Introduction to Synchrotron Radiation and Beamlines

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http://ast.coe.berkeley.edu/sxr2009
http://ast.coe.berkeley.edu/srms
The short wavelength region of the electromagnetic spectrum

Wavelength

Photon energy

- See smaller features
- Write smaller patterns
- Elemental and chemical sensitivity

\[ \hbar \omega \cdot \lambda = h c = 1239.842 \text{ eV nm} \]

\[ n = 1 - \delta + i \beta \quad \delta, \beta \ll 1 \]
Synchrotron radiation

Bending Magnet:
\[ h\omega_c = \frac{3eB\gamma^2}{2m} \] (5.7)

Wiggler:
\[ h\omega_c = \frac{3eB\gamma^2}{2m} \] (5.80)
\[ n_c = \frac{3K}{4} \left( 1 + \frac{K^2}{2} \right) \] (5.82)
\[ P_T = \frac{\pi eK^2\gamma^2 IN}{3\epsilon_0\lambda_u} \] (5.85)

Undulator:
\[ \lambda = \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K^2}{2} + \gamma^2\theta^2 \right) \] (5.28)
\[ K = \frac{eB_0\lambda_u}{2\pi mc} \] (5.18)
\[ \theta_{cen} = \frac{1}{\gamma^*\sqrt{N}} \] (5.15)
\[ \frac{\Delta\lambda}{\lambda} \bigg|_{cen} = \frac{1}{N} \] (5.14)
\[ P_{cen} = \frac{\pi e\gamma^2 I}{\epsilon_0\lambda_u \left( 1 + \frac{K^2}{2} \right)^2} f(K) \] (5.41)
Electron binding energies, in electron volts (eV), for the elements in their natural forms

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Broadly tunable radiation is needed to probe the primary \((n = 1 \& n = 2)\) resonances of the elements.
Typical applications of synchrotron radiation

• Surface science
• Magnetic materials
• Materials chemistry
• Environmental sciences
• Protein crystallography
• Biomicroscopy
• Chemical dynamics
3rd Generation facilities, like Elettra, have many straight sections and a small electron beam

- Many straight sections for undulators and wigglers
- Brighter radiation for spatially resolved studies (smaller beam more suitable for microscopies)
- Interesting coherence properties at very short wavelengths
Synchrotron radiation from relativistic electrons

Note: Angle-dependent doppler shift

\[ \lambda = \lambda' \left(1 - \frac{v}{c} \cos\theta\right) \]

\[ \lambda = \lambda' \gamma \left(1 - \frac{v}{c} \cos\theta\right) \]

\[ \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \]
Synchrotron radiation in a narrow forward cone

Frame moving with electron

\[ \tan \theta = \frac{\sin \theta'}{\gamma (\beta + \cos \theta')} \]  

(5.1)

\[ \theta \approx \frac{1}{2\gamma} \]  

(5.2)

Laboratory frame of reference
Three forms of synchrotron radiation

- **Bending magnet radiation**

- **Wiggler radiation**

- **Undulator radiation**
Bending magnet radiation covers a broad region of the spectrum, including the primary absorption edges of most elements.

\[ E_c = \hbar \omega_c = \frac{3e\hbar B \gamma^2}{2m} \quad (5.7a) \]

\[ E_c(\text{keV}) = 0.6650E_e^2(\text{GeV})B(\text{T}) \quad (5.7b) \]

\[ \gamma = \frac{E_e}{m c^2} = 1957E_e(\text{GeV}) \quad (5.5) \]

Advantages:
- covers broad spectral range
- least expensive
- most accessible

Disadvantages:
- limited coverage of hard x-rays
- not as bright as undulator

What is \( E_c \) at a facility near you?
What is \( 4E_c \)?
Undulator radiation from a small electron beam radiating into a narrow forward cone is very bright.

\[ \lambda = \frac{\lambda_u}{2\gamma^2} \]

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

\[ \left[ \frac{\Delta \lambda}{\lambda} \right]_{cen} = \frac{1}{N} \]

\[
\text{Brightness} = \frac{\text{photon flux}}{\Delta A \ (\Delta \Omega)}
\]

\[
\text{Spectral Brightness} = \frac{\text{photon flux}}{\Delta A \ (\Delta \Omega) \ (\Delta \lambda/\lambda)}
\]
Undulator radiation

**Laboratory Frame of Reference**

- $E = \gamma mc^2$
- $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$
- $N = \#\,\text{periods}$

**Frame of Moving $e^-$**

- $e^-$ radiates at the Lorentz contracted wavelength:
  - $\lambda' = \frac{\lambda_u}{\gamma}$

**Frame of Observer**

- Doppler shortened wavelength on axis:
  - $\lambda = \lambda' \gamma (1 - \beta \cos \theta)$
  - $\lambda = \frac{\lambda_u}{2\gamma^2} (1 + \gamma^2 \theta^2)$

Accounting for transverse motion due to the periodic magnetic field:

- $\lambda = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2\right)$

where $K = eB_0 \lambda_u / 2\pi mc$

**Following Monochromator**

- For $\frac{\Delta \lambda}{\lambda} \approx \frac{1}{N}$
  - $\theta_{cen} \approx \frac{1}{\gamma \sqrt{N}}$
  - typically $\theta_{cen} \approx 40 \mu\text{rad}$
Comments on undulator harmonics

First and second harmonic motions

- 1 cycle for $V_x$
- 2 cycles for $V_z$

Radiation patterns in the electron and laboratory frames

(a) and (b) show the radiation patterns for different harmonics.

(c) illustrates the relationship between the fundamental and second harmonic radiation patterns.

Mathematical expressions:

$$\lambda_n = \frac{\lambda_u}{2\gamma^2 n} \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2\right)$$  \hspace{1cm} (5.30)$$

$$\left(\frac{\Delta \lambda}{\lambda}\right)_n = \frac{1}{nN}$$  \hspace{1cm} (5.31)$$
**Undulator harmonics**

Recall that the axial velocity has a double frequency component

\[ v_z = c \left[ 1 - \frac{1 + K^2/2}{2\gamma^2} \cos(2k_u z) \right] \]

which in the frame of reference moving with the electrons, gives

\[ z'(t') \simeq \frac{K^2}{8k_u} \sin 2\omega_u' t' \tag{5.70} \]

where \( k'_u = \gamma k_u \) and \( \omega'_u = \gamma \omega_u \). The transverse motion in this frame is

\[ x'(t') \simeq -\frac{K}{k_u \gamma} \cos \omega_u \gamma' \left( t' + \frac{z'}{c} \right) \]

To a higher degree of accuracy, we now keep the \( z'/c \) term

\[ x'(t') \simeq -\frac{K}{k_u} \cos \left( \omega_u' t' + \frac{K^2}{8} \sin 2\omega_u' t' \right) \tag{5.71} \]

for small \( K \)

\[ x'(t') \simeq -\frac{1}{k_u} \left[ K \cos \omega_u' t' + \frac{K^3}{16} \cos 3\omega_u' t' \right] \tag{5.72} \]

Taking second derivatives to find acceleration, and squaring \( |a'(t')|^2 \)

\[ \frac{dP'}{d\Omega'} \propto n^4 K^{2n} \]

Thus harmonics grow very rapidly for \( K > 1 \).
The transition from undulator radiation \((K \leq 1)\) to wiggler radiation \((K >> 1)\)

Undulator radiation \((K \leq 1)\)
- Narrow spectral lines
- High spectral brightness
- Partial coherence

\[
\lambda = \frac{\lambda_u}{2 \gamma^2} \left( 1 + \frac{K^2}{2} + \frac{\gamma^2}{2} \right)
\]

\[
K = \frac{e B_0 \lambda_u}{2 \pi m c}
\]

Wiggler radiation \((K >> 1)\)
- Higher photon energies
- Spectral continuum
- Higher photon flux \((2N)\)

\[
\hbar \omega_c = \frac{3}{2} \frac{\hbar \gamma e B_0}{m}
\]

\[
n_c = \frac{3K}{4} \left( 1 + \frac{K^2}{2} \right)
\]
For very large $K >> 1$, and large $\Delta \theta$, a continuum emerges.
Wiggler radiation

At very high $K >> 1$, the radiated energy appears in very high harmonics, and at rather large horizontal angles $\theta = \pm K/\gamma$ (eq. 5.21). Because the emission angles are large, one tends to use larger collection angles, which tends to spectrally merge nearby harmonics. The result is a continuum at very high photon energies, similar to that of bending magnet radiation, but increased by $2N$ (the number of magnet pole pieces).

$$E_c = \hbar \omega_c = \frac{3e B \gamma^2}{2m}$$
$$n_c = \frac{3}{4} \left( 1 + \frac{K^2}{2} \right) \quad (5.7a \& 82)$$

$$\frac{d^2 F}{d\theta d\omega / d\omega} \bigg|_0 = 2.65 \times 10^{13} N E^2_c(GeV)J(A)H_2(E/E_c)$$
$$\frac{\text{photons/s}}{\text{mrad}^2(0.1\%\text{BW})} \quad (5.86)$$

$$\frac{d^2 F}{d\theta d\omega / d\omega} = 4.92 \times 10^{13} N E^2_c(GeV)I(A)G_1(E/E_c)$$
$$\frac{\text{photons/s}}{\text{mrad} \cdot (0.1\%\text{BW})} \quad (5.87)$$
Time structure of synchrotron radiation

The axial electric field within the RF cavity, used to replenish lost (radiated) energy, forms a potential well “bucket” system that forces electrons into axial electron “bunches”. This leads to a time structure in the emitted radiation.

\[
\begin{align*}
E &= 1.90 \text{ GeV} \\
C &= 197 \text{ m} \\
I &= 400 \text{ mA}
\end{align*}
\]

328 buckets available, nominally operated with some fraction unfilled. \( \Gamma_{\text{FWHM}} \approx 35 \text{ ps (nominal)} \)

Gaussian pulse

\[
\begin{align*}
\Gamma_{\text{FWHM}} &= 2.35 \sigma_t \\
\sigma_t (\text{rms})
\end{align*}
\]

500 MHz RF
Beamlines are used to transport photons to the sample, and take a desired spectral slice.

Observe at sample:
- Absorption spectra
- Photoelectron spectra
- Diffraction
  - Focusing lens (pair of curved mirrors, zone plate lens, etc.)
A typical beamline: monochromator plus focusing optics to deliver radiation to the sample

Courtesy of James Underwood (EUV Technology Inc.)
High spectral resolution (meV) beamline
Beamline 7.0 at Berkeley’s Advanced Light Source
MAESTRO: A new varied-line-space grating monochromator beamline for angle-resolved-photo-electron-spectroscopy with high spectral and spatial resolution at the Advanced Light Source

Jason Wells, Derek Yegian, Ken Chow, Eli Rotenberg, Aaron Bostwick, Geoff Gaines and Tony Warwick

The latest soft x-ray undulator spectroscopy beam line planned for the ALS serves MAESTRO a new high resolution Angle Resolved Photo Emission facility with zone-plate focused nano-ARPES. The beam line design offers spectral resolution 1:30000 from 60eV to 400eV with an extended energy range from 20eV to 1000eV. Challenges include optical figure quality, thermal engineering, source size and stability and vibrations in the monochromator. The optical design is radical in that a VLS grating will provide all of the focusing in the dispersion direction, and the mirrors are plane, except for a sphere to collect and focus horizontally.

Courtesy of Eli Rotenberg and Tony Warwick (ALS)
Varied line space gratings

Varied-Line-Space Plane Gratings provide focusing and aberration correction along with the dispersion that they generate in the monochromator. They can be used to erect the monochromator focal plane, making the position of the focus at the exit slit (almost) stationary as the grating rotates to select the photon energy. Beyond that, they are now being used to replace the focusing from shaped optics, making beam lines cheaper and easier to align.

The PEEM3 beam line at 11.0.2 uses a Triple-Ruled Varied-Line-Space grating:

1) to erect the focal plane on a stationary set of exit slits
2) to keep the zero-order light in focus, for easy tuning, and for monitoring of the photon energy.

AFM measured groove shapes

Courtesy of Tony Warwick (ALS)
MAESTRO: A new varied-line-space grating monochromator beam line at the ALS

Maestro EPU

9.25m

M201

7.25m (to grating)

M202

G201a
G201b
G202a
G202b

Monochromator

2.00m

Switch-yard

2.50m

0.50m

0.80m

1.5m

M201

M202

M211

M213

M214

M212

M213 KB focusing mirrors

Exit slit

Exit slit

~2.75m

Zone plate

NanoARPES

MicroARPES

Courtesy of Tony Warwick (ALS)
MAESTRO at the ALS: gratings and efficiencies

![Graph showing diffraction efficiency and coherent flux at nominal R=30,000](image-url)

- 300 lines/mm C=4 60nm .2/.8
- 600 lines/mm C=2.2 20nm .35/.65
- 600 lines/mm C=4 25nm .25/.75
- 1500 lines/mm C=2.2 7nm .4/.6

Courtesy of Tony Warwick (ALS)
Water-cooled optics are essential: correcting slope errors due to a thermal bump

Body plate showing pockets for cooling channels

Courtesy of Tony Warwick (ALS)
Ray tracing beamlines is an important tool

Significant degradation of the spectral resolution occurs due to localized heating of M202. It is almost entirely corrected by adjusting the monochromator focusing parameter from 3.93 to 4.02. The engineering design will allow this mirror to be built with 1mm thick hot-wall and the actual thermal deformation is expected to be less.

600lines_60eV_10000_c=3.93034_18.7_0.038_1.5mmheatbump

600lines_60eV_10000_c=4.02_18.7_0.038_1.5mmheatbumpcorrected

Courtesy of Tony Warwick (ALS)
References


The original SHADOW package is available at www.nanotech.wisc.edu/CNTLABS/shadow.html and with an IDL user interface at www.esrf.fr/computing/scientific/xop


D Fluckiger - Grating Solver Development Company Dec 2006 www.gsolver.com
### What are the relative merits?

<table>
<thead>
<tr>
<th>Bending magnet radiation</th>
<th>Wiggler radiation</th>
<th>Undulator radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Broad spectrum</td>
<td>• Higher photon energies</td>
<td>• Brighter radiation</td>
</tr>
<tr>
<td>• Good photon flux</td>
<td>• More photon flux</td>
<td>• Smaller spot size</td>
</tr>
<tr>
<td>• No heat load</td>
<td>• Expensive magnet structure</td>
<td>• Partial coherence</td>
</tr>
<tr>
<td>• Less expensive</td>
<td>• Expensive cooled optics</td>
<td>• Expensive</td>
</tr>
<tr>
<td>• Easier access</td>
<td>• Less access</td>
<td>• Less access</td>
</tr>
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</table>
A single storage ring serves many scientific user groups
## Typical parameters for synchrotron radiation

<table>
<thead>
<tr>
<th>Facility</th>
<th>ALS</th>
<th>ELETTRA</th>
<th>Australian Synchrotron</th>
<th>APS</th>
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</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>1.90 GeV</td>
<td>2.0 GeV</td>
<td>3.0 GeV</td>
<td>7.00 GeV</td>
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<td>$\gamma$</td>
<td>3720</td>
<td>3910</td>
<td>5871</td>
<td>13,700</td>
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<tr>
<td>Current (mA)</td>
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<td>300</td>
<td>200</td>
<td>100</td>
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<td>Circumference (m)</td>
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<td>216</td>
<td>1100</td>
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<tr>
<td>RF frequency (MHz)</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>352</td>
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<tr>
<td>Pulse duration (FWHM) (ps)</td>
<td>35-70</td>
<td>37</td>
<td>~100</td>
<td>100</td>
</tr>
</tbody>
</table>

### Bending Magnet Radiation:
- Bending magnet field (T) 1.27
- Critical photon energy (keV) 3.05
- Critical photon wavelength 0.407 nm
- Bending magnet sources 24

### Undulator Radiation:
- Number of straight sections 12
- Undulator period (typical) (cm) 5.00
- Number of periods 89
- Photon energy ($K = 1, n = 1$) 457 eV
- Photon wavelength ($K = 1, n = 1$) 2.71 nm
- Tuning range ($n = 1$) 230-620 eV
- Tuning range ($n = 3$) 690-1800 eV
- Central cone half-angle ($K = 1$) 35 µrad
- Power in central cone ($K = 1, n = 1$) (W) 2.3
- Flux in central cone (photons/s) $3.1 \times 10^{16}$
- $\sigma_x, \sigma_y$ (µm) 260, 16
- $\sigma_x', \sigma_y'$ (µrad) 23, 3.9
- Brightness ($K = 1, n = 1$) $[\text{photons/s/mm}^2 \cdot \text{mrad}^2 \cdot (0.1\%\text{BW})]$ $2.3 \times 10^{19}$
- Total power ($K = 1, all n, all \theta$) (W) 83
- Other undulator periods (cm) 3.65, 8.00, 10.0

### Wiggler Radiation:
- Wiggler period (typical) (cm) 16.0
- Number of periods 19
- Magnetic field (maximum) (T) 2.1
- $K$ (maximum) 32
- Critical photon energy (keV) 5.1
- Critical photon wavelength 0.24 nm
- Total power (max. $K$) (kW) 13

---

$q$Using Eq. (5.65). See comments following Eq. (5.64) for the case where $\sigma_{x,y} = \theta_{cen}$. 

![Ch05_T1c_AustralSynch_Nov05.ai](Ch05_T1c_AustralSynch_Nov05.ai)
Typical parameters for synchrotron radiation

<table>
<thead>
<tr>
<th>Facility</th>
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<th>MAX II</th>
<th>BESSY II</th>
<th>APS</th>
<th>ESRF</th>
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</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>1.90 GeV</td>
<td>1.50 GeV</td>
<td>1.70 GeV</td>
<td>7.00 GeV</td>
<td>6.04 GeV</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>3720</td>
<td>2940</td>
<td>3330</td>
<td>13,700</td>
<td>11,800</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>400</td>
<td>250</td>
<td>200</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Circumference (m)</td>
<td>197</td>
<td>90</td>
<td>240</td>
<td>1100</td>
<td>884</td>
</tr>
<tr>
<td>RF frequency (MHz)</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>352</td>
<td>352</td>
</tr>
<tr>
<td>Pulse duration (FWHM) (ps)</td>
<td>35-70</td>
<td>200</td>
<td>20-50</td>
<td>100</td>
<td>70</td>
</tr>
</tbody>
</table>

**Bending Magnet Radiation:**
- Bending magnet field (T) 1.27 1.48 1.30 0.599 0.806
- Critical photon energy (keV) 3.05 2.21 2.50 19.5 19.6
- Critical photon wavelength 0.407 nm 0.560 nm 0.50 nm 0.636 Å 0.634 Å
- Bending magnet sources 24 20 32 35 32

**Undulator Radiation:**
- Number of straight sections 12 10 16 40 32
- Undulator period (typical) (cm) 5.00 5.20 4.90 3.30 4.20
- Number of periods 89 49 84 72 38
- Photon energy ($K = 1, n = 1$) 457 eV 274 eV 373 eV 9.40 keV 5.50 keV
- Photon wavelength ($K = 1, n = 1$) 2.71 nm 4.53 nm 3.32 nm 1.32 Å 0.225 nm
- Tuning range ($n = 1$) 230-620 eV 130-410 eV 140-560 eV 3.5-12 keV 2.6-7.3 keV
- Tuning range ($n = 3$) 690-1800 eV 400-1200 eV 410-1100 eV 10-38 keV 7.7-22 keV
- Central cone half-angle ($K = 1$) 35 μrad 59 μrad 33 μrad 11 μrad 17 μrad
- Power in central cone ($K = 1, n = 1$) (W) 2.3 0.88 0.95 12 14
- Flux in central cone (photons/s) $3.1 \times 10^{16}$ $2.0 \times 10^{16}$ $1.6 \times 10^{16}$ $7.9 \times 10^{15}$ $1.6 \times 10^{16}$
- $\sigma_x$, $\sigma_z$ (μm) 260, 16 300, 45 314, 24 320, 50 395, 9.9
- $\sigma_x'$, $\sigma_z'$ (μrad) 23, 3.9 26, 20 18, 12 23, 7 11, 3.9
- Brightness ($K = 1, n = 1$) $\left[\frac{\text{photons/s/mm}^2\cdot\text{mrad}^2\cdot(0.1\%BW)}{}\right]$ $2.3 \times 10^{15}$ $7.8 \times 10^{15}$ $4.6 \times 10^{15}$ $5.9 \times 10^{15}$ $5.1 \times 10^{15}$
- Total power ($K = 1$, all $n$, all $\theta$) (W) 83 17 32 350 480
- Other undulator periods (cm) 3.65, 8.00, 10.0 5.88, 6.60 4.1, 5.6, 12.5 2.70, 5.50, 12.8 2.3, 3.2, 5.2, 8.5

**Wiggler Radiation:**
- Wiggler period (typical) (cm) 16.0 17.4 12.5 8.5 8.0
- Number of periods 19 13 32 28 20
- Magnetic field (maximum) (T) 2.1 1.80 1.15 1.0 0.81
- $K$ (maximum) 32 29.3 12.8 7.9 6.0
- Critical photon energy (keV) 5.1 2.69 2.11 33 20
- Critical photon wavelength 0.24 nm 0.46 nm 0.59 nm 0.38 Å 0.62 Å
- Total power (max. $K$) (kW) 13 5.9 1.8 7.4 4.8

*aUsing Eq. (5.65). See comments following Eq. (5.64) for the case where $\sigma_x, \gamma = \theta_{cen}$.
SOFT X-RAYS AND EXTREME ULTRAVIOLET RADIATION

Principles and Applications

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