High-Energy X-Ray Optics Development at

SRI-CAT Sec. 1

S. D. Shastri

X-Ray Physics Group
APS - XFD

- bent double-Laue monochromator (50 - 200 keV)
- high-resolution post-monochromatization with CRLs and flat crystals
Cryogenically-Cooled Bent Double-Laue Monochromator for High Energies (50 - 200 keV)

Properties:
- cryo-cooling, no filtration-induced flux sacrifice at closed ID gap
- high flux, e.g., $>10^{12}$ ph/s in 1x1mm aperture at 60 m at 80 keV
- brilliance preserving (unlike mosaic monochromators)
- fully tunable (unlike single-reflection schemes)
- in-line, fixed exit (unlike single-reflection schemes)
- over 10 times more flux than flat crystals, but **without increased energy spread** ($\Delta E/E=10^{-3}$)

Need for Higher Energy Resolution

Modest resolution of above scheme is sufficient for numerous high-energy x-ray applications:
- powder diffraction
- stress/strain determination
- fluorescence
- pair distribution function measurements

However, a narrower energy window ($\Delta E/E=10^{-4}$ or better) would benefit:
- high-resolution powder diffraction and stress/strain measurements (i.e., lineshape analysis)
- anomalous scattering
- excitation of nuclear resonances (e.g., nuclear lighthouse effect)
- high-resolution spectroscopy (e.g., Compton scattering, atomic physics)
- improved stability (in post-monochromatization approach)
Flat, Perfect Si(111) Monochromator in APS Undulator A Beam

10 keV performance

\[ \Delta E/E = 4 \times 10^{-5} \]

Si(111), \( \theta = 11.4^\circ \)
29 \( \mu \)rad acceptance

white beam
9 \( \mu \)rad

10 \( \mu \)rad

100 keV performance

\[ \Delta E/E = 5 \times 10^{-4} \]

Si(111), \( \theta = 1.1^\circ \)
3 \( \mu \)rad acceptance

white beam
53 \( \mu \)rad

10 \( \mu \)rad
Bent Double-Laue Monochromator for High Energies

Geometry

\[ \Delta E/E = \cot \theta \sqrt{\Delta \theta_{\text{inc}}^2 + \Delta \theta_{\text{acc}}^2} \]

2.5 x 10^{-3} \rightarrow 2.0 x 10^{-3}  
53 \mu rad \rightarrow 1.6 \mu rad

Over 10 Times Flux, but Energy Width Unchanged

100 keV

flat Si(111), symmetric Bragg

bent Si(111), asymmetric Laue, R = 32 m, \( \alpha = 10^6 \)
2.5 mm thick

Rowland circles, diameter \( \approx \) 32 m

divergence unaffected

asymm Si(111) bent Laue
Post-Monochromatization Approach for Higher Energy Resolution: Using Compound Refractive Lenses (CRLs) and Flat Crystals

Why not: - alter Laue premono parameters?
- or use flat crystal mono and slit down?
- or use flat crystal mono and CRL in white beam?

Is the Pre-Mono Really Brilliance-Preserving ? A Simple Test

Mono set to 81 keV, location 32 m

<table>
<thead>
<tr>
<th>Distance</th>
<th>Horizontal FWHM</th>
<th>Vertical FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 m</td>
<td>0.8 x 0.8 mm</td>
<td></td>
</tr>
<tr>
<td>35 m</td>
<td>1.04 x 1.04 mm</td>
<td>1.06 x 1.07 mm</td>
</tr>
<tr>
<td>58 m</td>
<td>1.72 x 1.72 mm</td>
<td>1.74 x 1.72 mm</td>
</tr>
</tbody>
</table>
Is the CRL Collimating?

collimating CRL, 
f = 35 m at 81 keV, 
90 cylindrical elements of Al, 
1 mm diam, 50 µm walls 
(from Adelphi Tech., Palo Alto, CA)

asymm Si(111) bent 
Laue pre-monochromator

81 keV, 
1 x 1 mm

FWHM
0.52 mm measured

58 m

FWHM
0.51 mm calculated 
0.52 mm measured

35 m

28.6 µrad

vertical beam expansion and collimation
Setup and Expected Performance

additional factor of 10 loss due to monochromatization to $\Delta E/E = 0.0014$, $2 \times 10^{11}$ ph/s, $\Delta E = 11$ eV

collimated beam, 1 x .5 mm, 50% loss thru CRL

Si(111) high-resolution monochromator (+ - - +)

collimating CRL, f = 35 m, 86 cylindrical elements of Al, 1 mm diam, 50 µm walls, (from Adelphi Tech., Palo Alto, CA)

flux (high-res mono) \[\frac{\text{flux (pre-mono)}}{\text{flux (pre-mono)}} = \frac{1}{23}\]

flux out (CRL in) \[\frac{\text{flux out (CRL in)}}{\text{flux out (CRL out)}} = 8.3\]

source-to-CRL distance: 35 m

Measured Performance

Flux (high-res mono) \[\frac{\text{Flux (pre-mono)}}{\text{Flux (pre-mono)}} = \frac{1}{52} \text{ (discrepancy factor 2.3)}\]

flux out (CRL in) \[\frac{\text{flux out (CRL in)}}{\text{flux out (CRL out)}} = 4.0 \text{ (discrepancy factor 2.1)}\]

$\Delta E = 7$ eV
DuMond Representation of Optics (to scale)

beam from pre-mono
28.6 µrad divergence
\( \Delta E/E = 0.0016 \)

collimated beam after CRL
few µrad divergence
\( \Delta E/E = 0.0016 \) (unchanged)

final delivered beam
\( \Delta E/E = 0.00014 \)

acceptance of combined high-resolution Si(111) crystal system

11 eV energy Darwin width

3.5 µrad angular Darwin width

acceptances of individual high-resolution Si(111) crystals

energy

angle
Influence of Cylindrical Aberrations on Collimation

90 elements, diam=1.02 mm, 35 m from source

\[ \phi \] (\( \mu \text{rad} \))

\[ T(y) \approx 30\% \text{ lost - rejected by high-resolution mono} \]
Approx 1:0.7 focusing CRL,
f = 14 m at 81 keV,
215 cylindrical elements of Al,
1 mm diam, 50 µm walls
(from Adelphi Tech., Palo Alto, CA)

81 keV,
1 x 1 mm
4 x 10^{12} ph/s
ΔE/E = .0015
29 µrad divergence

Vertically focused spot,
1.7 x 0.089 mm (h x v),
27% transmission thru CRL,
1.0 x 10^{12} ph/s

Source-to-CRL distance: 35 m

Source-to-focus distance: 59 m
Combining All: Collimation, High Energy Resolution, Focusing at 67.4 keV

- **Source-to-CRL Distance**: 35 m
- **Source-to-Focus Distance**: 59 m

**APS Undulator A Source**

- **Si(111) High-Resolution Monochromator**: (+ - - +)
  - Collimating CRL, \( f = 35 \text{ m} \), 61 cylindrical elements of Al, 1 mm diam, 50 \( \mu \text{m} \) walls, 60 \% trans
  - Collimated Beam, 1 x 0.5 mm, 54\% trans thru CRL
  - Additional factor of 20 loss due to monochromatization to \( \Delta E/E = 0.0007 \), 1 x 10\(^{11}\) ph/s, \( \Delta E = 5 \text{ eV} \)

**Vertically Focused Spot**: 1.7 x 0.67 mm (h x v)
- 6 x 10\(^{10}\) ph/s

**Pre-Mono**

- 67 keV, 1 x 1 mm, 4 x 10\(^{12}\) ph/s, \( \Delta E/E = 0.012 \), 28.6 \( \mu \text{rad} \) divergence

**Focused Spot**: 1.7 x 0.067 mm (h x v)
- 6 x 10\(^{10}\) ph/s
Improvements

- Eliminate cylindrical aberrations with parabolic CRLs.
- Optimize high-res mono (reflection order, asymmetries)
- For μrad control, need easily variable number of elements to compensate for unknowns:
  CRL profile errors
distance uncertainties
  refractive index (density, composition) uncertainty
  pre-mono uncertainties
- A. Khounsary (APS-XFD) has developed a parabolic, variable focus lens using extrusion fabrication:

Acknowledgements

A. Mashayekhi - SRI-CAT Sec. 1, X-Ray Physics Group
R. Beguiristain - Aledphi Technology, Inc., Palo Alto, CA

Use of the APS is supported by US-DOE, BES, Office of Science, under Contract No. W-31-109-Eng-38.