Accelerator physics, hardware, and operations at NSLS and NSLS-II.

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Primary authors : Dr. PODOBEDOV, Boris (BNL)

Co-authors :

Presenter : Dr. PODOBEDOV, Boris (BNL)
Principles of Synchrotron Radiation and Storage Ring Light Sources

Boris Podobedov
boris@bnl.gov
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Outline

• Synchrotron Radiation (SR) Primer
  • SR definition & properties (brightness, flux, opening angle, polarization, BW, power)
  • Generation of SR
  • Bend magnets, Undulators and Wigglers

• Principles of Synchrotrons
  • How to build a synchrotron light source
  • Performance metrics
  • Properties of e-beam that affect performance

• Few generations of synchrotron light sources (LS)
• Summary
• Not Covered (but important)
  • Injection System, Vacuum, RF, power supplies, controls, etc.
  • Beamlines, Detectors, SR Uses and Techniques

Thanks to
 J.B. Murphy
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Charged Particle Radiation Processes

- Synchrotron
- Bremsstrahlung
- Diffraction / Transition
- Cerenkov

Periodicity in the “structure” yields a repetitive pulse train in the time domain, resulting in a spectral narrowing in the frequency domain!
Synchrotron Radiation

SR is EM radiation emitted when charged particles are radially accelerated (move on a curved path).

Electrons accelerating by running up and down in a radio antenna emit radio waves.

Both cases are manifestation of the same physical phenomenon:

*Charged particles radiate when accelerated.*
Why Do Particles Emit SR?

• A charge moving in free space is “surrounded” by a cloud of virtual photons that indissolubly travel with it.

• When accelerated, the particle receives a “kick” separating it from the photons that become real and independently observable.

• Lighter particles are easier to accelerate so they radiate photons more efficiently

=> light sources use electrons

In a light source electrons follow curved trajectories in bend magnets and insertion devices. The transverse acceleration creates e⁻ - γ separation generating synchrotron radiation.
SR Angular Distribution

At low electron velocity (non-relativistic case) the radiation is emitted in a non-directional pattern.

\[ \gamma \equiv \frac{E}{mc^2} >> 1 \]

When the electron velocity approaches the velocity of light, the emission pattern is folded sharply forward.

\[ \text{Cone aperture } \sim \frac{1}{\gamma} \]

Radiation becomes more focused at higher energies.

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SR Bandwidth

Due to the small opening angle the observer sees the electron first when it arrives on its trajectory at an angle of $-1/\gamma$ with respect to the z-axis and last when this angle is $+1/\gamma$. The length of the electromagnetic pulse observed is just the difference in travel time between the electron and the photon going from the point at $-1/\gamma$ to the point at $+1/\gamma$,

$$\Delta T = T_e - T_\gamma = \frac{2\rho}{\beta \gamma c} - \frac{2\rho \sin(1/\gamma)}{c} \approx \frac{2\rho}{\beta \gamma c} \left(1 - \beta + \frac{\beta}{6\gamma^2}\right) \approx \frac{4\rho}{3c \gamma^3}.$$

The characteristic frequency is then,

$$\omega_c \approx \frac{2\pi}{\Delta T} = \frac{3\pi c \gamma^3}{2\rho}.$$
To “see” atoms, molecules & nanostructures you need light with wavelengths comparable to the size of those objects (UV, X-rays)
SR Geometry

\[ \rho \] – orbit radius
\[ \phi \] – rotation angle
\[ \psi \] - out of plane observation angle
\[ \Omega \] - solid angle, \( d\Omega = d\phi \cdot d\psi \)

A. Hoffmann, CERN-98-04
Most power in hor. polarization, distribution peaks at \( \psi=0, \psi_\sigma_{\text{rms}}(\omega_c) \approx 1/\gamma \)

Less power in ver. polarization; double peaks around \( \psi=0, \psi_\pi_{\text{rms}}(\omega_c) \approx 1/\gamma \)
Synchrotron Radiation Power

**Spectral Power**

\[
\frac{dP}{d\omega} = \int \frac{d^2P}{d\omega d\Omega} d\Omega = \frac{P_0}{\omega_c} \left[ S_\sigma \left( \frac{\omega}{\omega_c} \right) + S_\pi \left( \frac{\omega}{\omega_c} \right) \right]
\]

**Total Power & Loss/turn**

\[P_0 \sim \gamma^4/\rho^2 \sim \gamma^2 B^2 \sim E^2 B^2\]

Rises fast with beam energy!

**Electron energy loss per turn**

\[U_0(\text{KeV}) = 88.5 \frac{E^4(\text{GeV})}{\rho(\text{m})}\]

**Total Power**

\[P_{\text{total}}(\text{kW}) = 88.5 \frac{E^4(\text{GeV}) I(\text{A})}{\rho(\text{m})}\]

for beam current I

\[\int_0^1 S \left( \frac{\omega}{\omega_c} \right) d(\omega/\omega_c) = 0.50 \quad \omega_c = \frac{3c\gamma^3}{2\rho}\]

Half the power is below \(\omega_c\), the other half is above 7/8 is horiz. polarization; 1/8 is vertical polarization.

SR power sharply falls down at \(\omega >> \omega_c\)

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Bend (Dipole) Magnets

Typical Synchrotron Dipole Magnet

Field in gap $B = \mu_0 NI / g$ (typ. 1.4 T)
Water-cooled copper coils
Low-carbon steel C-frame yoke

NSLS X-ray Ring Dipole

$\rho = 6.875 \text{ m}, L = 2.7 \text{ m}, \text{gap}=55 \text{ mm}$

At $E=2.8 \text{ GeV}$:

$\epsilon_c = 7.1 \text{ keV}, B = 1.36 \text{ T}, I = 1.5 \text{ kA}$
Motivation for Having Insertion Devices

- **Wigglers (K >> 1)**
  - Wavelength shifter to get harder photons,
  - \( \varepsilon_c = 0.665 B [T] E^2 [GeV] \)
  - Increased flux \( \approx 2N_w \) (Arc source flux)
  - Typical parameters: \( \lambda_w = 10 \text{ cm} \) & \( B = 5 \text{ T} \)

- **Undulators (K ~ 1)**
  - Concentrate photons in frequency & position leading to higher brightness
  - Lower power consumption
  - Variable polarization (for some designs)
  - Typical parameters: \( \lambda_u = 6 \text{ cm} \) & \( B = 0.2 \text{ T} \)

- High Intensity
- Tunable, Narrow Spectrum
- Natural Vertical Collimation
- High Degree of Polarization
- High Brightness

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Wigglers & Undulators:
Arrays of Dipoles of Alternating Polarity

Photon flux from N bends = \sim N \times \text{flux from single bend;}

Peak field \( B = B_{\text{rem}} \exp[-\pi(g/\lambda_u)] \)

Deflection parameter \( K \): \( K = 0.0934 \lambda_u [\text{mm}] B [\text{T}] \)

Resonant wavelengths:
\( \lambda_m = \frac{\lambda_u}{2m\gamma^2} \left( 1 + \frac{K^2}{2} \right) \), \( m = 1, 3, 5 \ldots \)

In a **Wiggler** \( K \gg 1 \);
- Radiation from poles adds **incoherently**, producing a broad, dipole-like spectrum

**Wiggler Spectrum**

- In a **Undulator** \( K < 3 \);
- Radiation from poles adds **coherently** at resonant wavelengths, thus a sharply peaked spectrum.
- Spectral peaks are **tunable** by varying \( K \) (i.e., \( B \)) by varying the gap

**Undulator Spectrum**
More on Wigglers & Undulators

**Halbach Pure-PM Undulator**
- Horizontally magnetized blocks boost on-orbit field

**Halbach PM-hybrid Undulator**
- Iron poles concentrate flux from larger magnet blocks

**In-Vacuum Undulator**
(For hard x-rays)

- Put magnet arrays *inside* vacuum chamber
- Minimum gap can be reduced to stay-clear required by electron and photon beams (a few mm)
- Reduce period → more periods → more photons!
- Shorter period → higher photon energies
- Must be UHV-compatible → Ni- or Ti-N-coated
- PM must withstand baking to >100°C without demagnetizing → Use Hybrid car motor grades of PM

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Mini-Gap In-Vacuum Undulators

**NSLS X13 MGU**

- Installed 2002
- Lower array @ pulsed wire bench
- 3.3 mm gap, $\lambda_p = 12.5$ mm, $K \sim 1.1$

**NSLS X25 MGU**

- NdFeB Magnets: new "hybrid car motor" grade
- Vanadium Permendur Poles
- Design:
  - NSLS (magnetic)
  - ADC, Inc (mech.)
- Installed Dec. 2005
- 5.6 mm gap, $\lambda_p = 18$ mm, $K \sim 1.5$

• MGUs are one of greatest successes at NSLS
• Provide hard X-ray photons on the cheap
• Paved the way for Intermediate Energy Light Sources
• Will be heavily used at NSLS-II
Elliptically Polarizing Wiggler

- Vertical field: PM hybrid
- Horizontal field: Electromagnet
- Hor. array offset by \(\frac{1}{4}\) period
- Switching polarity of current switches helicity (RH & LH) at up to 100 Hz (typ. 22 Hz)

Varying horizontal field “moves” the beamline in-and-out of orbit plane => time-varying elliptical polarization
APPLE-II Variable Polarization Undulator

Planned for NSLS-II

4 Movable PM Arrays

Apple II on the ESRF
Period: 88 mm
Gap: 16 mm,
Power density @ 30m

Linear incline Field & Polar.

Vertical Field
Horizontal Traj. & Polar.

Horizontal Field
Vertical Traj. & Polar.

Helical Field
Helical Traj. & Circul Polar.

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Superconducting Wigglers

- $B_0 = 4.2$ Tesla
- Period = 17.5 cm
- $K = 68$
- $E_{\text{crit}} = 22$ keV

NSLS X17 SCW
Provides the hardest (up to 100 keV) usable x-rays at NSLS

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1) Take evacuated beam pipe

ADD:

2) Bends (dipoles) to form e-beam trajectory (& as SR sources)

3) Quadrupole magnets to focus e-beam transversely

4) Sextupoles for achromatic focusing

5) RF to make up for energy loss; also provides longitudinal focusing (bunching)

6) Injection system

7) IDs into avail. straight sections

8) Beamlines to deliver photons to the Users
Essential Elements of a Light Source

VUV Ring Construction ~1980

Sextupoles
Bend magnet
Quadrupoles
Beamline ports

53 MHz RF cavity

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**Beam Brightness**

- **Phase Space**
  - $X'$, angle
  - $X$, position

- **Emittance**, $\varepsilon$, is the area occupied in phase space.

- **Brightness** is the density in phase space:
  
  \[
  \text{Number of “fish”/unit time} \quad \propto \frac{I}{\varepsilon_x \varepsilon_y}
  \]

- **Average Brightness** ~ photons/pulse x pulse rate
- **Peak Brightness** ~ photons/pulse/pulse time

\[
B_{\text{peak}} \approx \frac{B_{\text{ave}}}{f \times \tau_{\text{pulse}}}
\]

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Beam Brightness Continued

- **brightness** is the key parameter of any particle source, incl. SR sources

- **brightness** is defined as 6-D phase space \((x, p_x, y, p_y, t, E)\) density of particles

- The same definition applies to the photon case; taking into account that the Pauli exclusion principle does not apply to bosons => no limitation to achievable photon brightness exists from Quantum Mech.

\[
\text{Brightness} = \frac{\text{# of photons in given } \Delta \lambda / \lambda}{\text{sec, mrad } \theta, \text{ mrad } \varphi, \text{ mm}^2}
\]

\[
\text{Flux} = \frac{\text{# of photons in given } \Delta \lambda / \lambda}{\text{sec}}
\]

\[
\text{Flux} = \frac{d\dot{N}}{d\lambda} = \int \text{Brightness} \, dS \, d\Omega
\]

• For a given flux, **smaller emittance** (transverse phase space area) **sources** have **larger brightness**
How Bright Are We?

X1 Undulator

X-Ray Ring Bend Magnet

NSLS

Brightness (photons/sec/mm²/mrad²/0.1% BW)

10^20
10^19
10^18
10^17
10^16
10^15
10^14
10^13
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10

X Ray Tube

60-W Light Bulb

Candle

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NSLS-II Brightness Curves

EPU49 APPLE-II Undulator
\( \lambda_u = 49 \text{ mm}, L = 4 \text{ m (low-} \beta \text{)} \)
\( K_{\text{max lin}} = 4.34, K_{\text{max circ}} = 3.69 \)

U(100) PM Und.
\( \lambda_u \approx 100 \text{ mm} \)
\( L \approx 6 \text{ m (high-} \beta \text{)} \)
\( K_{\text{max}} \approx 9.2 \)

In-Vacuum Undulators:
IVU20: \( \lambda_u = 20 \text{ mm}, K_{\text{max}} = 1.83, L = 3 \text{ m (low-} \beta \text{)} \)
IVU21: \( \lambda_u = 21 \text{ mm}, K_{\text{max}} = 1.79, L = 1.5 \text{ m (low-} \beta \text{)} \)
IVU22: \( \lambda_u = 22 \text{ mm}, K_{\text{max}} = 1.52, L = 6 \text{ m (high-} \beta \text{)} \)

SCW(60)
Supercond. Wiggler
\( B \approx 3.5 \text{ T}, \lambda_w \approx 60 \text{ mm} \)
\( K \approx 19.6, \epsilon_c \approx 21 \text{ keV} \)
\( I \approx 1 \text{ m (low-} \beta \text{)} \)

DW90 Damping Wiggler
\( B = 1.85 \text{ T}, \lambda_w = 90 \text{ mm} \)
\( K = 15.8, \epsilon_c = 11 \text{ keV} \)
\( L = 7 \text{ m (high-} \beta \text{)} \)

Three-Pole Wiggler
\( B = 1.14 \text{ T}, \epsilon_c = 6.8 \text{ keV} \)

Bend Magnet
\( B = 0.4 \text{ T}, \epsilon_c = 2.4 \text{ keV} \)

Spectral Brightness [Pb/s/1%bw/mm²/mrad²]

Photon Energy

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Equilibrium Beam Sizes in Storage Ring: Transverse Emittance

- For bright source photon beam emittances need to be small
- Photon beam emittance is due to convolution of e-beam emittance and “light emittance” $\lambda/4\pi$
- In storage ring LS typically $0.1\,\text{nm} < \varepsilon_x < 100\,\text{nm}$, $\varepsilon_y = \varepsilon_x / 100$
- Diffraction limited (x-rays) in vert. plane, but not in the horizontal
- $\Rightarrow$ electron beam emittance is important until its $< \lambda/4\pi$
- Emittance is invariant, but beam sizes vary around the ring, i.e.
  \[
  \sigma_y = (\beta_y(z) \varepsilon_y)^{1/2},
  \]
  here $\beta_y(z)$ is periodic $\beta$-function

\[
\varepsilon_{x,y} = 68 \pm 3, 0.36 \pm 0.05 \,\text{nm}
\]
\[
\varepsilon_y / \varepsilon_x \sim 0.53 \pm 0.08 \%
\]
Transverse Emittance Cont’d

- Emittance in electron storage rings is due to balance of SR damping (makes it smaller) and quantum excitation (increases it), i.e. $\varepsilon_x = S_x \tau_x$

$$S_x \approx E^5 \int B^3 \frac{\eta_x^2 + \left( \beta_x \eta_x - \frac{\beta'_x}{2} \eta_x \right)^2}{\beta_x} \, ds, \quad \frac{1}{\tau_x} \approx J^3 \int B^2 \, ds$$

- When e emits a photon, it goes on a different energy orbit => increase in beam energy spread and beam size.

- Emittance generated by SR where there is dispersion $\eta_x$.

- Vertical emittance is usually due to coupling from the horizontal.

- Modern LS minimize the dispersion => many short magnet cells, $N \gg 1$, $\varepsilon_x \sim N^{-3}$
Longitudinal Beam Sizes in Storage Ring and Bunch Train Structure

- RF cavity provides longitudinal E-field that makes up beam energy loss/turn due to SR:
  \[ V_{RF}(\tau) \sim \cos(2\pi f_{RF}\tau) \]

- Beam arrival and RF phase are synchronized => there are maximum
  \[ h = \frac{f_{RF}}{f_{rev}} \]
bunches stored in the ring

- Each electron randomly loses discrete photons to SR, each exciting energy-time oscillations

- Balance of quantum excitation and SR radiation damping determines bunch length and energy spread

**Time structure @ NSLS**

- \(~19\) ns
- \(~10\) cm (X)
- 10-50 cm (U)

\[ f_{RF} = 53 \text{ MHz} = \frac{1}{(19\ \text{ns})} \]
\[ h = 30 \ (\text{X-ray}) \]
\[ h = 9 \ (\text{VUV}) \]

Longitudinal Bunch shape is constant around the ring

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Light Sources: Definition of Generation

- **1st Gen**: parasitic synchrotron radiation source from the dipoles of HEP ring (SPEAR, CESR, etc)
- **2nd Gen**: dedicated ring for synchrotron radiation, dipole rad & some undulators; medium brightness
- **3rd Gen**: dedicated ring optimized for undulator radiation; high brightness
- **4th Gen**: dedicated free electron lasers, IR to X-Ray

NSLS X-ray and VUV rings are (one of the first) 2nd generation LS
NSLS-II ring will be 3rd generation LS
Recently commissioned LCLS at SLAC is 4th generation X-ray LS
# Synchrotron Light Source Quality Factors

<table>
<thead>
<tr>
<th>ID Capacity</th>
<th>Ave Flux</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{ID} \gg 1$</td>
<td>$\Phi \sim I E$</td>
<td>$\frac{\Delta_{x,x',...}}{\sigma_{x,x',...}} &lt; \Delta_{\text{limit}}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ave Brightness</th>
<th>Pulse length &amp; rep. rate</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \propto \frac{I N_u}{\left(\varepsilon_x + \frac{\lambda}{2}\right)\left(\varepsilon_y + \frac{\lambda}{2}\right)}$</td>
<td>$\sigma_t = 1-100$ ps (0.1 ps @ low rep. rate)</td>
<td>$$ &lt; $_{\text{limit}}$</td>
</tr>
</tbody>
</table>

Try to break new ground on the first 5 without violating the last!

$$\frac{\lambda}{2} \equiv \frac{\lambda}{4\pi} \quad \text{Diffraction limit}$$

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3rd & 4th Generation Sources Survey

Figure 5.1: Proposed and legacy x-ray light sources and R&D facilities around the world.

Key:
- Red - funded (operational or under construction)
- Blue - funded R&D program
- Black - concepts and proposals
Photon beam brightness is determined (mostly) by electron beam emittance that defines the source size and divergence.
Summary

• **SR generation and properties**: spectrum, BW, power, polarization, angular distribution, ...
• **Brightness, emittance and diffraction limit**
• **Benefits of having IDs** (wigglers and undulators)
• **LS Performance Metrics**: brightness, flux, \( N_{ID} \), ...
• **Building blocks of a storage ring**: dipoles, quads, sextupoles, RF system, ...
• **Emittances and beam sizes in a storage ring**: balance of SR damping and SR quantum excitation
• **SR lightsources worldwide**
For primers and further information, link to www.lightsources.org

Good reviews of synchrotron radiation and electron storage ring physics
• M. Sands: http://www.slac.stanford.edu/pubs/slacreports/slac-r-121.html

Review of present state-of-the art and future directions in LS world
• Scientific Needs for Future X-Ray Sources in the U.S.