Design and Performance of GSECARS Large KB Focusing Optics

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Introduction - Scientific Requirements

• Many earth science problems involve heterogeneous systems on length scales ranging from 500µm to 0.5µm.
• The high brilliance of the APS undulater allows us to strongly focus the beam while keep the divergence to levels acceptable to most of our measurements.
• Achromatic focusing needed to support spectroscopy, and multi wave length scattering experiments.

• Techniques:
  – Micro-crystal diffraction
    • Ambient conditions mounted on tapered glass fiber
    • DAC single crystals up to 20Gpa
  – Surface Scattering
    • CTR
    • Reflectivity
  – Surface Spectroscopy
  – Micro-Probe
    • Elemental mapping
    • Spectroscopy
    • Tomography
  – Q-dependent inelastic scattering
Recent Science – Inelastic Scattering in DAC
Recent Science – Inelastic Scattering Analyzer
Recent Science – Inelastic Scattering in DAC

- Inelastic scattering at high pressure:
  - Na plasmon
  - Boron Nitride: Boron K-edge, Nitrogen K-edge
  - Water plasmon and oxygen K-edge

![Graph showing Na at 9.2 GPa with energy and normalized counts on the x and y axes respectively. The graph includes data points for Na plasmon and Be plasmon at different angles (4, 6, 8, 10, 12, 14 degrees).]
Recent Science – Inelastic Scattering in DAC

Boron K-edge

- 12 GPa, Chi=90
- 12 GPa, Chi = 0
- 5 GPa, Chi = 0

Energy [eV]

Normalized Counts [Ct/Sec] 240 sec/pt
Recent Science – Inelastic Scattering in DAC

Nitrogen K-edge

O - K edge

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Design Philosophy - Beamline layout & Optics Location

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Design Philosophy - Geometry

Ellipse

Source Point

Focal Point

X-Rays

Elliptical Mirror

Storage Ring

Horizontal Focusing Mirror

Vertical Mirror Focusing

Focal Spot ~1μm Dia.

f₁~50m

f₂~100mm
Design Philosophy - Mirror Dimensions

- **Length**
  - Fraction of the beam intercepted over the desired energy range.

\[ F = \text{erf} \left( \frac{\sqrt{2} \cdot 0.9 \cdot \alpha \cdot L}{4 \cdot \Sigma'} \right) \]

- **Thickness**
  - Maximal allowable figure error due to gravitational sag.
  - Maximal safe Bending stress

\[ RMS'_{g} = \left( \frac{1}{\sqrt{L}} \right) \sqrt{\frac{1}{\pi} \int_{-\frac{L}{2}}^{\frac{L}{2}} (\text{Slope}_\text{Gravity}(x) - \text{Slope}_\text{Circle}(x))^2 \, dx} \]

\[ RMS'_{g}[\mu rad] = 6.5 \cdot 10^{-6} \frac{(L[mm])^3}{(c[mm])^2} \quad \text{For Si} \]

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For Si
Design Philosophy - Mirror Dimensions – Predicted Performance

We compute RMS slope error of the mirror by performing a non-linear LSQ fit to an ideal ellipse of the beam weighted two moment slope function and gravitational sag.

\[
W(x) = \frac{\sin(\theta_\theta) \cdot e^{-\frac{1}{2}} \left( \frac{x \sin(\theta_\theta)}{\Sigma \cdot S} \right)}{\sqrt{2\pi} \cdot \Sigma \cdot S \cdot \text{erf} \left( \frac{\sqrt{2} \cdot \sin(\theta_\theta) \cdot L}{4 \cdot \Sigma \cdot S} \right)}
\]

\[
\text{Slope Mirror}(x, K, \eta) = \text{Slope Bender}(x, K, \eta) - \text{Slope Gravity}(x)
\]
Design Philosophy - Thermal Analysis

• White beam operation
  – Limited to 100W with a power limiting aperture.
  – For the modeling we used a footprint at 5mrad of 1.5 mm wide by 180 mm long resulting in a worst case power density of 0.4 W/mm².

• Mirror is internally water cooled.
Design Philosophy - Thermal Analysis – Thermal Transient and Displacement

- Thermal Transient
  - Mirror achieves 97% of the max Temperature in 2 sec
  - Achieves steady state in approximately 18 sec

- Thermal Displacement
  - Determined by feeding the thermal results into ANSYS structural package
Design Philosophy - Thermal Analysis – Slope Error and Thermal Stability

- **Slope Error**
  - Over the beam foot print the slope error is the same
  - Off axis cooling
    - $R = 14.8 \text{ km}$
    - Slope Error = 0.9urad
  - On axis cooling
    - $R = 9.3 \text{ km}$
    - Slope Error = 0.9urad

- **Thermal Stability**
  - For ring current starting at 100ma and dropping to 50ma with an initially corrected thermal bump $R$ and foot print $x_o$ the slope error would increase to:
    \[
    RMS' = \frac{x_o}{4\sqrt{3} \cdot R}
    \]
  - For the off axis case $RMS' = 1.8 \mu\text{rad}$
  - Resulting in a increase in focal size by a factor of 4!
• The maximum thermal equivalent stress for off axis cooling is 1.57 MPa (228 psi) well below the safe limit for Si of 100 psi.
Design Philosophy - Dynamic Figuring

- Once the length, thickness and cooling geometry are determined, the mirror support and bender interface can be designed.
A simple expression for the maximum contact pressure of the bending rod is:

\[ P = \frac{M}{d \cdot \text{Area}} = \frac{Y \cdot c^3}{12 \cdot R \cdot d \cdot g} \]

For our mirror dimensions we find assuming a contact angle of 60deg at maximum curvature (R = 1.8 km) the maximum:
- contact force is 200 lb
- pressure 239 psi
Performing ANSYS modeling we find:

- Maximum equivalent stress to be 3.8 MPa (544 psi) just below the inner bending hole contact point.
- The stress then drops to 2.9 MPa (424 psi) on the back surface near the bending hole.
• The longitudinal stress of the bent mirror can be estimated using the analytical expression:

\[ \sigma_{\text{Bending}} = \frac{M \cdot \frac{y}{I}}{R} = \frac{Y \cdot \frac{y}{R}}{R} \]

Yielding in our case: \( \sigma_{\text{Bending}} = 292 \text{ psi} = 2 \text{MPa} \)

• The analytical result is in good agreement with ANSYS model below resulting in a maximum longitudinal stress component of 2.2MPa
Design Philosophy - Dynamic Figuring – End effects

- Optical aperture equal to the distance between the inner bending rods
- Last 25mm contributes about 0.6urad of slope error
- Nearly the full length is a perfect circle.
Design Philosophy - Polishing Aperture for and Coatings Arrangement
Bender Design – Stable Two Moment Mirror Bender

- Radial Bearing
- Leaf Spring
- Cu Bushings
- Leaf Spring
- Cu Bushings
Bender Design – Reaction Platform and In Vacuum Actuator
Bender Design – Complete Mirror Bender Subassembly

- Support Leg
- Water Inlet
- Reaction Platform
- Water Outlet
- Bending Rods
- Crossed Bending Arms
- DS Moment Actuator
- US Moment Actuator
- Cu Cooling Mask
- Support Leg
Bender Design – Auto Collimator Test of Mirror Bender

DS = US
Mirror in DS Position

Mirror Angle [urad]

1200
1000
800
600
400
200
0
-200
-400

Actuator Position [mm]

-10
-5
0
5
10
15
20
25

Slope = 39.40 urad/mm

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Bender Design – Mirror Bender Mounted on Actuators in Vacuum Tank
Bender Design – Vertical and Horizontal Mirrors Systems Installed in SOE

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Bender Design – Horizontal Mirrors Fully Installed (Ready to Bolt Up Cover)
The image was produced by focusing the beam onto a thin YAG single crystal producing visible light that is imaged with a 20X objective coupled to 1k x 1k cooled CCD camera.

The effective resolution is about 3 \( \mu \text{m} \).
Performance – Knife Edge Scans

GSECARS Double Focused 12.7 keV
Undulator "A" Beam
Total Flux Density Gain = 1,232

- RMS Slope Error = 1.2 µrad
- Total mirror length = 1.2 m
- Optical Aperture = 1.0 m
- θ = 2.5 mrad
- Available Entrance Aperture = 2.5 mm
- Beam Height at Mirror (Defined by Slits) = 1.7 mm
- Beam Height at Mirror (Defined by Source) = 2.3 mm FWHM
- Percentage of Horizontal Beam use = 74%
- Horizontal Gain = 28
- Source Size = 700 µm FWHM
- f₁ = 46.6 m, f₂ = 4.28 m
- De-mag = 10.9
- Ideal focus = 64 µm

- FWHM= 61.4 µm
- RMS Slope Error = 0.8 µrad
- Total mirror length = 1.2 m
- Optical Aperture = 1.0 m
- θ = 2.5 mrad
- Available Entrance Aperture = 1.75 mm
- Beam Height at Mirror (Defined by Slits) = 1.0 mm
- Beam Height at Mirror (Defined by Source) = 0.6 mm FWHM
- Percentage of Vertical Beam use = 100%
- Vertical Gain = 44
- Vertical Height at Mirror (Defined by Source) = 0.6 mm FWHM
- Effective Slope Error = 0.4 µrad
- Source Size = 45 µm FWHM
- f₁ = 44.9 m, f₂ = 6.00 m
- De-mag = 7.5
- Ideal focus = 6.0 µm

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