ESI2013: 3rd EIROforum School on Instrumentation

An Introduction to Synchrotron Radiation

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Part I

Introduction to synchrotron radiation (SR)

Part II

SR Research

Mostly Illustrated by examples from the ESRF
PART I
Introduction to synchrotron radiation

1. Origin and physics
2. Historical evolution
3. Synchrotron radiation facilities
4. Three forms of synchrotron radiation
5. Sources and their operation
What's a synchrotron radiation source?

- An extremely intense source of X-rays (also IR & EUV)
- Typically produced by highly energetic electrons (or positrons) moving in a large circle in the synchrotron (or more usually Storage Ring).

Highly collimated X-rays are emitted tangentially to the storage ring and simultaneously serve multiple beamlines for scientific applications spanning physical, chemical and life sciences.
Synchrotron radiation is electromagnetic energy emitted by charged particles (e.g., electrons and ions) that are moving at speeds close to that of light when their paths are altered, e.g. by a magnetic field.

It is thus termed because particles moving at such speeds in particle accelerators known as synchrotrons produce electromagnetic radiation of this type.

The Crab Nebula – a natural SR source

CHANDRA (2001)
**Basic Principles**

### Classical case

**V << C**

- Isotropic emission
- Orbit
- Centripetal acceleration

### Relativistic case

**V ~ C**

- Emission concentrated within a narrow forward cone
- Orbit
- $\Psi = 1/\gamma$

**Emission Calculations**

\[ \gamma = \frac{E_e}{mc^2} \]

- $E_e = 6$ GeV (ESRF)
- $mc^2 = 511$ keV
- $\Psi = 10^{-4}$ rad = a few $10^{-3}$ deg
Man-made synchrotron radiation

1947
First observation of synchrotron radiation at General Electric (USA).

1930
First particle accelerators

1947
More and more energetic particles, bigger and bigger machines

1980
Construction of the first dedicated machines

Considered first as a nuisance by particle physicists, synchrotron radiation was recognised in the 70s as having exceptional properties to explore matter.
3rd Generation Storage Rings

ESRF
- Storage ring: 844 m circumf.
- 6 GeV electrons
- ~200 mA fill current
- Typical beam lifetime ~ 50 h
- Reinjection twice/day
- 24 hour operation 6 days/week

Fully optimized to produce bright X-ray beams

Timeline
- 1994 ESRF
- 1981 SRS
- 1968 Tantalus
- 1961 Parasitic use
- 1950 Characterization
- 1947 Observation
- 1897-1946 Predictions

Polygon = Arcs + Straights
ESRF was the world’s first 3rd generation hard X-ray source

Other hard X-ray sources: APS (USA) - SPring-8 (Japan) – Petra-III (D)

New national sources in Europe: Swiss Light Source (CH), Soleil (F) in 2006, Diamond (UK) in 2007, Petra-III (D) in 2009, ALBA (E) in 2010, Max IV (Sweden), Poland, Russia......

New plans also in Brasil, China, India,......
Brilliance or Brightness (flux density in phase space) is an invariant quantity in statistical mechanics, so that no optical technique can improve it.

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

Spectral Brilliance = \( \frac{\text{photon flux}}{(\Delta A) (\Delta \Omega) (\Delta \lambda/\lambda)} \)

[Photons/sec] [mm]² [mrad]² [0.1% bandwidth]
The ESRF storage ring

- Focusing magnets
- Bending magnets
- Insertion devices (undulators/ wigglers)
Bending Magnet Radiation

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

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

\[ E_c \text{ (keV)} = 0.665 E_e^2 \text{ (GeV)} B \text{ (T)} \]
Insertion devices

• A Periodic magnetic field causes local oscillations of electron trajectory. The influence of the field on the electron motion is characterized by the deflection parameter $K$

\[ K = \frac{0.934}{\lambda_u \ [cm] \ B_0 \ [T]} \]

• The maximum angular deflection of the orbit is $K/\gamma$

• $K \gg 1$ Wiggler regime
  radiation from different parts of the electron trajectory adds incoherently
  $\rightarrow$ interference effects are less important

• $K < 1$ Undulator regime
  radiation from different periods interferes coherently
  $\rightarrow$ strong interference phenomena
Undulator Radiation – K< 1

**Fundamental + harmonics**

On-axis

\[
\lambda_1 = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2}\right)
\]

\[
E(keV) = \frac{0.949 E_e^2 (GeV)}{\lambda_u (cm)(1 + \frac{K^2}{2})}
\]

\[
\frac{\Delta \lambda}{\lambda} = \frac{1}{N}
\]

To tweak (or to scan) energy:

- \( E = f[K] \)
- \( K = f[B(z)] \)
- \( B(z) = f[gap] \)
Three forms of Synchrotron Radiation

From "Introduction to Synchrotron Radiation", D. Attwood, Univ. California, Berkeley

On-axis

Horizontal linear polarisation

Bending magnet radiation

\[ F_{BM} \approx f[E^2, I] \]

Wiggler radiation

\[ F_{wiggler} \approx 2N \times F_{BM} \]

Undulator radiation

\[ F_{undulator} \approx N^2 \times F_{BM} \]

Control of polarisation
Insertion devices

Brilliance (photons/s/mm²/mrad²/0.1% BW)

1 Bending magnet
2 Wiggler
3 Undulator

Energy (keV)

2 10 50

10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰
## Filling patterns & radiation time structure

### Filling patterns

<table>
<thead>
<tr>
<th>Uniform</th>
<th>7/8+1</th>
<th>24*8+1</th>
<th>16 Bunch</th>
<th>4 Bunch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of bunches</td>
<td>992</td>
<td>870</td>
<td>24x8+1</td>
<td>16</td>
</tr>
<tr>
<td>Maximum current [mA]</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>90</td>
</tr>
<tr>
<td>Rms bunch length [ps]</td>
<td>20</td>
<td>20</td>
<td>25</td>
<td>48</td>
</tr>
</tbody>
</table>

*Typical filling modes at the ESRF*
X-ray beams at 3rd generation SR sources

- **Brightness**
  - $10^{+22}$ ph/sec/mrad$^2$/mm$^2$/0.1% b.w. (10$^{+11}$ higher than conventional sources)

- **Small source and highly collimated beam**
  - ~ 10µm and 10µrad

- **Broad emission spectrum: wavelength tunability**
  - $0.1\text{eV} < E < 100\text{keV}$ or $1.2\mu\text{m} < \lambda < 0.01\text{Å}$

- **Polarized radiation**
  - 100% linear or circular or elliptical

- **Pulsed radiation**
  - 50 ps pulses every ns

- **Power**
  - several kW total power, several 100 W/mm$^2$ power density.

- **High degree of coherence**
PART II
SR Research

1. SR techniques
2. Some examples

"Whatever it is, it's very, very little."
A complete suite of techniques

X-Ray Fluorescence
- Composition
- Quantification
- Trace element mapping

Fluorescence

Diffraction & scattering
- Long/short range structure
- Electron density mapping
- Crystal orientation mapping
- Stress/strain/texture mapping

Absorption & Phase contrast

X-ray imaging
- 2D/3D Morphology
- High resolution
- Density mapping

Infrared FTIR-spectroscopy
- Molecular groups & structure
- High S/N for spectroscopy
- Functional group mapping

Specific Sample environments

X-ray imaging

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A typical synchrotron source layout

http://www.synchrotron-soleil.fr/
A broad range of applications

Chemistry 12%
Electronic & Magnetic Properties 12%
Crystals & Ordered Structures 10%
Disordered Systems 4%
Applied Materials, Engineering 10%
Environment & Culture 7%
Medicine 4%
Macromolecular Crystallography 15%
Methods & Instrumentation 2%
Soft Condensed Matter 10%
Surfaces & Interfaces 4%
Other: Training, feasibility tests, proprietary research 4%

Shifts delivered for Experiments, 2010
List of ESRF beamlines

Over 40 different experiments can be conducted simultaneously.

BM01  Swiss–Norwegian
BM02  D2AM (France)
BM08  GILDA (Italy)
BM14  (EMBL)
BM16  (Spain)
BM20  ROBL (Germany)
BM25  SPLINE (Spain)
BM26  DUBBLE (Netherlands, Belgium)
BM28  XMAS (UK)
BM30  FIP (France)
BM30  FAME (France)
BM32  IF (France)

ID01  Anomalous scattering
ID02  High brilliance
ID03  Surface diffraction
ID06  Instrumentation development
ID08  Dragon / Spectroscopy using polarised soft X-rays
ID09  Biology / High pressure
ID10  Troika / Multipurpose
ID11  Materials science
ID12  Circular polarisation
ID13  Microfocus
ID14  Protein crystallography
ID15  High energy diffraction
ID16  Inelastic scattering
ID17  Medical
ID23  Structural biology (MAD)
ID25  Structural biology (MAD)
ID26  Structural biology (MAD)
ID27  Structural biology (MAD)
ID28  Structural biology (MAD)
ID29  Structural biology (MAD)
ID30  Structural biology (MAD)
ID32  Structural biology (MAD)

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Extreme conditions (T, P, M)

One can better understand the structure of matter at the center of the Earth …

Diamond Anvil Cell (DAC)

… by studying samples put under extreme conditions of pressure and temperature.

- 200GPa (2Mbar)
- T=3600K
Down to the picosecond

Molecular movies obtained by using the pulsed time structure of the SR

Migration of photodissociated CO in myoglobin (iron- and oxygen-binding protein in muscle tissue) using time-resolved single crystal diffraction in pump-probe experiment

Courtesy: M. Wulff, ESRF ID09

Jurassic Park

Cretaceous enigmatic tiny eggs from Thailand

Courtesy P. Tafforeau et al. ESRF-ID19