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, an angular resolution of 1/2 arc second, 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
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.
Application – National Ignition Facility (NIF) for Inertial Confinement Fusion (ICF)

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

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

**Result**

- Improvement in RMS slope error from 12 to 7 arc secs

**Graphs:**

- Test coating on glass with 5mm slit
- Desired profile
- Profile before correction
- Profile after correction
- Simulated profile

- Profile height (µm) vs. Axial position along mirror (mm)
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

Radial Brightness Profiles across Ring
40mm from Focus
BEFORE Correction, HPW=17.7 arcsec
AFTER Correction, HPW=7.8 arcsec
AFTER w/o Overlap Region, HPW=7.2 arcsec

Higher frequency correction
Radial Brightness Profiles across Ring
40mm from Focus
BEFORE Correction, HPW=16.3 arcsec
AFTER Correction, HPW=8.5 arcsec
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 result 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

- 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
- Active slit 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.

- Detailed stress analysis