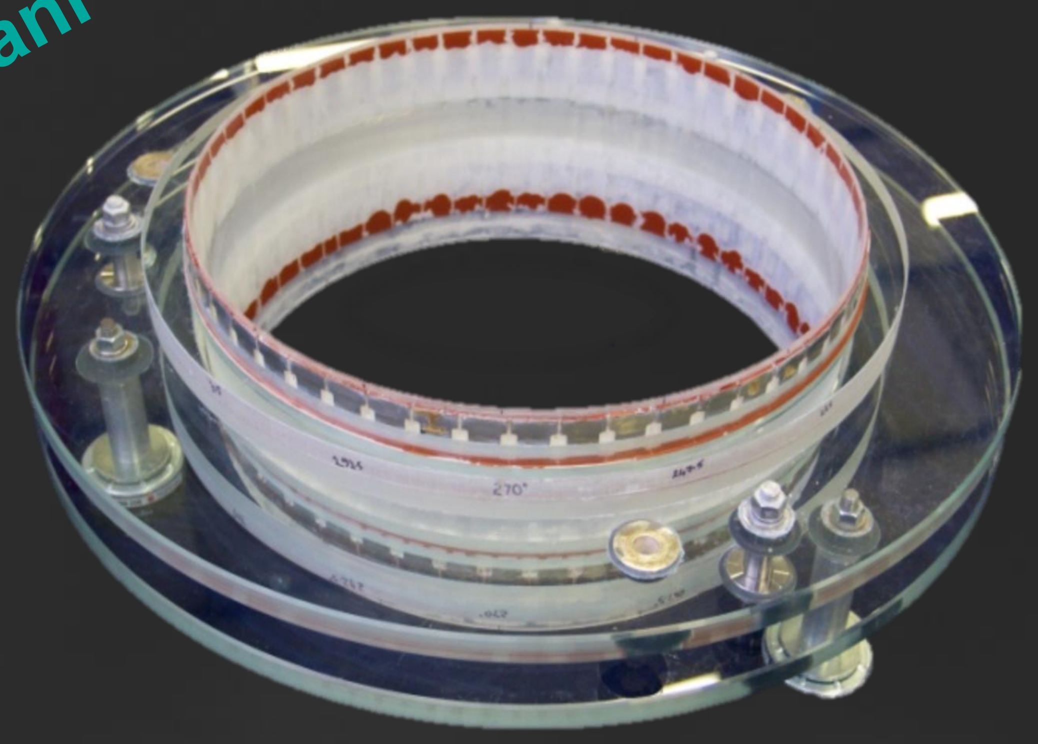
0.5’’ on-axis 1’’ *to* 10’ off-axis ~2 m^2 *of* effective area

Will Zhang Talk

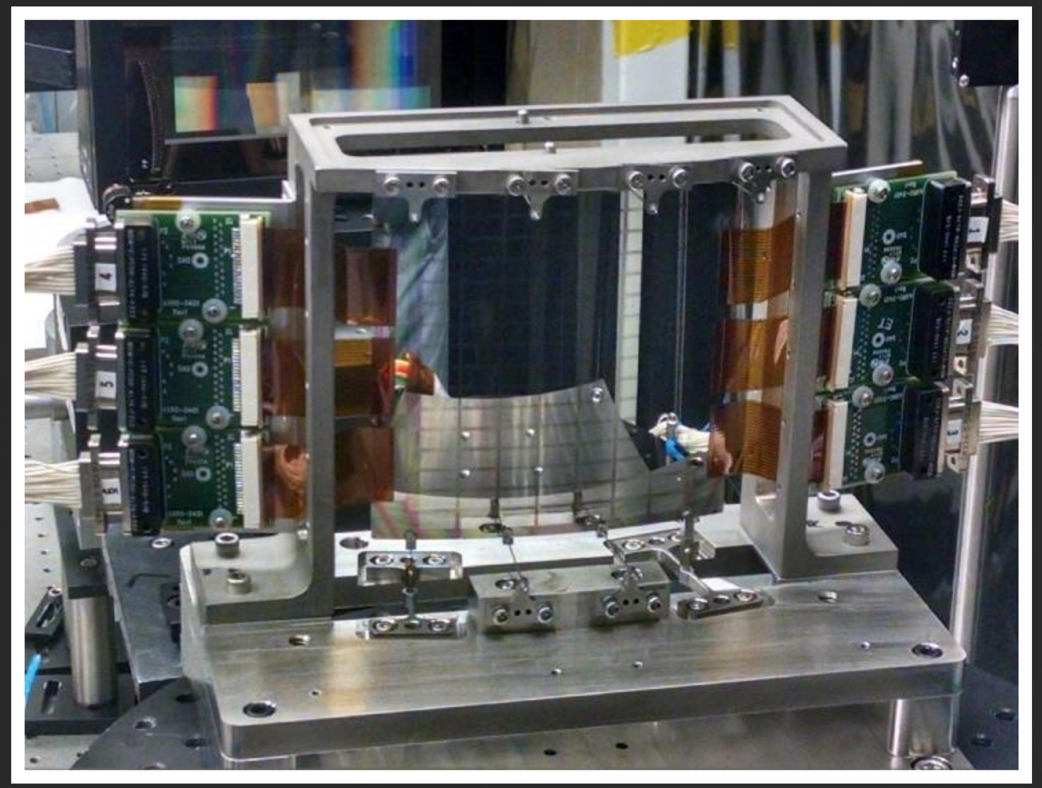


Silicon Meta-shell Optics
NASA GSFC

Marta Civitani Talk



Full Shell/Monolithic Optics
NASA MSFC/INAF Brera



Adjustable Optics
SAO

Lynx Mirror Architecture Trade (LMAT): Community working group conducted an open, science, technical, and programmatic evaluation.

A broad consensus was reached on the recommendation

- Team from industry, universities, and NASA Centers
- ~5,000 person-hours over 6 months
- ~100 documents produced (~650 pages of material)

Recommendation: The LMAT recommends Silicon Meta-Shell Optics as the DRM concept Mirror Optical Assembly Architecture to focus the design for the Final Report. Full Shell and Adjustable Optics are determined to be feasible alternates.

X-ray optics at SAO

SAO

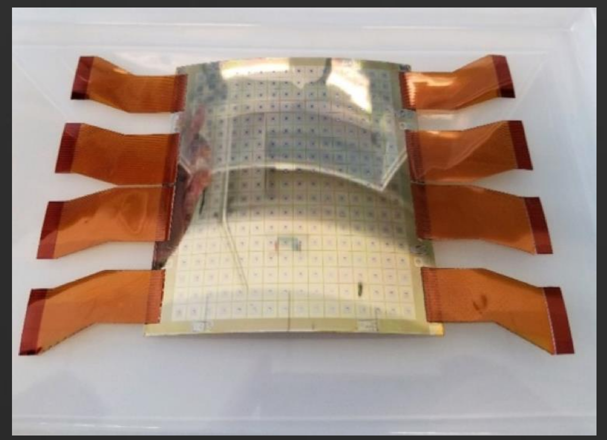
P. Reid

Development of Row-Column Addressing with integrated thin film transistors (TFTs) forming "active" pixels

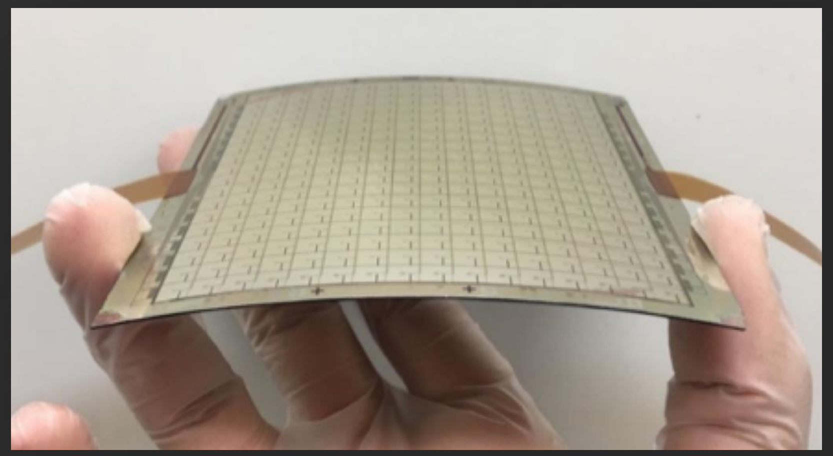
- Developing zinc oxide (ZnO) TFTs fabricated directly on an adjustable mirror segment for control of the individual piezoelectric cells
- Have demonstrated the ZnO TFTs do not impact performance of the piezoelectric cell, nor does the piezoelectric cell impact the performance of the TFT.
- Have demonstrated small scale (4 x 4) row-column addressing of an flat adjustable optic test mirror
- Fabricated ZnO TFTs with electrostatic discharge protection circuitry directly on cylindrical mirror segments (100mm x 100mm x 220mm radius of curvature).

Row-column addressing enables going from:

THIS



to THIS



Mirror on left has 288 individually addressed cells. Mirror on right has 288 row-column addressed piezo cells.

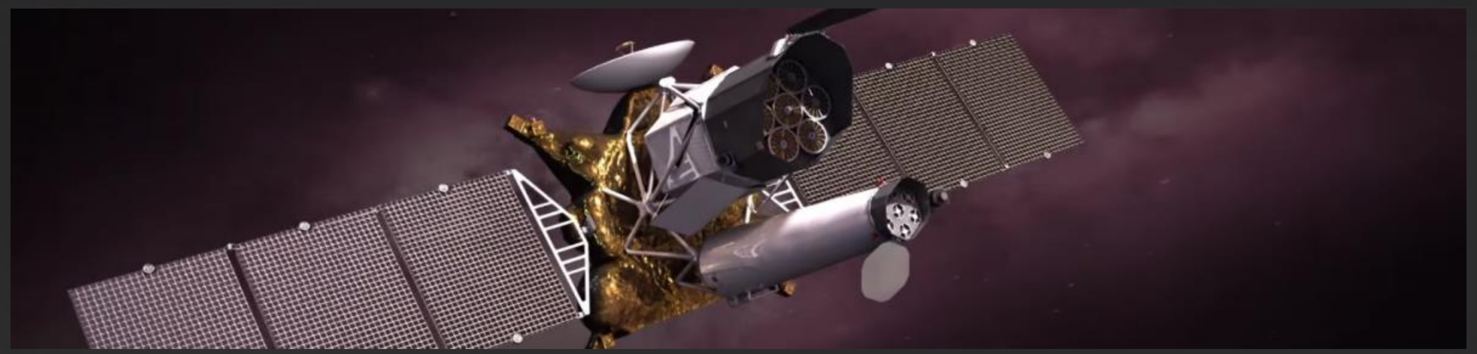
X-ray optics at MSFC

Astronomical applications (past & current)

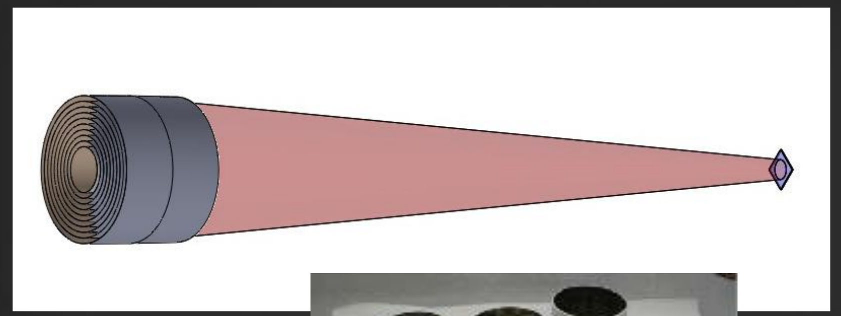
IXPE (satellite)

HERO/HEROES (balloon)

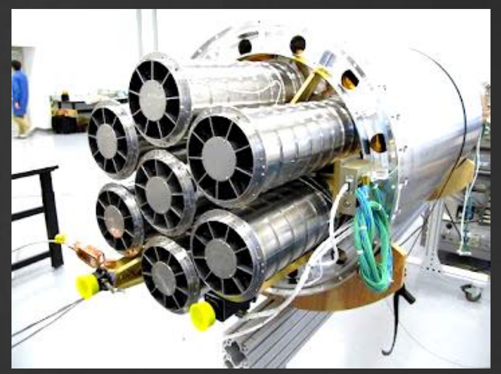
ART-XC on SRG (satellite)



MiXO (satellite)



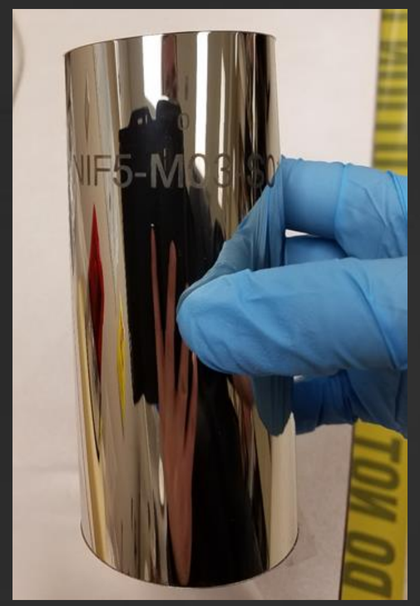
FOXSI/FOXSI-2/FIERCE MIDEX



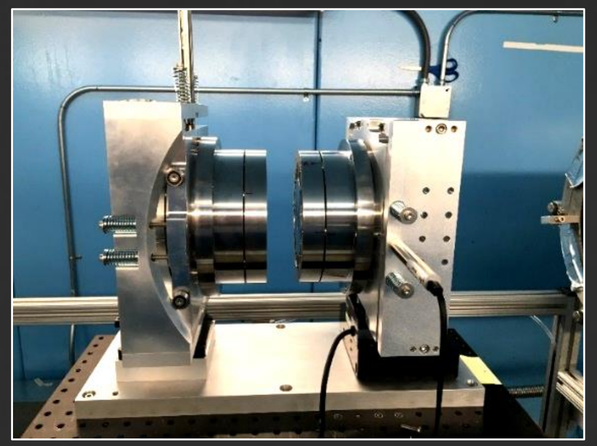
Non-astronomical applications

Z pulsed energy Machine (Sandia)

Imaging & Plasma Diagnostics (NIF)



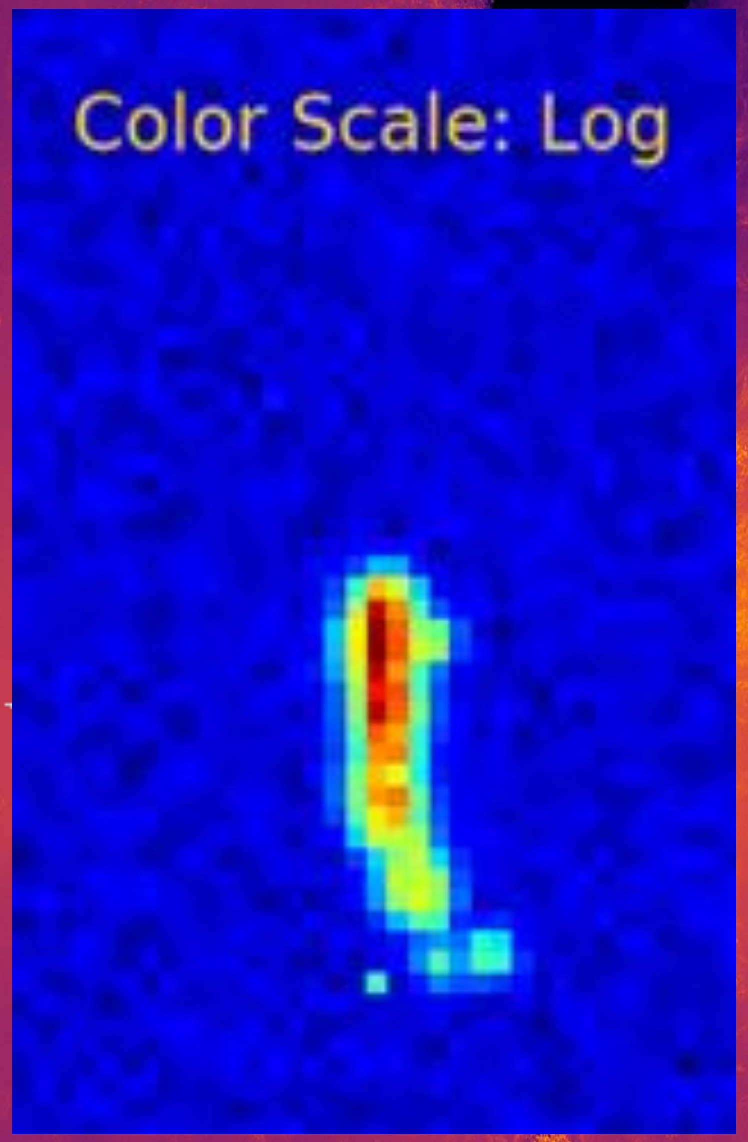
Neutron imaging (NIST)



the state of MIRROR TECHNOLOGY

SILICON METASHELL OPTICS

W. ZHANG & TEAM (GSFC)



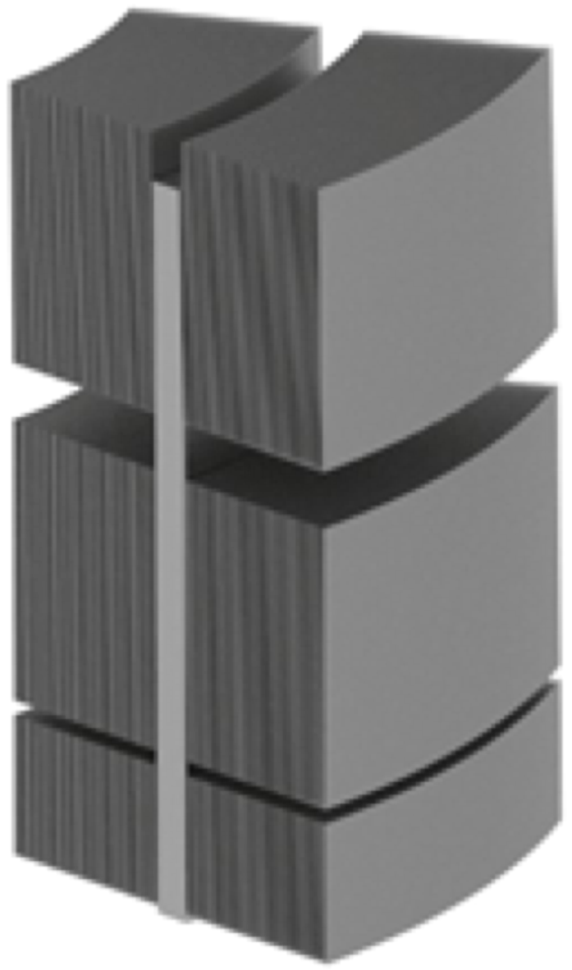
Presented Earlier this year at APS2020

0.83’’ (HPD) at 4.5 keV,
dominated by gravity distortions

Full-illumination X-ray test of aligned mirror pair

MASS-PRODUCIBLE, MODULAR, PARALLELIZABLE

37,492 **SEGMENTS**



611 **MODULES**

12 **META-SHELLS**

1 **ASSEMBLY**

LYNX TECHNOLOGY MATURATION

No Maturation Needed

Spacecraft bus and structures & all spacecraft subsystem elements, including GN&C, C&DH, propulsion, power, thermal (some modification), avionics, mechanisms, etc…

Some Maturation Needed

Advanced Payload Technologies

TECHNOLOGY GAP	TRL
High resolution, lightweight optics	3 ⟶ 4
Megapixel X-ray Imaging Detectors (HDXI)	3 ⟶ 4
X-ray grating arrays (XGS)	4 ⟶ 5
Large format, high spectral resolution X-ray detectors (LXM)	3 ⟶ 4

TRL 4 [03/2021]: Demonstrate that modules containing at least three co-aligned pairs of mirror segments can be repeatedly built and tested and shown to meet Lynx requirements.

TRL 5 [01/2024]: Meet spaceflight environment requirements: thermal vacuum, vibrations, acoustics, and shocks.

TRL 6 [01/2027]: An engineering model X-ray mirror assembly will be made. Mirror modules accurately aligned and integrated into meta-shells. The finished assembly engineering model meets all science and environmental requirements. The production logistics, schedule, and cost risks are retired.

*** No fundamental barriers to developing multi-mirror module assembly demonstrator (TRL6).**

PLANS for BUILDING the FLIGHT LMA

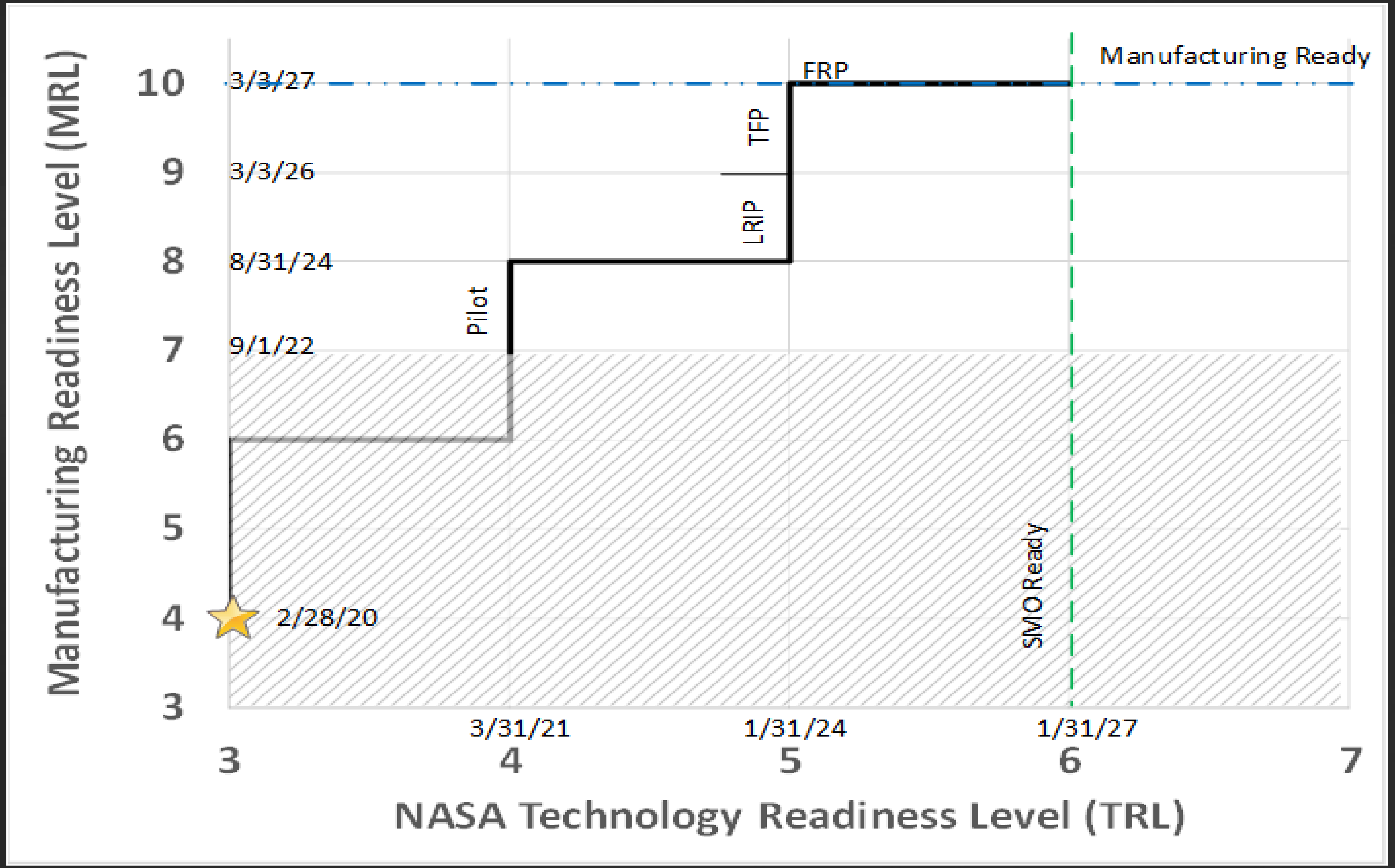
Detailed Manufacturing Plan

- CAN initiated to apply principles of industrial engineering to optimize equipment and labor across multiple parallel lines with the capability to minimize bottlenecks and wait times, with definite savings potential already identified

LCIT *only* concern: "The scale of the Lynx mirror assembly, with its many mirror segments, is orders of magnitude more complex than previous and current X-ray mirrors. Fabrication and integration of the Lynx Mirror Assembly and…"

Timely Completion of XMA Requires Technology and Manufacturing Readiness

- Transition of mirror production from laboratory to factory
  - Industrialization of manufacturing process
  - Optimization of manufacturing flow
- XMA delivery in 2031 requires development in the near term of both technology and manufacturing

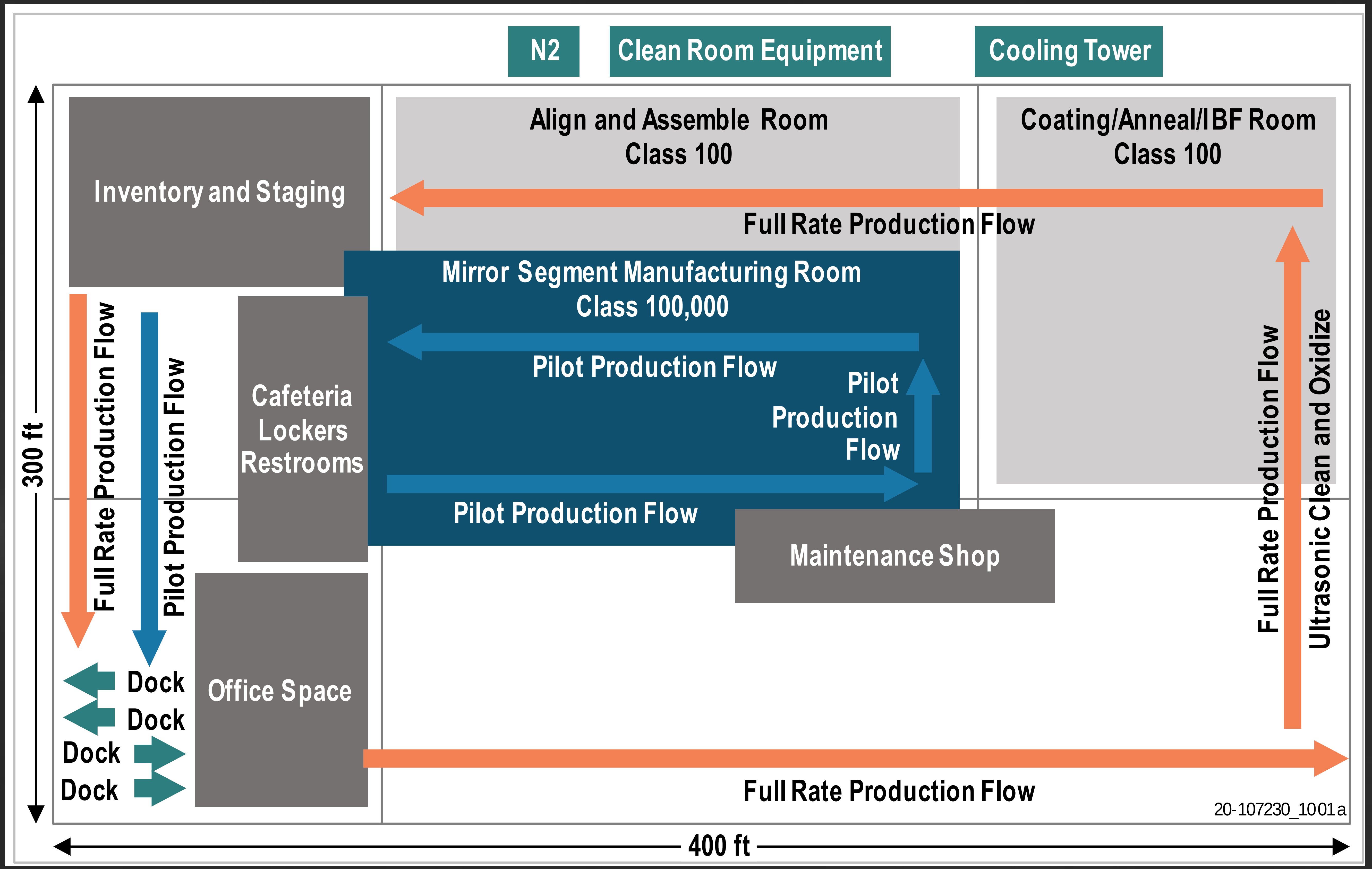


Further process optimization possible

J. Arenberg

Factory and Staffing are Executable

- A single facility will be used for pilot and full rate production
  - Facility needed is a typical large industrial facility
- Staffing and training plan and procurement of machinery also studied– found to be similar to many other production jobs
  - Time to acquire staff and equipment studied and built into time line



C O S T I N G A N D S C H E D U L E O F X M A

- A mathematical model XMA production has been developed [1-4] and is central to the quantification of manufacturing process optimization

- Risk is treated as uncertainty in the model, both statistical and non-statistical

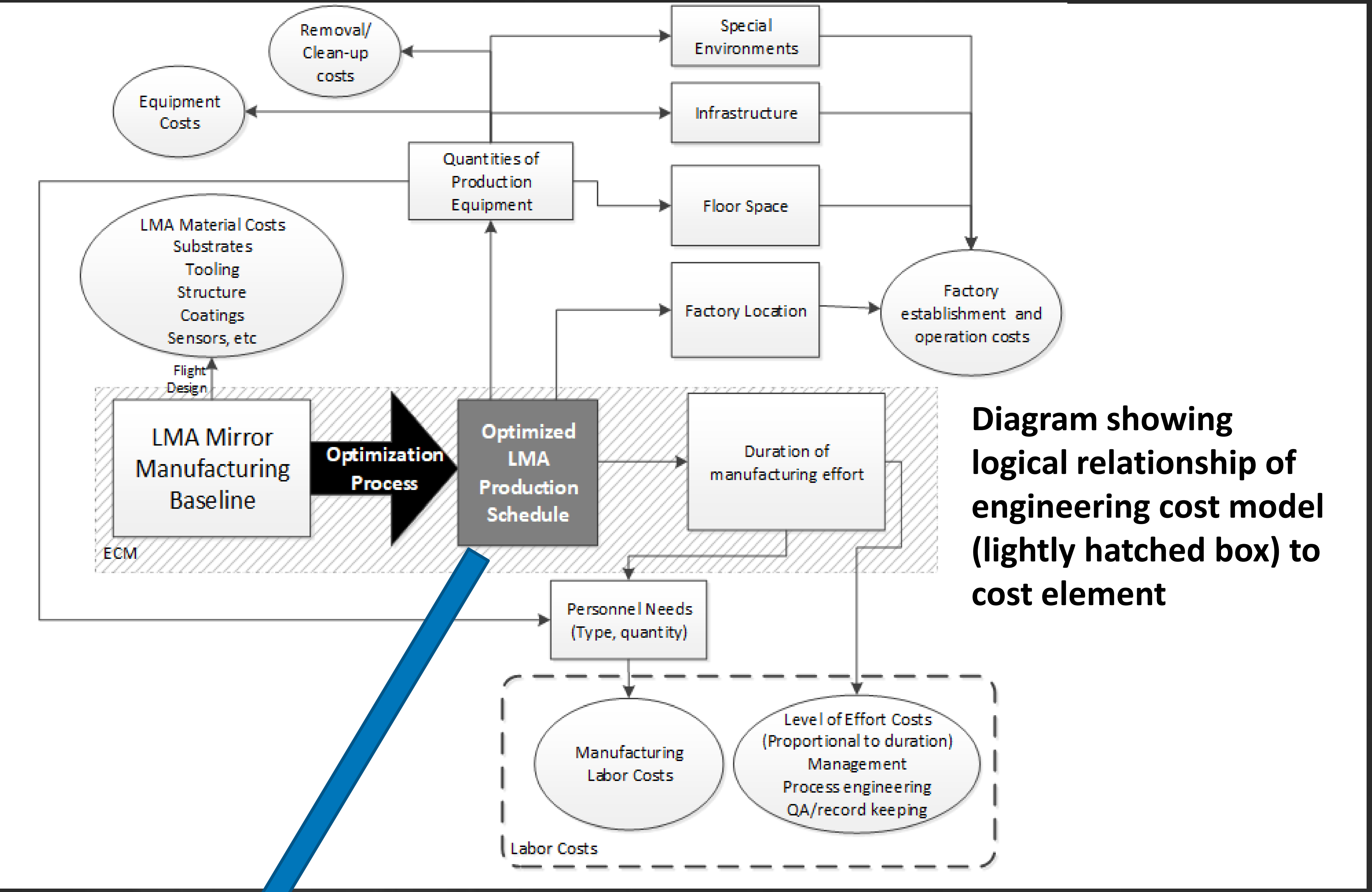
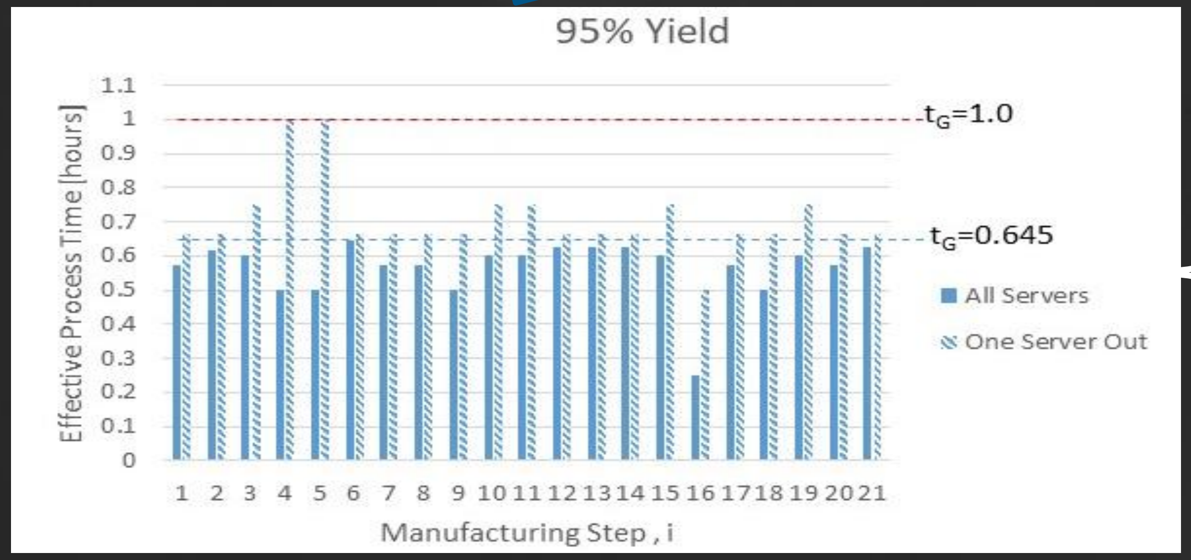


Diagram showing logical relationship of engineering cost model (lightly hatched box) to cost element



Effective Process Times for 95% average manufacturing yield: All servers functioning (solid bars) and one server failed (hatched bars)

Optimized plan will consider statistical and non-statistical risks, to design the most efficient manufacturing process

[1] Jonathan W. Arenberg, Lynn N. Allen, James Mooney, Bill Purcell, Steven Jordan, "Cost, schedule and siks modeling for the Lynx Mirror Array," Proc. SPIE 10699, Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray, 1069916 (10 July 2018)

[2] Jonathan W. Arenberg, "Formulation of the production time and cost of the Lynx x-ray mirror assembly based on queuing theory," J. Astron. Telesc. Instrum. Syst. 5(2), 021016 (2019),doi: 10.1117/1.JATIS.5.2.021016.

[3] Jonathan Arenberg and William Zhang, "Analysis of the cost, schedule, and risk for Lynx mirror assembly production", SPIE San Diego 2019.

[4] Jonathan W. Arenberg, "Uncertainty in the time to complete a complex manufacturing campaign", in preparation for SPIE Astronomical Telescopes and Instruments Conference, San Diego, 2020

OTHER CONSIDERATIONS FOR LYNX AND BEYOND

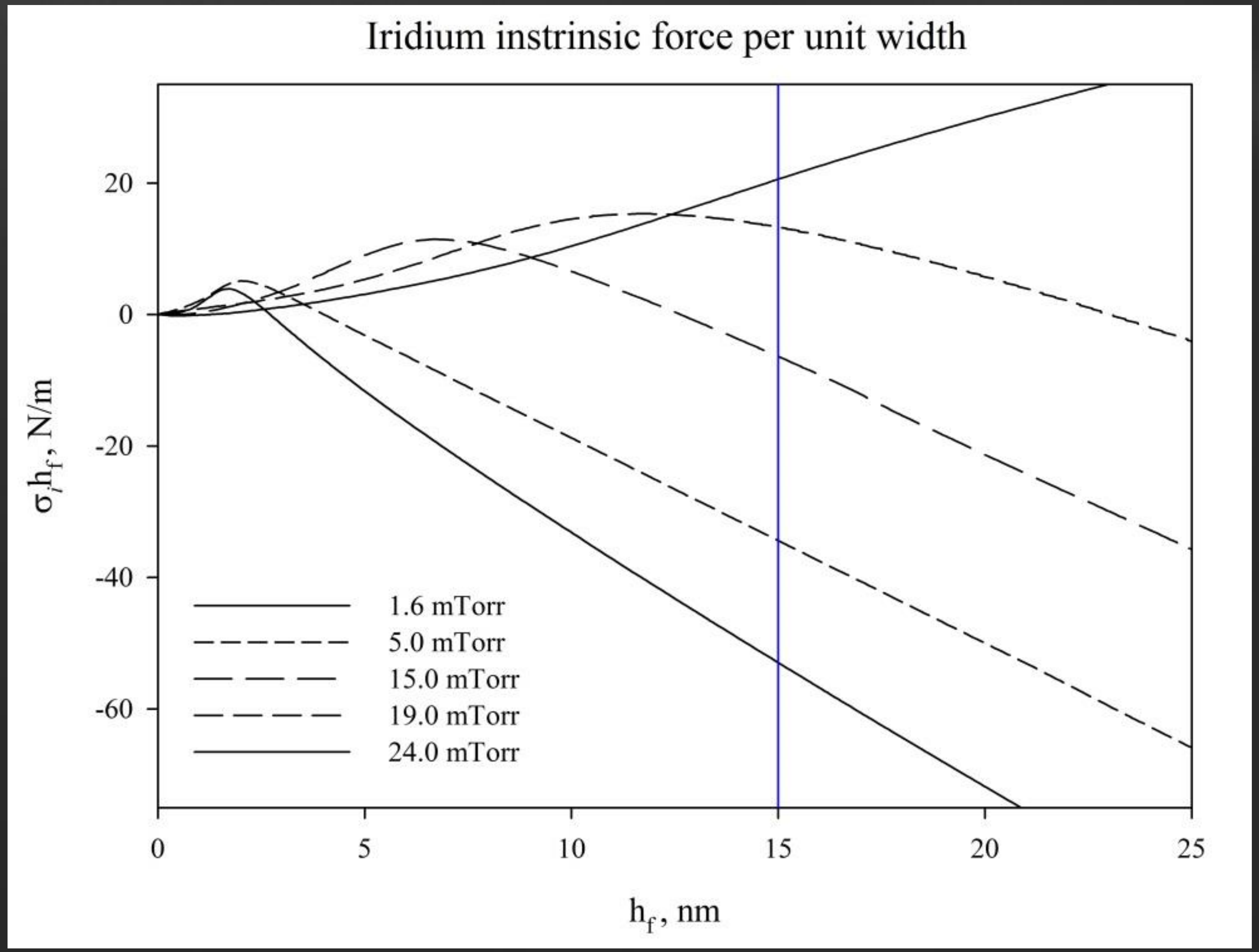
- Coatings (without distortion)
- Metrology for All Phases of Fabrication & Assembly of XMA
- X-ray Test & Detailed Calibration Planning

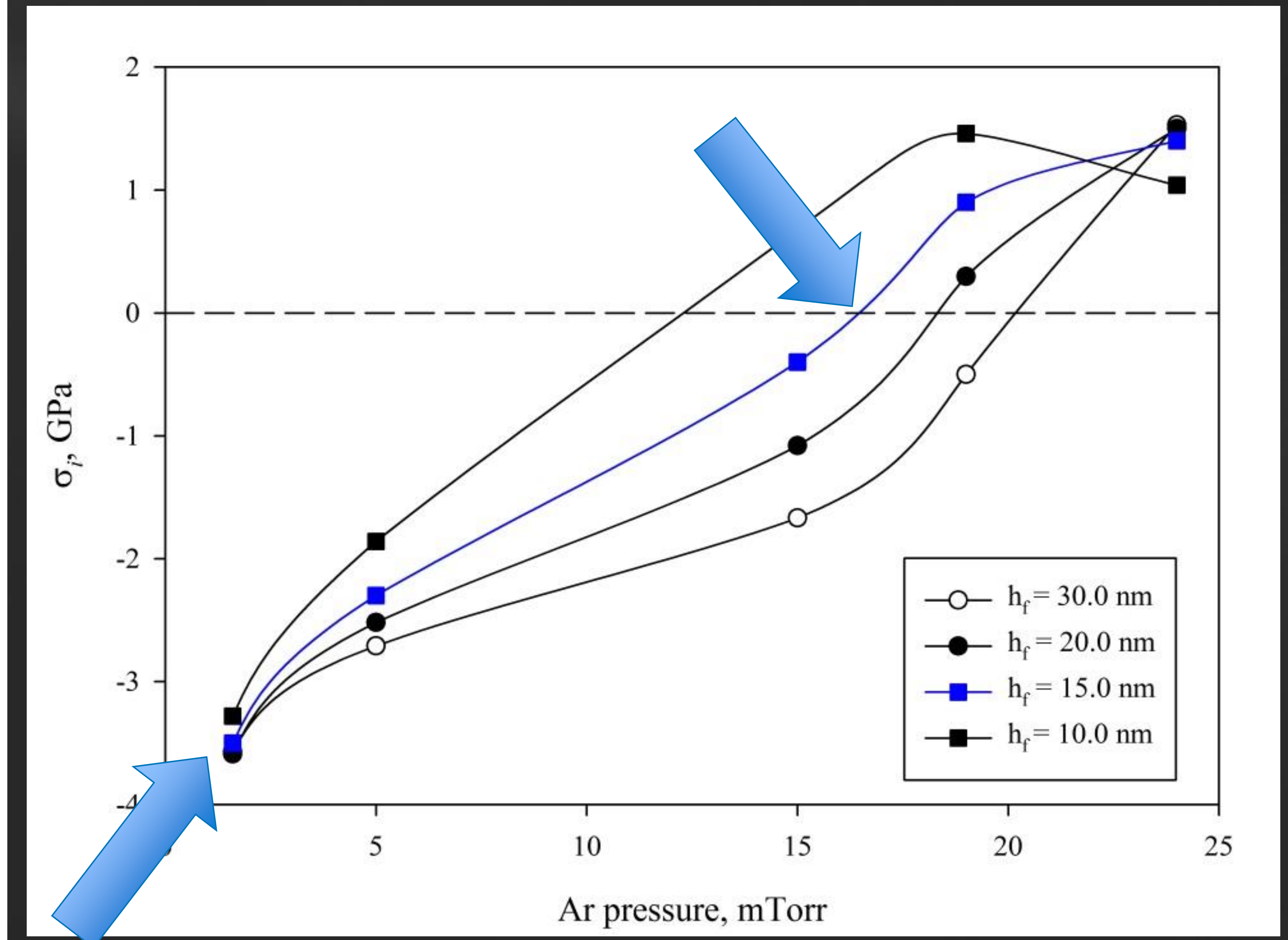
It’s all in the details!

THIN FILM COATINGS - ZERO STRESS IRIDIUM

- A 10-15 nm thick x-ray reflective Iridium (Ir) layer is needed to meet Lynx's effective area requirement of 2 m^2 @1keV.
- While Ir is the most attractive material (among Au or Pt) for extending the critical angle of the Lynx mirrors, it exhibits notoriously high intrinsic film stress. The film stress will severely distort the thin optic's precise figure and compromise the telescope's imaging resolution.
- To address this technological challenge, we have developed a **novel method for measuring the stress in Ir, in-situ, during its deposition process**. This measurement capability revealed a feature during the evolution of the film's growth which was exploited through argon process pressure optimization to achieve near-zero film stress on a flat substrate.

Zero stress @ 16.5 mTorr





-3.7 GPa @1.5 mTorr

Next Steps – Upgrade existing chamber to test on a curved substrate.

Other Work:

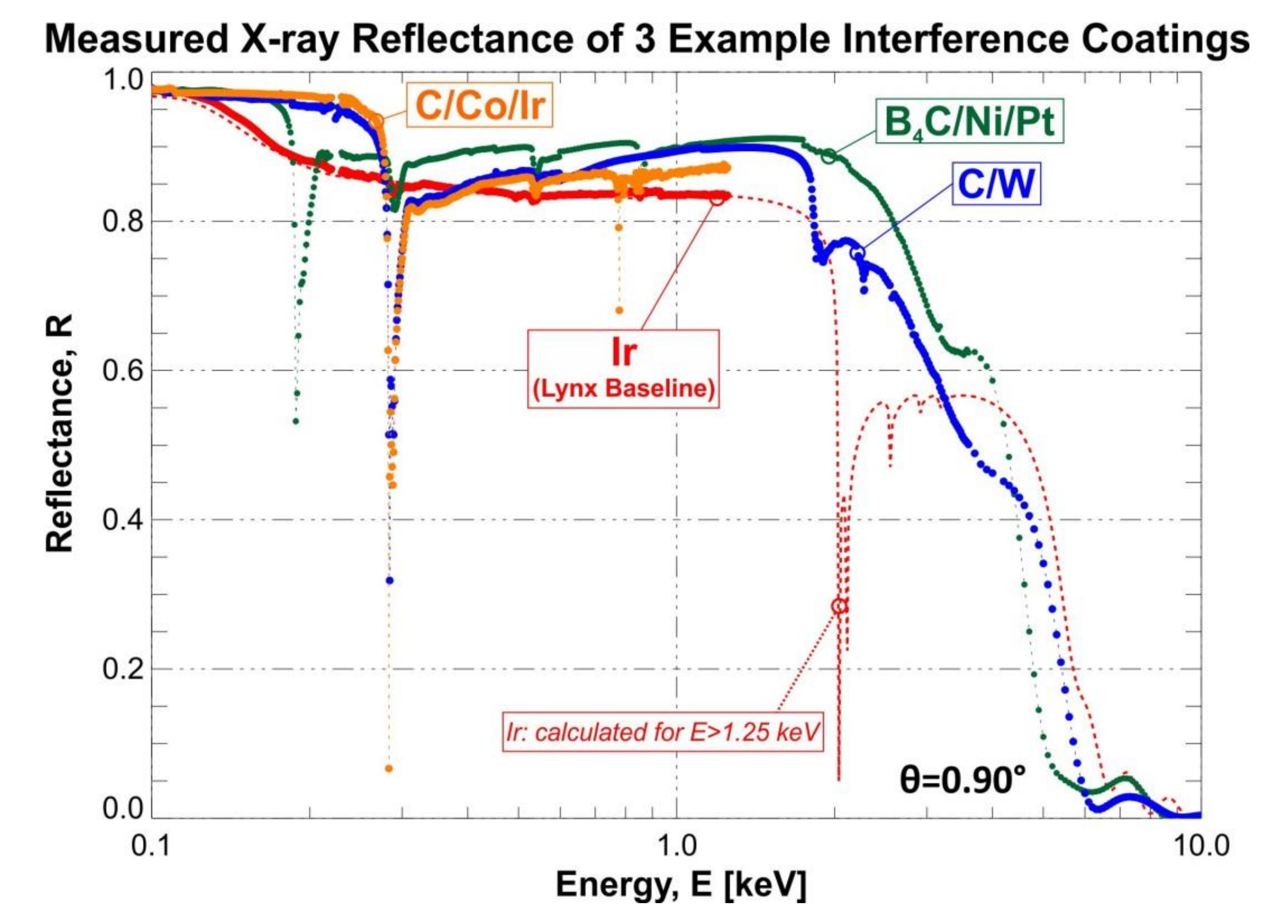
- Develop advanced multilayer coatings for extending the reflective spectral response of X-ray optics (i.e. >150 keV)
- Develop thin film deposition capability on a variety of substrates including: segments, mandrels, and full shells.

D. Broadway

X-RAY REFLECTIVE COATINGS FOR LYNX

Twelve new reflective interference coatings have been fabricated & tested to date:

- Four W-based bilayers & trilayers: C/W, B_4C/W, C/Co/W, B_4C/Ni/W
- Four Pt-based bilayers & trilayers: C/Pt, B_4C/Pt, C/Co/Pt, B_4C/Ni/Pt
- Four Ir-based bilayers & trilayers: C/Ir, B_4C/Ir, C/Co/Ir, B_4C/Ni/Ir



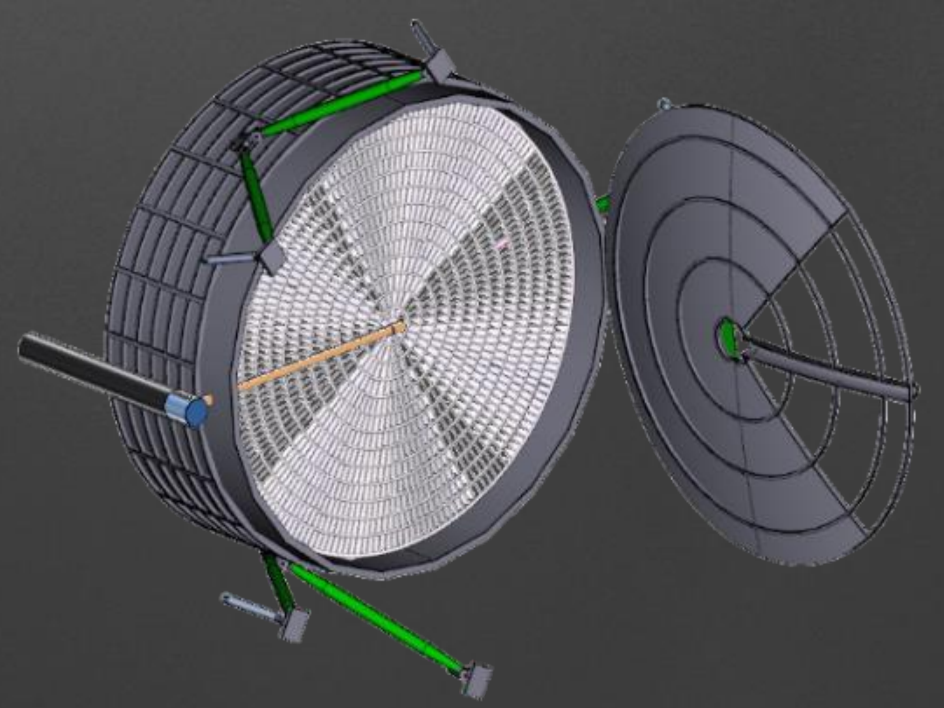
- X-ray reflectance is higher than the Lynx baseline coating, single-layer Ir, in all cases.
  → Increased telescope effective area
- Film stress is lower than the Lynx baseline coating, single-layer Ir, in all cases.
  → Reduced telescope mirror deformation; higher angular resolution
- Stability of reflectance and film stress over time is currently being assessed.

D.L. Windt

X-RAY MIRROR ASSEMBLY (XMA) METROLOGY

State-of-the-art metrology is required to determine the mirror quality over the entire range of spatial frequencies.

XMA has a 3-m outer diameter, and contains hundreds or thousands of mirror elements!



X-ray Mirror Assembly (XMA)

- Highest spatial frequency (microroughness) *(**sub-nm accuracy required**)*
  - Assessed with a phase-shifting interferometer with a millimeter-class FOV
  - Or using X-rays, or AFM
- Lowest spatial frequency (figure error) *(**several-nm accuracy required**)*
  - Assessed with a phase-shifting interferometer with a much larger FOV
    - For full-shell cylindrical optics, the optic must be extremely precisely rotated about its axis to allow stitching of multiple FOV's
    - For segmented optics, the interferometer may cover the entire segment, but there are then additional, difficult alignment metrology requirements
      - For segmented optics with active figure correction, the correctors' influence functions must also be precisely measured
- Mid-spatial frequency *(**few-nm accuracy required**)*
  - Usually assessed interferometrically, either by
    - Swapping the objective in the microroughness interferometer to expand the FOV
    - Taking great care to get very high resolution and excellent sensitivity and calibration accuracy in the low spatial frequency interferometer
    - (or both, for greatest spatial frequency overlap!)

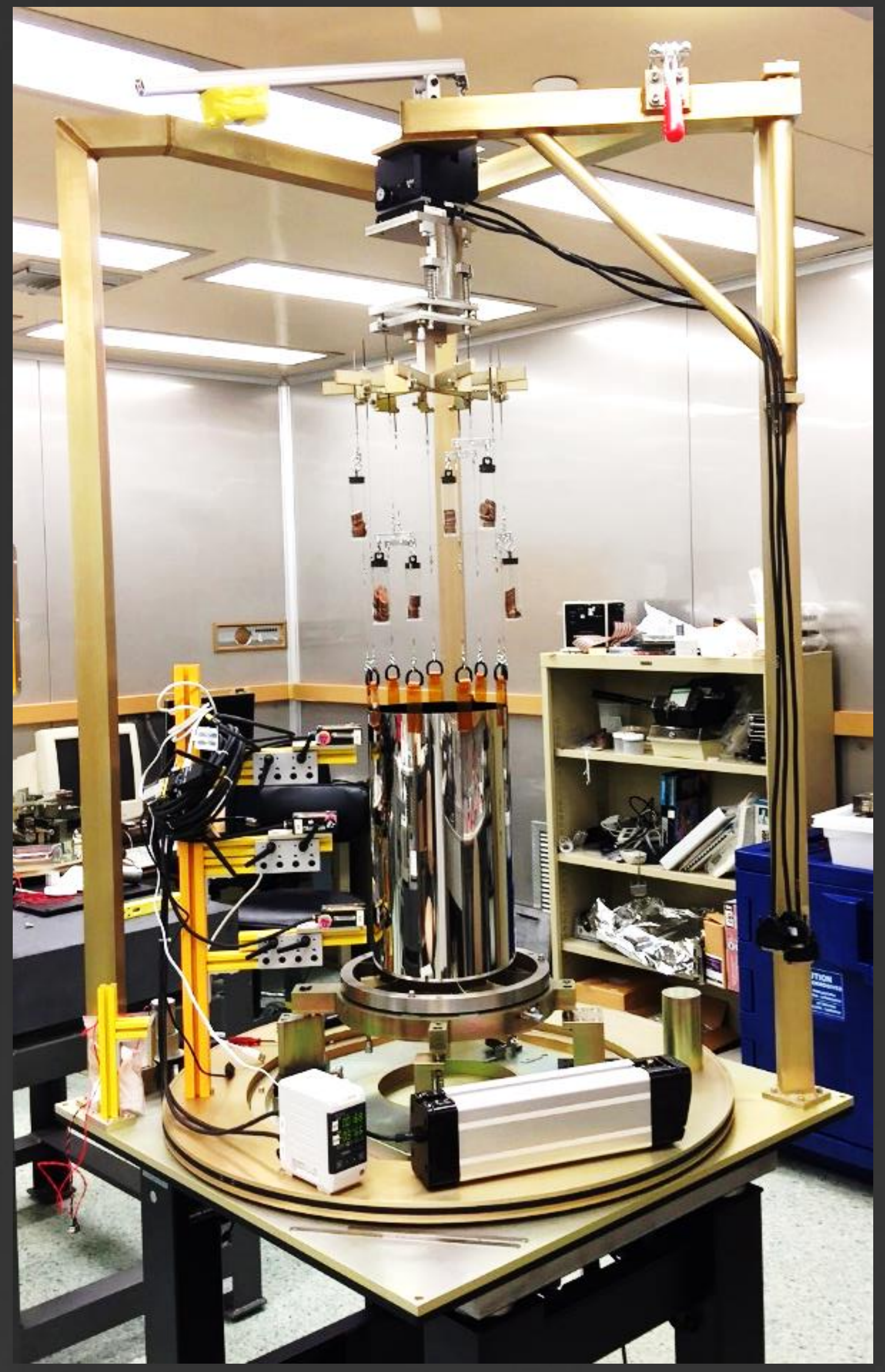
Slide Provided by Paul Glenn (Bauer, Inc.)

ALIGNMENT METROLOGY

- The traditional dividing line between metrology and alignment is blurred for Lynx, because of
  - The large number of mirrors
  - The possibility of a segmented architecture
  - The flexibility of the thin mirrors

- For full-shell cylindrical optics:
  - The flexibility puts strenuous requirements on the transition from holding the optics for metrology, and ultimately attaching them to the structure while monitoring the alignment and aggregate image quality over the full aperture

- For segmented optics:
  - Precision metrology is required as the mirror elements are assembled into modules
  - This metrology may combine direct measurements of the surface figure with indirect measurements of a module's image quality
  - Multiple modules must ultimately be coaligned, either by
    - Monitoring the alignment and aggregate image quality over the full aperture, or
    - Introducing transfer optics to each module that can generate an alignment reference to be compared against those of other modules



Credit: MSFC X-Ray Group

In all these cases, sub-arc-second accuracy is required, which at a focal length of 10 meters implies detection of image shifts or distortions of only a few microns.

Slide Provided by Paul Glenn (Bauer, Inc.)

Thank You!