Synchrotron Radiation for Materials Science Applications

David Attwood

University of California, Berkeley
and
Center for X-Ray Optics
Lawrence Berkeley National Laboratory

(http://www.coe.berkeley.edu/AST/srms)
Synchrotron Radiation for Materials Science Applications
(www.coe.berkeley.edu/AST/srms)

• Instructor: Prof. David T. Attwood Email: attwood@berkeley.edu
• Co-listed at UC Berkeley as EE290F and AST290S
• Spring semester, January 16 to May 8, 2007, Tu & Th 2:10–3:30 PM

2007 Class Schedule

• Starting 1/16/2007, this class will be broadcast live over the Internet (Berkeley Webcast) and electronically archived for later viewing

• New paperback textbook:

Soft X-Rays and Extreme Ultraviolet Radiation: Principles and Applications Cambridge University Press or amazon.com or ASUC bookstore

• Table of contents
• Errata

If not yet available through Cambridge University Press (Feb. 1, 2007), a smaller paperback version can be obtained through the UC Berkeley ASUC bookstore website, http://ucberkeley.bkstr.com Click on: (Find your textbooks) and follow prompts to book required for EE290F.

• Lecture material used in class:
  1. Intro. to Synchrotron Radiation
• Homework problems:
  Chapter 1
  Etc.
<table>
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<th>Lecture Number</th>
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<td>X-Ray Interaction with Matter: Absorption, Scattering, Refraction</td>
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<td>Radiation by an Accelerated Charge: Scattering by Free and Bound Electrons</td>
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<td>Refraction and Reflection, Total Internal Reflection, Brewster's Angle, Kramers-Kronig</td>
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<td>Multilayer Interference Coatings, Scattering, Diffraction, Reflectivity and Applications</td>
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<td>Introduction to Synchrotron Radiation, Bending Magnet Radiation</td>
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<td>Spatial and Temporal Coherence; Coherent Undulator Radiation</td>
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<td>Applications of Coherent Undulator Radiation</td>
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<td>Visit the Advanced Light Source, Berkeley (ALS)</td>
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<td>Advanced Spectroscopy for Atomic and Molecular Physics; given by Prof. Anders Nilsson, Stanford University</td>
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<td>28</td>
<td>Student Projects (oral reports on related material)</td>
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The Short Wavelength Region of the Electromagnetic Spectrum

- See smaller features
- Write smaller patterns
- Elemental and chemical sensitivity
Characteristic Absorption Edges for Almost All Elements in this Spectral Region

![Diagram of atomic structure and energy levels](image)

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Energy Levels, Quantum Numbers, and Allowed Transitions for the Copper Atom

Absorption edges for copper (Z = 29):

- $E_{N_1, \text{abs}} = 7.7 \text{ eV}$
- $E_{N_1, \text{abs}} = 7.7 \text{ eV}$
- $E_{M_3, \text{abs}} = 75 \text{ eV}$
- $E_{M_1, \text{abs}} = 123 \text{ eV}$
- $E_{L_3, \text{abs}} = 933 \text{ eV}$
- $E_{L_2, \text{abs}} = 952 \text{ eV}$
- $E_{L_1, \text{abs}} = 1,097 \text{ eV}$

Cu $K\alpha_1 = 8,048 \text{ eV (1.541\text{Å})}$
Cu $K\alpha_2 = 8,028 \text{ eV (1.544\text{Å})}$
Cu $K\beta_1 = 8,905 \text{ eV}$
Cu $L\alpha_1 = 930 \text{ eV}$
Cu $L\alpha_2 = 930 \text{ eV}$
Cu $L\beta_1 = 950 \text{ eV}$

Instructor: Professor David Attwood
Course: Intro to Synchrotron Radiation, EE290F, 16 Jan 2007
## Electron Binding Energies, in Electron Volts (eV), for the elements in their Natural Forms

**Electron Binding Energies (eV) for Elements**

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Broadly Tunable Radiation is Needed to Probe the Primary Resonances of the Elements

Professor David Attwood
Univ. California, Berkeley
Intro to Synchrotron Radiation, EE290F, 16 Jan 2007

Typical Applications of Synchrotron Radiation

- Surface science
- Magnetic materials
- Materials chemistry
- Environmental sciences
- Protein crystallography
- Biomicroscopy
- Chemical dynamics
Bright and Powerful X-Rays from Relativistic Electrons

Synchrotron radiation

- $10^{10}$ brighter than the most powerful (compact) laboratory source
- An x-ray “light bulb” in that it radiates all “colors” (wavelengths, photons energies)

Undulator radiation

- Lasers exist for the IR, visible, UV, VUV, and EUV
- Undulator radiation is quasi-monochromatic and highly directional, approximating many of the desired properties of an x-ray laser
Synchrotron Radiation from Relativistic Electrons

Note: Angle-dependent doppler shift

\[
\lambda = \lambda' \left(1 - \frac{v}{c} \cos \theta\right) \\
\lambda = \lambda' \gamma \left(1 - \frac{v}{c} \cos \theta\right) \approx \frac{\lambda'}{2\gamma} \left(1 + \gamma^2 \theta^2\right)
\]

\[
\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}
\]
Synchrotron Radiation in a Narrow Forward Cone

Frame moving with electron

Laboratory frame of reference

\[
\tan \theta = \frac{\sin \theta'}{\gamma (\beta + \cos \theta')} \quad (5.1)
\]

\[
\theta \approx \frac{1}{2\gamma} \quad (5.2)
\]
Relativistic Electrons Radiate in a Narrow Forward Cone

Dipole radiation

Frame of reference moving with electrons

Laboratory frame of reference

\[ k' = 2\pi/\lambda' \]

\[ k_z = 2\gamma k'_z (\text{Relativistic Doppler shift}) \]

\[ \theta \approx \frac{k_x}{k_z} \approx \frac{k'_x}{2\gamma k'_z} = \frac{\tan \theta'}{2\gamma} \approx \frac{1}{2\gamma} \]
Some Useful Formulas for Synchrotron Radiation

\[ \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - \beta^2}} ; \quad \beta = \frac{v}{c} ; \quad (1 - \beta) \approx \frac{1}{2\gamma^2} \]

\[ E_e = \gamma mc^2, \quad p = \gamma mv \]

\[ \gamma = \frac{E_e}{mc^2} = 1957 \, E_e(\text{GeV}) \]

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

1 watt \( \Rightarrow 5.034 \times 10^{15} \lambda[\text{nm}] \frac{\text{photons}}{s} \)

Bending Magnet: \( E_c = \frac{3e \hbar B \gamma^2}{2m} \), \( E_c(\text{keV}) = 0.6650 E_e^2(\text{GeV}) B(\text{T}) \)

Undulator: \( \lambda = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right) ; \quad E(\text{keV}) = \frac{0.9496 E_e^2(\text{GeV})}{\lambda_u(\text{cm}) \left(1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right)} \)

where \( K \equiv \frac{e B_0 \lambda_u}{2\pi mc} = 0.9337 B_0(\text{T}) \lambda_u(\text{cm}) \)
Three Forms of Synchrotron Radiation

Bending magnet radiation

Wiggler radiation

Undulator radiation

\[ e^{-} \quad \lambda \quad \frac{1}{\gamma} \]

\[ e^{-} \quad e^{-} \quad \lambda \quad \frac{1}{\gamma} \quad \gg \quad \frac{1}{\gamma} \]

\[ e^{-} \quad \lambda \quad \frac{1}{\gamma \sqrt{N}} \]

\[ F \quad h\omega \]

\[ F \quad h\omega \]

\[ F \quad h\omega \]
Third Generation Facilities, Like Electtra, Have Many Straight Sections and a Small Electron Beam

Modern Synchrotron Radiation Facility

- Many straight sections containing periodic magnetic structures
- Tightly controlled 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
### Third Generation Synchrotron Facilities

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<tr>
<th>Facility</th>
<th>Energy (GeV)</th>
<th>Country</th>
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<tr>
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<td>6</td>
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<tr>
<td>ALS</td>
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<td>USA</td>
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<td>APS</td>
<td>7</td>
<td>USA</td>
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<tr>
<td>BESSY II</td>
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<td>Germany</td>
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<td>2.0</td>
<td>Italy</td>
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<td>SPring-8</td>
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<td>Japan</td>
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<td>Diamond</td>
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### Facilities Under Construction

<table>
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<tbody>
<tr>
<td>Australian</td>
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<td>Australia</td>
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</table>

Others are in the design stage or planning an upgrade to third generation.

Courtesy of Herman Winick, SSRL, Stanford

www-ssrl.slac.stanford.edu/SR_SOURCES.HTML
**Synchrotron Radiation**

**Bending Magnet:**

$$\hbar \omega_c = \frac{3e \hbar B y^2}{2m} \quad (5.7)$$

**Wiggler:**

$$\hbar \omega_c = \frac{3e \hbar B y^2}{2m} \quad (5.80)$$

$$n_c = \frac{3K}{4} \left(1 + \frac{K^2}{2}\right) \quad (5.82)$$

$$P_T = \frac{\pi e K^2 y^2 I N}{3 \varepsilon_0 \lambda_u} \quad (5.85)$$

**Undulator:**

$$\lambda = \frac{\lambda_u}{2y^2} \left(1 + \frac{K^2}{2} + y^2 \theta^2\right) \quad (5.28)$$

$$K = \frac{e B_0 \lambda_u}{2\pi mc} \quad (5.18)$$

$$\theta_{cen} = \frac{1}{\gamma^* \sqrt{N}} \quad (5.15)$$

$$\left| \frac{\Delta \lambda}{\lambda} \right|_{cen} = \frac{1}{N} \quad (5.14)$$

$$\bar{P}_{cen} = \frac{\pi e \gamma^2 I}{\varepsilon_0 \lambda_u} \frac{K^2}{\left(1 + \frac{K^2}{2}\right)^2} f(K) \quad (5.41)$$
Bending Magnet Radiation Covers a Broad Region of the Spectrum, Including the Primary Absorption Edges of Most Elements

\[ E_c = \hbar \omega_c = \frac{3e \hbar B \gamma^2}{2m} \]  

(5.7a)

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

(5.7b)

\[ \frac{d^2 F_B}{d\theta d\omega/\omega} = 2.46 \times 10^{13} E_c(\text{GeV}) I(A) G_1(E/E_c) \text{photons/s mrad} \cdot (0.1\%BW) \]  

(5.8)

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

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

\[ E_e = 1.9 \text{ GeV} \]
\[ I = 400 \text{ mA} \]
\[ B = 1.27 \text{ T} \]
\[ \hbar \omega_c = 3.05 \text{ keV} \]
Undulator Radiation from a Small Electron Beam Radiating into a Narrow Forward Cone is Very Bright

Magnetic undulator (N periods)

Relativistic electron beam, \( E_e = \gamma mc^2 \)

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

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

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

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

Spectral Brightness = \( \frac{\text{photon flux}}{(\Delta A) (\Delta \Omega) (\Delta \lambda/\lambda)} \)
An Undulator Up Close

ALS U5 undulator, beamline 7.0, $N = 89$, $\lambda_u = 50$ mm
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\(^-\)**

\[ e^- \text{ radiates at the Lorentz contracted wavelength:} \]

\[ \lambda' = \frac{\lambda_u}{\gamma} \]

\[ \text{Bandwidth:} \]

\[ \frac{\lambda'}{\Delta\lambda'} \approx N \]

**Frame of Observer**

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

Doppler shortened wavelength on axis:

\[ \lambda = \lambda' \gamma (1 - \beta \cos \theta) \]

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

Accounting for transverse motion due to the periodic magnetic field:

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

\[ \text{where } K = eB_0 \lambda_u / 2\pi mc \]

**Following Monochromator**

\[ \theta_{\text{cen}} \approx 40 \text{ rad} \]

For \[ \frac{\Delta \lambda}{\lambda} \approx \frac{1}{N} \]

\[ \theta_{\text{cen}} \approx \frac{1}{\gamma \sqrt{N}} \]
The Equation of Motion in an Undulator

Magnetic fields in the periodic undulator cause the electrons to oscillate and thus radiate. These magnetic fields also slow the electrons axial (z) velocity somewhat, reducing both the Lorentz contraction and the Doppler shift, so that the observed radiation wavelength is not quite so short. The force equation for an electron is

$$\frac{dp}{dt} = -e(E + v \times B) \quad (5.16)$$

where \( p = \gamma mv \) is the momentum. The radiated fields are relatively weak so that

$$\frac{dp}{dt} \approx -e(v \times B)$$

Taking to first order \( v \approx v_z \), motion in the x-direction is

$$m\gamma \frac{dv_x}{dt} = +e v_z B_y$$

$$m\gamma \frac{dv_x}{dt} = e \frac{dz}{dt} \cdot B_0 \cos \left( \frac{2\pi z}{\lambda_u} \right) \quad (0 \leq z \leq N\lambda_u)$$

$$m\gamma \, dv_x = e \, dz \, B_0 \cos \left( \frac{2\pi z}{\lambda_u} \right)$$
Calculating Power in the Central Radiation Cone: Using the well known “dipole radiation” formula by transforming to the frame of reference moving with the electrons

\[ \mathbf{d}P = -e \left( \mathbf{E} + \mathbf{v} \times \mathbf{B} \right) \]

\[ m\gamma \frac{d\mathbf{v}_x}{dt} = e \frac{dz}{dt} B_0 \cos \frac{2\pi z}{\lambda_u} \]

\[ v_x(t); a_x(t) = \cdots \]

\[ v_z(t); a_z(t) = \cdots \]

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

\[ \frac{\lambda}{\Delta \lambda} = N \]

\[ \sin^2 \Phi = \frac{\lambda'}{\Delta \lambda'} = N \]

\[ x', z', t' \text{ motion} \]

\[ a'(t') \text{ acceleration} \]

Dipole radiation:

\[ \frac{dP'}{d\Omega'} = \frac{e^2 \gamma f^2 \sin^2 \Theta'}{16\pi^2 \varepsilon_0 c^3} \]

\[ \frac{dP'}{d\Omega'} = \frac{e^2 c^2 f^2}{4\varepsilon_0 \lambda_u^2 \left(1 + K^2/2\right)^2} \left(1 - \sin^2 \theta' \cos^2 \phi'\right) \cos^2 \omega_u t' \]
Power in the Central Cone

\[ \lambda_x = \frac{\lambda_u}{2\gamma^2} (1 + \frac{K^2}{2} + \gamma^2\theta^2) \]

\[ \bar{P}_{\text{cen}} = \frac{\pi e\gamma^2 I}{\epsilon_0\lambda_u} \frac{K^2}{(1 + \frac{K^2}{2})^2} f(K) \]

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

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

\[ K = \frac{eB_0\lambda_u}{2\pi m_0c} \]

\[ \gamma^* = \gamma\sqrt{1 + \frac{K^2}{2}} \]
Power in the Central Radiation Cone
For Three Soft X-Ray Undulators

**ALS**
- $\gamma = 3720$
- $\lambda_u = 50$ mm
- $N = 89$
- $I = 400$ mA
- $\theta_{cen} = 35$ µr

\[
\theta_{cen} = \frac{1}{\gamma N} \\
\left(\frac{\Delta \lambda}{\lambda}\right)_1 = \frac{1}{N} \\
\left(\frac{\Delta \lambda}{\lambda}\right)_3 = \frac{1}{3N}
\]

**BESSY II**
- $\gamma = 3330$
- $\lambda_u = 49$ mm
- $N = 84$
- $I = 200$ mA
- $\theta_{cen} = 35$ µr

**MAX II**
- $\gamma = 2940$
- $\lambda_u = 52$ mm
- $N = 49$
- $I = 250$ mA
- $\theta_{cen} = 59$ µr
Power in the Central Radiation Cone
For Three Hard X-Ray Undulators

\[
\bar{P}_\text{cen} (W)
\]

**ESRF**
\[
\begin{align*}
\gamma &= 11,800 \\
\lambda_u &= 42 \text{ mm} \\
N &= 38 \\
I &= 200 \text{ mA} \\
\theta_{\text{cen}} &= 17 \mu\text{r}
\end{align*}
\]
\[
\frac{\Delta\lambda}{\lambda} = 120 \\
n = 3
\]

**APS**
\[
\begin{align*}
\gamma &= 13,700 \\
\lambda_u &= 33 \text{ mm} \\
N &= 72 \\
I &= 100 \text{ mA} \\
\theta_{\text{cen}} &= 11 \mu\text{r}
\end{align*}
\]

**SPring-8**
\[
\begin{align*}
\gamma &= 15,700 \\
\lambda_u &= 32 \text{ mm} \\
N &= 140 \\
I &= 100 \text{ mA} \\
\theta_{\text{cen}} &= 6.6 \mu\text{r}
\end{align*}
\]

\[
\bar{P}_\text{cen} (W)
\]

\[
\theta_{\text{cen}} = \frac{1}{\gamma^{*}\sqrt{N}}
\]
\[
\left[\frac{\Delta\lambda}{\lambda}\right]_1 = \frac{1}{N}
\]
\[
\left[\frac{\Delta\lambda}{\lambda}\right]_3 = \frac{1}{3N}
\]
Brightness and Spectral Brightness

Brightness is defined as radiated power per unit area and per unit solid angle at the source:

$$B = \frac{\Delta P}{\Delta A \cdot \Delta \Omega}$$  \hspace{1cm} (5.57)

Brightness is a conserved quantity in perfect optical systems, and thus is useful in designing beamlines and synchrotron radiation experiments which involve focusing to small areas.

Perfect optical system:
$$\Delta A_s \cdot \Delta \Omega_s = \Delta A_i \cdot \Delta \Omega_i ; \eta = 100\%$$

Spectral brightness is that portion of the brightness lying within a relative spectral bandwidth $\Delta \omega/\omega$:

$$B_{\Delta \omega/\omega} = \frac{\Delta P}{\Delta A \cdot \Delta \Omega \cdot \Delta \omega/\omega}$$  \hspace{1cm} (5.58)
Spectral Brightness is Useful for Experiments that Involve Spatially Resolved Studies

- Brightness is conserved (in lossless optical systems)

\[ d_{\text{source}} \cdot \theta_{\text{source}} = d_{\text{focus}} \cdot \theta_{\text{optic}} \]

Smaller after focus
Large in a focusing optic

- Starting with many photons in a small source area and solid angle, permits high photon flux in an even smaller area

![Graph showing spectral brightness vs. photon energy for different sources.](image)

- 1-2 GeV Undulators
- 6-8 GeV Undulators
- Wigglers
- Bending magnets

![Diagram illustrating the relationship between source and focus angles.](image)
Coherence at Short Wavelengths

\[ l_{coh} = \frac{\lambda^2}{2\Delta\lambda} \quad \text{[temporal (longitudinal) coherence]} \]  

\[ d \cdot \theta = \frac{\lambda}{2\pi} \quad \text{[spatial (transverse) coherence]} \]  

\[ \text{or } d \cdot 2\theta_{\text{FWHM}} = 0.44 \lambda \]  

\[ \bar{P}_{coh,N} = \frac{(\lambda/2\pi)^2}{(d_x \theta_x)(d_y \theta_y)} \bar{P}_{cen} \]  

\[ \bar{P}_{coh,\lambda/\Delta\lambda} = \frac{\epsilon \hbar \eta(\Delta\lambda/\lambda)N^2}{8\pi\epsilon_0 d_x d_y} \cdot \left[ 1 - \frac{\hbar \omega}{\hbar \omega_0} \right] f(K) \]
Spatial and Spectral Filtering to Produce Coherent Radiation

Courtesy of A. Schawlow, Stanford
Spatially Coherent Undulator Radiation

\[ \lambda = 13.4 \text{ nm} \]

\[ \lambda = 2.5 \text{ nm} \]

1 \( \mu \text{m} \) pinhole
25 mm wide CCD at 410 mm

\[ d \cdot \theta = \frac{\lambda}{2\pi} \]

Courtesy of Patrick Naulleau, LBNL / Kris Rosfjord, UCB and LBNL
Coherent Power at the ALS

U5

1.9 GeV, 400 mA
\( \lambda_u = 50 \text{ mm}, N = 89 \)
\( 0.5 \leq K \leq 4.0 \)
\( \sigma_x = 260 \mu \text{m}, \sigma_x' = 23 \mu \text{r} \)
\( \sigma_y = 16 \mu \text{m}, \sigma_y' = 3.9 \mu \text{r} \)
\( \eta_{\text{euv}} = 10\%, \eta_{\text{sxr}} = 2\% \)
Coherent Power at BESSY II

1.7 GeV, 200 mA
\( \lambda_u = 49 \text{ mm}, N = 84 \)
\( 0 \leq K \leq 2.5 \)
\( \sigma_x = 314 \text{ } \mu \text{m}, \sigma_x' = 18 \text{ } \mu \text{r} \)
\( \sigma_y = 24 \text{ } \mu \text{m}, \sigma_y' = 2 \text{ } \mu \text{r} \)
\( \eta_{euv} = 10\% ; \eta_{sxr} = 2\% \)
Spatially Coherent Soft X-Rays With Pinhole Spatial Filtering: Airy Patterns at 600 eV

\[ \lambda = 2.48 \text{ nm (600 eV)} \]
\[ d = 2.5 \text{ \(\mu\text{m}\)} \]
\[ t = 200 \text{ msec} \]
\[ \lambda_u = 80 \text{ mm, } N = 55, n = 3 \]

Courtesy of Kristine Rosfjord, UC Berkeley and LBNL
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

$K = 1$

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

$K = 2$

$K = \frac{eB_0 \lambda_u}{2\pi mc}$

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

$\hbar \omega_c = \frac{3}{2} \frac{\hbar^2 eB_0}{m}$

$n_c = \frac{3K}{4} \left( 1 + \frac{K^2}{2} \right)$

$\lambda_u = 5 \text{ cm}, N = 89$

$\lambda_u = 6.0 \text{ cm}
N = 72
K = 3.7
n_c = 22$

(Courtesy of K.-J. Kim)

(Courtesy of R.P. Walker and B. Diviacco)
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).

\[
E_c = \hbar \omega_c = \frac{3e \hbar B \gamma^2}{2m}; \quad n_c = \frac{3K}{4} \left( 1 + \frac{K^2}{2} \right)
\]

(5.7a & 82)
Stanford Permanent Magnet Wiggler

LBNL/EXXON/SSRL (1982), SSRL Beamline VI
55 pole (N = 27.5), $\lambda_w = 7$ cm
### Typical Parameters for Synchrotron Radiation

#### Facility

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<th>BESSY II</th>
<th>ESRF</th>
<th>SP-8</th>
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<tr>
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<td>3330</td>
<td>11,800</td>
<td>15,700</td>
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<td>200</td>
<td>200</td>
<td>100</td>
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<tr>
<td><strong>Circumference (m)</strong></td>
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<td>240</td>
<td>884</td>
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<tr>
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<td>500</td>
<td>500</td>
<td>352</td>
<td>509</td>
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<tr>
<td><strong>Pulse duration (FWHM) (ps)</strong></td>
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<td>20-50</td>
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#### Bending Magnet Radiation:

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<td>0.679</td>
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<tr>
<td>Critical photon energy (keV)</td>
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<td>2.50</td>
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<td>28.9</td>
</tr>
<tr>
<td>Critical photon wavelength</td>
<td>0.407 nm</td>
<td>0.50 nm</td>
<td>0.634 Å</td>
<td>0.429 Å</td>
</tr>
<tr>
<td>Bending magnet sources</td>
<td>24</td>
<td>32</td>
<td>32</td>
<td>23</td>
</tr>
</tbody>
</table>

#### Undulator Radiation:

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Number of straight sections</td>
<td>12</td>
<td>16</td>
<td>32</td>
<td>48</td>
</tr>
<tr>
<td>Undulator period (typical) (cm)</td>
<td>5.00</td>
<td>4.90</td>
<td>4.20</td>
<td>3.20</td>
</tr>
<tr>
<td>Number of periods</td>
<td>89</td>
<td>84</td>
<td>38</td>
<td>140</td>
</tr>
<tr>
<td>Photon energy ($K = 1, n = 1$)</td>
<td>457 eV</td>
<td>373 eV</td>
<td>5.50 keV</td>
<td>12.7 keV</td>
</tr>
<tr>
<td>Photon wavelength ($K = 1, n = 1$)</td>
<td>2.71 nm</td>
<td>3.32 nm</td>
<td>0.225 nm</td>
<td>0.979 Å</td>
</tr>
<tr>
<td>Tuning range ($n = 1$)</td>
<td>230-620 eV</td>
<td>140-500 eV</td>
<td>2.6-7.3 keV</td>
<td>4.7-19 keV</td>
</tr>
<tr>
<td>Tuning range ($n = 3$)</td>
<td>690-1800 eV</td>
<td>410-1100 eV</td>
<td>7.7-22 keV</td>
<td>16-51 keV</td>
</tr>
<tr>
<td>Central cone half-angle ($K = 1$)</td>
<td>35 µrad</td>
<td>33 µrad</td>
<td>17 µrad</td>
<td>6.6 µrad</td>
</tr>
<tr>
<td>Power in central cone ($K = 1, n = 1$) (W)</td>
<td>2.3</td>
<td>0.95</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>Flux in central cone (photons/s)</td>
<td>$3.1 \times 10^{16}$</td>
<td>$1.6 \times 10^{16}$</td>
<td>$1.6 \times 10^{16}$</td>
<td>$7.9 \times 10^{15}$</td>
</tr>
<tr>
<td>$\sigma_x, \sigma_y$ (µm)</td>
<td>260, 16</td>
<td>314, 24</td>
<td>395, 9.9</td>
<td>380, 6.8</td>
</tr>
<tr>
<td>$\sigma'_x, \sigma'_y$ (µrad)</td>
<td>23, 3.9</td>
<td>18, 12</td>
<td>11, 3.9</td>
<td>16, 1.8</td>
</tr>
<tr>
<td>Brightness ($K = 1, n = 1$)</td>
<td>$2.3 \times 10^{19}$</td>
<td>$4.6 \times 10^{18}$</td>
<td>$5.1 \times 10^{18}$</td>
<td>$1.8 \times 10^{20}$</td>
</tr>
<tr>
<td>Total power ($K = 1, all n, all \theta$) (W)</td>
<td>83</td>
<td>32</td>
<td>480</td>
<td>2,000</td>
</tr>
<tr>
<td>Other undulator periods (cm)</td>
<td>3.65, 8.00, 10.0</td>
<td>4.1, 5.6, 12.5</td>
<td>2.3, 3.2, 5.2, 8.5</td>
<td>2.4, 10.0, 3.7, 12.0</td>
</tr>
</tbody>
</table>

#### Wiggler Radiation:

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wiggler period (typical) (cm)</td>
<td>16.0</td>
<td>12.5</td>
<td>8.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Number of periods</td>
<td>19</td>
<td>32</td>
<td>20</td>
<td>37</td>
</tr>
<tr>
<td>Magnetic field (maximum) (T)</td>
<td>2.1</td>
<td>1.15</td>
<td>0.81</td>
<td>1.0</td>
</tr>
<tr>
<td>$K$ (maximum)</td>
<td>32</td>
<td>12.8</td>
<td>6.0</td>
<td>11</td>
</tr>
<tr>
<td>Critical photon energy (keV)</td>
<td>5.1</td>
<td>2.11</td>
<td>20</td>
<td>43</td>
</tr>
<tr>
<td>Critical photon wavelength</td>
<td>0.24 nm</td>
<td>0.59 nm</td>
<td>0.62 Å</td>
<td>0.29 Å</td>
</tr>
<tr>
<td>Total power (max. $K$) (kW)</td>
<td>13</td>
<td>1.8</td>
<td>4.8</td>
<td>18</td>
</tr>
</tbody>
</table>

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*Using Eq. (5.65). See comments following Eq. (5.64) for the case where $\sigma'_{x,y} = \theta_{cen}$.}
Beamlines are Used to Transport Photons to the Sample, and Take a Desired Spectral Slice

- Observe at sample:
  - Absorption spectra
  - Photoelectron spectra
  - Diffraction
  - ...

- Sample

- Focusing lens (pair of curved mirrors, zone plate lens, etc.)

- Monochromator

- Exit slit

- Grating or crystal

- Curved focusing mirror (glancing incidence reflection)

- Photon flux

- Photon flux

- \(\hbar\omega\)

- \(\epsilon\)
A Typical Beamline: Monochromator Plus Focusing Optics to Deliver Radiation to the Sample

Bending Magnet

M1 (spherical)

M2 (spherical)

Plane VLS gratings

G1

G2

G3

Sample

Scan

Fixed exit slit

Detector

e⁻

Courtesy of James Underwood (EUV Technology Inc.)
High Spectral Resolution (meV) Beamline

Sample

Vertical focusing mirror

Horizontal deflection/focusing mirror

Translating exit slit

Spherical grating

Translating entrance slit

Vertical focusing mirror

Horizontal focusing mirror

Elliptically Polarizing Undulator

Professor David Attwood
Univ. California, Berkeley
Intro to Synchrotron Radiation, EE290F, 16 Jan 2007
Variable Polarization Undulator Radiation

Crossed planar undulators

Variable phase delay (electron path length modulator)

Aperture and monochromator

0°, π/2, π, −π/2

(Courtesy of Kwang-Je Kim)

(Following S. Sasaki)
A Single Storage Ring Serves Many Scientific User Groups


