New High Resolution X-ray Mirror System

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Why did we pursue an X-ray mirror design

- We were asked to pursue technologies that might enable a high-resolution X-ray observatory.
- We are experienced in mirror design, alignment, and we have developed optics that have similar alignment and scaling challenges.
- We have worked on X-ray mirror systems that include:
  - Deformable optics (laboratory effort)
  - Ni replication (SSAXI, among others)
  - SPO (Arcus)
  - Full shell (Chandra, Hinode XRT)
- We have decades of experience developing high resolution, super-smoothed normal incidence optics:
  - TRACE
  - SDO-AIA
  - IRIS
  - MUSE
- We felt that we had the most to offer in the realm of high-resolution X-ray optics.

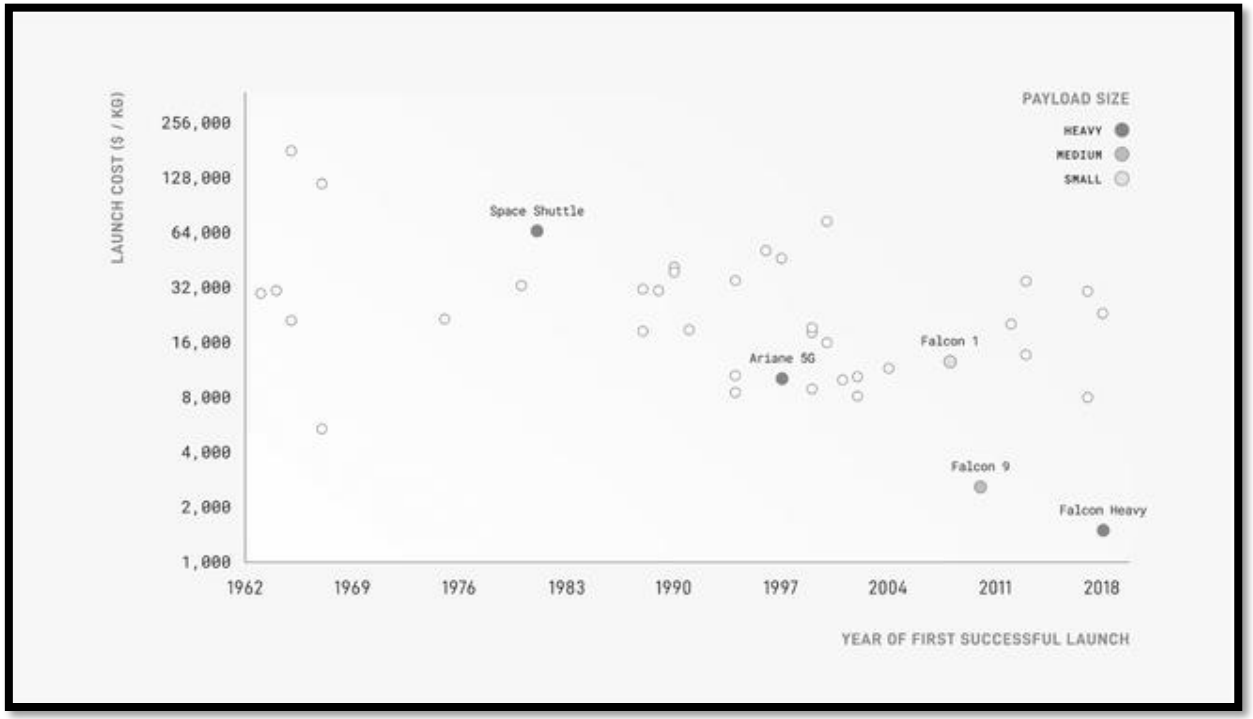
Specific Design requirements

- Meet Explorer to Flagship requirements
  - Effective Area > 1.0 m^2 @ 1KeV
  - Resolution < 1 arcsec HPD, at the center of the field, < 2 arcsec HPD to the edge of a 10 arcmin sq. FOV
- Scalability
  - Baseline available industrial level figuring and smoothing processes, specifically Ion Beam Figuring (IBF).
  - Use streamlined alignment and mounting techniques that have been tested, specifically the Coordinate Measurement Assembly (CDA) developed for Chandra
- Stability
  - Increase each mirror's stiffness to minimizing the effects of gravity and other external forces.
  - Use low or near-zero CTE mirror materials and support materials (CFRP, etc.) to minimize the effects of temperature using

Three key insights: 1. Mass

- The cost per unit mass to put the telescope in orbit has dropped considerably in the last 25-30 years.
  - We used this fact to increase the substrate thickness which eased all aspects of the mirror fabrication, assembly, and testing.

- Orbital Radar quotes current launch cost at between $1k/kg - $6k/kg.
- Drop since ~1997 between 8X – 60X.
- Price is expected to drop 10X more.
- Preliminary design increases mirror substrate thickness by 6X, and stiffness 200X.



From SpaceX Form S-1 2026

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Three key insights: 2. Alignment

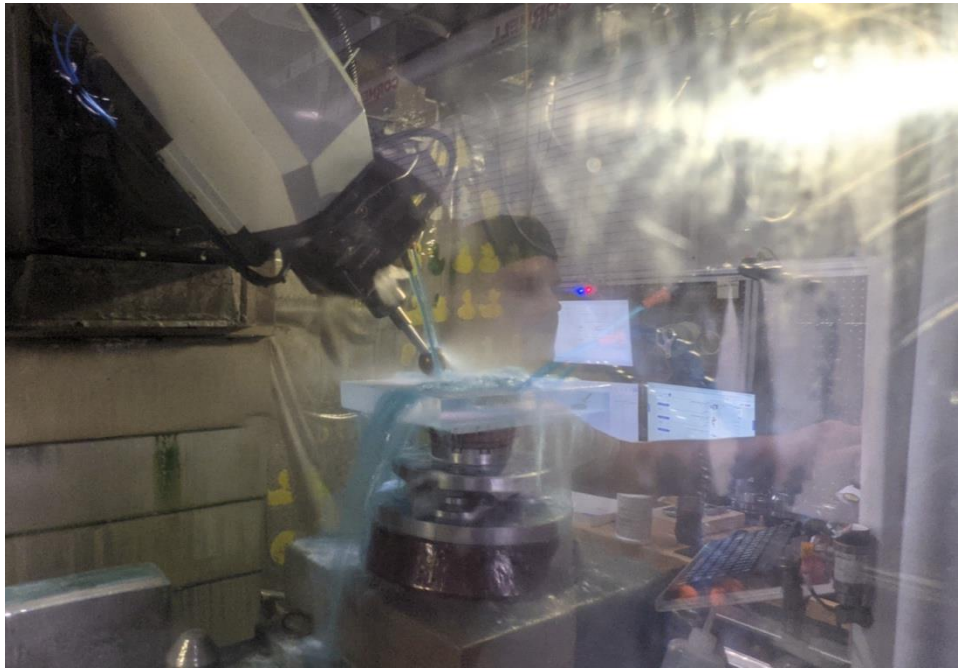
- Aligning the primary and the secondary mirrors to each other is the most difficult, tightest part of the aperture alignment.
  - This drove us to place the primary and secondary mirrors on a single substrate;
  - Making this change allows us to move this alignment step to a deterministic fabrication process, away from an iterative process, for every mirror pair.
    - This removes thousands of critical alignments.
    - P to H angular coalignments errors have at least 10X more effect than all other alignment error sources

Single mirror pair alignment budget

	Sensitivity	Allowable Error	Effect on Resolution
Mirror to mirror alignment error	**arcs/micron or arcs/arcs**	**micron or arcsec**	**arcsec RMS dia**
X linear motion	0.00164	50	0.08
Y linear motion	0.00164	50	0.08
Z linear motion	0.00015	1000	0.15
X-rotation	0.15885	2	0.32
Y-rotation	0.15940	2	0.32
Z-rotation	0.00575	50	0.29
Single Substrate spot size			**0.57**

Three key insights: 3. Advances in fabrication

- The state of the art of mirror fabrication has advanced. Tight figure/highly smoothed mirrors are made near-deterministically, without repeated cycles of figuring and smoothing.
  - This reduces cost and schedule risk, and lowers cost overall.
  - This steered us away from mandrel-based replicated systems and to fabricating each mirror pair



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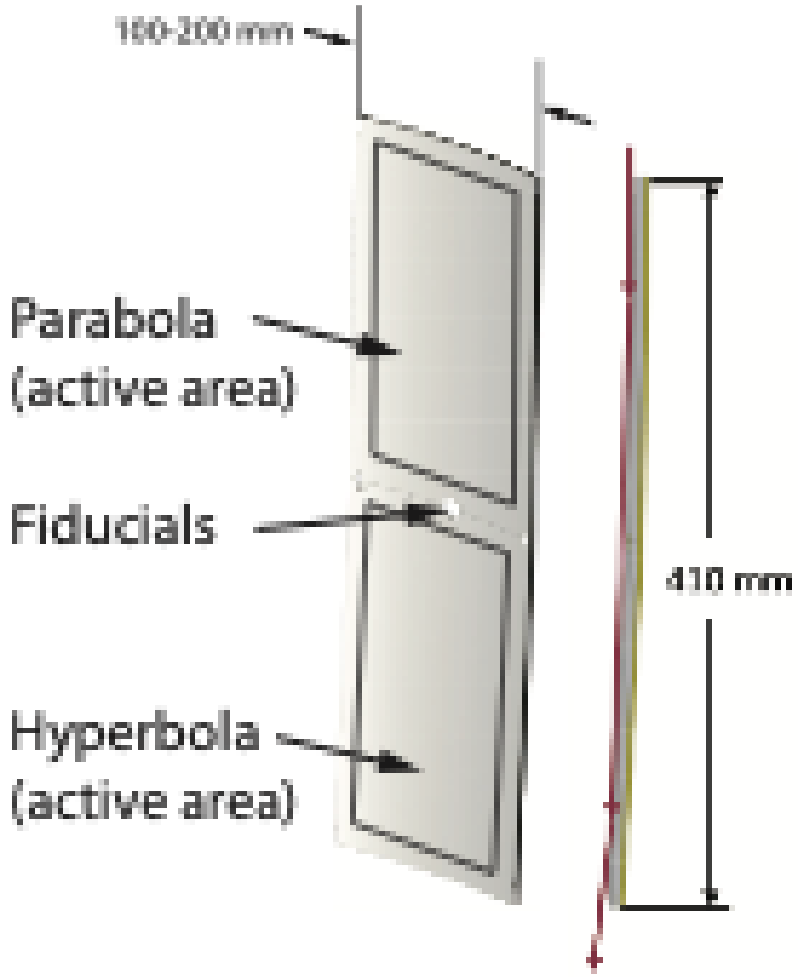
Mirror Design

- The preliminary 2-mirror substrate design:
  - **Substrate size**: up to 200mm wide X 410 mm long X 3 mm thick with a parabola and a hyperbola.
  - **Mirror layout**: up to 190mm wide X 195mm long parabola. Hyperbola width matches the parabola, length set to catch the rays that reflect off the parabola. There is a 10mm unfigured strip centered on the intersection radius for tool run-out.
  - **Mirror surface design**: We starting with Wolter-1. However, the design is compatible with other mirror designs (e.g., Wolter-Schwarzschild, optimized polynomial, etc.)



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Module Design: Reference design

Spectrometer grating module is the reference design for the X-ray mirror module design

View looking along the optical direction

View of the CFRP side plate supporting the fused silicon support rods

View of the titanium flexure and UV curing epoxy supporting the mirror

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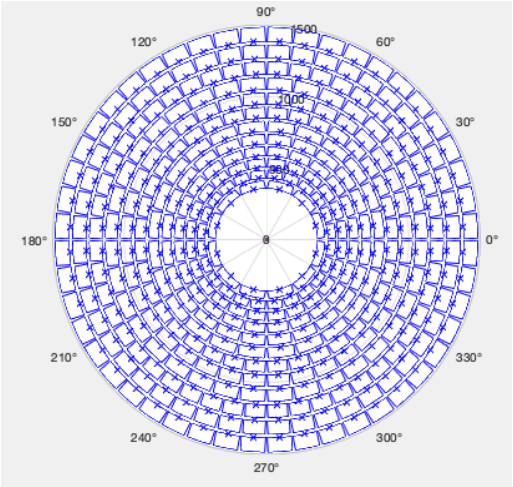
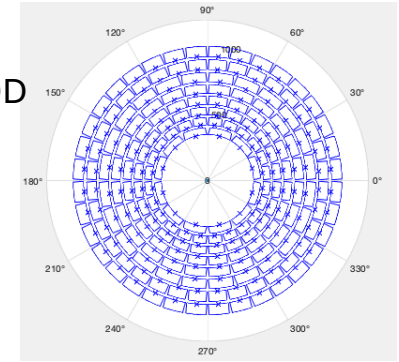
Aperture Design

- The mirrors are combined into modules (4-10 mirrors per module, still being optimized);
- Modules subtend 1/12*n (n = 1, 2, 3 , etc. = 30°, 15°, 7.5°…) of a ring;
- The inner and outer diameter is set by the desired energy response.

2800mm OD
560mm ID



2000mm OD
560mm ID



4000mm OD
720mm ID

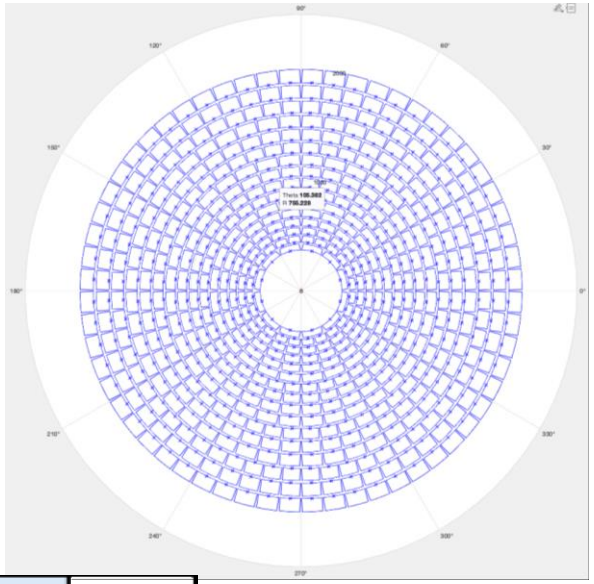


Table shows:

- Effective Area for different aperture layouts across various energies.
- These numbers assume Ir coating.
- Mass is for mirrors only.

	keV	1	3	6.4	7	10	
OD	ID	Effective Area for different apertures at the above energy					mass
mm	mm	m^2	m^2	m^2	m^2	m^2	kg
2800	560	1.14	0.22	0.061	0.05	0.01	1347
2000	560	0.56	0.20	0.060	0.05	0.01	744
4000	720	2.09	0.21	0.042	0.03	0.00	2380
2000	480	0.56	0.21	0.064	0.05	0.01	757

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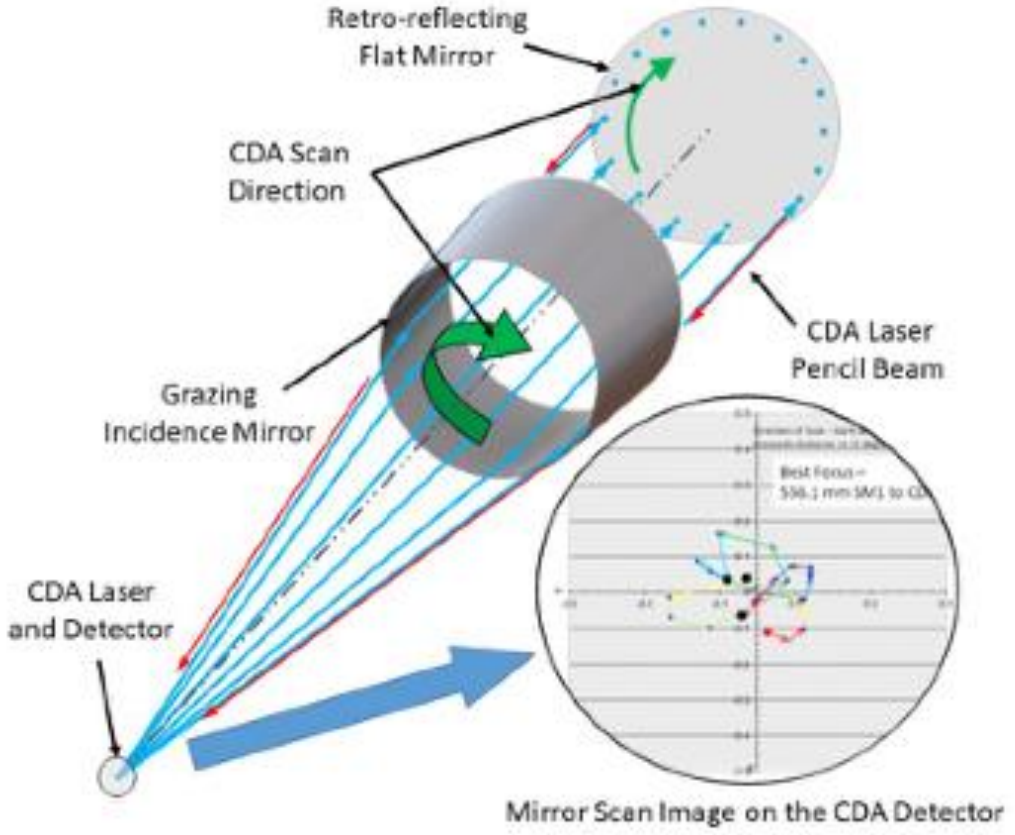
Mirror Alignment

- Each mirror pair is mounted on a hexapod and inserted roughly in place
- The orientation of the mirror is determined using precision non-contacting gauges set up to measure the fiducials in the substrate.
- The mirror is adjusted again based on the gauge measurements.
- The Centroid Detector Assembly (CDA) is used to compare the new mirror to the other mirrors in the module to ensure that the system is aligned.
- Then the mirror pair is bonded in place.
- The final check of the performance is carried out in an X-ray beamline.



Schematic of the CDA being used to align the MAGIXS spectrometer see: doi.org/10.1117/12.2232820

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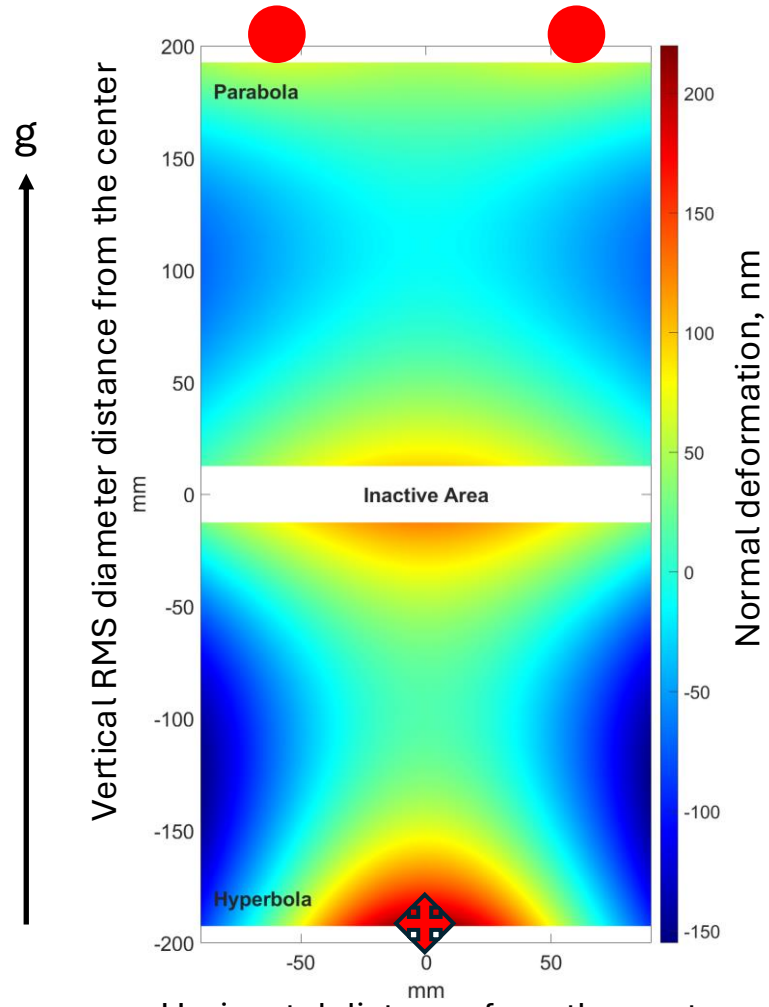
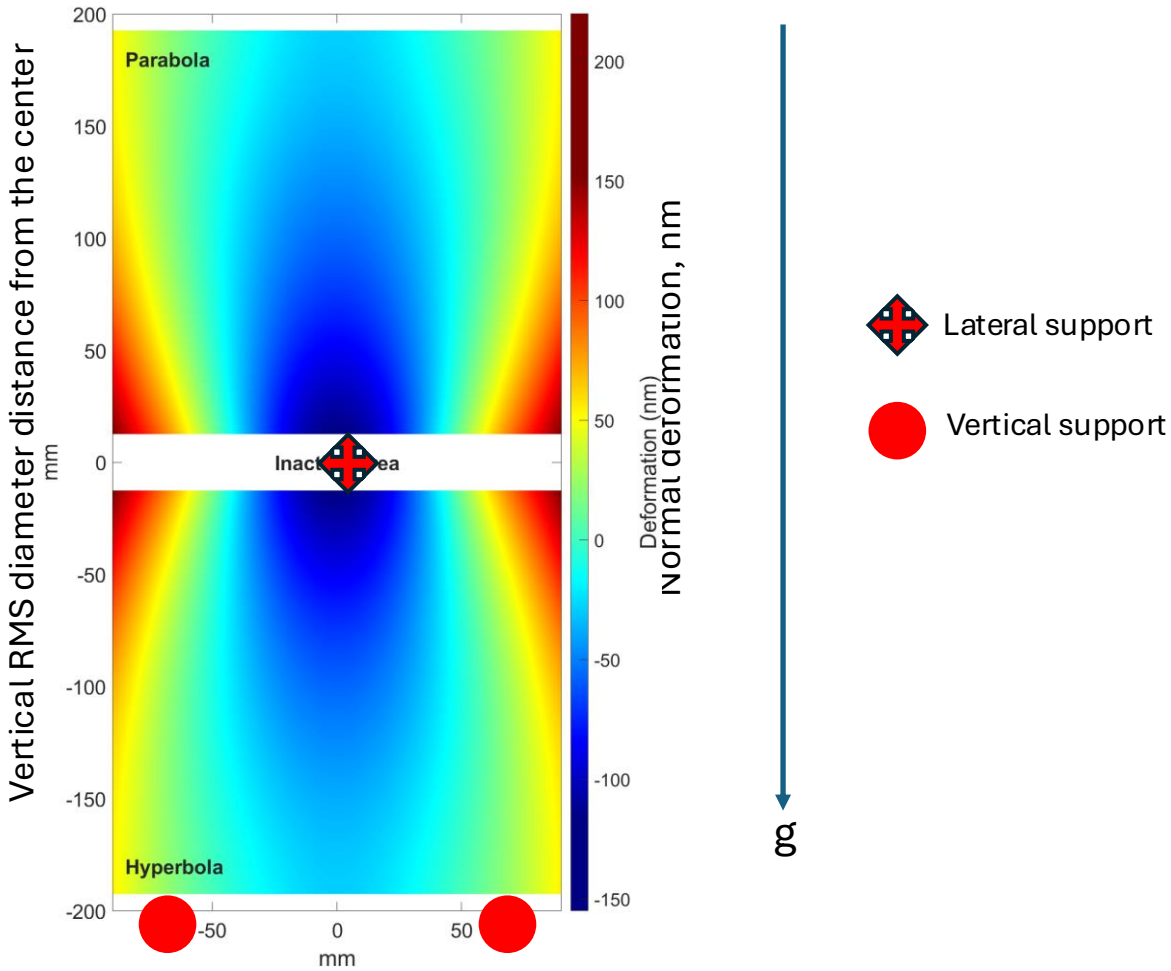
Current work: Analysis of alignment



Supported on the parabola side



Supported on the hyperbola side

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Upcoming Work

- Detailed design of the alignment system will be developed and constructed.
- Mirrors will continue to be fabricated.
- 3 mirrors (2@ 725mm, and 1@ 732mm mirror pairs) will be mounted and testing in an X-ray beamline.
- Pending added money:
  - 2 mirror modules, each holding 4 mirror pairs, will be constructed, aligned, and tested in a beamline.
  - The modules will be subject to environmental testing to raise their TRL.

END

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