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Adjustable X-ray Optics

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Adjustable X-ray Optics – Quick Intro I

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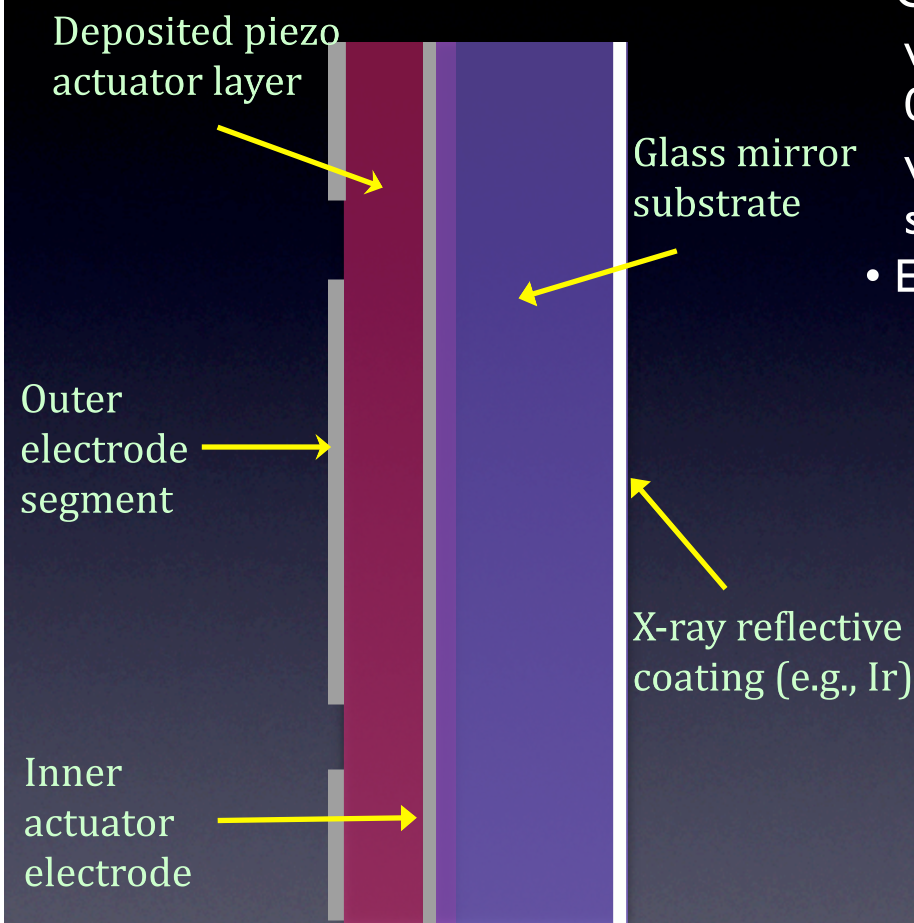
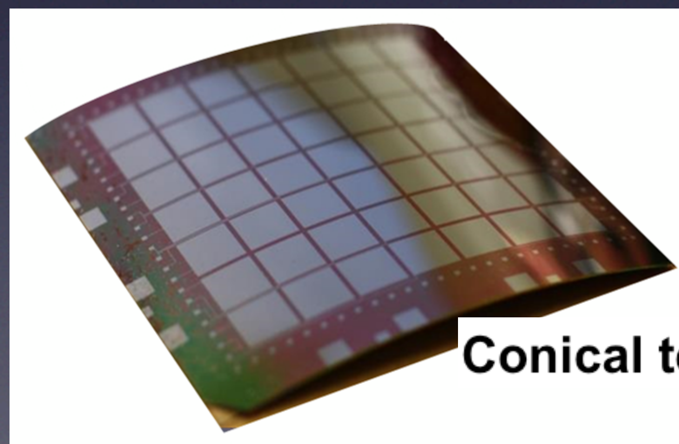
Schematic X-section



- Continuous, thin film (1.5 μm) piezo actuators with independently addressable electrodes on 0.4 mm thick mirror substrate. Low (<10) DC voltage thru piezo thickness produces in-plane stress in piezo, yielding localized bending of mirror.
- Enables efficient correction of mirror figure for:
  - fabrication errors
  - mounting induced distortions
  - *on-orbit* changes due to thermal environment
    - on-orbit correction enabled by integral strain gauges directly on piezo cells.



Conical test mirror

Adjustable Optics: Simulations I

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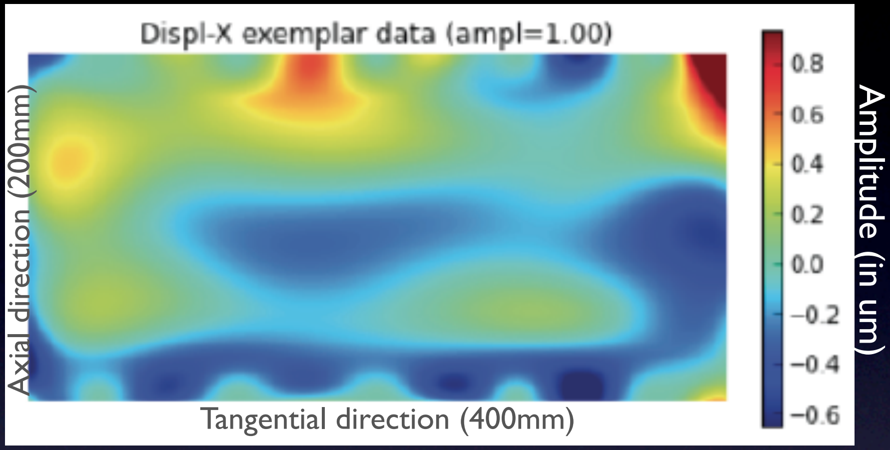
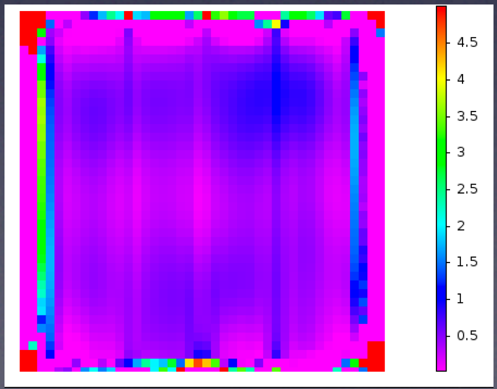
- Simulation modeling of smaller sized piezoelectric actuator cells
  - Use representative mounted mirror segment data
  - Use modeled influence functions – look-up table for each cell
    - Influence functions vary depending location on the mirror

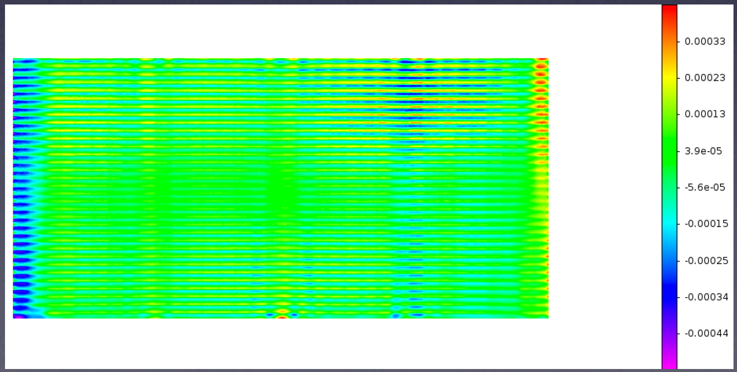


  - Optimize the strain required for each piezo cell to minimize RMS surface slope error
    - Imaging performance more closely related to slope error than amplitude error
    - Bounded, constrained, least squares optimization – 0 ≤ strain ≤ 500ppm



Left, cell strain x 100 ppm

Right, residual slope error, 0.4 arcsec rms diam. image



Point design for adjustable segmented optics

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- Purpose of this is not to review the design performance, but to give some parameters for the design
  - Wolter-Schwarzschild: no practical impact on mirror fabrication
  - 3 radial sets of modules (inner, middle, outer, like IXO) ranging from ~ 200 mm radius (at the intersection of P & S) to 1500mm radius
  - 292 shells (allowing for space between module rows)
  - 42 modules (6 inner, 12 middle, 24 outer)
  - ~ 8200 segments (P and S combined)
  - Azimuthal spans range from ~ 200 mm to ~ 400 mm
  - Axial length 200 mm
  - ~ 10^7 piezoelectric adjuster cells in total
- Modeled performance: 2.3 m^2 at 1 keV with Ir coating
  - Includes geometric obscuration, P/S misalignment, particulates, scatter

Adjustable Optics

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- Adjustable [active] optics technology is not new
- Adjustable optics technologies are readily scalable
- The adjustable optics technologies are already well developed in the microelectronics and coating industries
- Adjustable optics approach is semi-independent of mirror substrate (glass, Si, metal, as long as not so thick and stiff that can't be deformed, or too rough on [back] surface)

Fabrication Process

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- We use slumped LCD glass as a substrate
  - Corning Eagle™ XG 0.4 mm thick
    - Measured smooth pre-slump: ~ 3 A rms over 1 to 1000 mm^{-1} bandwidth
    - Use mono-Si mandrel with sputtered Pt release layer
    - Strain temp ~ 669C: this is important as will mention later
    - So far, appears that slumping copies the mandrel mid frequency errors (1 to 10 mm periods), or ~ 2 nm rms for our test mandrel (1 nm rms req'd for Lynx)
- Slump over-sized, then commercially laser cut with fs pulsed CO2 laser to 101.6 x 101.6 mm^2
  - Current size dictated by PSU piezoelectric material sputter chamber.
- Lead zirconate titanate (PZT, 52:48, 2 % Mn doped) deposited on Pt/Ti barrier/ground electrode, annealed at 550 - 650C, then electrodes lithographically printed

Complexity Reduction

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- ZnO thin film transistors (TFTs) printed directly on piezo cells
  - Enables use of row-column addressing for the adjusters (just like all LCD displays)
  - Reduces required number of electrical connections for controlling M x N adjuster array on a segment from M•N+1 to M+N+1
    - For a 40 x 40 array, reduction from 1601 to 81 connections
- Digital command bus and central power lines with few (<10) connections per segment
  - Piezo cells have large RC time constant (50 – 100sec)
  - Use ASIC or FPGA to strip out command for each segment and adjuster
    - On segment ASIC – only a few connections to each segment from central bus
- Anisotropic Conductive Films (ACF): micro-electronics industry high density electric connections (up to 100/linear mm)
  - Use for electrical connections to mirror segment with flex cable

On-orbit Monitoring and Adjustment

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- Deposited semiconductor strain gauges on piezoelectric cells used to monitor on-orbit piezo aging, mirror temp and figure
  - Require ~ 2 to 20 ppb strain measurement for 0.5 arcsec - challenging
  - Strain gauges sensitive to temperature and strain. Use out-of-plane gauges for temp monitoring, in-plane gauges for strain monitoring (after temp corrected)
- Three potential operating modes:
  - PZT aging - simplest mode - once/twice per year, drive piezos with AC voltage and synchronously monitor strain to determine piezo coeff to better than 1 per cent, sufficient to maintain sub 0.5 arcsec imaging.
  - On-orbit indirect monitoring – measure local temp using out-of-plane strain gauges and update thermal-mechanical models to determine adjuster voltage changes needed to correct thermal distortions
  - On-orbit direct monitoring and control – most complex mode – using temp corrected in-plane strains to determine mirror figure and re-optimize adjuster voltages as required
    - Requires greatest accuracy

Status: Piezoelectric adjusters are feasible

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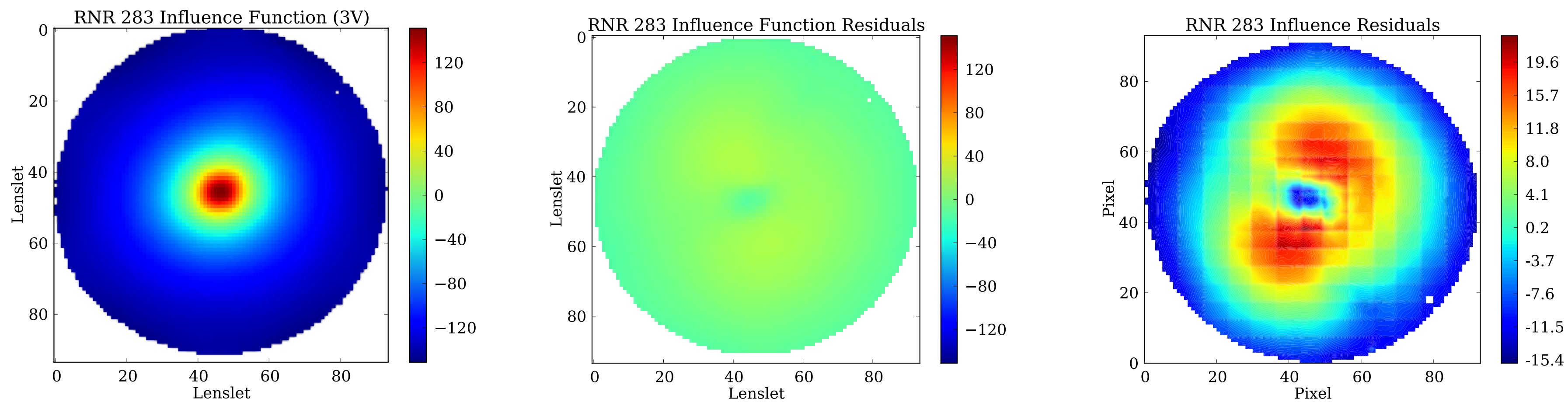
- Measured influence functions match modeled influence functions on both flats and cylindrical segments to ~ few nm.



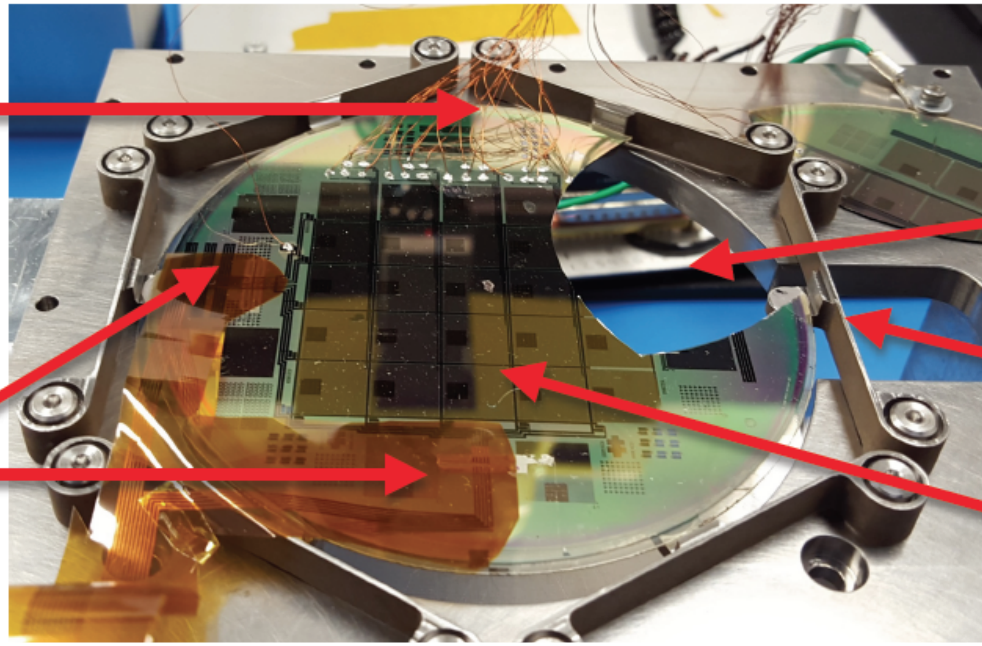
(Amplitudes in nm, X and Y axes in pixels)

- Influence functions are repeatable and deterministic
- Accelerated lifetime testing (ALT) yields median failure time MFT >10,000 years with very sharp Weibull distribution.

Status: ZnO TFTs and ACF connections work

Direct connections to cell top electrodes

Flex cables with ACF connections to mirror cells with row-column addressing via ZnO TFTs.

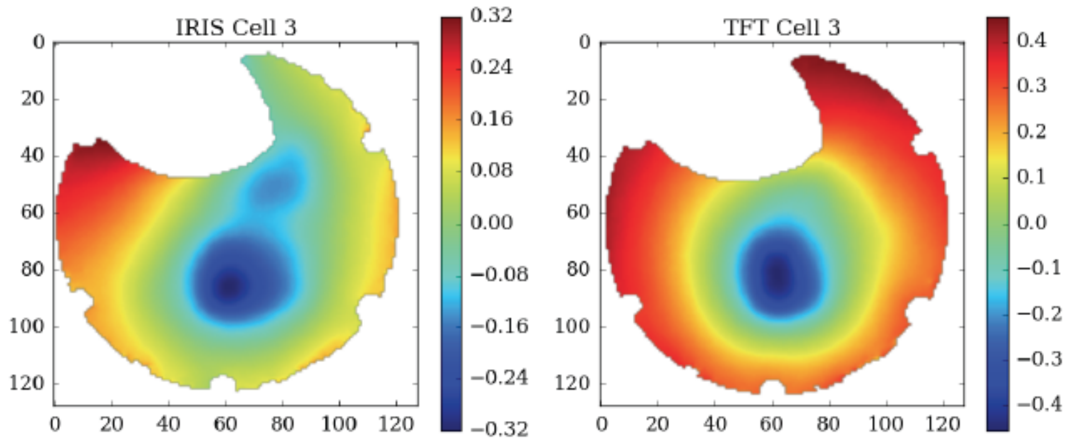


Broken portion of mirror (missing).

Bipod flexure

Piezoelectric cells

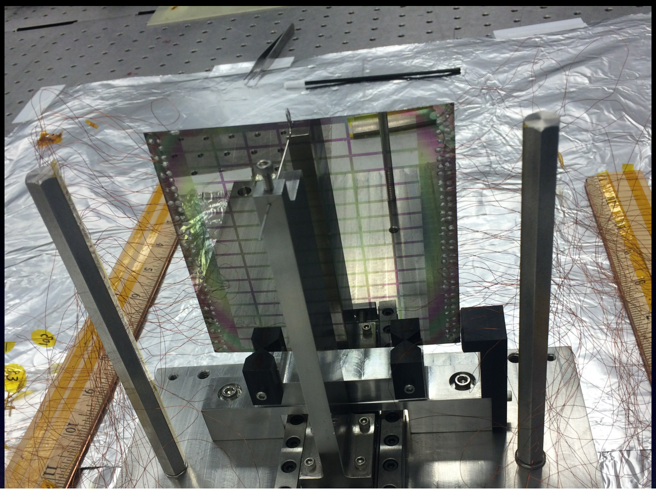
Direct connection to cell

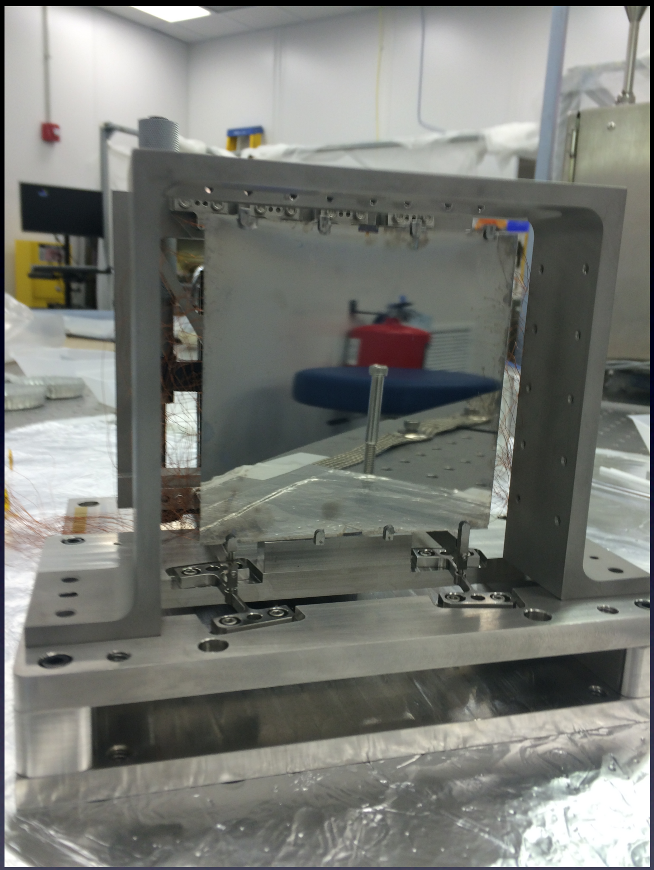


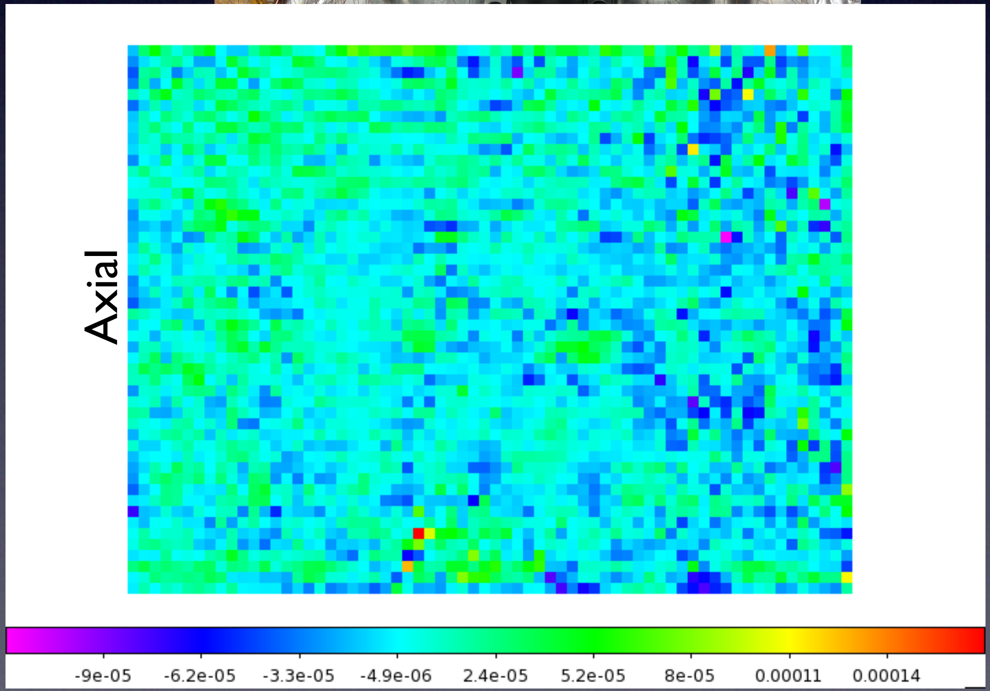
(Amplitude in um, X and Y axes in WFS pixels)

TFT connection to cell

Status: Control figure to within current noise limits







- (Pred. Δ fig – meas. Δ fig) = 0.45 arcsec, rms slope ≈ metrology noise.
- Plot color scale = slope, in rad. X 10

Status: Next figure control test and segmented mirror mounting

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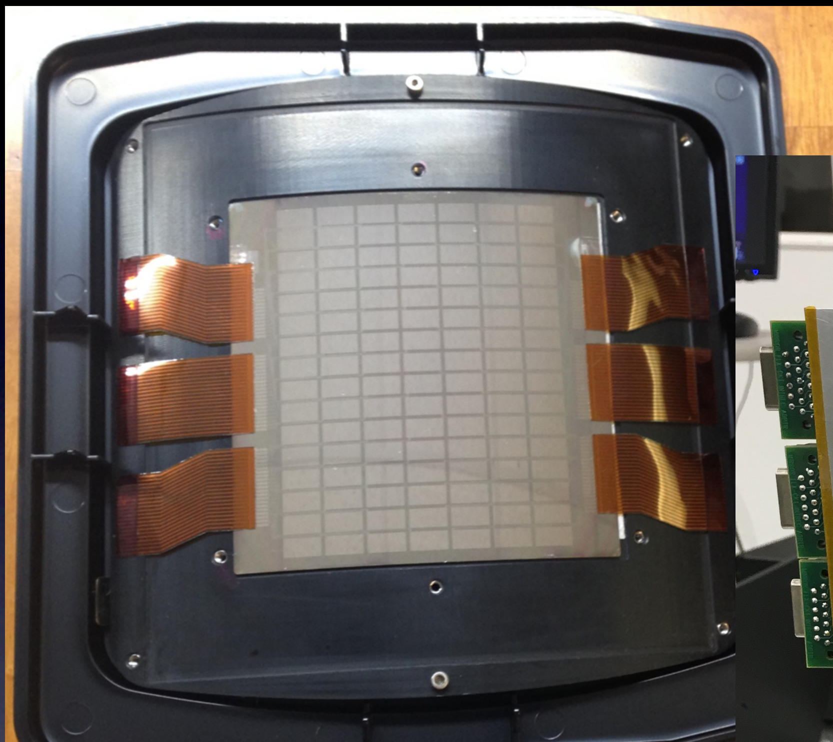
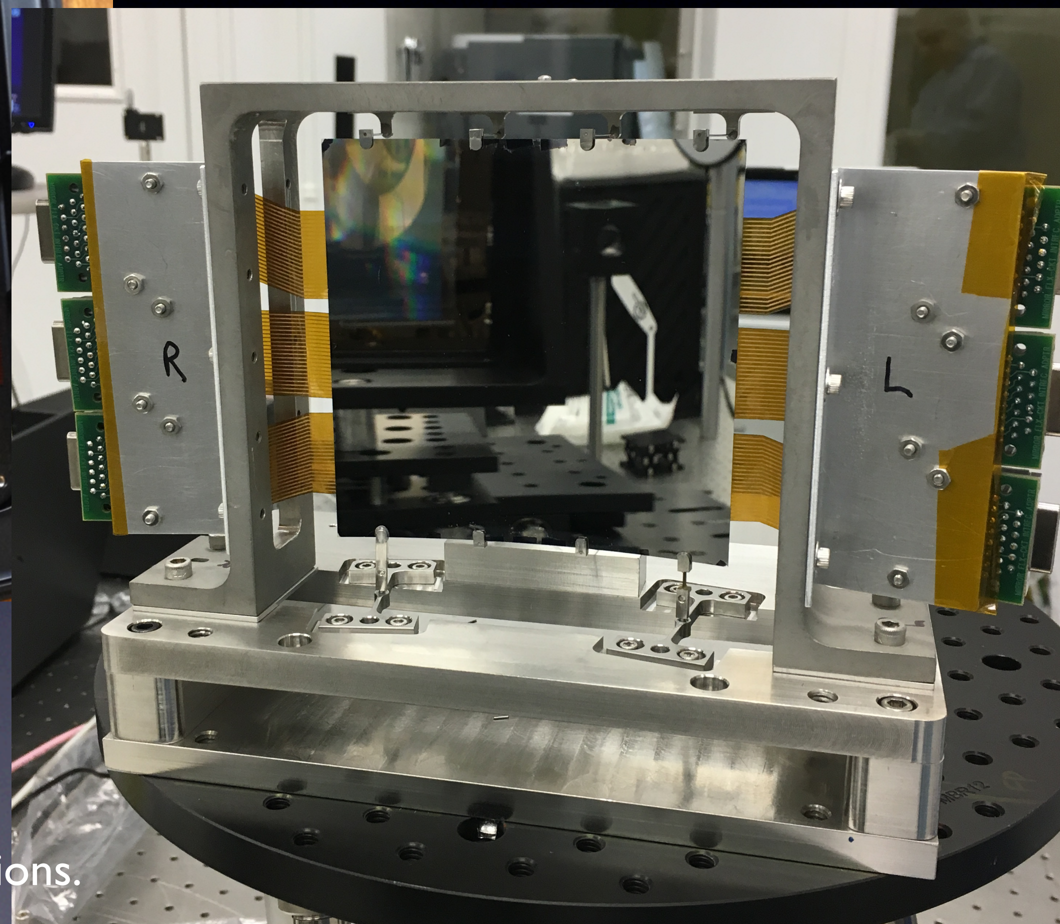


Unmounted mirror (back side) with ACF bonds and flex cables, in shipping box (left).



Mirror mounted in mirror housing. View from optical axis looking radially out (right).

Assessing impact of induced distortions.

Current Technical Issues

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- PZT processing-related mirror stress and stress compensation
  - Film stress due to PZT and electrode layer deposition, and PZT crystallization and annealing
  - Just discovering now large differences in film stress between box furnace anneal and Rapid Thermal Annealer (RTA) anneal
    - Film stress lower (~ 125 MPa) for furnace anneal, ~ 300MPa with RTA
    - Film stress uniform for box furnace, non-uniform for RTA
  - In past (several years ago) demonstrated film stress compensation with a front side film to ~ +/- 10-15 per cent.
  - Need to resolve the RTA/box furnace issue and compensation to < ~ 10 per cent of stress
- Mirror mounting
  - Latest attempt reveals introduction of distortions – still need to assess impact

How Can Industry Help?

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- For Lynx, require industry support for industrialization and mass production concepts
  - From our design, we will require:
    - >10,000 segments (with spares)
    - Several hundred precision slumping mandrels
  - PZT and thin film deposition (requires capability to evaporate Pb!); film stress control and repeatability; row-column addressing
  - Segment and mandrel production, contamination control, mounting, alignment
  - Metrology and metrology integration into alignment and calibration
  - Electronics design/conceptualization, including on-segment ASICs/FPGAs
- For "Now"
  - Mounting/alignment support
  - Stress compensation coatings
  - Strain gauging

Acknowlegements

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