Lecture 1: 3rd generation light sources

- Objectives
- Principle of synchrotron radiation emission
- Main characteristics and features
- What is a beamline?
- Examples of application
- Main facilities existing or in project
OBJECTIVES

Synchrotron radiation facilities are designed to provide light simultaneously to many beamlines.

The light ranges from Infra-Red up to hard X-Ray (~50 keV).

The characteristics of these beams make them very attractive to investigate matter be it solid, liquid or gazes.

A 3rd generation light source is a photon factory which enables scientists of many different fields to perform thousands of experiments per year.
Synchrotron generations

Enhancement of radiation sources last century

1\textsuperscript{st} generation: Parasitic use on Nuclear physics machines

2\textsuperscript{nd} generation: Dedicated machines. Radiation from Bending Magnets and Wigglers (Flux).

Multipurpose beamlines
3rd generation Synchrotron light sources

- **Machines optimised for High Brilliance**
  
- Smaller source sizes, higher current
  
- Highly performing **insertion devices** matched to the beamline needs
  
- Beamlines much more accurate (specific scientific use).
Synchrotron radiation is generated when a charged particle travelling at the speed of light is submitted to the action of a magnetic field. Its trajectory is bent (Lorentz Force) and the particle suffers a deceleration: It radiates some light and loses a small fraction of its energy.

The light is emitted in a fan tangent to the trajectory of the particle.
Due to the bending of their trajectory, the electrons are slowed down by their self field and lose energy. They emit photons in a direction tangent to their trajectory. => This is synchrotron radiation.
The Radiated Power with transverse acceleration in case of relativistic particle (v~c):

\[ P_{rad} = \frac{e^2 c}{6\pi\varepsilon_0 \left( m_0 c^2 \right)^4} \frac{E^4}{\rho^2} \]

\( c \) = light velocity ; \( \rho \) = radius of curvature ; \( E \) = particle energy ; \( m_0 c^2 \) = particle rest mass ;

Introducing \( \gamma \), with \( E=\gamma m_0 c^2 \) =>

\[ P_{rad} = \frac{e^2 c}{6\pi\varepsilon_0} \frac{\gamma^4}{\rho^2} \]

=> The power radiated is much easier to produce with electrons than with protons.
The energy loss per turn in a circular accelerator is:

\[ U_0 = \int P_{\text{rad}} dt = P_{\text{rad}} t_{BM} = P_{\text{rad}} \frac{2\pi \rho}{c} = \frac{e^2}{3\varepsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho} \]

\( c = \) light velocity ; \( \rho = \) radius of curvature ; \( E = \) particle energy ; \( m_0 c^2 = \) particle rest mass ; \( t_{BM} = \) traveling time in the bending magnets

or in practical units (for electrons)

\[ U_0[\text{keV}] = 88.5 \frac{E^4[\text{GeV}^4]}{\rho[\text{m}]} = 26.6E^3[\text{GeV}^3]B[T] \]

<table>
<thead>
<tr>
<th></th>
<th>L(m)</th>
<th>(GeV)</th>
<th>( \rho )(m)</th>
<th>B(T)</th>
<th>( U_0 )(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SOLEIL</strong></td>
<td>354.1</td>
<td>2.75</td>
<td>5.36</td>
<td>1.71</td>
<td>0.944</td>
</tr>
<tr>
<td><strong>ESRF</strong></td>
<td>844</td>
<td>6.0</td>
<td>23.40</td>
<td>0.855</td>
<td>4.9</td>
</tr>
<tr>
<td><strong>LEP</strong></td>
<td>(27 \times 10^3)</td>
<td>70.0</td>
<td>3000</td>
<td>0.078</td>
<td>708</td>
</tr>
</tbody>
</table>
The axially-symmetric radiation distribution in the moving frame $K'$ (a.) transforms into a sharply forward peaked distribution in the laboratory frame (b.), with a half opening-angle $\theta = 1/\gamma$.

### Emission angle (in the laboratory frame)

$$\tan \theta = \frac{p_y}{p_z} = \frac{p_0'}{\gamma \beta p_0} \approx \frac{1}{\gamma}$$

This is one of the most useful features of synchrotron radiation.

For $E = 2.75 \text{ GeV}$: $\gamma = 5382$ then $\tan \theta \sim \theta = 0.186 \text{ mrad} = 0.01^\circ$
Radiation from a bending magnet (magnetic field $B$):

Broad spectrum, with critical energy:

$$\epsilon_c [KeV] = 2.218 \frac{E^3 [GeV^3]}{\rho} = 0.665 E^2 [GeV^2] B [T]$$

Power radiated

$$P_{rad} \propto E^2 B^2$$
### SOLEIL Bending Magnet

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B ) (T)</td>
<td>1.71</td>
</tr>
<tr>
<td>( \rho ) (m)</td>
<td>5.36</td>
</tr>
<tr>
<td>( \varepsilon_e ) (keV)</td>
<td>8.6</td>
</tr>
<tr>
<td>( \lambda_c ) (Å)</td>
<td>1.44</td>
</tr>
<tr>
<td>( P ) (kW)</td>
<td>472</td>
</tr>
<tr>
<td>( dP/d\theta ) (W/mrad)</td>
<td>75</td>
</tr>
</tbody>
</table>

![Graph showing the energy of photons and brightness of a bending magnet](image)

**Brillance d'un aimant de courbure**

**Energie des photons**

**Phot/s/0.1%bw/mm²/mr²**
The Undulator technology: Periodic magnetic field +B/-B summing up many oscillations enables to enhance the radiation brightness by several orders of magnitude.
Insertion Device: **sinusoidal field**

$$B_Z = B_0 \cos\left(\frac{2\pi s}{\lambda_0}\right)$$

**Electron trajectory**

$$X = -\frac{K\lambda_0}{2\pi\gamma} \cos\left(\frac{2\pi s}{\lambda_0}\right) \quad X_{max} = \frac{K\lambda_0}{2\pi\gamma}$$

$$X' = \frac{K}{\gamma} \sin\left(\frac{2\pi s}{\lambda_0}\right) \quad X'_{max} = \frac{K}{\gamma} = \alpha$$

**Insertion strength**

$$K = 0.0934 \ B_0[T] \lambda_0[mm]$$

It consists of a periodic arrangement of short bending magnets of alternating polarity.

$$K = \alpha \ \gamma$$

with $\alpha = \text{max deflection angle}$
In the wiggler regime $K \gg 1$ the observer sees a train of distinct light pulses, which adds incoherently $\Rightarrow$ Broad spectrum

Bending Magnet: Flux $\sim N e^-$

Wiggler: Flux $\sim N e^- \times N_{\text{period}}$ (10 – 100)
Undulator Synchrotron radiation

Undulator Regime $\alpha \sim 1/\gamma$

In the undulator regime $K \sim 2$ the angle and the transverse displacement of the electron is so small that the observer can see the electron during the full length of the ID therefore during a much longer time interval. This results in a much thinner spectrum around privileged photon energies called **undulator harmonics**.

Undulator: $\text{Flux} \sim N e^{-} \times [N_{\text{period}}]^{2}$

Gain ($10^{4} - 10^{5}$)
Undulator Synchrotron radiation

Interferences along the N periods =>
Discrete lines spectrum with:
• Line width scaling as $(\Delta\lambda/\lambda)_{\text{harm } n} \sim 1/nN$
• Peak value scaling as $N^2$
Undulator Synchrotron radiation

Wave length emitted on harmonic n
\[ \lambda_n = \lambda_u \left(1 + \frac{K^2}{2} + \frac{\gamma^2 \theta^2}{2}\right) \left(\frac{1}{2n \gamma^2}\right) \]

\( \lambda_u \) is the undulator magnetic period
\( \theta \) is the angle of observation

⇒ Photon energy depends on the observation angle
⇒ Great sensitivity to spread in \( \theta \) or \( \gamma \)
Undulator Synchrotron radiation

The energy (or wave length) of the emitted photons can be finely tuned by varying the magnetic field (gap or current) in the undulator. The table below shows the energy (Eo) of the emitted photons at different gaps:

<table>
<thead>
<tr>
<th>gap (mm)</th>
<th>Eo (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>6.56</td>
</tr>
<tr>
<td>19</td>
<td>6.13</td>
</tr>
<tr>
<td>18</td>
<td>5.72</td>
</tr>
<tr>
<td>17</td>
<td>5.29</td>
</tr>
<tr>
<td>16</td>
<td>4.83</td>
</tr>
<tr>
<td>15</td>
<td>4.40</td>
</tr>
<tr>
<td>14</td>
<td>3.97</td>
</tr>
<tr>
<td>13</td>
<td>3.53</td>
</tr>
<tr>
<td>12</td>
<td>3.15</td>
</tr>
<tr>
<td>11</td>
<td>2.77</td>
</tr>
</tbody>
</table>

ESRF
Undulator Synchrotron radiation

The energy (or wavelength) of the emitted photons can be finely tuned by varying the magnetic field (gap or current) in the undulator.

![Graph showing photon energy vs. 10 keV with curves for different magnetic fields.]

Onduleur sous vide
Nuance: NdFeB, Br:1.25 T
- U20

SOLEIL
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- Main facilities existing and in project: ESRF, SOLEIL, DIAMOND, SLS, ELETTRA, BESSSY II, ALBA, PETRA3, NSLSII, MAXIV
Synchrotron radiation properties:
Broad Spectrum which covers from IR to hard X-rays.

White source (Bending magnets) or Narrow spectrum tunable (Undulators)

**High Flux**: high intensity photon beam

\[
\text{Flux} = \frac{\text{Photons}}{(s \times 0.1\% \text{ BW})}
\]

**High Brilliance** (Spectral Brightness): highly collimated photon beam generated by a small divergence and small size source (partial coherence)

\[
\text{Brilliance} = \frac{\text{Photons}}{(s \times \text{mm}^2 \times \text{mrad}^2 \times 0.1\% \text{ BW})}
\]

Polarisation: both linear and circular (tunable with IDs)

Pulsed Time Structure: pulsed durations down to tens of picoseconds
Synchrotron radiation

From FAR INFRA RED

Up to HARD X RAYS

Radiation Source

Radiation type

Observable object

Energy (eV)

Wavelength (m)

Frequency (Hz)

10^9

10^8

10^7

10^6

10^5

10^4

10^3

10^2

10^1

10^0

10^{-1}

10^{-2}

10^{-3}

10^{-4}

10^{-5}

10^{-6}

10^{-7}

10^{-8}

10^{-9}

10^{-10}

10^{-11}

10^{-12}

10^{-13}

10^{-14}

10^{-15}

10^{-16}

10^{-17}

10^{-18}

10^{-19}

10^{-20}

10^{-21}

10^{-22}

10^{-23}

10^{-24}

Radiation Source

AM
Antenne radio
FM
Four micro ondes
Téléphone portable
Radar
Ampoule électrique

Bronzage
Rayonnement synchrotron
Stérilisation

Radiographie
Source radioactive
Accélérateurs de particules

Observable object

visible light

Visible light

Infra rouges

Ultra violets

Rayons X mous

Rayons X durs

Rayons gamma

Source radioactive

Accélérateurs de particules

Radiographie

Rayonnement synchrotron

Stérilisation

Bronzage

Ampoule électrique

Téléphone portable

Four micro ondes

FM
Antenne radio

AM

Energy (eV)

Wavelength (m)

Frequency (Hz)
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Synchrotron radiation facility

All beamlines get beam simultaneously
Movable absorbers in the front-end enable each beamline to stop the X-ray beam inside the SR tunnel.
A Beamline = several hutches

- Neighbouring beamline
- Storage Ring
- Optical hutch
- Experiment hutch
- Control hutch
A Beamline = several hutches

**Optical hutch**: where the photon energy is selected, the X-ray beam focused = Monochromator, mirrors, slits
Lead shielding required to stop bremsstrahlung from SR tunnel

Monochromator: High resolution
\( \delta \lambda / \lambda \sim 10^{-4} \)
**Experimental hutch**: where the sample is exposed to SR

=> Goniometer, diffractometer, detectors,...

Lead shielding required if $E_{\text{xray}} > \sim 5$ keV
A Beamline = several hutches

**Control hutch**: where the scientists control the experiment.
Computers, storage disks (up to Gbit/sec!),.. Coffee machine.
These techniques enable to analyse
• the chemical composition (with ultra high sensitivity)
• the atomic order, or the type of chemical bonding,
• ...

SYNCHROTRON SPECIFICITIES:
- Enhanced performances in fluorescence, in diffraction and in Xray micro-tomography
- specific techniques in Xray absorption and Xray microscopy (energy scanning, phase contrast)
Détection de substances polluantes, optimisation de pôts catalytiques, nouveaux matériaux…

Connaissance de la structure des matériaux du manteau terrestre…

Procédés catalytiques, exploration de la matière et connaissance de ses propriétés électroniques, magnétiques (ex: stockage magnétique haute densité)

Recherche de nouveaux médicaments, imagerie des tissus osseux, vaisseaux sanguins, étude de l’ADN…

Élaboration de nouveaux matériaux, (ex : semi et supra conducteurs, disque durs et mémoire magnétique, batteries, étude de la prise rapide de ciment)

Dans tous les domaines, un large accueil est prévu pour les industriels

Archéologie, patrimoine, aéronautique, pharmacologie, microélectronique…
Protein crystallography

1) Frozen crystal
2) Diffraction
3) Laue patterns recording
4) Data processing
5) Protein Structure
Millions of atoms!
From the analysis of micro samples =>
Composition of the pen: silver + copper, Traces of mercury: impairing phenomenon
Environmental science

Microfluorescence mapping of polluted soil:
spatial correlation between concentrations of lead and iron in the soil of a shooting stand
(D. Vantelon et R. Kretzschmar)

High sensitivity to identify week traces of material
Varnishes often present a complex structure of layers often thinner than 10-20 µm (mixture of organic (oils, natural resins,…) and inorganic (pigments, siccatives,…) materials.

re-create an ideal ancient varnish, typically the one of Antonio Stradivari

The IR microscope at SMIS has a complementary fluorescence accessory, which helps identifying the region of interest (a)

Presence of protein has been identified through its characteristic IR spectrum (b)

One of layer is made of protein (c)

This is the first time a protein layer has been identified in an ancient violin multilayers

Dr J.P. Echard (Cité Musique Paris) Dr. Loïc Bertrand (SOLEIL), Dr. A.S Le Hô (SOLEIL), Dr. S. Vaiedelich (Cité Musique) Dr. S. Le Conte (Cité Musique). Alex VON BOHLEN (Germany)
Surface reaction kinetics

Time dependent study of the adsorption modes for the

N,N,N’,N’ Tetra methyl ethylenediamine on Si(001)-2×1

2 possible adsorption configurations on Si

C.Mathieu, J.-J. Gallet,
F. Bournel, G. Dufour, F. Rochet

TEMPO Beamline  March 2008
Surface reaction kinetics

N - 1s Photoemission spectra
Integration time 0.5 s
Binding energy variation: 2 eV

Time Evolution:
Constant Nitrogen amount
Transformation:
Dative → dissociative
During exposure
## Existing 3rd GLS

<table>
<thead>
<tr>
<th>Year</th>
<th>Facility</th>
<th>Location</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>ESRF</td>
<td>France (EU)</td>
<td>6 GeV</td>
</tr>
<tr>
<td></td>
<td>ALS</td>
<td>US</td>
<td>1.5-1.9 GeV</td>
</tr>
<tr>
<td>1993</td>
<td>TLS</td>
<td>Taiwan</td>
<td>1.5 GeV</td>
</tr>
<tr>
<td>1994</td>
<td>ELETTRA</td>
<td>Italy</td>
<td>2.4 GeV</td>
</tr>
<tr>
<td></td>
<td>PLS</td>
<td>Korea</td>
<td>2 GeV</td>
</tr>
<tr>
<td></td>
<td>MAX II</td>
<td>Sweden</td>
<td>1.5 GeV</td>
</tr>
<tr>
<td>1996</td>
<td>APS</td>
<td>US</td>
<td>7 GeV</td>
</tr>
<tr>
<td></td>
<td>LNLS</td>
<td>Brazil</td>
<td>1.35 GeV</td>
</tr>
<tr>
<td>1997</td>
<td>Spring-8</td>
<td>Japan</td>
<td>8 GeV</td>
</tr>
<tr>
<td>1998</td>
<td>BESSY II</td>
<td>Germany</td>
<td>1.9 GeV</td>
</tr>
<tr>
<td>2000</td>
<td>ANKA</td>
<td>Germany</td>
<td>2.5 GeV</td>
</tr>
<tr>
<td></td>
<td>SLS</td>
<td>Switzerland</td>
<td>2.4 GeV</td>
</tr>
<tr>
<td>2004</td>
<td>SPEAR3</td>
<td>US</td>
<td>3 GeV</td>
</tr>
<tr>
<td></td>
<td>CLS</td>
<td>Canada</td>
<td>2.9 GeV</td>
</tr>
<tr>
<td>2006</td>
<td>SOLEIL</td>
<td>France</td>
<td>2.8 GeV</td>
</tr>
<tr>
<td></td>
<td>DIAMOND</td>
<td>UK</td>
<td>3 GeV</td>
</tr>
<tr>
<td></td>
<td>ASP</td>
<td>Australia</td>
<td>3 GeV</td>
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<tr>
<td></td>
<td>MAX III</td>
<td>Sweden</td>
<td>700 MeV</td>
</tr>
<tr>
<td></td>
<td>Indus-II</td>
<td>India</td>
<td>2.5 GeV</td>
</tr>
<tr>
<td>2008</td>
<td>SSRF</td>
<td>China</td>
<td>3.4 GeV</td>
</tr>
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</table>
3rd GLS under construction

under construction or planned

<table>
<thead>
<tr>
<th>Year</th>
<th>Facility</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>ALBA, Spain</td>
<td>3 GeV</td>
</tr>
<tr>
<td></td>
<td>Petra-III, Germany</td>
<td>6 GeV</td>
</tr>
<tr>
<td>&gt; 2009</td>
<td>NSLS-II, US</td>
<td>3 GeV</td>
</tr>
<tr>
<td></td>
<td>SESAME, Jordan</td>
<td>2.5 GeV</td>
</tr>
<tr>
<td></td>
<td>MAX-IV, Sweden</td>
<td>3 GeV</td>
</tr>
<tr>
<td></td>
<td>TPS, Taiwan</td>
<td>3 GeV</td>
</tr>
<tr>
<td></td>
<td>CANDLE, Armenia</td>
<td>3 GeV</td>
</tr>
</tbody>
</table>
The 3rd Generation Light Sources can be sorted in 2 categories:

**The medium size / low energy Storage Rings**

⇒ Circumference = 100 to 300 m,
⇒ Energy = 1 to 3 GeV
⇒ X-Ray energy = 10 eV to 30 keV

**The large size / high energy Storage Rings**

⇒ Circumference = 800 to 1300 m,
⇒ Energy = 6 to 8 GeV
⇒ X-Ray energy = 0.1 to 300 keV

ESRF (Grenoble, France), APS (Chicago, USA), SPRING8 (Hyogo, Japan)
Brilliance

Thanks to the progress with IDs technology storage ring light sources can cover a photon range from few tens of eV to tens 10 keV or more with high brilliance.

Medium energy storage rings with In-vacuum undulators operated at low gaps (e.g. 5-7 mm) can reach 10 keV with a brilliance of $10^{20}$ ph/s/0.1%BW/mm²/mrad².