Differential deposition- a post-fabrication figure correction for grazing incidence X-ray optics

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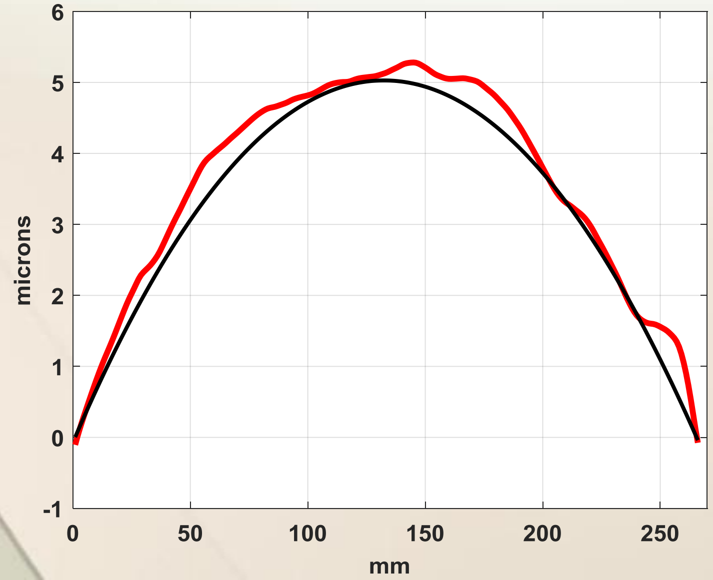
X-ray optics - State of art

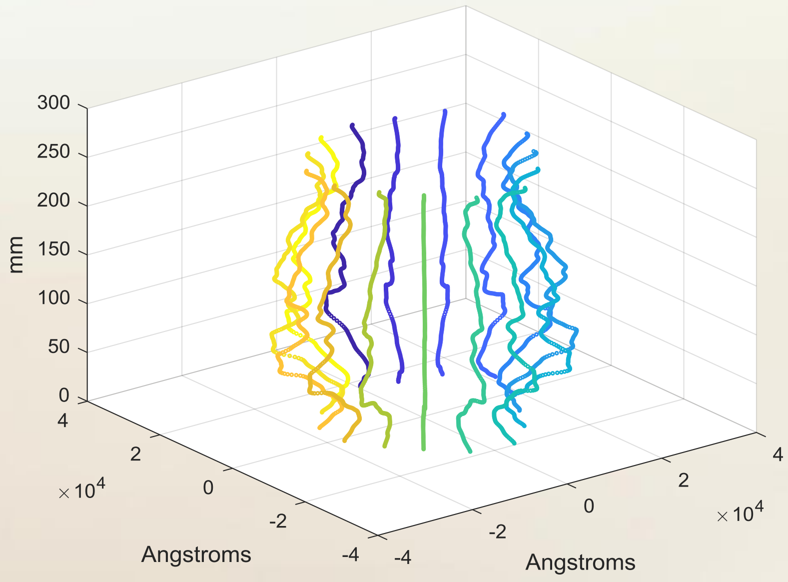
- **Current state of art-**

  Full-shell: 8 arc sec FWHM; 10 to 15 arc sec HPD

  Segmented: Demonstrated 5 arc secs HPD

- **A key factor that limits the angular resolution is Figure Imperfections**
- **Post-fabrication figure correction is a key step in achieving arc-sec level resolution – regardless of the optics type and fabrication procedure**





Application - Lynx

- **Lynx will take X-ray astronomy to new levels by combining a large gain in collecting area over Chandra and XMM, <u>an angular resolution of 1/2 arc second</u>, and high-throughput spectroscopy over a large field of view.**

- **Optics approaches under consideration: Segmented / Full-shell / Active optics**

- **Differential deposition is a highly suitable approach for correcting mid–spatial frequency figure deviations**

Application – neutron microscope for energy and material research

- **Neutron Imaging: Optics to improve flux and resolution**
- **Conventional pinhole imaging – tradeoff between resolution and throughput**
- **Need for higher-spatial resolution without compromising the flux**
- **Use of Wolter optics – world's first neutron microscope**
- **Collaborative project between NASA MSFC, NIST's Physical measurement laboratory and MIT**

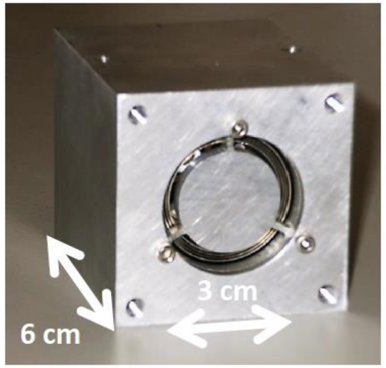
Applications:

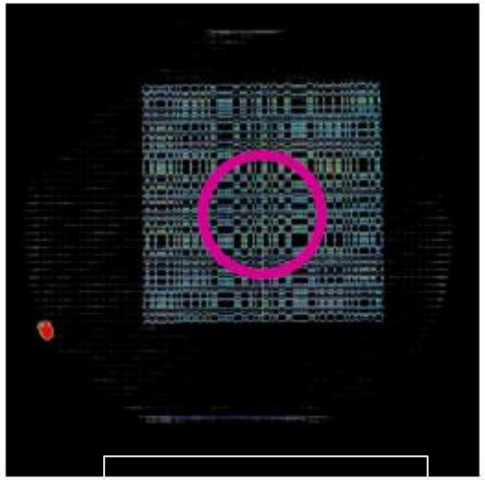
- **Fuel cell development (resolving concentration gradients in electrodes requires the highest possible spatial resolution)**
- **Lithium-air batteries development (lithium-air batteries have 10x storage capacity of commercial lithium-ion batteries)**
- **Non-destructive evaluation of nuclear fuel rods life cycle**
  - **Also:**
  - **Understand targeted drug delivery ; Advance oil and gas recovery ; Improve the safety of nuclear fuel cladding by imaging the grain structure of ZrH ; Develop additive manufacturing of metal alloys ; Reveal solar cell morphologies to reduce the cost of large area solar arrays ; Enhance efficiency of room temp. magnetic refrigeration by imaging 3D magnetic structures ; Solve protein structures in solution, 2/3 of all proteins can't be crystallized ; Understand polymer and block copolymer self-assembly and hydrogels ; Distinguish internal structure and morphology of graded nanoparticles ; Understand magnetic nanoparticles for hyperthermic cancer treatment, MRI contrast agents**

Neutron Microscope

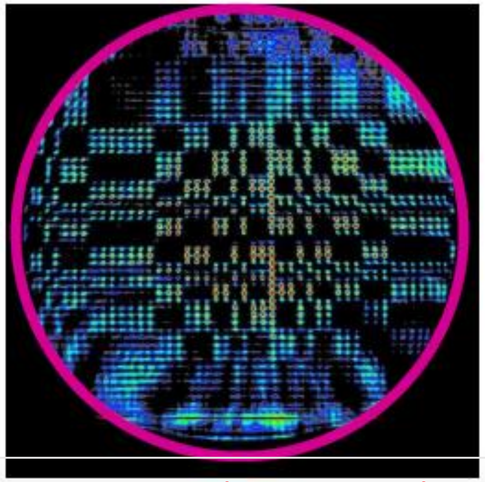
- **Prototype microscope**
  - **3 nested mirrors with ellipsoid and hyperboloid sections**
  - **Object to image distance of 3.2 m**
  - **Neutron imaging was demonstrated with 1cm FOV 4X magnification, 75 microns spatial resolution and 5mm depth of focus**
  - **2cm x 2cm pinhole mask, with 0.1mm diameters on 0.2mm centers**

- **Immediate Goal:10 μ spatial resolution**
  - **1:1 design with 2 parabolic sections**
  - **Object to image distance of 700 cm**
  - **10 nested mirrors -radius 68 cm to 55 cm**
  - **Long term goal of 1 μ spatial resolution**

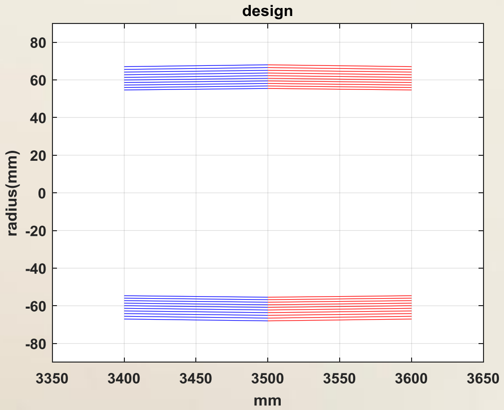


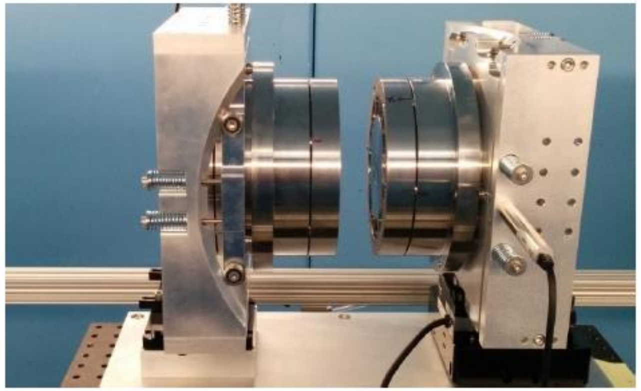


Contact image



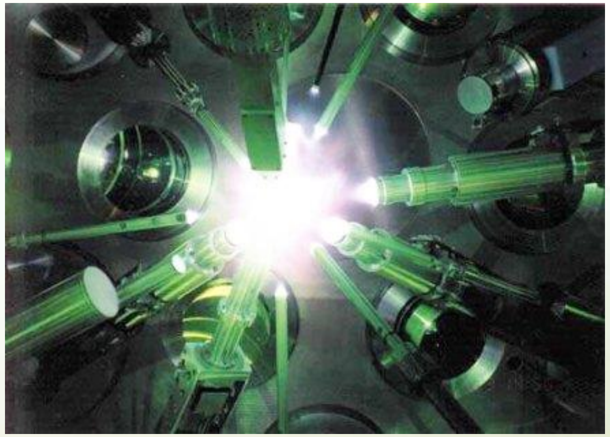
Prototype microscope image

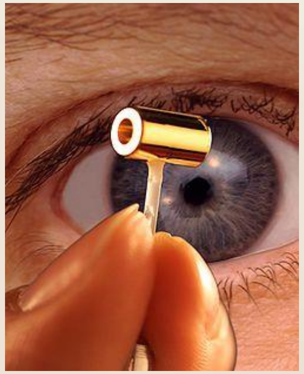


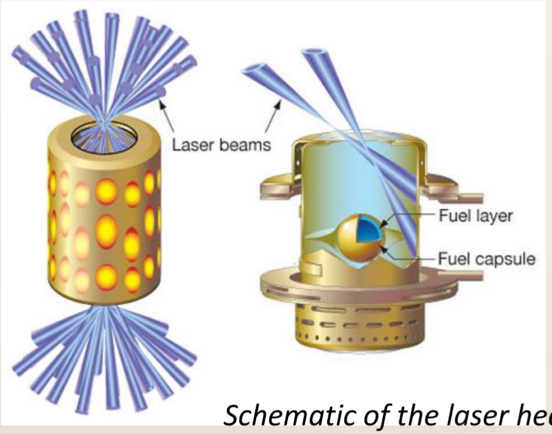


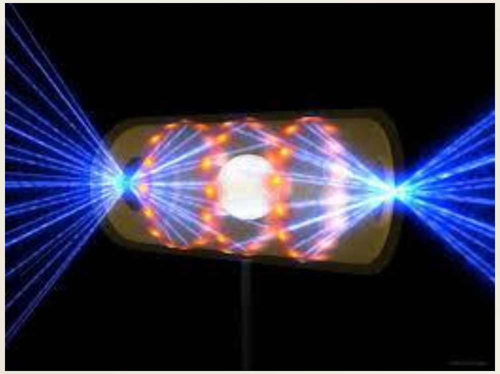
Application – National Ignition Facility (NIF) for Inertial Confinement Fusion (ICF)

- Collaborative project – LLNL,NASA MSFC
- ICF is a type of fusion energy research that attempts to initiate nuclear fusion reactions by heating and compressing a fuel target
- The energy of the laser heats the surface of the pellet into a plasma, which explodes off the surface.
- The remaining portion of the target is driven inward - when the temperature and density of that small spot are raised high enough, fusion reactions occur and release energy.
- NIF aims to create a single 500 TW peak flash of light that reaches the target from numerous directions at the same time, within a few picoseconds. The design uses 192 beamlines in a parallel system high power lasers.
- Plasma emits x-rays which can be used for imaging and diagnostics



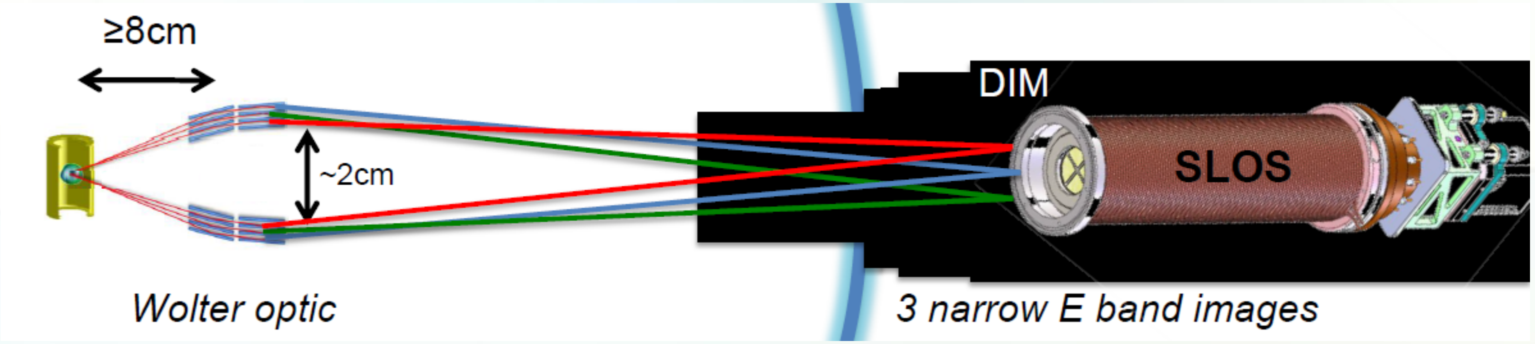


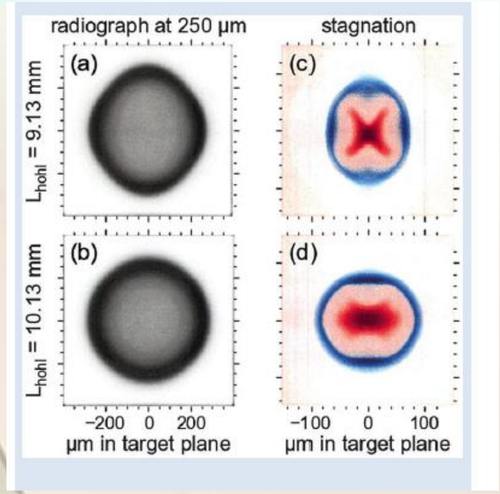




Schematic of the laser heating and compression of the fuel target

Application – National Ignition Facility (NIF) for Inertial Confinement Fusion (ICF)



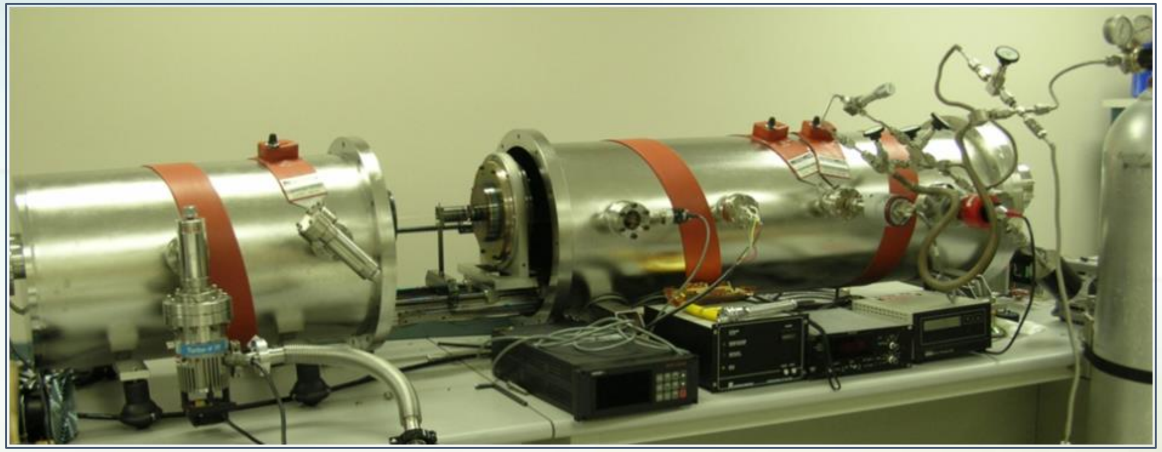


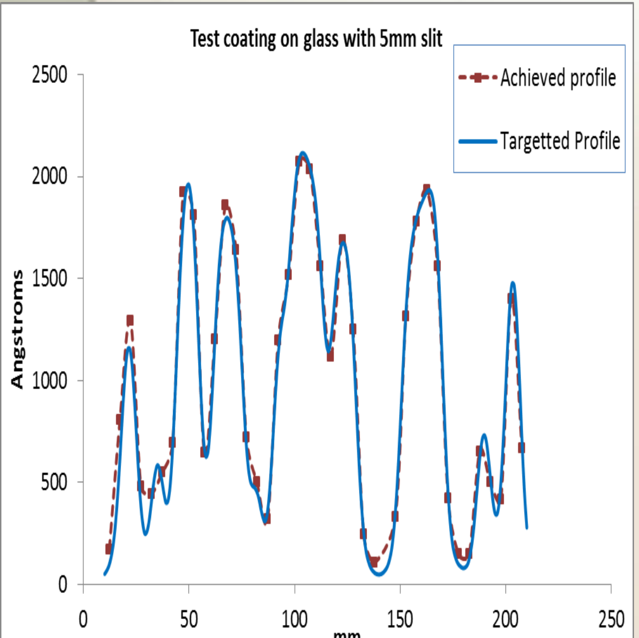
The roundness of the implosion at various points in time provides the tuning information, such as x-ray drive uniformity

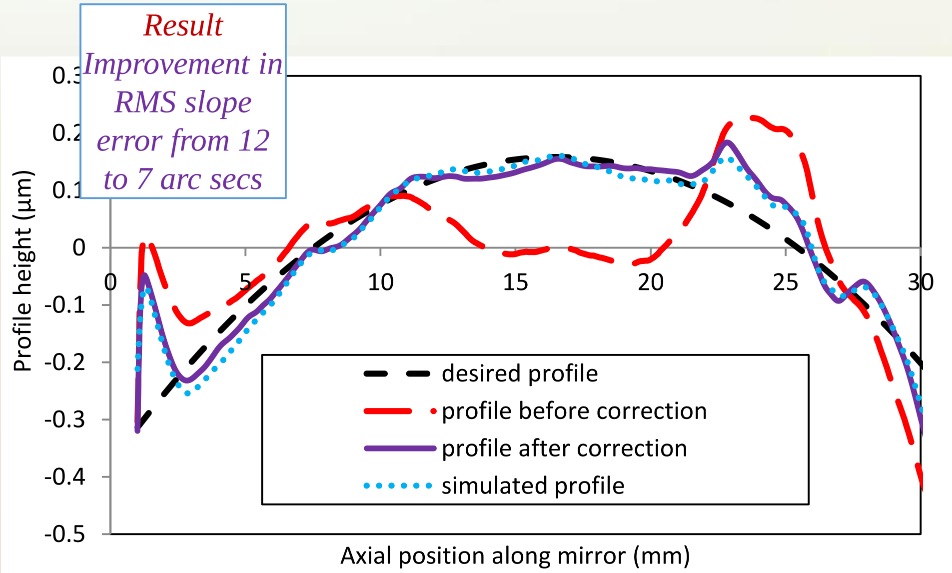
- **X-ray imaging is critical to the physical understanding of ICF implosions**
- **Need for high-resolution 5microns (FWHM) spatial resolution imaging optics for hard 10-25 keV x-rays**
- **Optics design is currently underway**
- **Will utilize differential deposition**

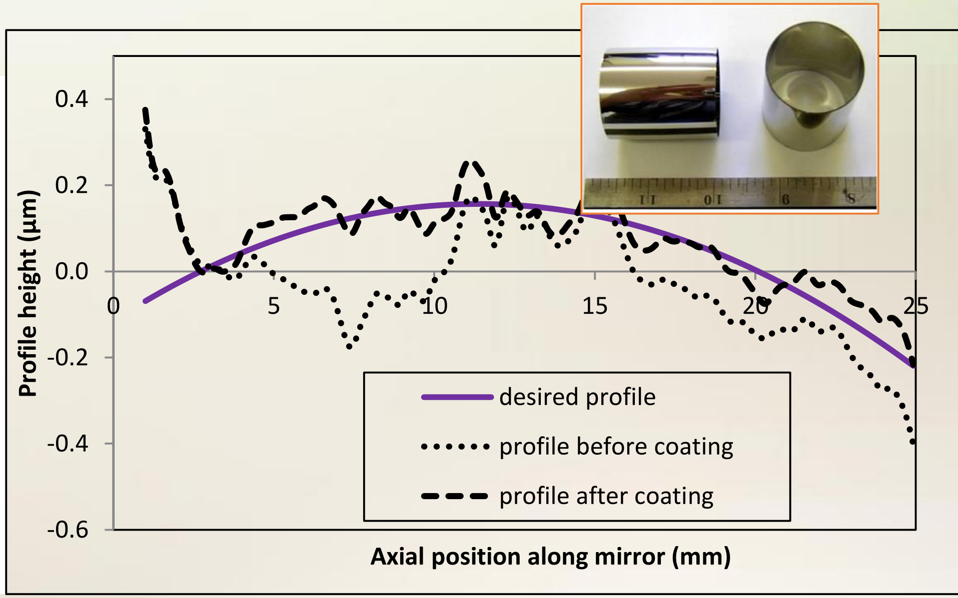
Differential deposition - Work to date – Proof of Concept

- **Proof of concept – 2010**
- **Modifications to existing RF sputtering chamber**
- **Optimization - Platinum, Tungsten, Nickel target materials – Xenon, Argon sputter gas**
- **On medical imaging optics of 32mm diameter – limited to contact profiler**

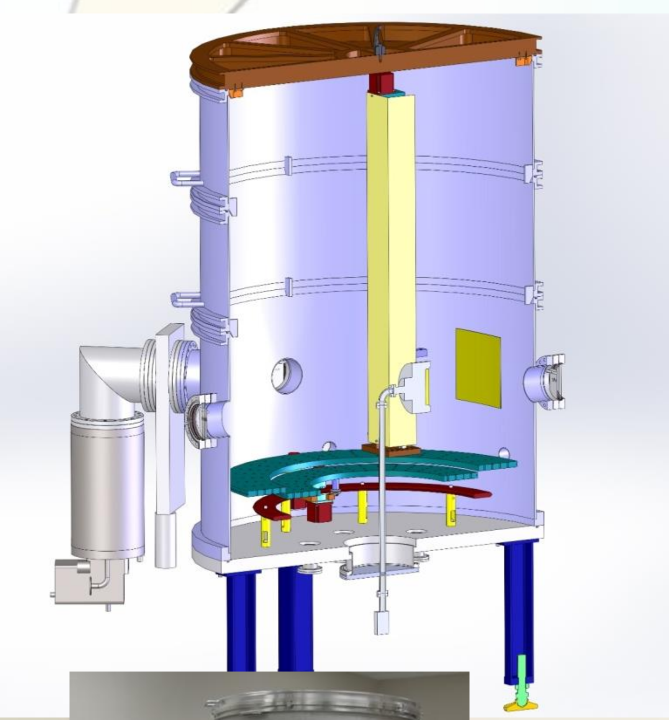




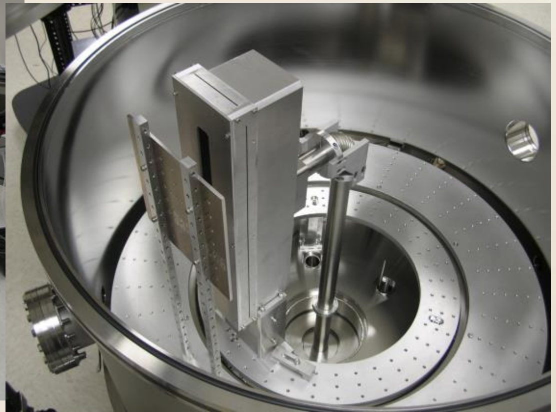


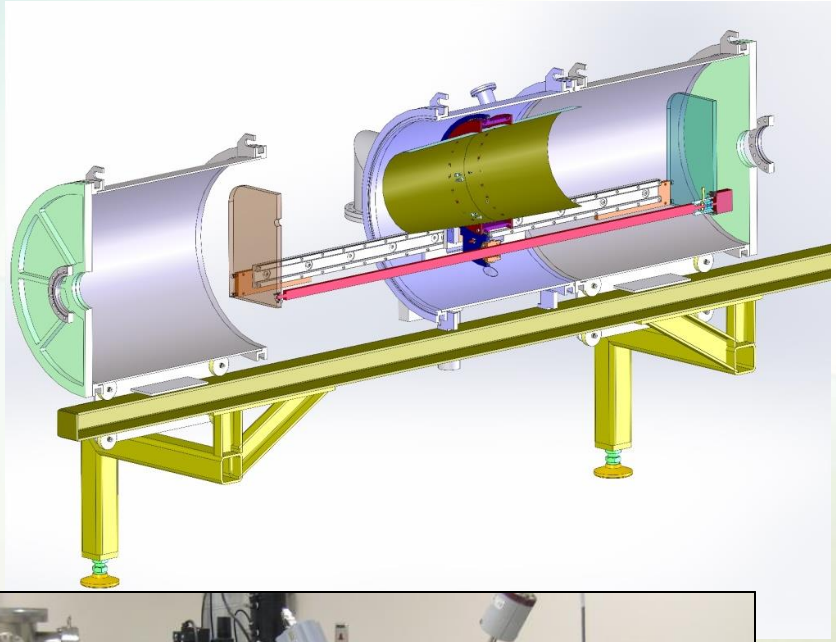


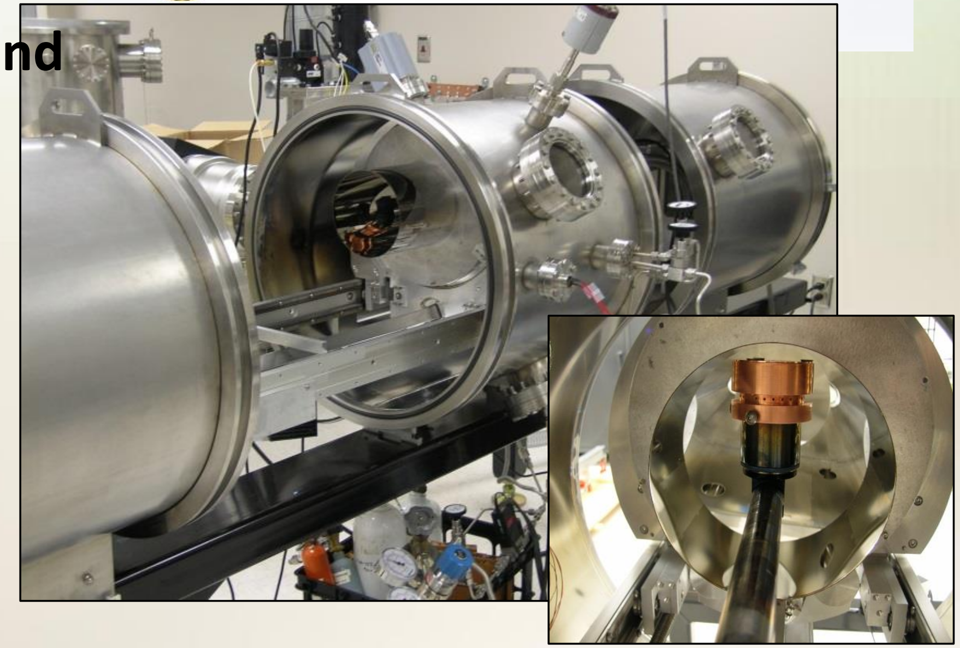
Work to date – Custom vacuum chambers



- Design and assembly of Custom vacuum chambers
- 2 different chambers for full-shell and segmented optics
- Can accommodate upto 0.5m diameter full-shell optics
- Computer controlled translation and rotation stages with encoders

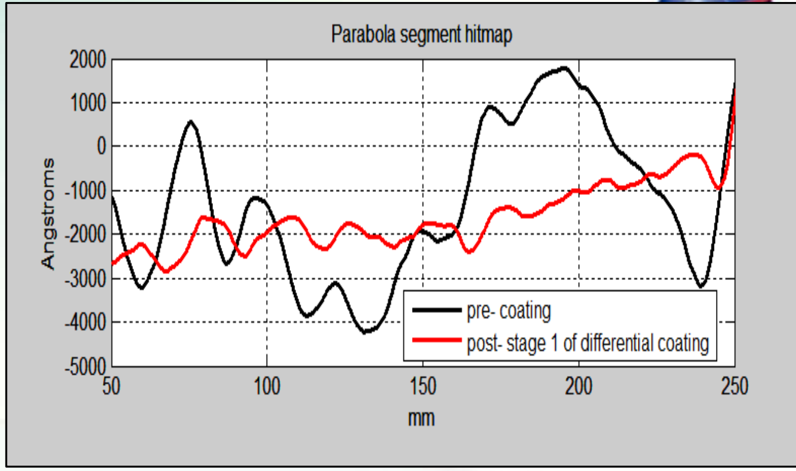


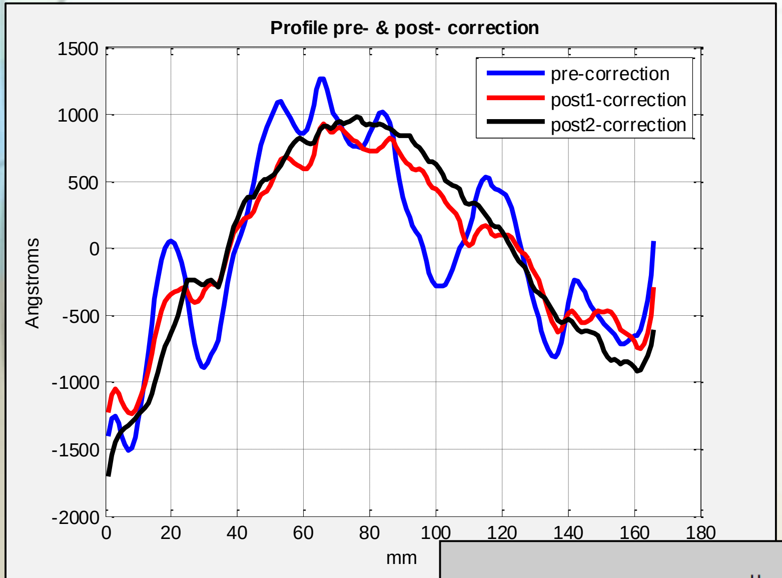


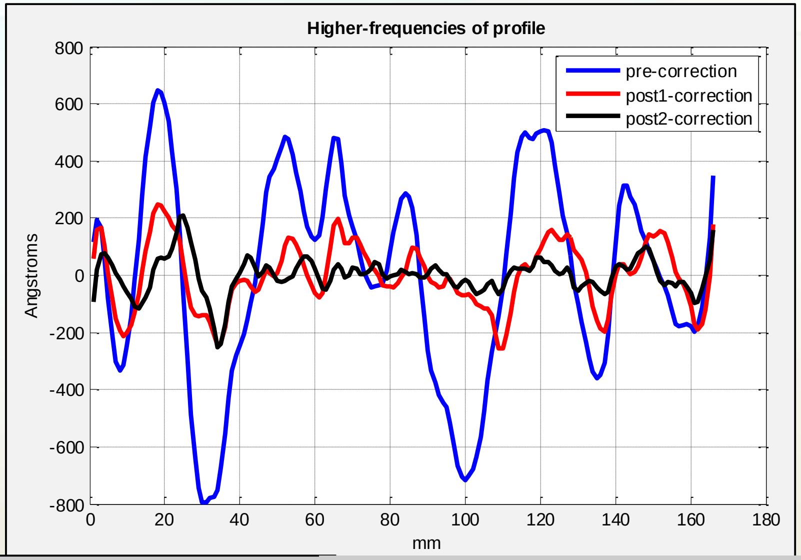


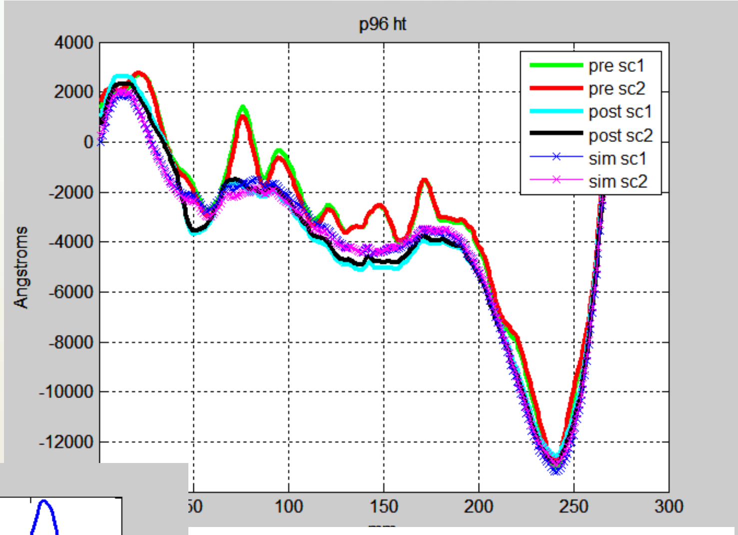
Work to date – metrology results

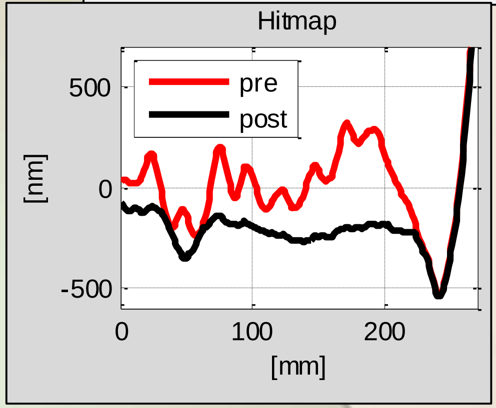
- **Several metrology results for correction stages 1 & 2 giving ~15 - 8 - 4 arc secs improvement**

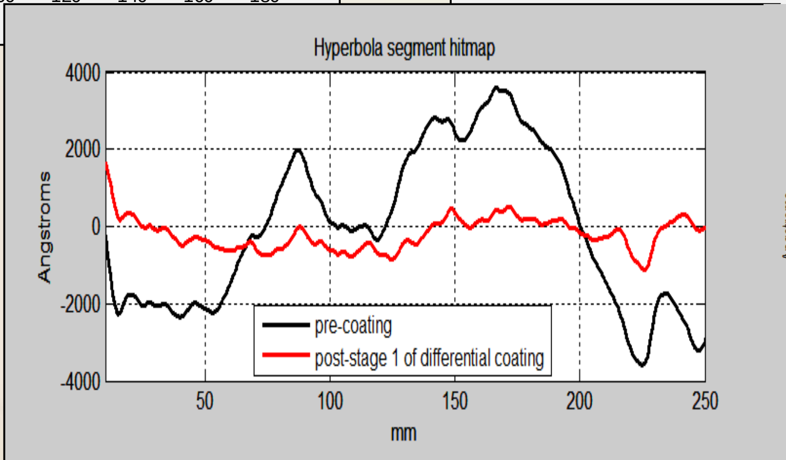


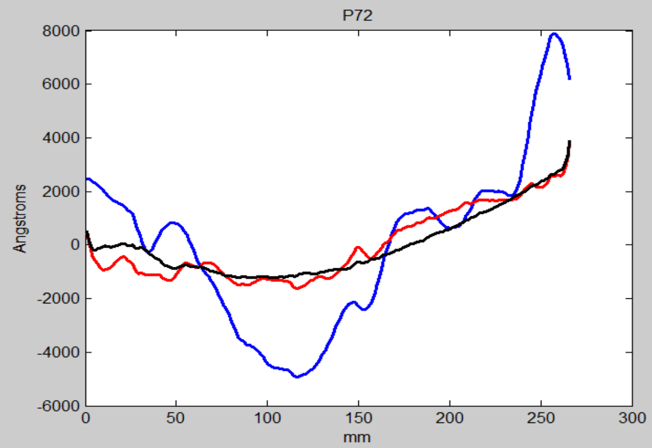


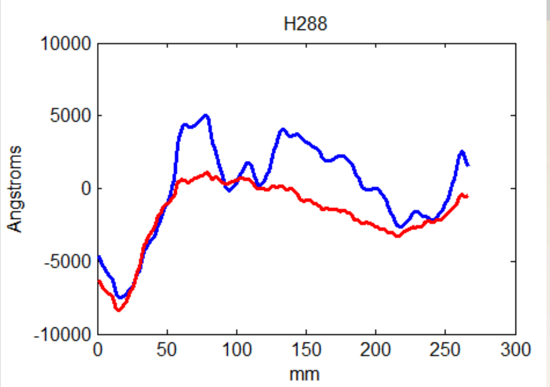




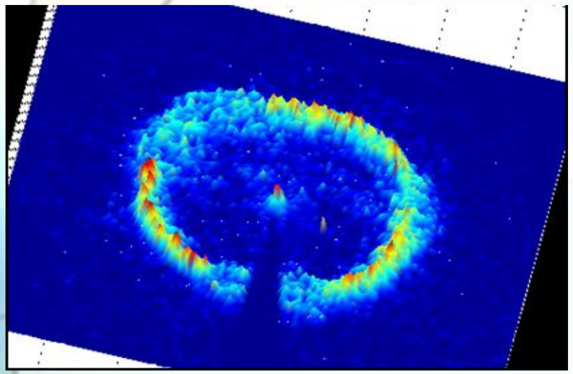


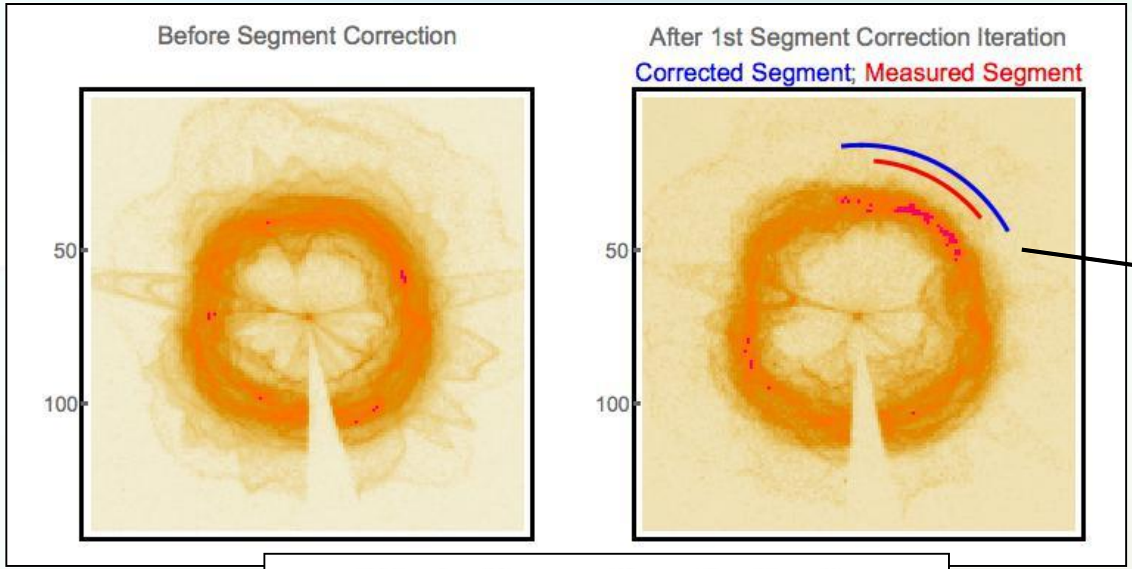


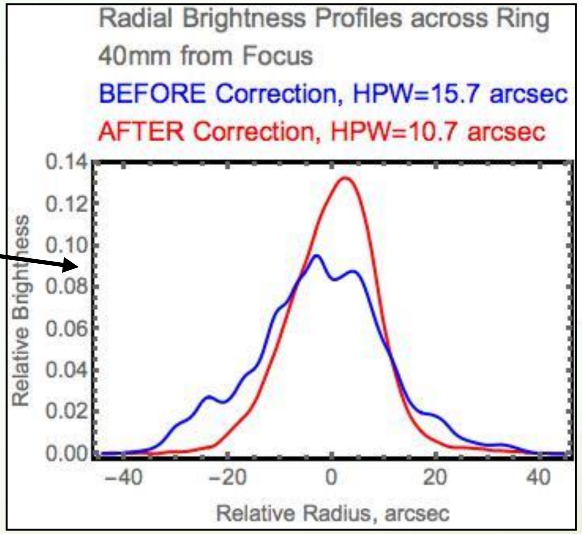


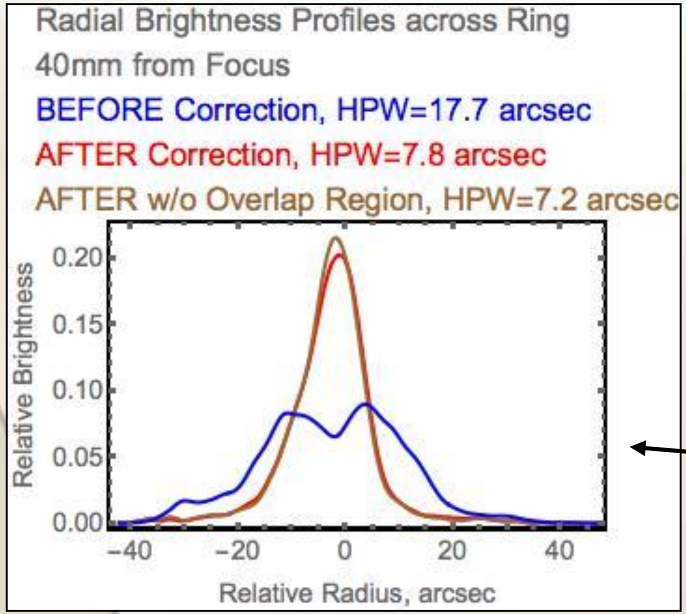


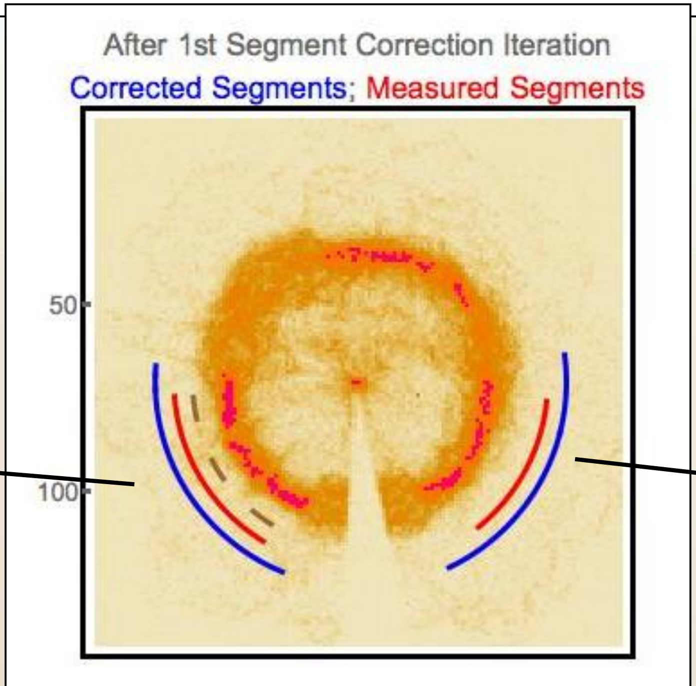
Work to date – X-ray testing – single stage



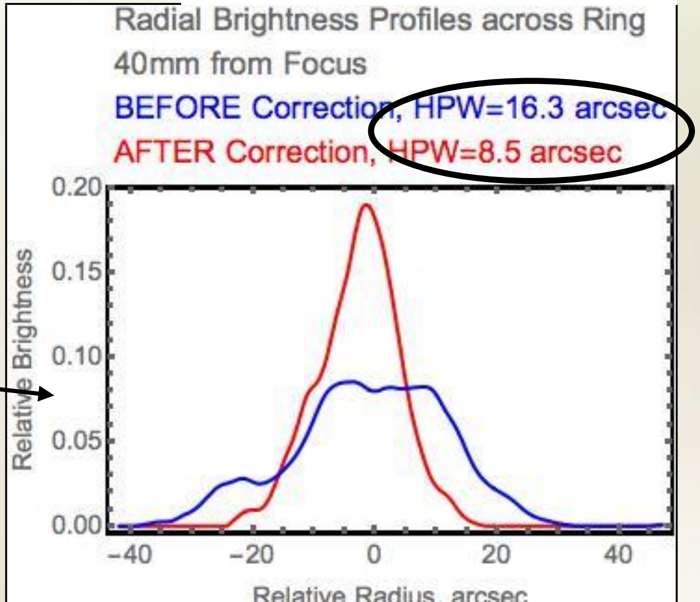




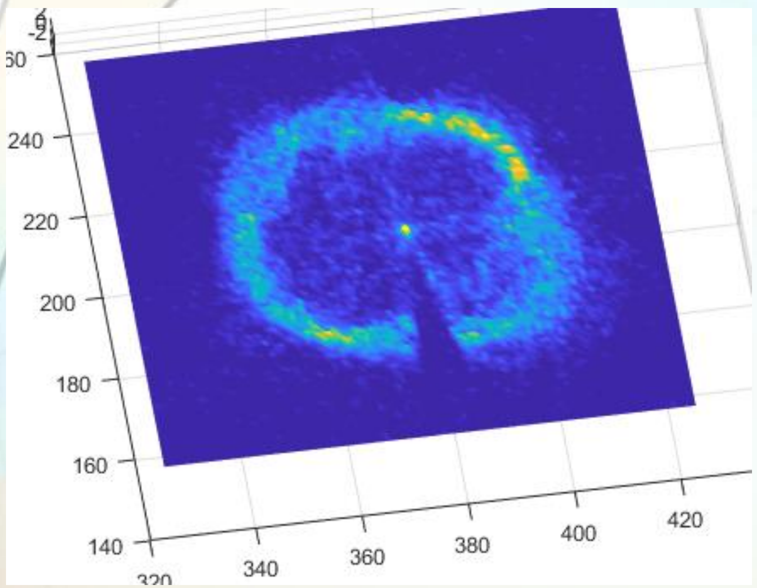




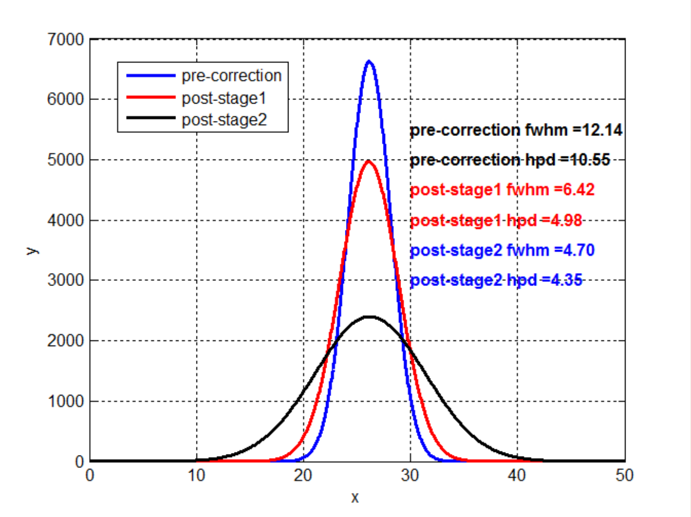
Higher frequency- correction

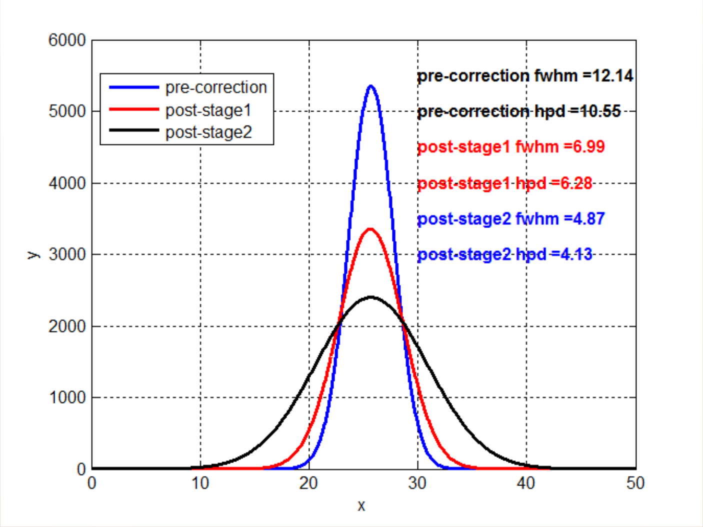


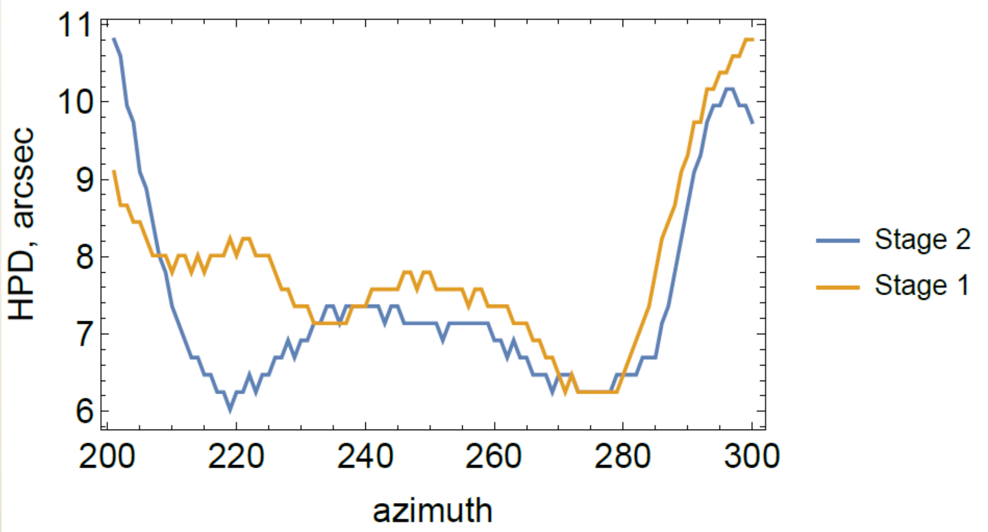
Work to date – X-ray testing



- **Need more work to confirm the improvements in the higher stages of correction**
- **Better shells to start-off with no low-frequency deviations**
- **Mandrel 8 to 10 arc secs - shells are 12 to 15 arc secs – combination of mid-and low-spatial frequency features**
- **Mid-spatial features from mandrel polishing – ideal for differential deposition**
- **Focus on replication process – what in the replication process causes low-frequency deviations**



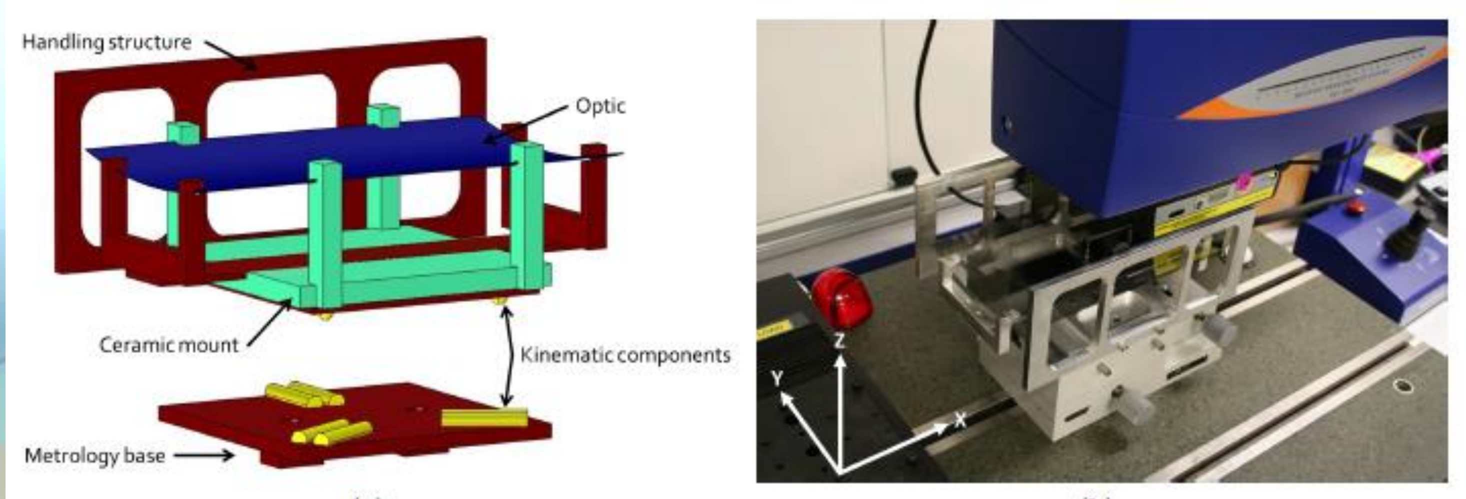




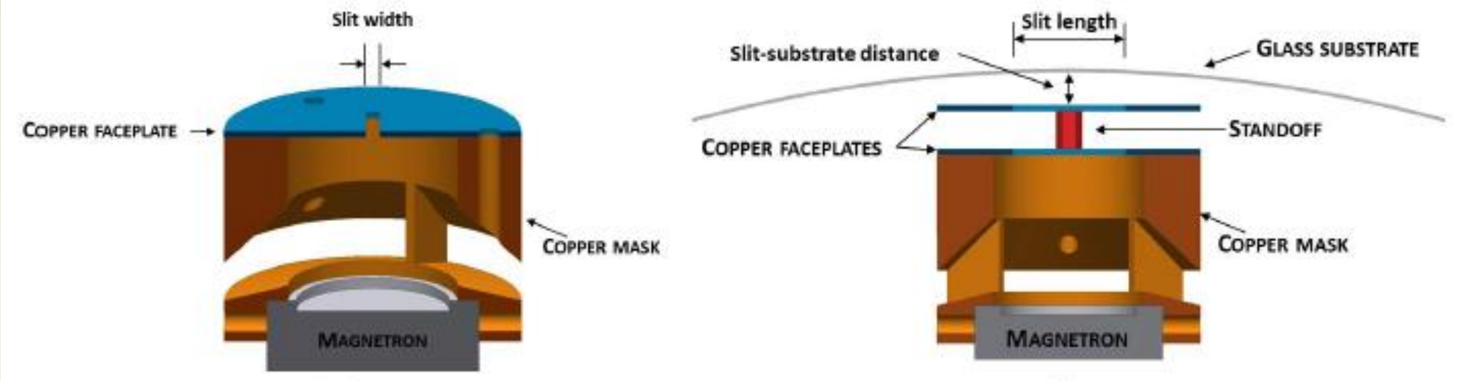
Stress effects

- **FEA simulations to characterize the stress effects**
- **Segmented optics are more sensitive to applied stress than full-shell optics, which are inherently more rigid**
- **Segmented optic - 0.25 mm thick - a typical corrective coating profile (maximum thickness 400 nm) with a stress of 0.1 GPa will results in an rms axial slope error of 19 arcsec**
- **Slope error scales linearly with stress - for a 1 arcsec HPD optic, coating stress must be kept below 1 MPa to have negligible effect on the final figure**
- **For a typical full shell nickel optic, of thickness 0.25 mm, 0.2 GPa stress - results in rms slope error of ~ 1.6 arcsec**
- **Need <10 MPa for 1 arcsec corrected optic**

Segmented optics



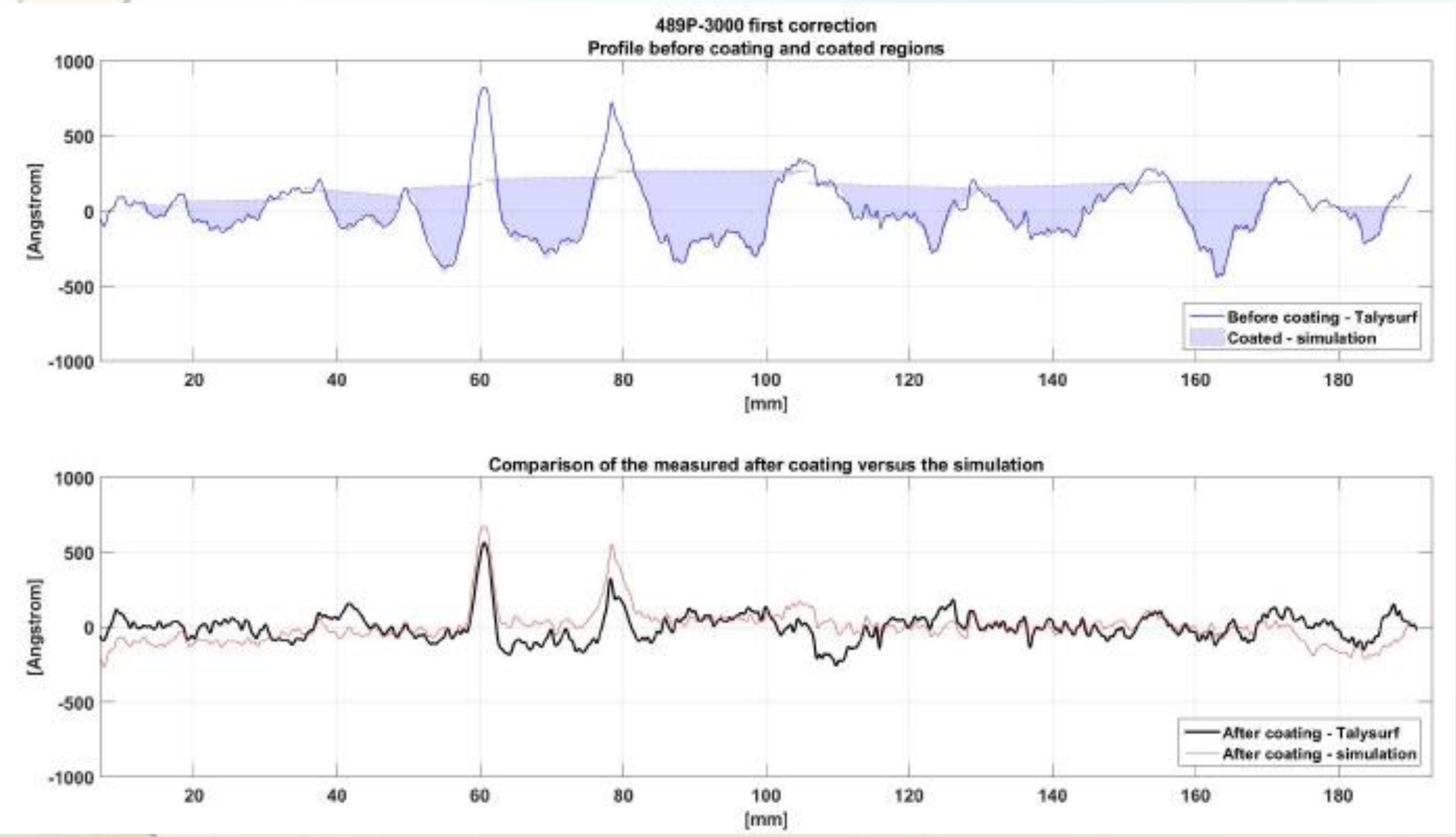
(a) (b)



(a) (b)

- **Optical mount – ceramic structure incorporated into an aluminum handling frame**
- **Kinematic interface was developed to allow unique and repeatable positioning of the optical mounting**
- **Mid-spatial frequency features – 15 to 2 mm are targeted**
- **Double slit arrangement for finer feature corrections**

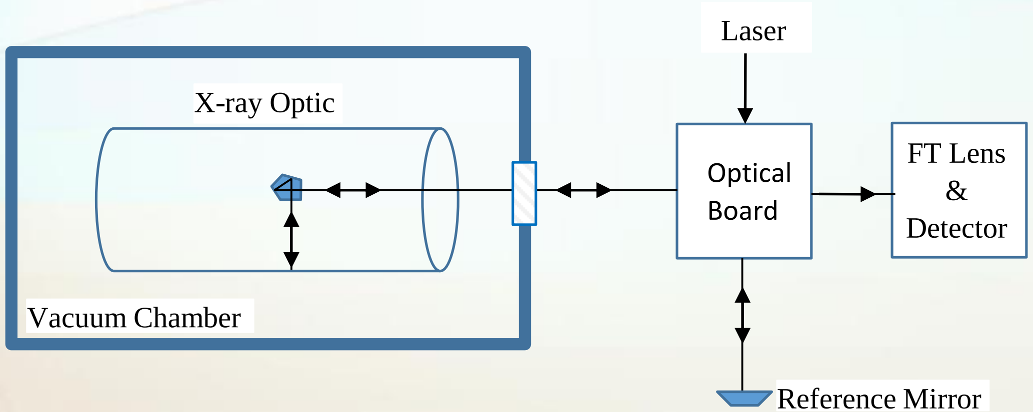
Segmented optics



- **GSFC's slumped glass substrate**
- **Improvement in RMS height: 200 Å to 96 Å**
- **To do: global correction**

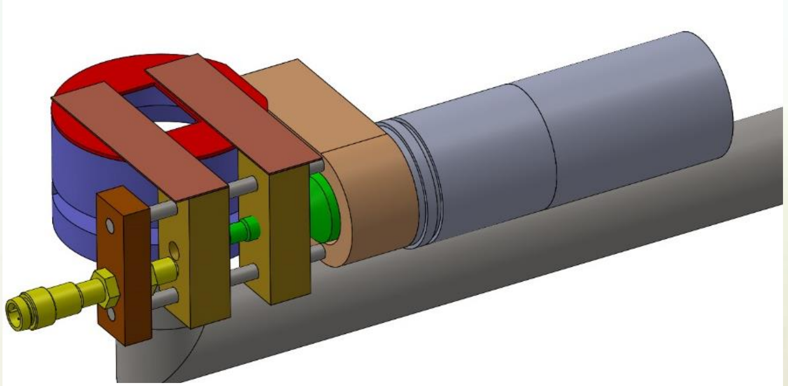
To do list

- **In-situ metrology - VLTP approach**



Schematic of in-situ metrology. The path from the optical board to the test surface passes into the vacuum chamber through an optical feed-through flange to a penta-prism which directs the laser light to and from the test surface.

- **Active slit approach**



Design concept of active slit approach

- **Detailed stress analysis**