Synchrotron Beam Lines

Stanford-Berkeley Summer School

on Synchrotron Radiation

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Tony Warwick

Advanced Light Source

Lawrence Berkeley National Laboratory
ALS delivers (soft) x-rays

1.9 Gev storage ring, bend magnet critical energy = 2.5 keV

Undulator radiation from 10 to 2000 eV for spectroscopy and microscopy

Hard x-rays from wigglers and superbends for structure studies up to about 40 keV
ALS Beam Lines
Synchrotron (soft x-ray) beam lines

- undulator sources *Maxwell’s equations tell all*
- diffractive structures for wavelength selection *you need this, sorry*
- diffraction gratings *ancient practice*
- aberration analysis *a simple thing made complicated*
- ray tracing *a complicated thing made simple*
- tuning and commissioning *you really know what you are doing*
- some beam lines *optics of modern designs*
- beam line technology *engineering of modern designs*
- micro-focusing *you want this*
- optimized user facilities *you want this too*
Two Elliptically Polarizing Undulators

- Undulator in the upstream position
- Undulator in the downstream position
- Corrector magnet
- Electron trajectory
- Front-end and first mirror
- Electron trajectory
- Approx. 0.2 m
- Approx. 6 m
- 1.08 mrad
Elliptically Polarizing Undulator

Undulator brightness, harmonics 1 through 7, linear polarization. 5.0cm period, 37 periods, 400mA, 1.9GeV, 1x10^-4 dE/E

horizontal polarization:
13.0mm gap ky≈4.307, lowest energy=66.753eV

vertical polarization:
13mm gap kx≈2.0, lowest energy=228.633eV

Note, the higher harmonics lose brightness if the energy spread increases.
Spherical Grating Monochromator Line at ALS

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5 cm x 89 period

10^{12} photons per second

\Delta E/E = 2 \times 10^{-4}
Grating Monochromator Undulator Line

User area
Exit Slits
Grating Chamber
First mirror
Storage ring shield wall
Diffraction Grating

\[ m\lambda = d (\sin \alpha + \sin \beta) \]
Double crystal monochromator. After satisfying the Bragg condition at the first crystal the second diffraction is almost 100% efficient.
### Data for selected crystals

**Data for selected crystals used as dispersive elements in x-ray spectrometers and monochromators.**

<table>
<thead>
<tr>
<th>Crystal</th>
<th>(111)*</th>
<th>6.2712</th>
<th>Si</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>(111)*</td>
<td>6.2712</td>
<td>Si</td>
<td>Very rugged and stable general-purpose crystal. High degree of perfection obtainable. Cryogenic silicon has zero expansion.</td>
</tr>
<tr>
<td>Germanium</td>
<td>(111)*</td>
<td>6.532</td>
<td>Ge</td>
<td>Eliminates second order. Useful for intermediate- and low-Z elements where Ge $K\alpha$ emission is eliminated by pulse-height selection.</td>
</tr>
<tr>
<td>Indium antimonide</td>
<td>(111)</td>
<td>7.4806</td>
<td>InSb</td>
<td>Important for $K$-edge of Si at 1.8keV.</td>
</tr>
<tr>
<td>Diamond</td>
<td>(400)</td>
<td>1.742</td>
<td>C</td>
<td>General purpose substitute for silicon when heat load is very high, better thermal properties.</td>
</tr>
</tbody>
</table>

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Side view of the Double Crystal Monochromator for I.D. 31 at E.S.R.F. on 50° position. The resolution for the roll of both the groups is 1 µrad as the resolution of the coarse pitch of the secondary group. On this movement an additional piezo actuator allows a much fine movement (0.5 µrad). The translations perpendicular to the crystal surface have a resolution of 0.1 µm for both the crystal groups. The translation of the secondary group has also a resolution of 0.5 µm.

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Diffraction from synthetic multilayers
The Bragg angle is 1.122 degrees to maximize the reflectivity at 16 keV (92%). The 3rd order contamination is about 4%.
Engineered Bandpass Multilayer X-ray Optics

Wide bandpass Mo/B4C at 12keV
theta = 1 degree

Figures from Osmic Inc.

Mo-B4C Performance

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Ruling Engines

Leonardo da Vinci
c1475

Henry Rowland c1875
Water Cooled Copper Diffraction Gratings

\[ m\lambda = d (\sin \alpha + \sin \beta) \]

rotation axis
Grating Specification for Holographic Ruling
Holographic Ruling

interfering laser beams

photo resist
nickel
copper

ion etch

shallow grooves in nickel
High Quality Product, AFM Verification

grooves about 1µm wide
20nm deep
Triple VLS grating (Carl Zeiss)

Efficiency can be calculated:

Just solve Maxwell’s equations with a conducting periodic boundary condition (Neviere)

Zeiss triple VLS grating. Neviere computations versus measured diffraction efficiency
2 theta = 176 degrees
Surface Figure Error for Diffraction Gratings

JY sent their product around the world to be measured before delivery to ALS

e.g. $1 \mu\text{rad} @ 5\text{m} = 10\mu\text{m}$
Cleanliness for Spectroscopy at C 1s edge 300eV

clean.....

New grating for ALS 5.3.2 (from Jobin-Yvon)

dirty.....

Jen-Optik mono at BESSY, ready for plasma cleaning

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Wavefront is a surface of specific phase.
It represents the uncertainty of the photon’s transverse position.

Rays (Poynting vector) follow the ‘optical path’.
They are all the same length, since the travel time at the speed of light must be the same, to maintain the phase condition as the wavefront advances.

Fermat’s principle.
Optical path length is stationary. \[ \int_{A_1}^{A_2} nds = c \int_{A_1}^{A_2} dt = \text{const} \]

Analysis: Express the optical path as a function of field and aperture variables, differentiate, and set the derivative to zero.
For example: A single photon, emerging from a point source is focused by a lens.

The lens (modifies the speed of light) has a thickness $t(w)$ that is a function of the aperture variable ‘$w$’.

Write down the length of the optical path passing through the lens at a distance ‘$w$’ from the axis in terms of $t(w)$ and $\Delta$.

Differentiate this with respect to $w$, set to zero, solve for $\Delta$ as a function of $w$, to describe the quality of the focus.
3.3.2 The principle of Fermat

The principle of Fermat, known also as the principle of the shortest optical path, asserts that the optical length

\[ \int_{P}^{F} \sqrt{ds} \]

of an actual ray between any two points \( P_1 \) and \( P_2 \) is shorter than the optical length of any other curve which joins these points and which lies in a certain regular neighbourhood.

If \( F(w, l, \ldots) \) is minimum

\[ \frac{\partial F}{\partial w}, \frac{\partial F}{\partial l}, \ldots \]

must be zero.

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Conditions to be In-Focus and Coma-Free

Spherical grating focus condition:

\[ T + T' = \left( \frac{\cos^2 \alpha}{r} - \frac{\cos \alpha}{R} \right) + \left( \frac{\cos^2 \beta}{r'} - \frac{\cos \alpha}{R} \right) = 0 \]

Spherical grating condition for vanishing of coma:

\[ \frac{\sin \alpha}{r} \left( \frac{\cos^2 \alpha}{r} - \frac{\cos \alpha}{R} \right) + \frac{\sin \beta}{r'} \left( \frac{\cos^2 \beta}{r'} - \frac{\cos \alpha}{R} \right) = 0 \]

(This condition is satisfied on the Rowland circle)

Rowland circle condition: \( r = R \cos \alpha \) and \( r' = R \cos \beta \)

Plane grating case: \( R = \infty \)

\[ r' = -r \frac{\cos^2 \beta}{\cos^2 \alpha} = -r \frac{c_{ff}^2}{\cos^2 \alpha} \]

Applications:

SGM’s, TGM’s

SGM’s

PGM’s, SX700 etc

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Rowland Circle

- Rowland Circle diameter equal to the grating radius
- Grating rotates, A and B need to move
- If A held fixed B moves to stay in focus and the Rowland condition is met at two points of the grating rotation
VLS features

Fermat optical path is same for all rays:

\[
\frac{\partial F(x,y,z)}{\partial x, \partial y, \partial z} = 0
\]

but optical path length must be same:

\[
\rightarrow \text{diffracted rays pick up a term } = n m \lambda \text{ in the optical path length. (F)}
\]

\[\frac{S_n}{\Delta w} \text{ is groove density}\]
Spectral Resolution of the Grating

\[ m \lambda = d (\sin \alpha + \sin \beta) \]
\[ \left( \frac{\partial \lambda}{\partial \beta} \right)_\alpha = \frac{d \cos \beta}{m} \]
\[ \frac{d \lambda}{dq} = \frac{d \lambda}{d \beta} \frac{d \beta}{dq} = \frac{d \cos \beta}{mr'} \equiv \frac{10^{-3} d (\text{Å}) \cos \beta}{mr'(m)} \text{ Å / mm} \]

From this we get the exit- and entrance-slit-width-limited resolutions

\[ \Delta \lambda_s = \frac{d \cos \alpha s}{mr} \quad \Delta \lambda_{s'} = \frac{d \cos \beta s'}{mr'} \]

Diffraction-limited resolution = \(1/N\)

BUT

Provided the grating is big enough, the number of illuminated grooves is always sufficient to achieve the slit-width-limited resolution because of diffraction at the entrance slit.
Undulator Radiation Patterns

\[ \theta_{\text{cen}} = \frac{1}{\gamma \sqrt{N}} \]

\[ \lambda_u \]

Figure 5.18. (a) Illustration of the figure eight electron motion in the frame of reference moving with the average electron velocity, and the resultant radiation patterns at the fundamental and second harmonic frequencies in both (b) the frame of reference moving with the electron and (c) the laboratory frame of reference.

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Undulator Harmonics Dispersed
Spectral Resolution by Gas Phase Absorption

Carbon in CO2

Nitrogen in N2

ion current (hv)

+100V
gas @
e.g.10mTorr

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Open the exit slits

Commissioning of the U49/2-PGM1 beamline


*BESSY, Albert-Einstein-Straße 15, 12489 Berlin, Germany
†HMI, Glienicker Straße 100, 14109 Berlin
‖Center for Advanced Technology, Indore-452 013, India

FIGURE 8. Nitrogen 1s→π⁺ spectrum in the exit slit plane recorded with a CCD-camera behind the refocussing mirror. The left figure shows the image obtained with the exit slit opened, the right with exit slit closed to 150 μm.
A Simple Beam Line

built for bend magnet illumination of Scanning Transmission X-ray Microscope

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Ray Trace

entrance slit

exit slit

299.8 eV  300.0 eV  300.2 eV
Modern Designs (variable included angle)

- Monochromator
- Retractable focus mirror (deflecting right)
- Fixed focus mirror (deflecting left)
- Exit slits (x2)
- Control racks (above the beam line)
- Scanning microscope
- KB refocus mirrors
- Spectroscopy stations
Collimated Variable-Included-Angle PGM

Cff = \( \frac{\cos \beta}{\cos \alpha} \)  

\( m\lambda = \sin \alpha - \sin \beta \)

\( 170^\circ < 2\theta < 178^\circ \)  

\( 80^\circ < |\beta| < 89^\circ \)
Forgiveness Factor in Sagittal Focusing

TANGENTIAL-PLANE DIAGRAM

Source $s_T, s_S$

slope errors $\Delta_T, \Delta_S$

$\Delta s'_T = 2r' \Delta_T$

$\Delta s'_T = 2r' \theta \Delta_T$

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Sagittal Focusing Water Cooled Mirror

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Mirror Cooling for High Heat Load

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Collimated Variable-Included-Angle PGM

\[
Cff = \cos \beta \div \cos \alpha \quad \quad m\lambda = \sin \alpha - \sin \beta
\]

\begin{align*}
170^\circ & < 2\theta < 178^\circ \\
80^\circ & < |\beta| < 89^\circ
\end{align*}
Optic Cooling for High Heat Load

The rms slope error (µrad) of the pre-mirror corresponding to a resolving power R=7500 (FWHM) from the 150l/mm grating.
Collimated Variable-Included-Angle PGM

\[ Cff = \frac{\cos \beta}{\cos \alpha} \quad m\lambda = \sin \alpha - \sin \beta \]

170° < 2θ < 178°
80° < |β| < 89°
Computed Diffraction Efficiency

First, second and third order efficiency calculations for a laminar grating 150 lines/mm
Collimated SX700 Capable of Very High Resolution

Picture from R. Follath, BESSY

- Doppler width 0.4 meV
- Monochromator contribution 0.65 meV
- Resolving power = $1.0 \times 10^5$
- Rotation increments
  - grating: 17 nrad
  - mirror: 9 nrad
- Measured with 1200/mm grating at $c_{ff} = 10$ to $12$
New Implementation of SX700 Monochromator

Seal joint below beam height for alignment access
External sine-bar drives and linear encoders
Aluminum structural vessel
External grating changer
Lightweight rigid honeycomb table
6-strut alignment
Heavy pump below bellows on separate support
Legs filled with epoxy granite
Monochromator fabrication by Johnsen Ultravac

Successful factory motion tests and preparation for final vacuum qualification September 10th 2004

Accepted, ready for shipment October 12th 2004
Bending Mirrors to Approximate an Ellipse

\[ x(p) \approx p \left\{ 1 + \left( \frac{x_0^2 b^2}{a^2} \right) / \left( a^2 - x_0^2 \right) \right\}^{-1/2} + x_0 \]

\[ \frac{1}{\rho_{\text{ellipse}}} = \pm a \ b \ \left\{ a^2 - x(p)^2 + x(p)^2 \frac{b^2}{a^2} \right\}^{-3/2} \]

\[ M(p) = \left\{ C_1(L/2 - p) + C_2(L/2 + p) \right\} / L + (\rho \tan(L/2 - p)) (L/2 - p) (L/2 + p) \]

\[ \frac{1}{\rho_{\text{bender}}} \approx \frac{d^2q}{dp^2} = \frac{12 M(p)}{E \ w(p) \ t^3} \]
Bending Mirrors to Approximate an Ellipse
Kirkpatrick-Baez Mirror Pairs for Micro-Focus

for focussed spot size down to about 0.5 µm
Final focus spot size

Figure 3. Measured x-ray spot profiles at the focus.

Figure 4. Defocused spot 500µm diameter.
Optimized Experiment Stations Keep Users Busy

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