High Resolution X-ray Grating and Mirror Development at MIT

Mark Schattenburg

Space Nanotechnology Laboratory

Kavli Institute for Astrophysics and Space Research

X-ray Science Analysis Group (XRSIG)

AAS Annual Meeting

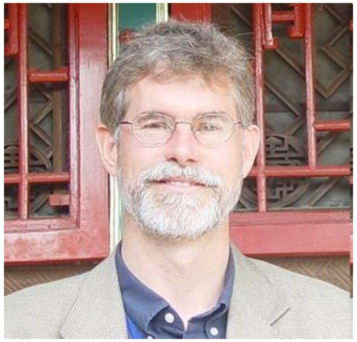
Washington, DC

January 5, 2014

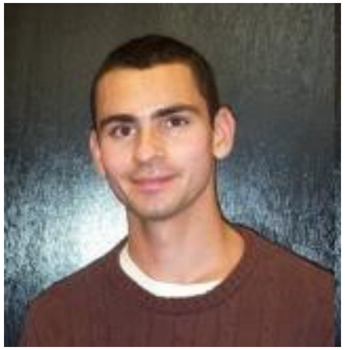
High-resolution X-ray Diffraction Gratings and Mirrors

- Critical-angle transmission (CAT) gratings
- Thin-shell x-ray mirror fabrication:
  - Thermal air bearing slumping
  - Ion implant figure correction

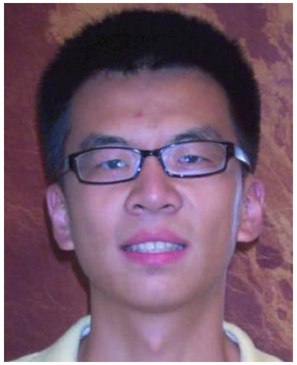
Key Team Members



Dr. Mark Schattenburg
PI, Lab Director



Dr. Alex Bruccoleri
Izentis, LLC
Nanofabrication



Dong Guan
Mech E
Nanofabrication

Edward Sung
Lam Research
Air-Bearing Slumping

Dr. Ralf Heilmann
Co-I, Associate Director

Jay Fucetola
Mech E
Lithography

Martin Klingensmith
Electrical Engineer
Vacuum & Plasma Systems

Brandon Chalifoux
Mech E
Ion Implant

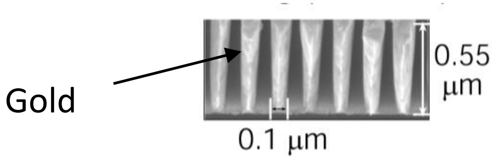
CAT Prototype Grating Fabrication Progress

Gold (*Chandra*) vs. CAT gratings

- Gold gratings
  - Electroplated gold bars
  - 200 nm pitch, 100 nm width
  - 550 nm height for aspect ratio 5.5
- CAT gratings
  - Etched silicon bars
  - 200 nm pitch, 40 nm width
  - 6000 nm height for aspect ratio 150

CAT grating (2008)

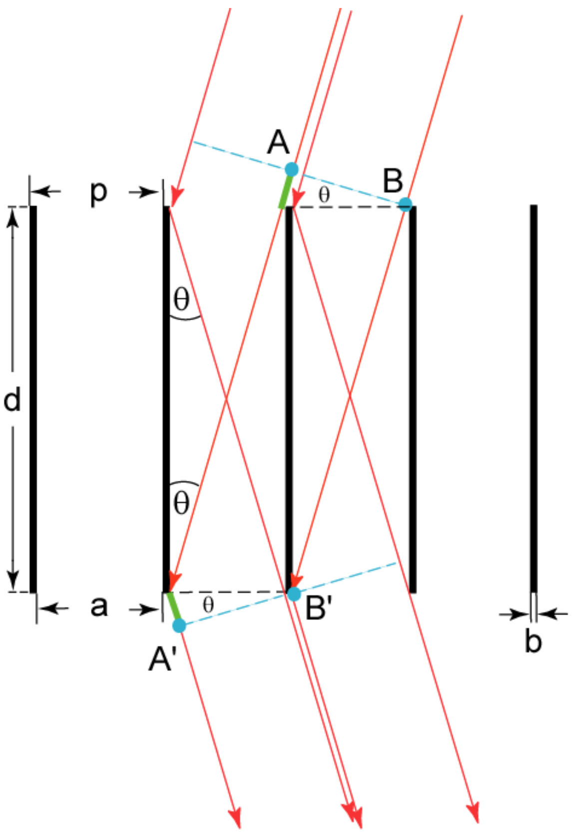
Chandra grating (1994)



Scanning Electron Micrographs of Grating Cross Sections (to scale)

CAT Grating Principle

CAT grating principle



Grating equation:

$m\,\lambda = p\,(\sin(\theta) + \sin(\beta_m))$,
m = diffraction order

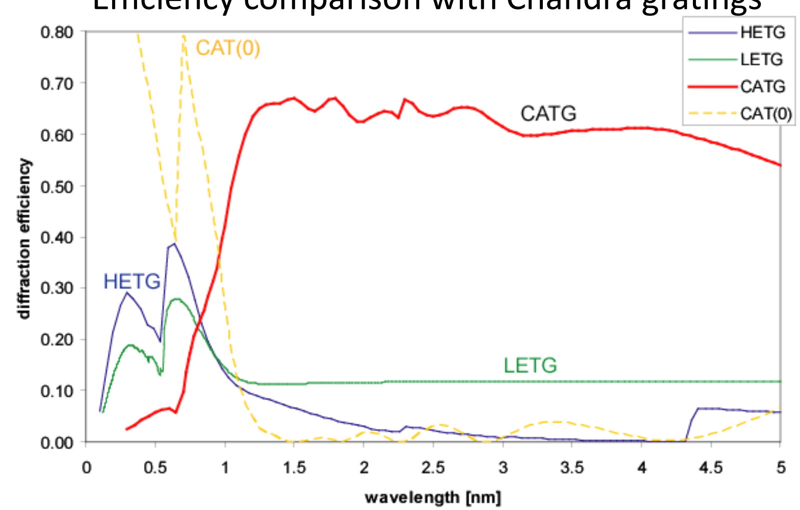
Blazing: $\beta_m \sim \theta$

High reflectivity:
$\theta < \theta_c$ = critical angle of total external reflection

Strawman:
Silicon grating, $\theta = 1.5^{o}$
p = 200 nm
b = 40 nm
d = 6 μm
aspect ratio d/b = 150

- CAT grating combines advantages of transmission gratings (relaxed alignment, low weight) with high efficiency of blazed reflection gratings.
- Blazing achieved via reflection from grating bar sidewalls at graze angles below the critical angle for total external reflection.
- High energy x rays undergo minimal absorption and contribute to effective area at focus.

Efficiency comparison with Chandra gratings

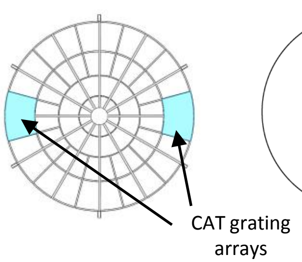


CAT Grating Spectrometer Concept

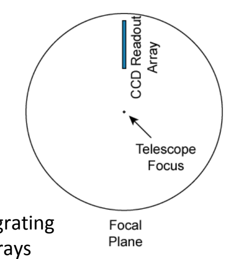
Advantages:
- low mass
- relaxed alignment & figure tolerances
- high diffraction efficiency
- up to 10X dispersion of Chandra HETGS
- no positive orders (i.e., smaller detector)

Optical Design:

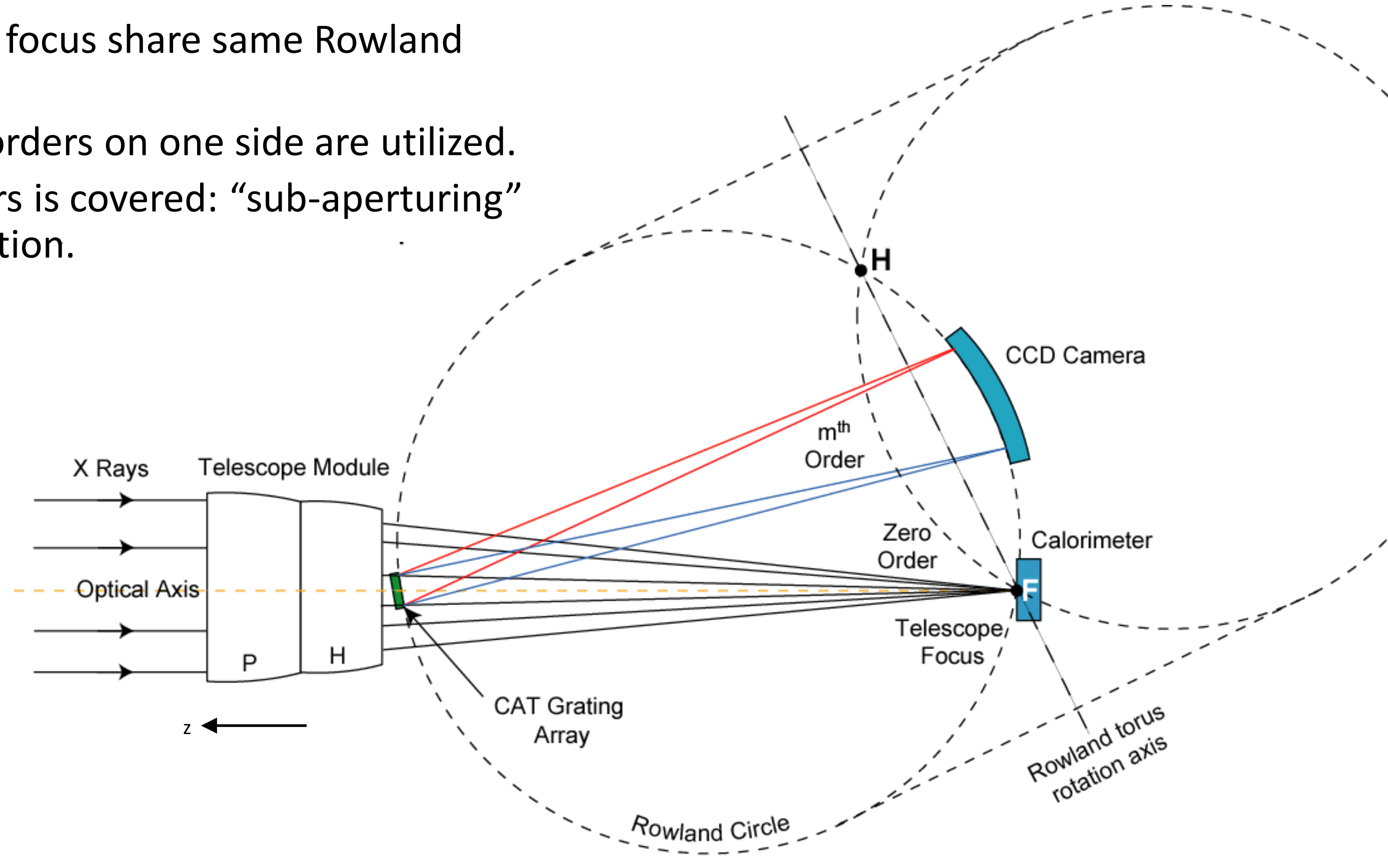
- Wolter I telescope mirrors.
- Diffraction gratings in converging beam just aft of mirrors.
- Gratings, camera, and focus share same Rowland torus.
- Blazed gratings; only orders on one side are utilized.
- Only fraction of mirrors is covered: “sub-aperturing” boosts spectral resolution.



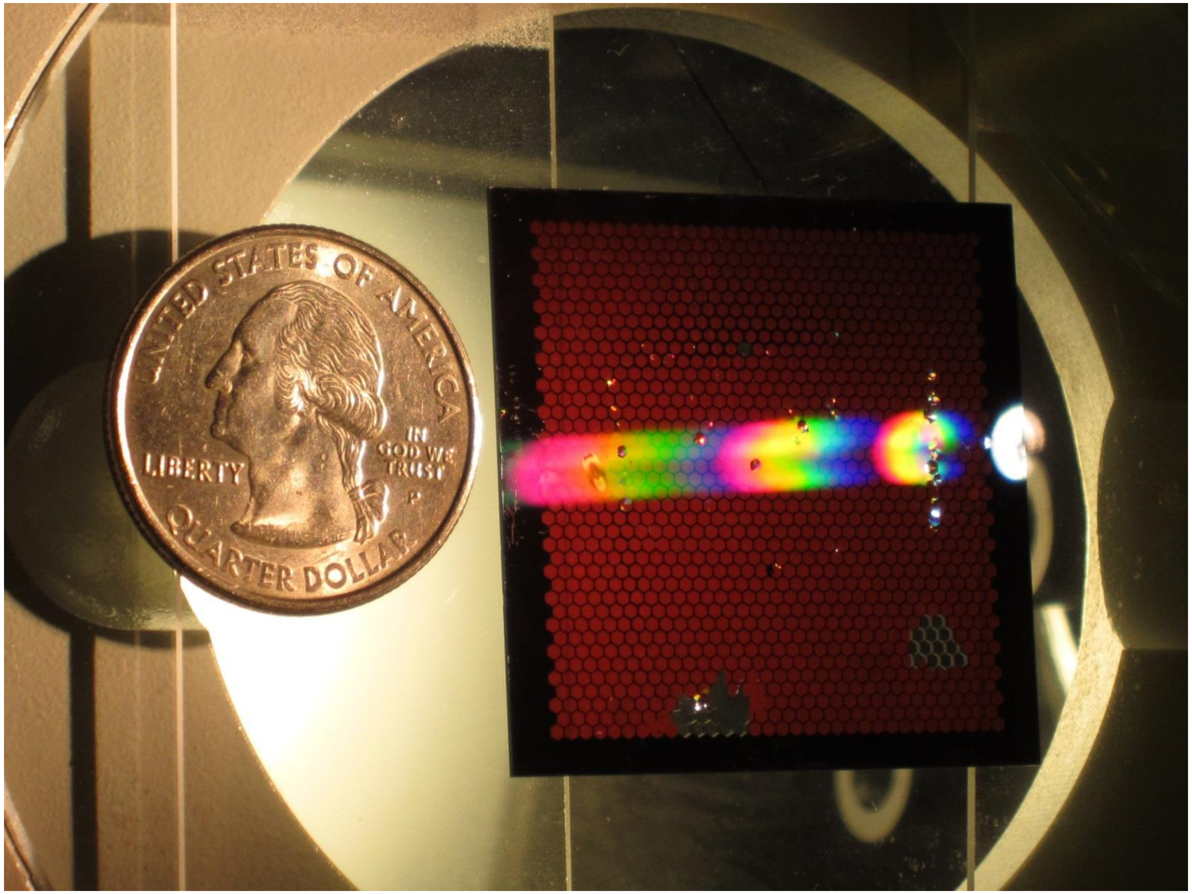
Flight mirror
assembly view



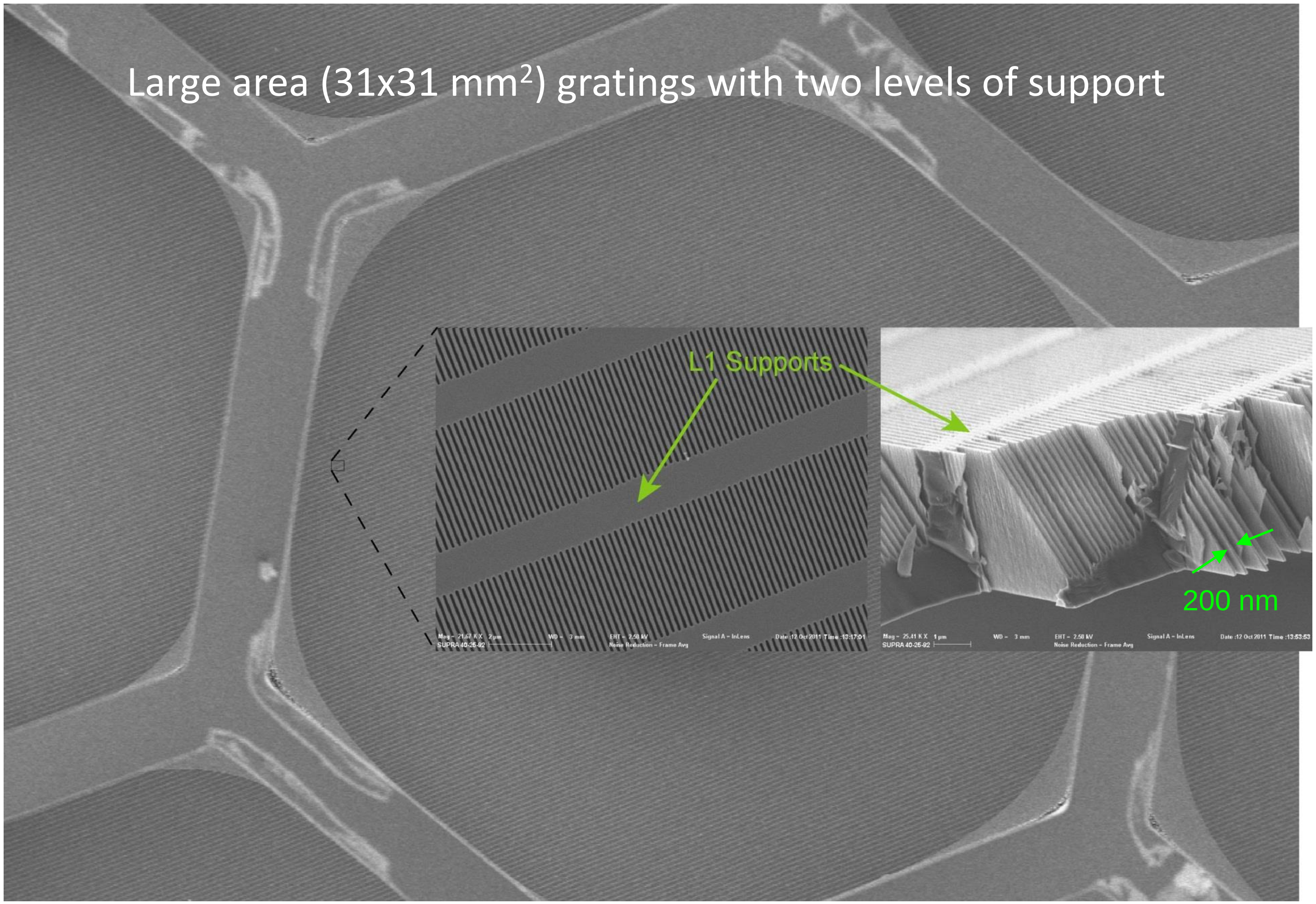
Focal plane
view



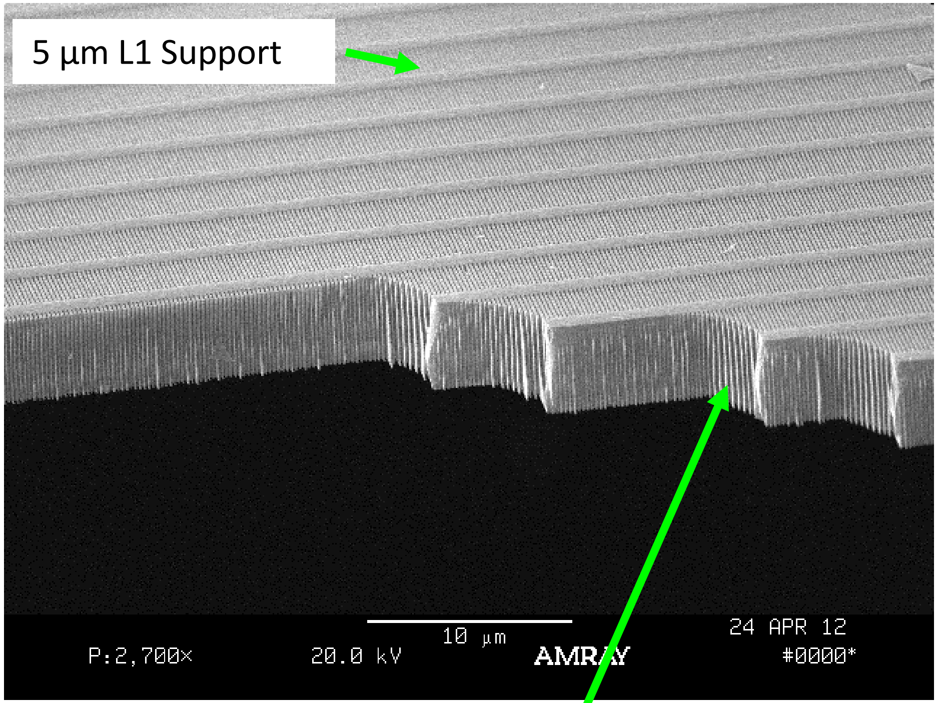
Prototype CAT Grating



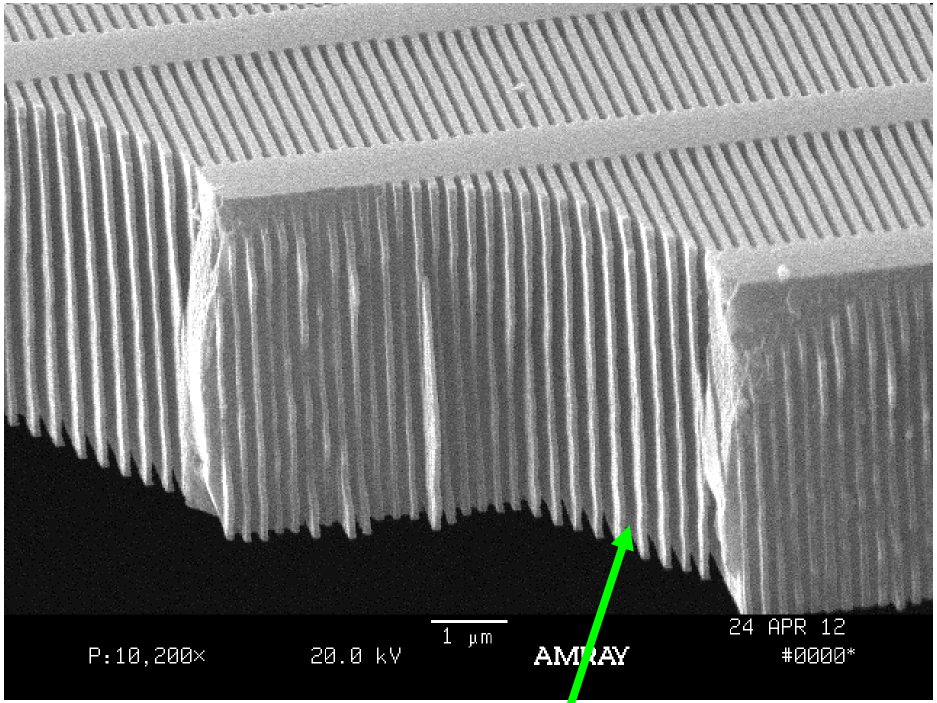
Prototype CAT Grating Detail



Cleaved Prototype Grating



200 nm pitch CAT grating bars

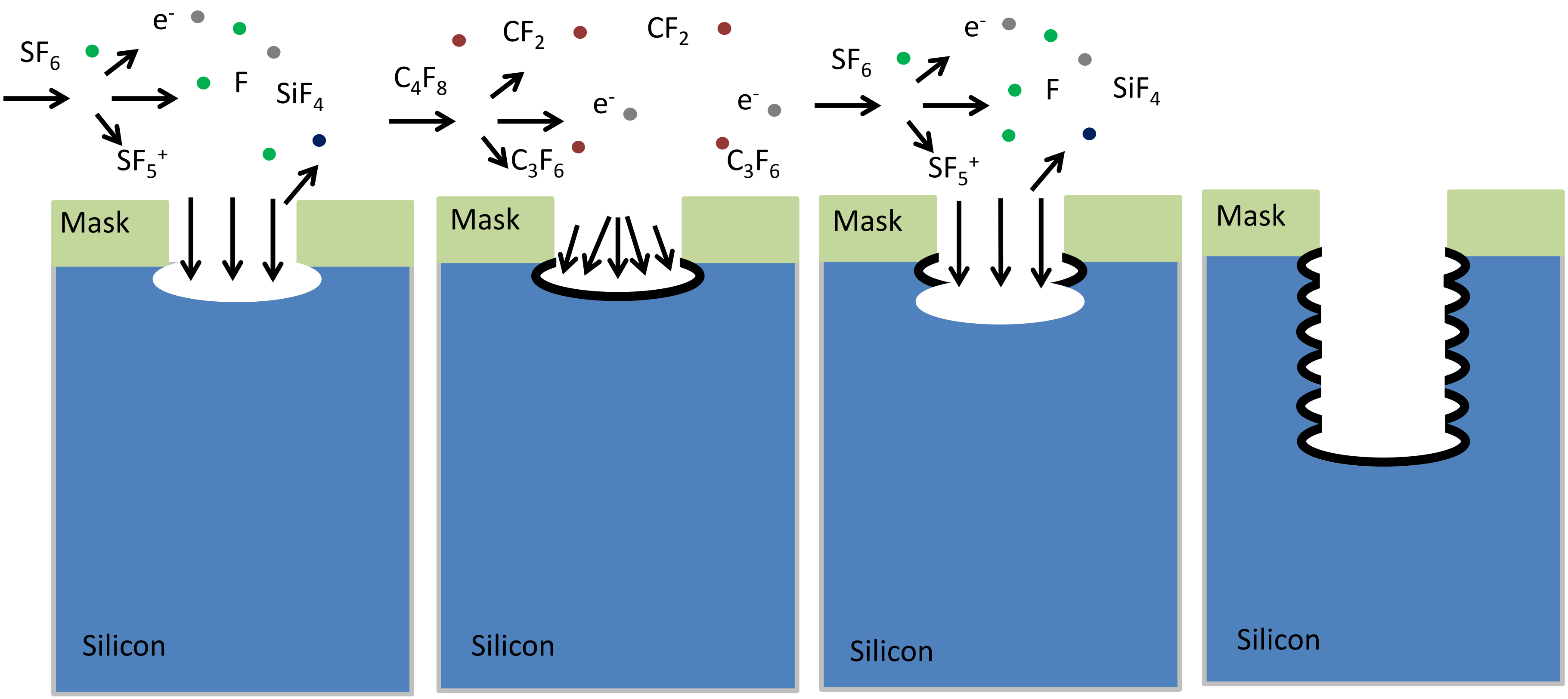


200 nm pitch CAT grating bars

Silicon Deep-Etch Process

A two-step process is used to form the CAT grating bars:

- A deep reactive-ion etch (DRIE) process is used to etch high aspect-ratio structures
- This is followed by a potassium hydroxide (KOH) polishing step to smooth sidewalls



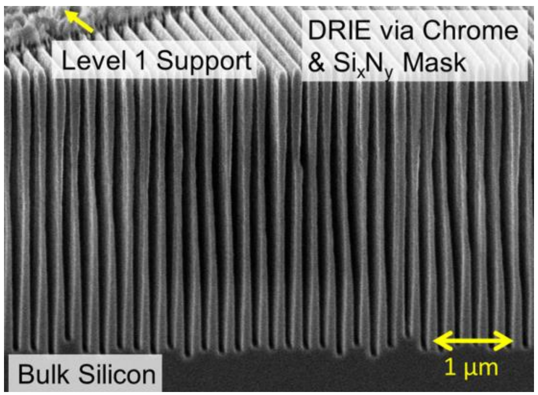
Etch silicon, Ion trajectories vertical

Passivate silicon
Isotropic neutral trajectory

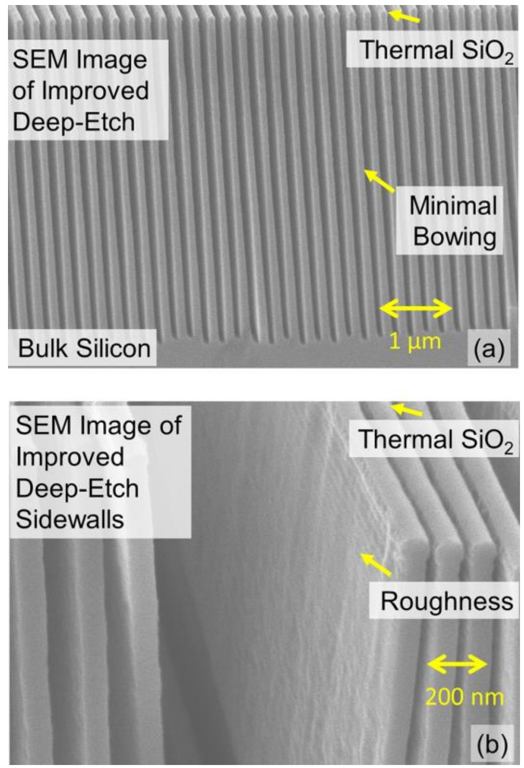
Etch silicon

Deep-etched structure
Scalloped Sidewalls

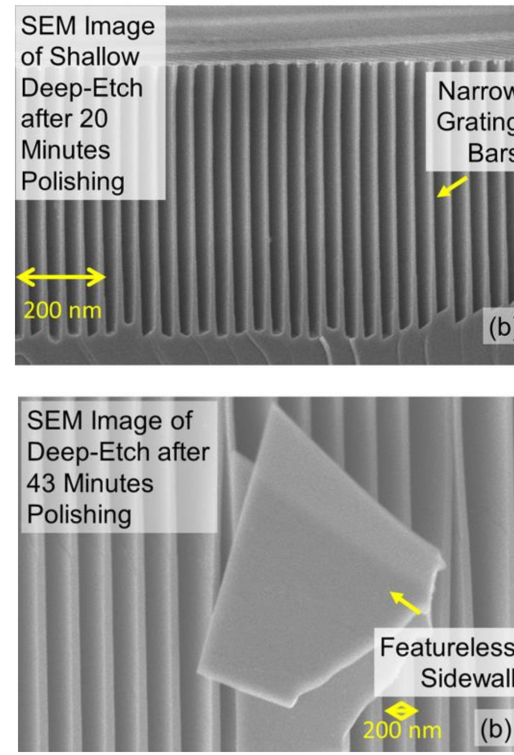
Process Development Results



Previous Deep-Etch Process



Improved Deep-Etch Process



Grating after KOH Polishing

Pegasus Plasma Etch Tool Installation

Its here!

Tool in SNL clean room

New facility hook-ups

Pump, chillers and heat exchanger in chase

X-ray Mirrors Fabrication by Air Bearing Slumping

X-ray Telescope Optics Tradeoffs

Photo: nasa.gov

Chandra mirrors: ~0.5 arcsec

- High resolution
- High cost
- Small aperture

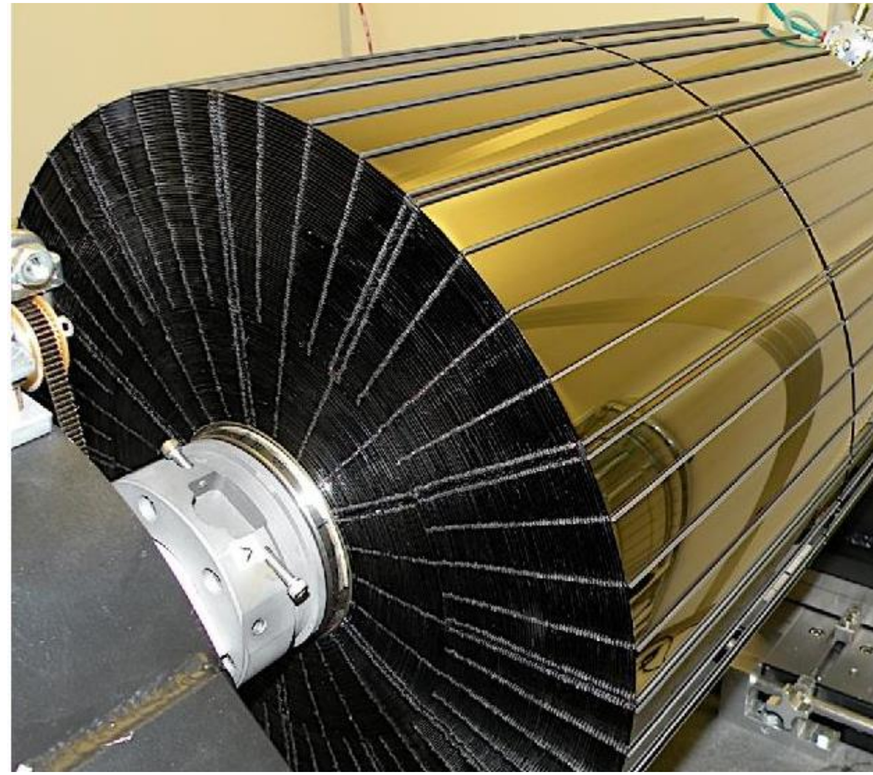


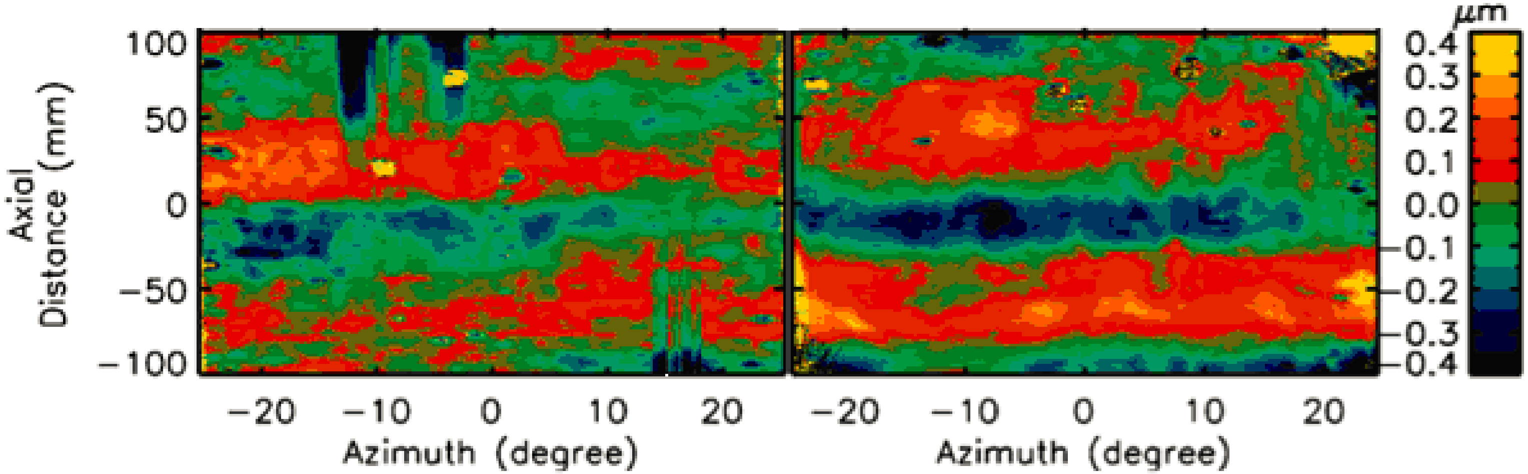
Photo: nasa.gov

NuSTAR mirrors: ~60 arcsec

- Lower resolution
- Lower cost
- Large aperture

Thermal Shaping at NASA GSFC

Zhang, et al., Lightweight and high angular resolution x-ray optics for astronomical missions. Proc. SPIE 2011



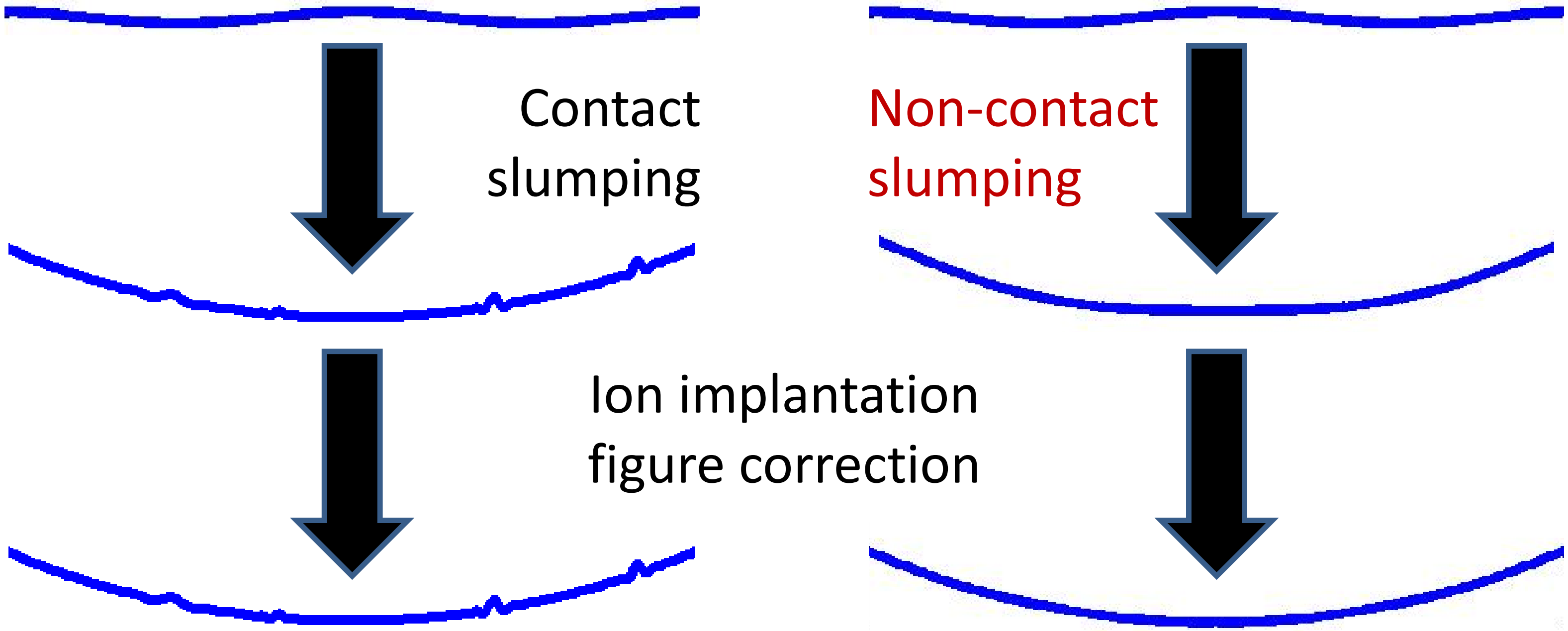
Freeman, et al., Advances in the active alignment system for the IXO optics. Proc. SPIE 2010

Plus: Excellent low spatial frequency fidelity

Minus: 48+ hour slumping cycle time

Mid-range ripples due to anti-stick coating

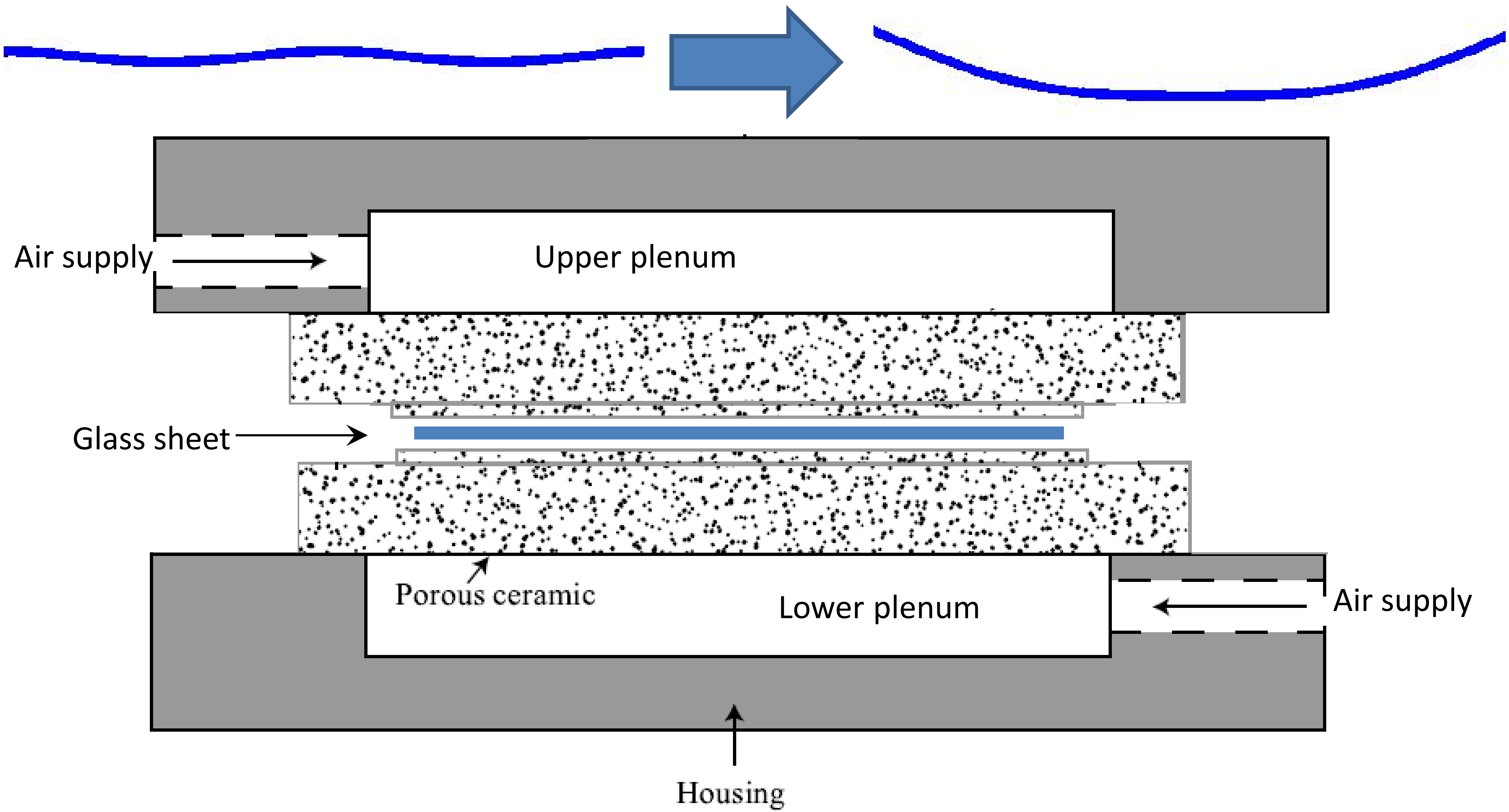
Pathway to High Resolution Thin X-ray Optics



Non-contact slumping enables high resolution segmented thin optics:

- Achieve good figure with no mid-spatial frequency errors
- Residual figure error corrected with ion implantation
- Fast, low-cost process

Thermal Shaping at MIT

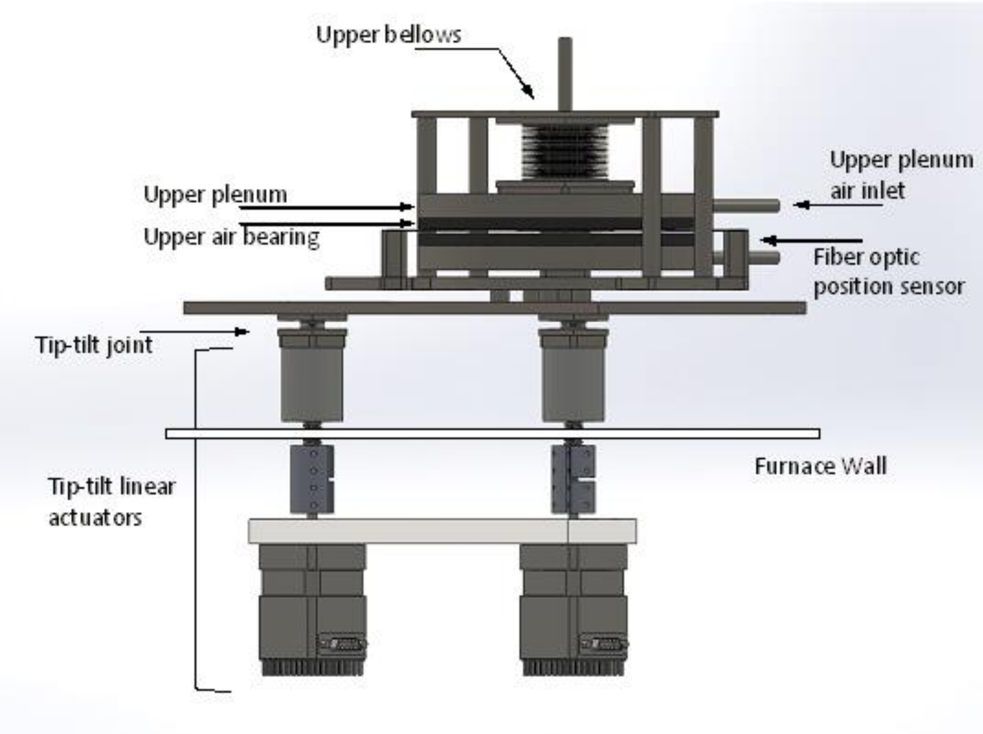


Slumping on air bearings mandrels: Viscous creeping flow supports glass

Contact-less slumping allows rapid and "soft" slumping

Gen 5.2 Slumping Tool

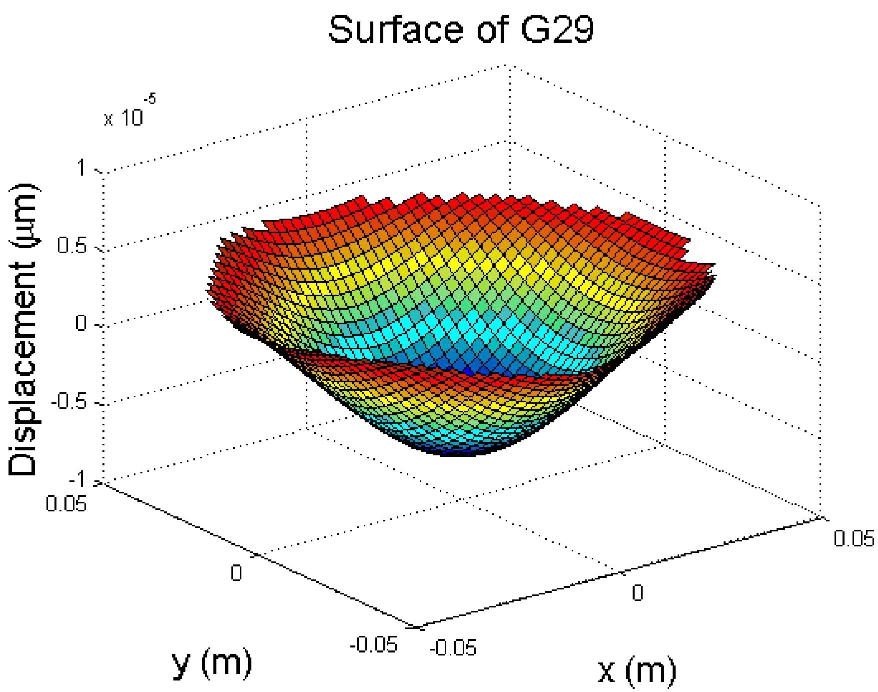
Demonstrates contact-less slumping

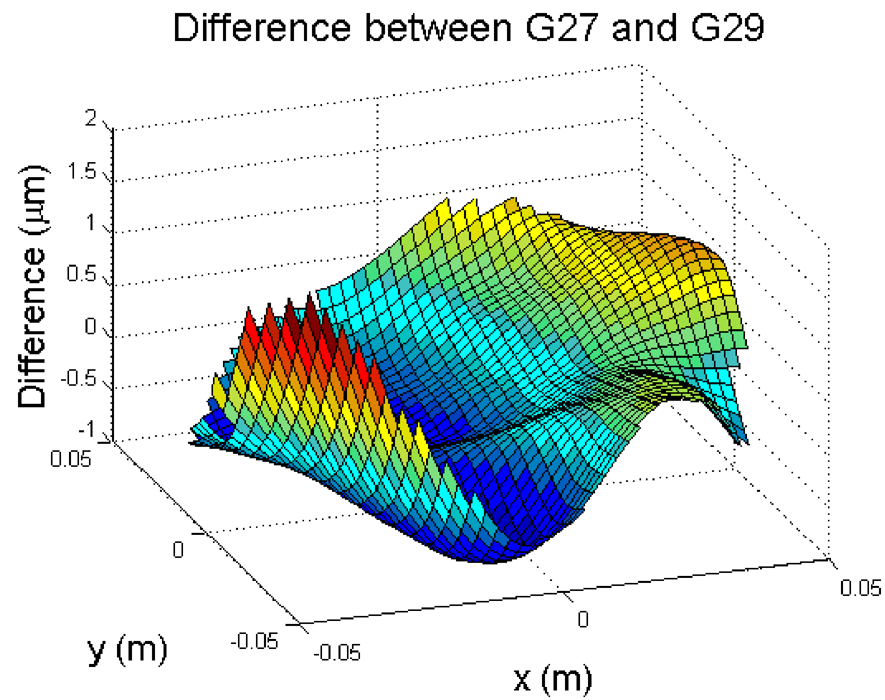


- High temperature operation
- Simple gap control
- Fiber position sensors and gravity tilt actuators set glass position under servo control

Slumping results

Good repeatability over entire substrate





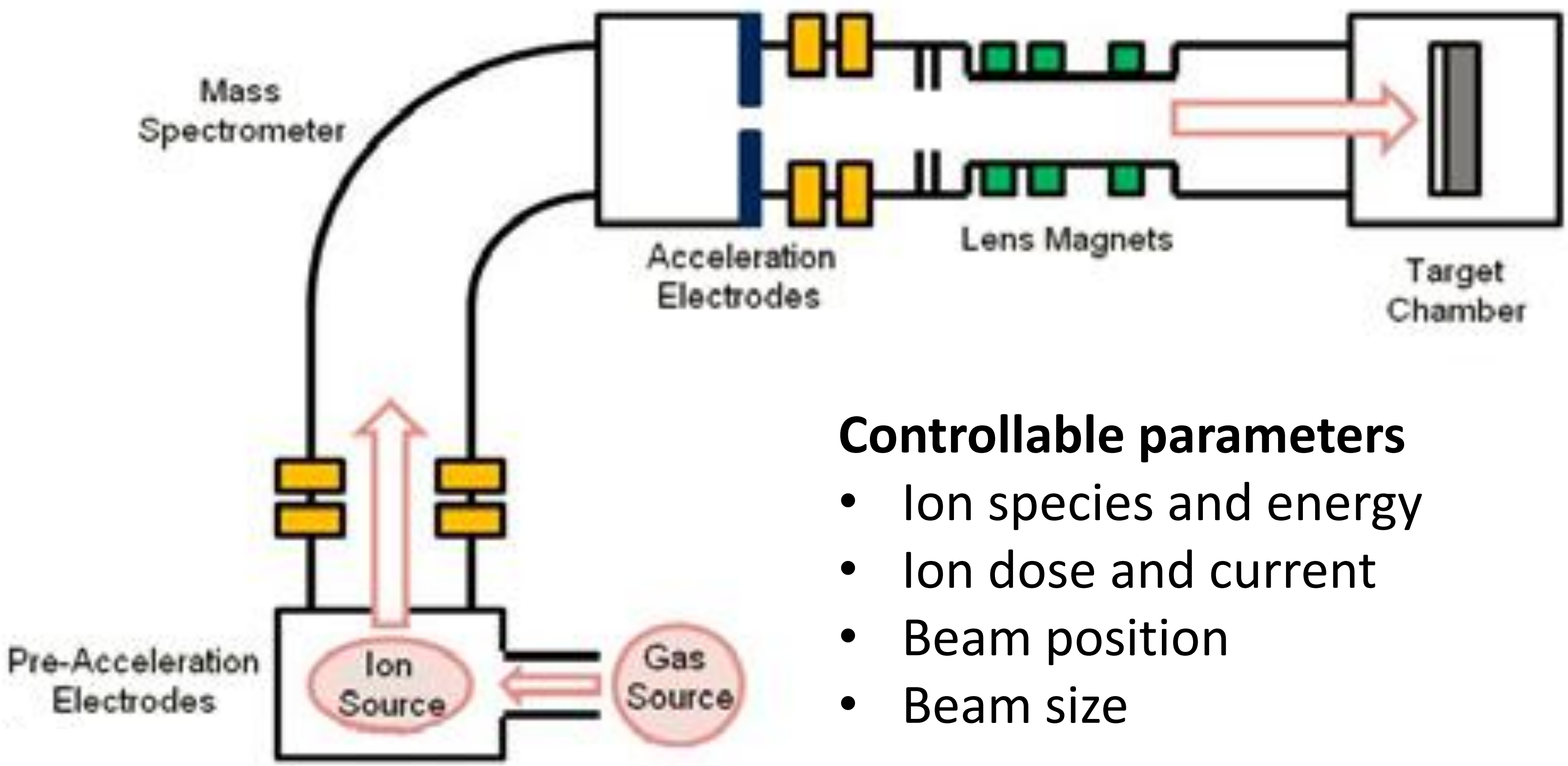
P-V error:	12.5 µm	P-V error:	2.7 µm	(60 mm) 0.7 µm
RMS slope error:	37.1 arcsec X	RMS slope error:	6.5 arcsec X	3 arcsec X
	38.0 arcsec Y		9.5 arcsec Y	4 arcsec Y

Repeatability of same order as thickness variation

X-ray Mirror Figure Correction via Ion Implantation

Ion Implantation

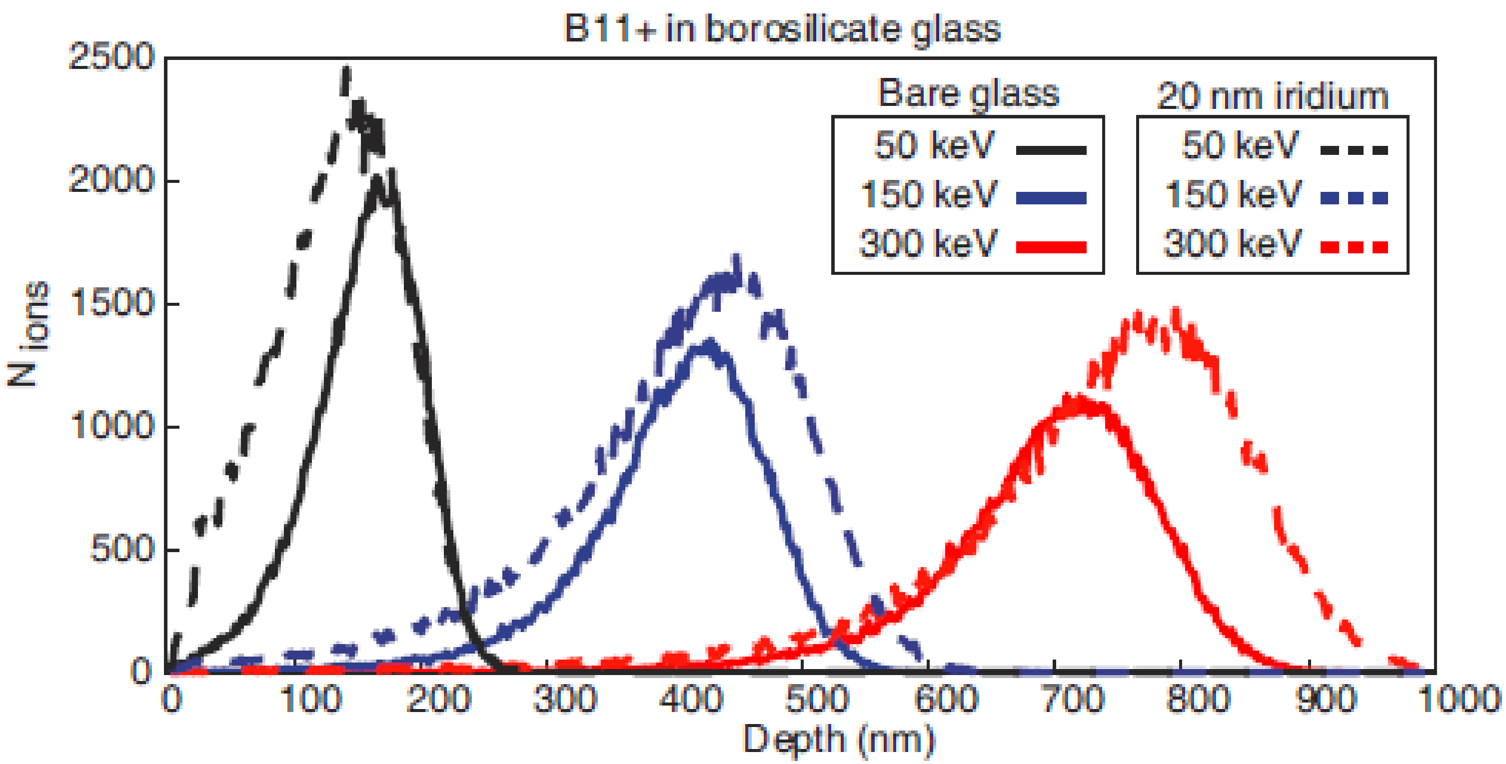
Sub-surface stress caused by damage and ion stuffing



Controllable parameters

- Ion species and energy
- Ion dose and current
- Beam position
- Beam size

Simulated Implant Depth

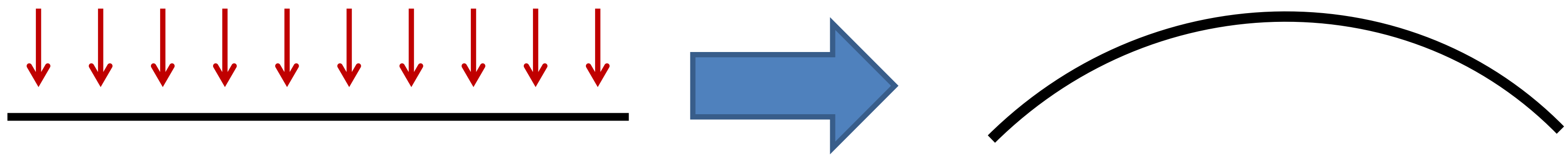


Implanting through high-Z surface layers is possible

Monte Carlo simulations performed with SRIM (www.srim.org)

Initial Experiments

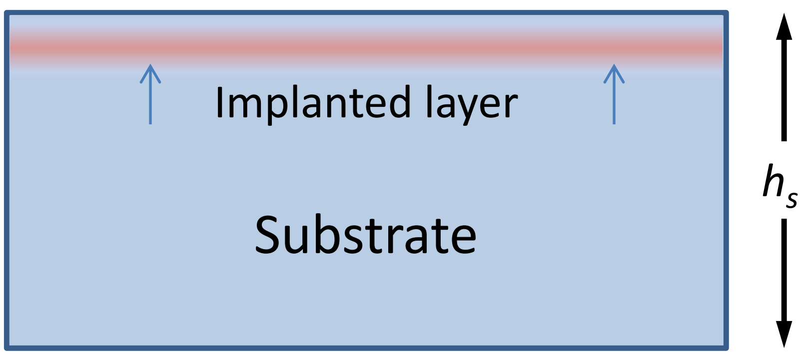
Understanding stress from ion implantation



Uniform implant dose

Radius of curvature changes according to **Stoney's equation**

Implanted substrate



$$\underbrace{\sigma_f t_f}_{\text{Integrated stress}} = \underbrace{\frac{E {h_s}^2}{6(1-\nu)}}_{\text{Substrate properties}} \underbrace{\left(\frac{1}{R_1} - \frac{1}{R_0}\right)}_{\text{Measured data}}$$

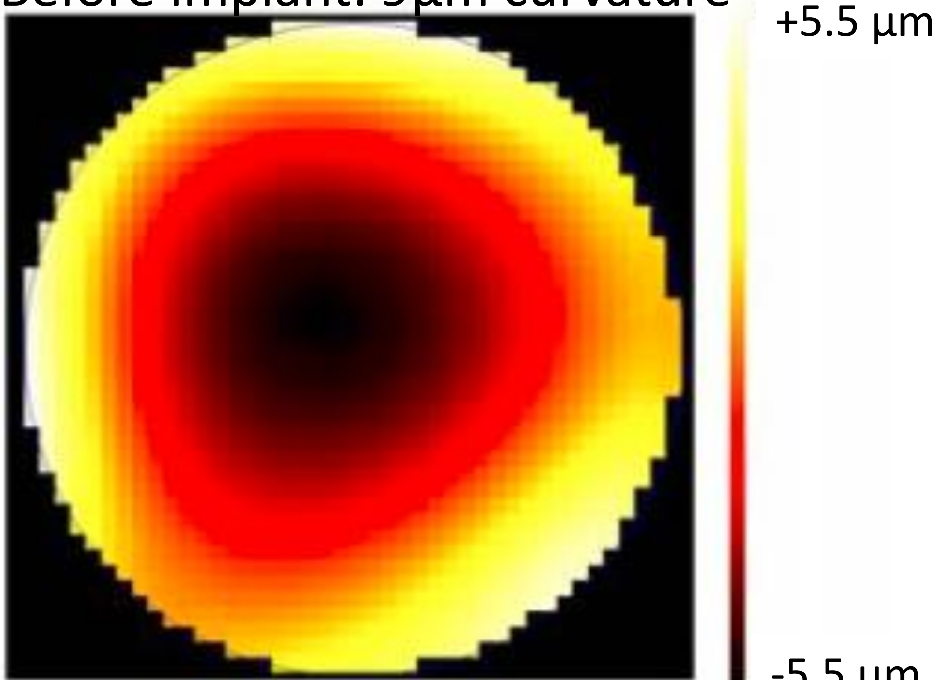
E – Young's modulus
ν – Poisson's ratio
R – radius of curvature
h_s – substrate thickness

Spherical Curvature Correction

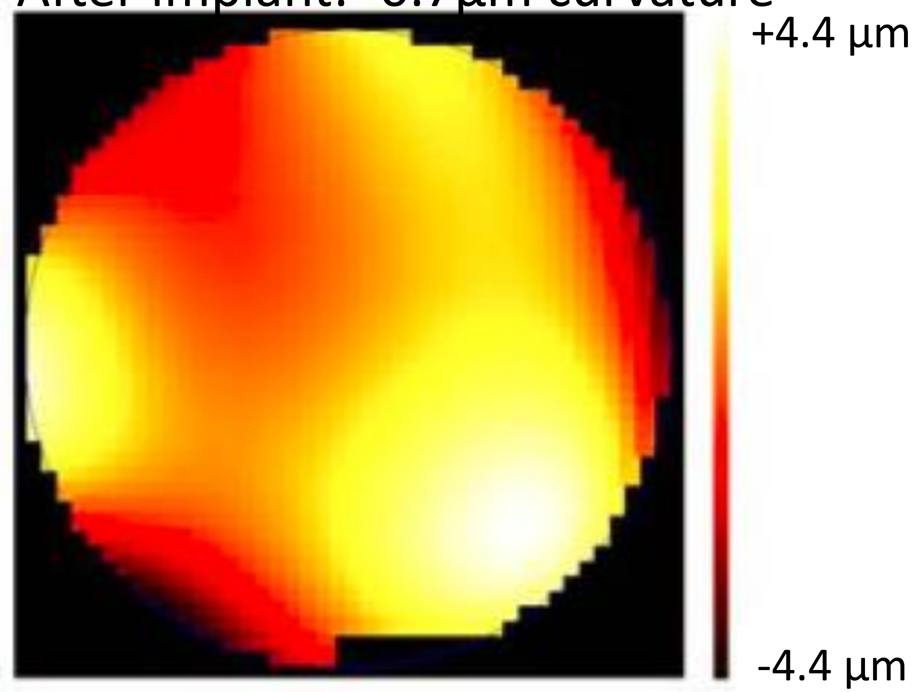
Spherical curvature reduced **>10x**

All other figure errors unaffected

Before implant: 9µm curvature



After implant: -0.7µm curvature



Implant details

Substrate: Silicon 100mm x 400 µm DSP

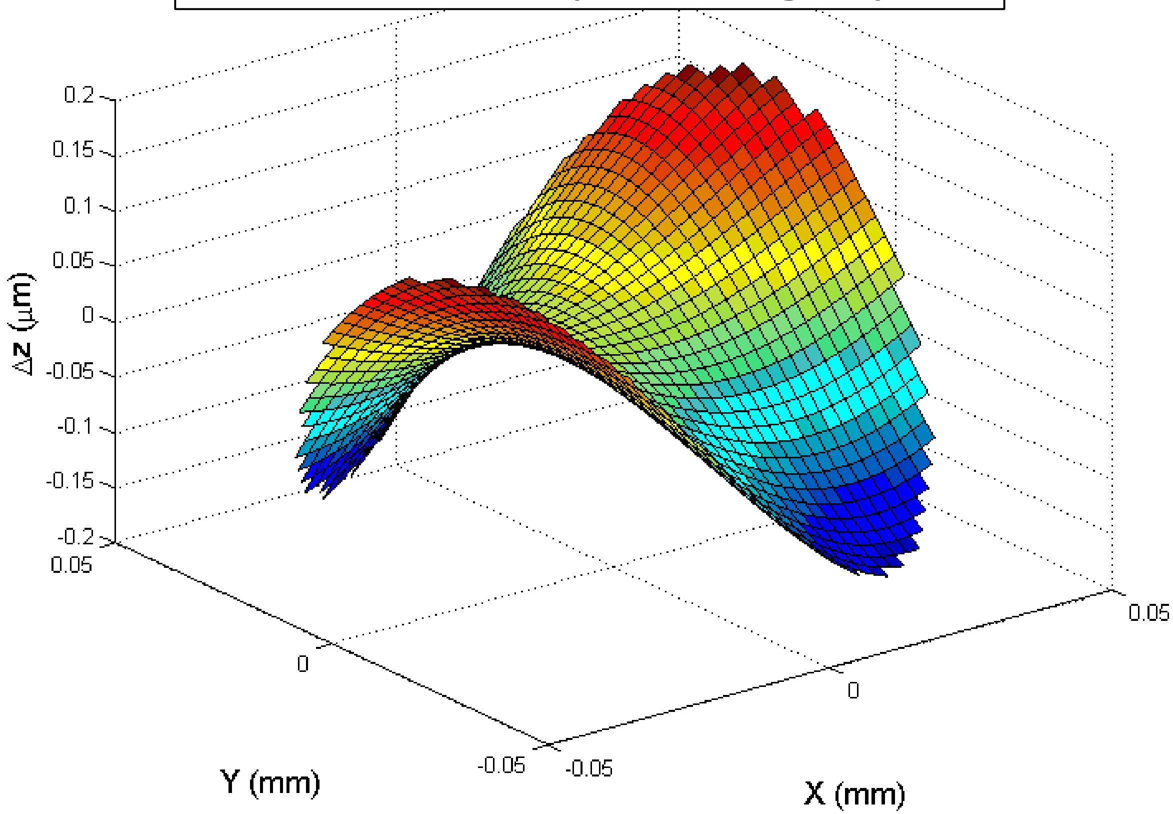
Species: Si+

Ion energy: 150 keV

Astigmatism Correction

Preliminary Experimental Result

Measured shape change (μm)



Successful result:

- One sample tested
- Shape change shows Astigmatism only

Implant details

Substrate: Silicon 100mm DSP

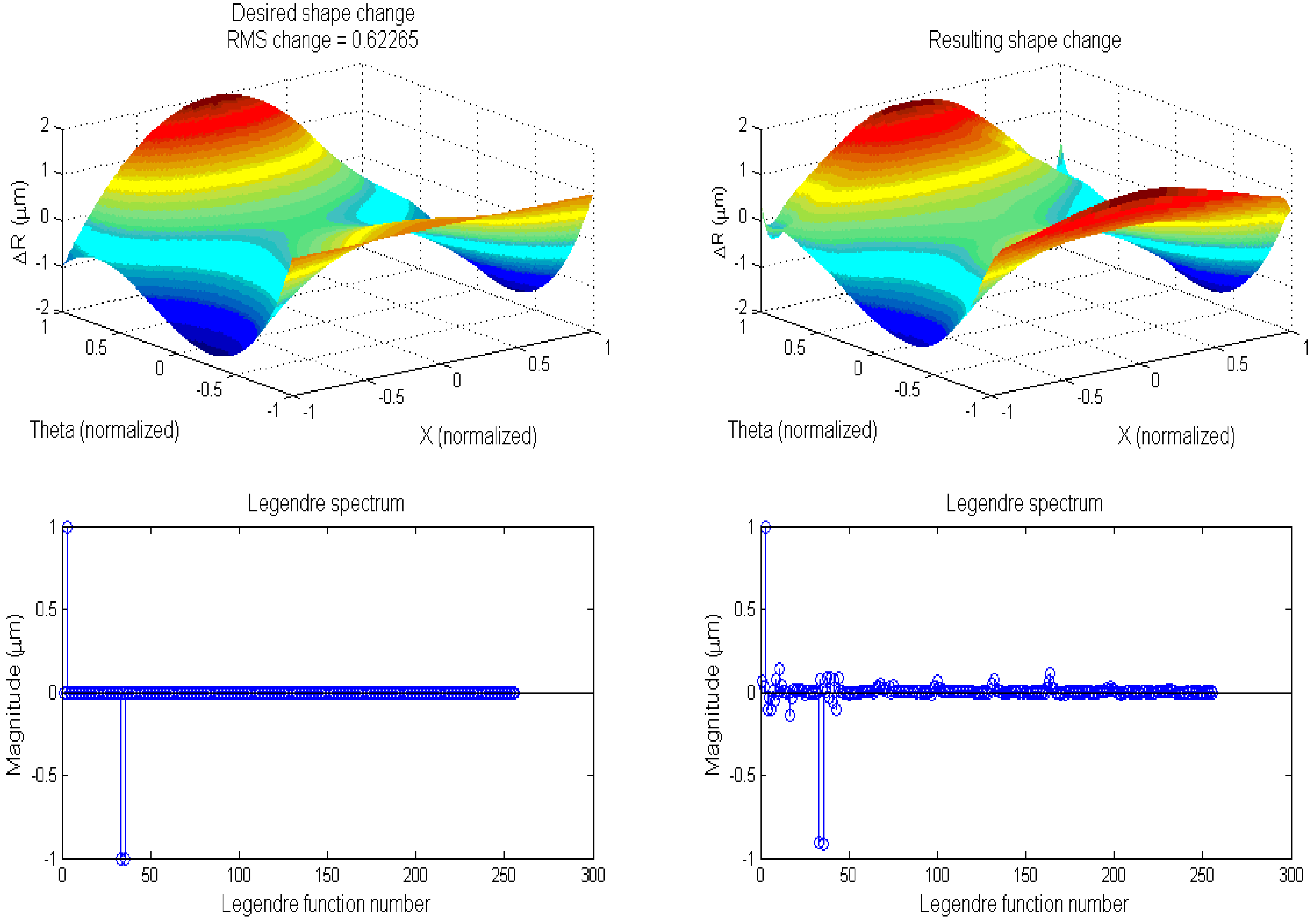
Species: Si+

Ion energy: 150 keV

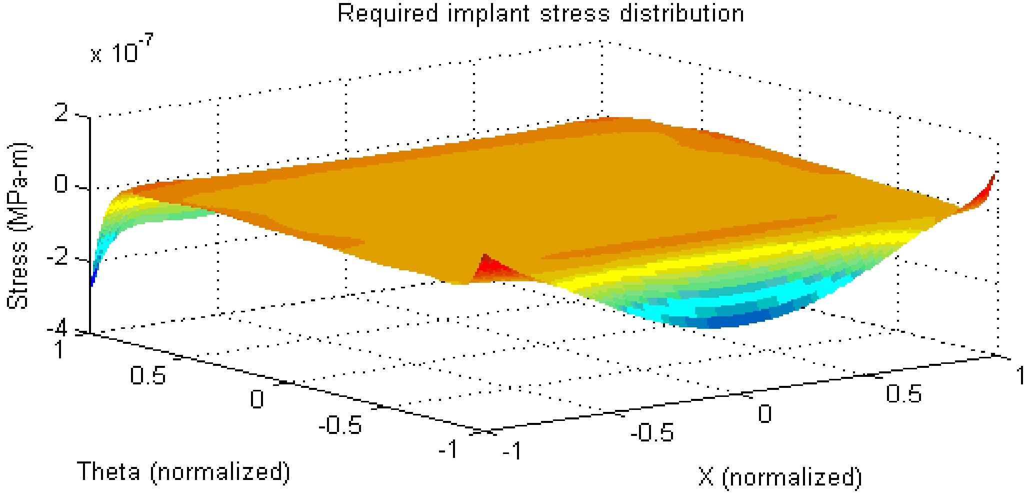
Ion dose: 5.88×10^{13} ions/cm^2

Correction of Wolter optics

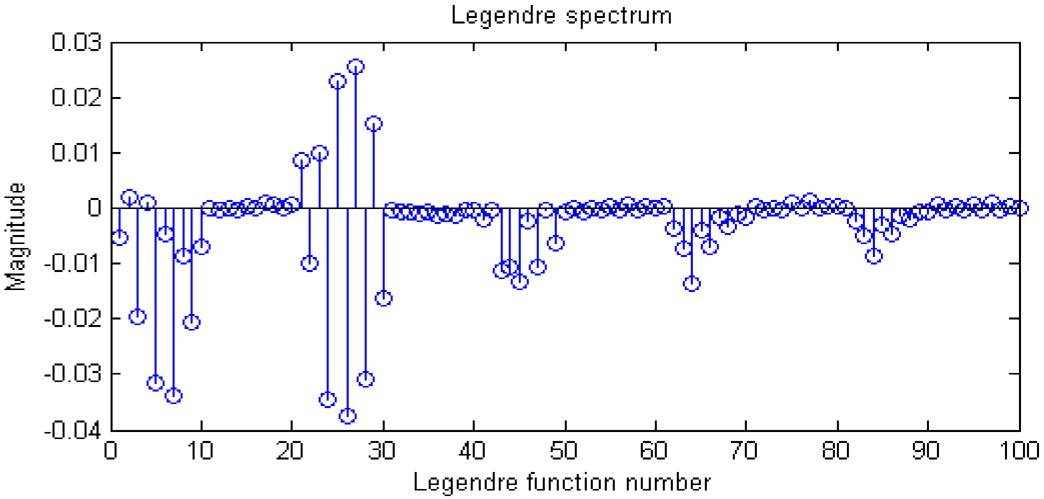
Preliminary Simulations



Correction of Wolter optics
Preliminary Simulations



Very low stresses required!



Summary

CAT Gratings

- All key technical fabrication steps have been demonstrated
- Extensive modeling and synchrotron tests
- New plasma tool will accelerate prototype fabrication effort
- Shooting for TRL 5/6 by end of 2014

Air Bearing Slumping

- First non-touch tool demonstrated
- Tool improvements to improve reliability and repeatability
- Build new tool to slump Wolter optics

Ion Impant Figure Correction

- Will build custom implanter or modify on-campus system
- Further understand implant stress
- Improve metrology
- Correct Wolter optics

Many thanks to the NASA APRA and SAT Programs!

Questions?