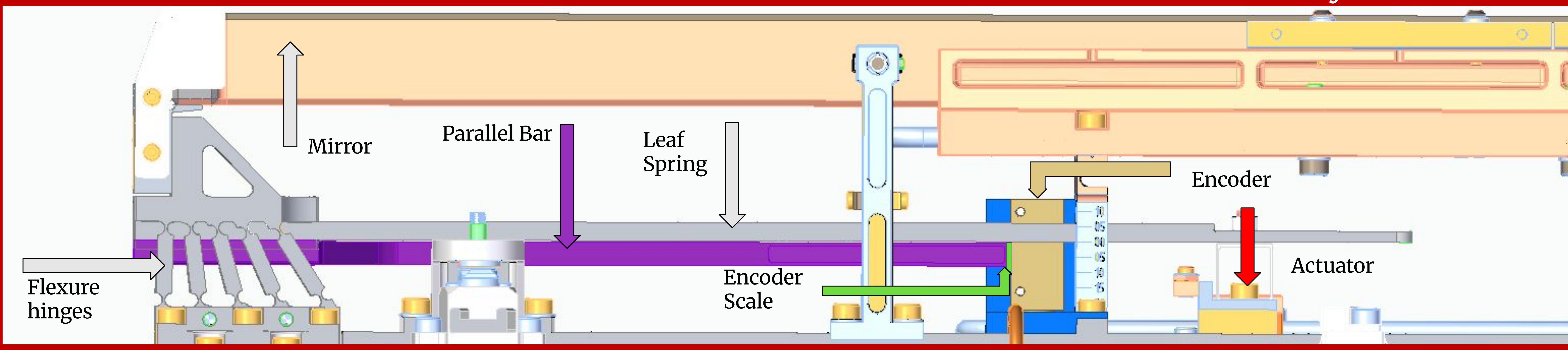
Enhanced Bending Moment Precision in Deformable X-ray Mirrors

[1] SLAC NAtional Accelerator Laboratory
[2] University of California Los Angeles

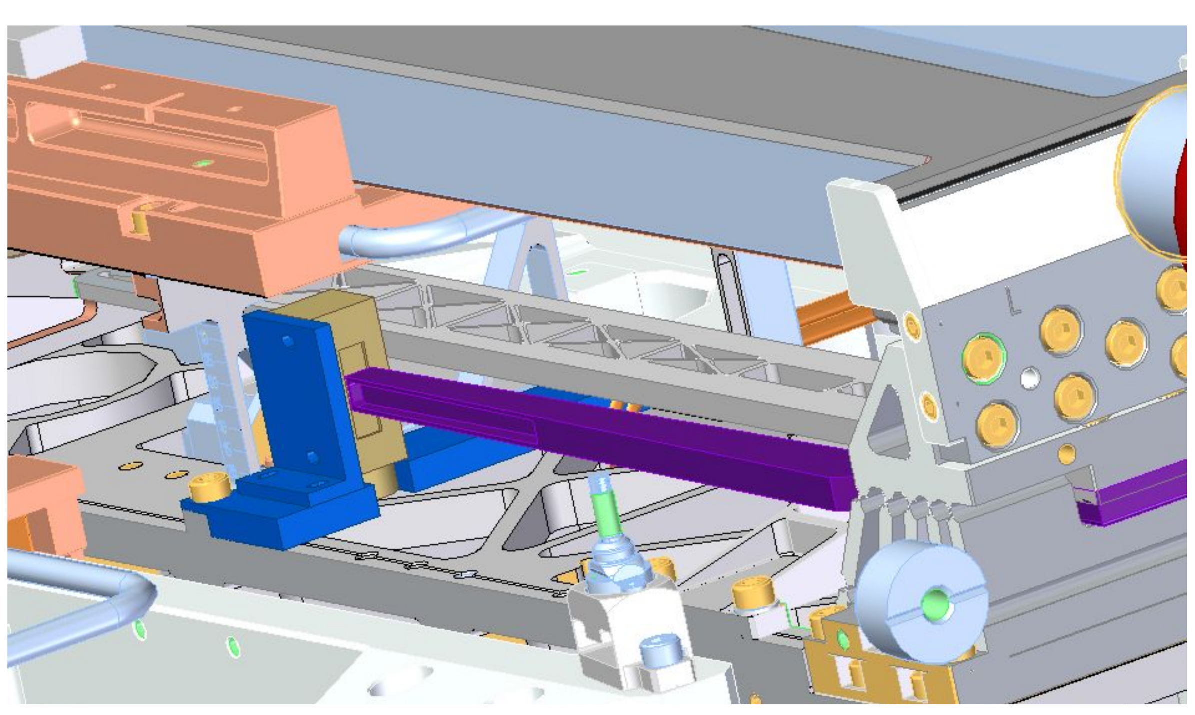
Chloe Whitmore[1,2] , Leinani Roylo[1] , Lance Lee[1]

SLAC NATIONAL ACCELERATOR LABORATORY   U.S. DEPARTMENT of ENERGY   Stanford University   UCLA



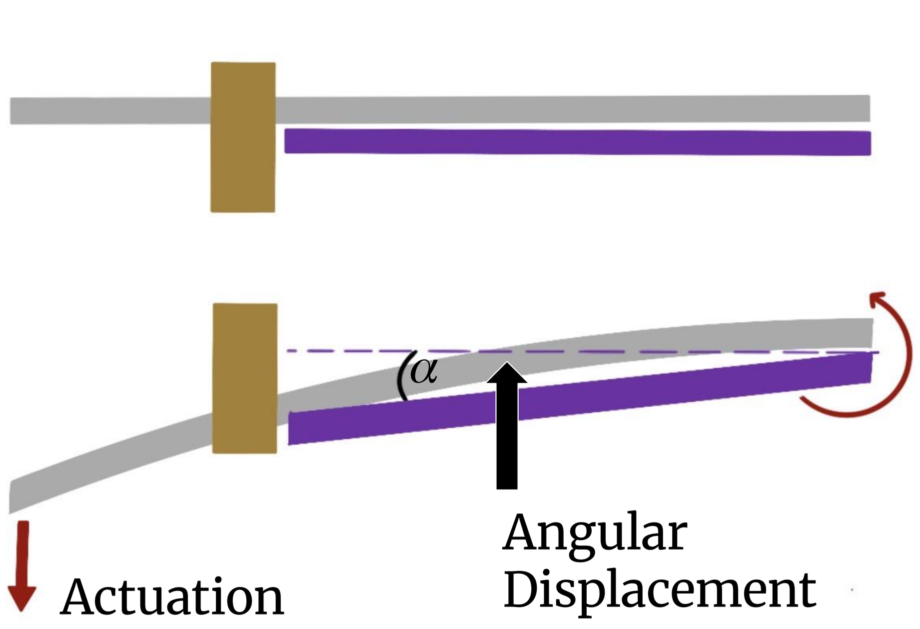
Background

- **Role of Mirrors:** The beamline uses specialized mirrors to focus high-intensity X-rays to a precise focal point.
- **Mechanical Errors:** Unpredictable deformations within the adhesive layer limit the ability to accurately measure moment transfer.
- **Complex Spring Geometry:** The leaf spring features a folded-back section designed to counteract its natural arc path—creating a complex kinematic joint where actuators attach, introducing errors.
- **Current Limitation:** Open-loop bending lacks real-time verification of the mirror's true shape.



Requirements

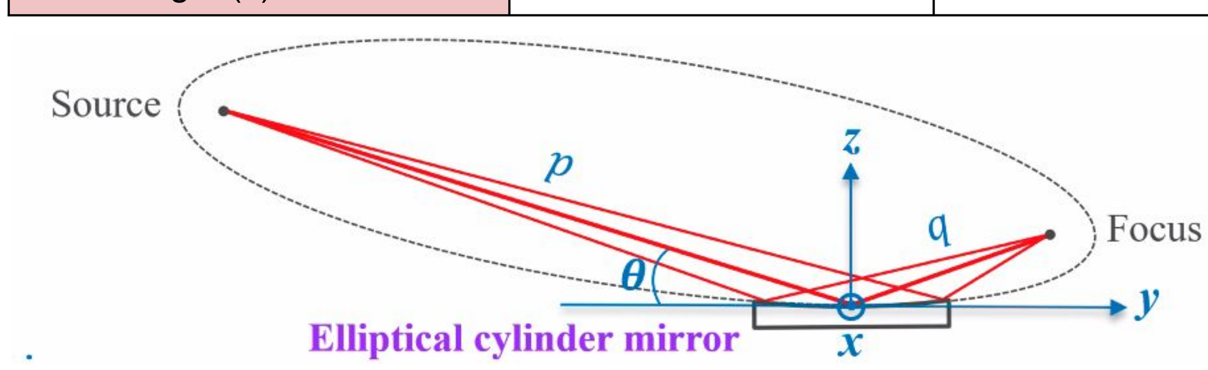
- **Direct Moment Sensing:** Measure applied force by tracking angular displacement at flexure hinges on each end of the mirror.
- **Signal Amplification:** Leverage a mechanical arm to amplify small angular shifts into measurable displacements.
- **Displacement Measurement:** Track lever arm displacement using a linear optical encoder and scale, mounted on a high-stability, adjustable fixture that simplifies scale alignment and cable routing.
- **Closed-Loop Control:** Able to translate encoder data into real-time bending moment values, driving a self-adjusting feedback loop for continuous auto-focusing.
- **UHV Compatibility:** Operate reliably within ultra-high vacuum environments without outgassing or performance degradation.
- **Dynamic Stability:** Maintain a high natural frequency to ensure rigid support and prevent vibration-induced noise in the data.



Methodology

We utilized MATLAB to analyze a specific CXI (MR4L0) mirror, modeling the target surface profiles to calculate the necessary shape changes and confirm the mechanical feasibility of the parallel bar.

Parameter	Unbent (pre-figure)	Target
Source distance (p)	13.2 m	377 m
Focus distance (q)	423 m	8.1 m
Grazing angle (θ)	2.4 µrad	2.4 µrad
Mirror length (x)	1 m	1 m



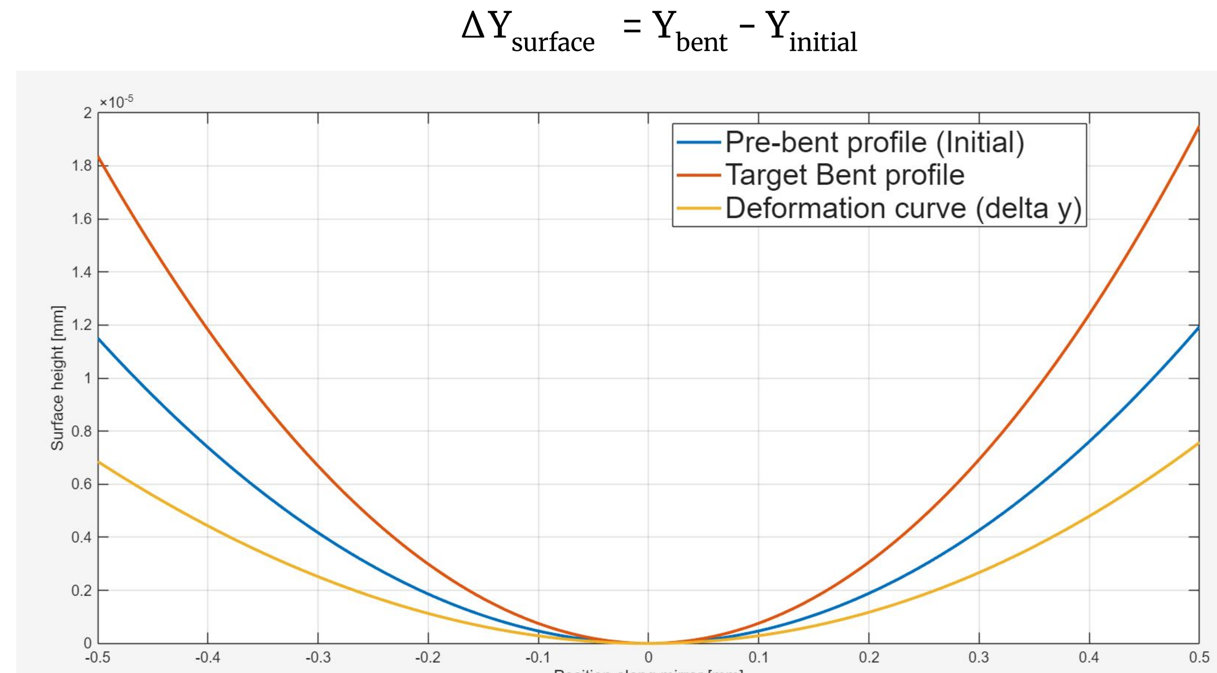
- **Surface Profiles:** Calculate initial ($Y_{initial}$) and target (Y_{bent}) 2D profiles using coordinate-transformed ellipse equations.

Semi-Major Axis: $a = \frac{p+q}{2}$

Semi-Minor Axis: $b = \sqrt{pq}\, sin\theta$

- **Differential Profile:** Determine required vertical shape change across mirror length to achieve the target surface profile.

$$\Delta Y_{surface} = Y_{bent} - Y_{initial}$$



- **End Rotations:** Extract boundary slopes using the small angle approximation to determine required end rotation angles (α)

$$tan(\alpha) \approx \alpha = \Delta(\Delta Y_{surface})/\Delta x$$

- **Parallel Bar Displacement:** Map rotations (α) into theoretical parallel bar end-point displacements using moment arm r = 0.2255 m (space constrained maximum)

$$\text{Horizontal displacement} = r\,(1 - cos(\alpha))$$
$$\text{Vertical displacement} = r\,sin(\alpha)$$

Predicts ideal mechanism kinematics while confirming displacements are within encoder limits.

	Encoder tolerance (mm)	Displacement	Parallel bar side 1 (mm)	Parallel bar side 2 (mm)	Meets metrics
Ride Height	0.8±0.15	Horizontal	8.055e-08	1.084e-07	✅
Pitch	±0.5°	Angular	0.00153°	0.00178°	✅
Resolution	0.000001	Vertical	0.00602	0.00698	✅

Analysis and Solution

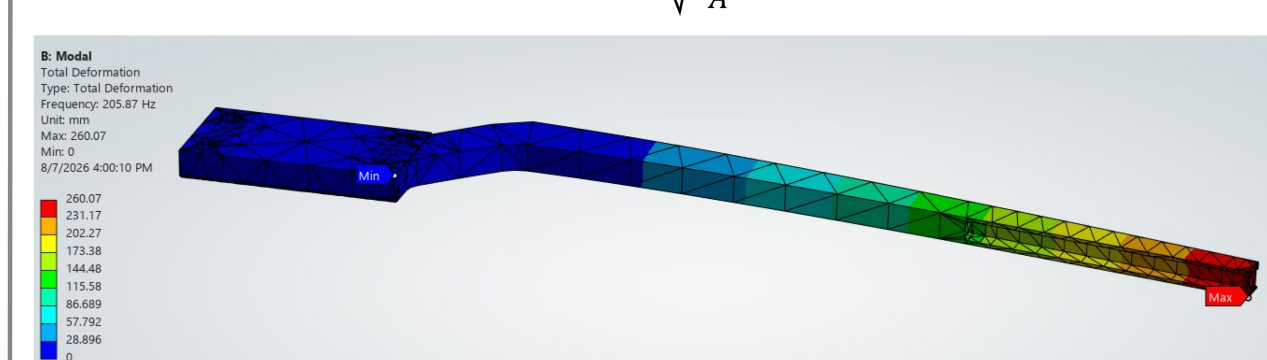
Vibrational

- To ensure micron-level measurement precision, the parallel bar was designed as a titanium tapered I-beam, pushing the natural frequency above 200 Hz to eliminate resonance-induced noise.
- The natural frequency of a beam is expressed as:

$$f = \frac{k}{2\pi}\sqrt{\frac{E \cdot I}{\rho \cdot A}}$$

- For a given material and length, f is maximized by optimizing the radius of gyration.

$$f \propto \sqrt{\frac{I}{A}}$$



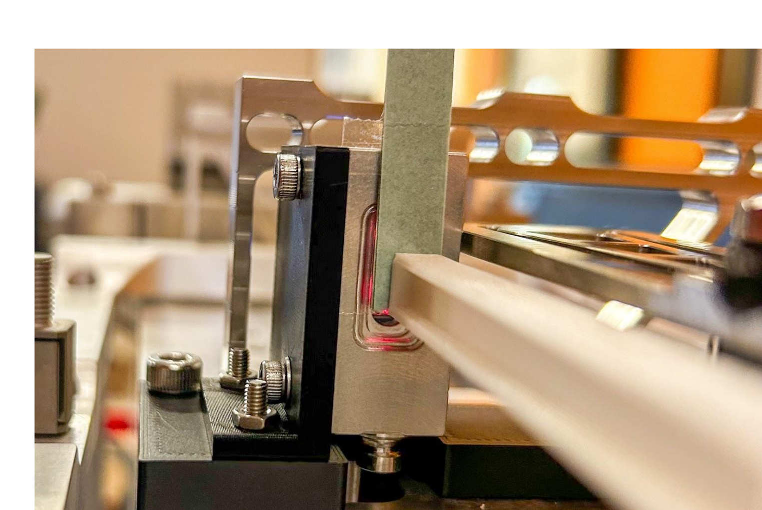
Mode	Frequency [Hz]
1	203.25
2	360.54
3	878.68

Structural Interference

- Finite Element Analysis (FEA) confirmed that the leaf spring and parallel bar maintain safe clearance without intersecting, even under maximum displacement.

Prototypes and Test Results

- **Fabrication & Setup:** Iteratively prototyped the encoder mount and parallel bar assembly using 3D printing to validate the mechanical design alongside a (non-UHV) encoder.
- **Test Methodology:** Applied manual deflection to the leaf spring as an alternative to mechanical actuation.
- **Data and Analysis:** Measured an average displacement of 0.002 mm. This correlates well with the 0.006 mm theoretical maximum displacement, reflecting partial manual actuation effort.



Future Plans

- Model flexure hinges in Ansys with parallel bar
- Assemble aluminium prototype
- Create program to self correct mirror bending

REFERENCES

[1] Xianbo Shi,. Optics Group, Advanced Photon Source, Argonne National Laboratory, Lemont, IL 60439, USA
[2] Lin Zhang,. LCLS Bendable Mirror Sustainable Capability Development Program, National Accelerator Laboratory, Menlo Park, California, 94025, USA

Portfolio Page

Want to learn more about my project?

Click here