3. Synchrotron Radiation – Generation, Properties and Applications

„Seeing“ means scattering of photons

Reveal the structure of matter by performing scattering experiments with photons

Use x-rays to reveal the inner structure of materials

\[ E_1, p_1 \rightarrow \text{sample} \rightarrow E_2, p_2 \text{ detector} \]
First x-ray detectors

The easiest scattering experiment is the transmission through a material

First commercial x-ray tube

Imaging with x-rays

1895: Discovery of x-rays by W. C. Röntgen
Detector: photographic plate

Exposure time: 5 min
Analyze the spatial distribution of scattered photons - Diffraction
Analyze the energy spectrum of scattered photons - Spectroscopy

The higher the momentum transfer, the better the spatial resolution.
This applies for any scattering experiment
Detector requirements for x-ray scattering experiments

• Single-photon counting in the range from 6 – 100 keV
• High quantum efficiency, preferably > 50 %
• Low background noise, preferably < 0.01 s\(^{-1}\)
• High count-rate capability, preferably > 10\(^7\) s\(^{-1}\)
• Good time resolution, preferably < 1 ns
• Good energy resolution
• Fast recovery/large dynamic range
• Large active area and high spatial resolution
• Operation at room temperature, radiation hardness, long-time stability

In general, not all of these properties can be met by single detector!
Radiation-source requirements for high-resolution structure determination:

a) Highly directional beams
b) Broad energy spectrum

Conventional x-ray sources are of limited use, because of

a) Isotropic emission and
b) Only characteristic lines

Solution: Synchrotron Radiation

(But this was not clear from the time of discovery (1947), when it was considered to be an undesired by-product of particle acceleration)
Generation of Synchrotron Radiation

Radiated power of an accelerated charged particle for nonrelativistic particles: Larmor formula

\[ P_S = \frac{e^2}{6\pi \epsilon_0 m_0 c^3} \left| \frac{d\vec{p}}{dt} \right|^2 \]

Lorentz transformation and application to circular acceleration:

\[ P_S = \frac{e^2 c}{6\pi \epsilon_0 (m_0 c^2)^4} \frac{1}{R^2} E^4 \]

Dependence on particle mass:

\[ \frac{P_{S,e}}{P_{S,p}} = \left( \frac{m_p}{m_e} \right)^4 \approx 10^{13} \]

Synchrotron radiation is only for electrons/positrons sufficiently intense
Emission pattern

Rest frame \xrightarrow{\text{Lorentz transformation}} \text{Laboratory frame}

\[ \gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} = \frac{E}{m_0c^2} \]

Opening angle

Radiation from a bending magnet

\[ \Delta \Theta = \frac{2}{\gamma} = 0.2 \text{ mrad} \approx 40'' \]

\[ E = 5 \text{ GeV} \]

\[ \implies \gamma = 10^4 \]

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Pulse duration and energy spectrum

\[ \Delta t = \frac{4R}{3c\gamma^3} \]

\[ R = 30 \text{ m} \quad \gamma = 10^4 \]

\[ \implies \Delta t = 10^{-19} \text{ s} \]

\[ \implies E_c = \frac{\hbar}{\Delta t} \approx 40 \text{ keV} \]
From bending magnets to undulators

Electrons travelling through periodic magnet structures:
Insertion devices: Wigglers and Undulators (1)

Wiggler regime: $\alpha > 1/\gamma$

Undulator regime: $\alpha < 1/\gamma$
Insertion devices: Wigglers and Undulators (2)

\[ \alpha = \frac{K}{\gamma} \]

\( K \): deflection parameter

\[ K = 0.934 \lambda_u (\text{cm}) B_0 (\text{T}) \]

\( \lambda_u \): magnetic period

\( B_0 \): magnetic field at orbit

\( K \) determines the shape of the energy spectrum of an insertion device:

- \( K \ll 1, N \) large
- \( K \approx 1, N \) large
- \( K > 1, N \) smaller

Energy of the \( n^{\text{th}} \) harmonic:

\[ E_n (\text{keV}) = n \frac{0.95 E^2 (\text{GeV})}{\lambda_u (\text{cm})(1 + K^2/2)} \]

Angular width of \( n^{\text{th}} \) harmonic:

\[ \sigma = \frac{1}{\gamma} \sqrt{1 + \frac{1}{2}K^2} \frac{1}{2Nn} \]
How to characterize the properties of a synchrotron radiation source?

Total flux ≡ \( \frac{\text{Photons}}{s} \)

Spectral flux ≡ \( \frac{\text{Photons/s}}{0.1\% \text{bandwidth}} \)

Brightness ≡ \( \frac{\text{Photons/s}}{\text{mrad}^2 \cdot 0.1\% \text{bandwidth}} \)

Brilliance ≡ \( \frac{\text{Photons/s}}{\text{mrad}^2 \cdot \text{mm}^2 \cdot 0.1\% \text{bandwidth}} \)

Brilliance is the figure of merit for the design of new synchrotron radiation sources.
**Evolution of Brilliance**

(SRS = Synchrotron Radiation Source)

1st generation: Exploitation of the light from the bending magnets of e+/e- colliders originally built for elementary particle physics

2nd generation: Radiation from bending magnets and introduction of first insertion devices, lower e-beam emittance, optimization of light extraction

3rd generation: dedicated storage rings, very low e-beam emittance, brilliance is figure of merit, mainly undulators, long straight sections
Brilliance = \frac{\text{Spectral Flux}}{\text{Phase space volume}}

\epsilon_x = \text{horizontal emittance}
\epsilon_z = \text{vertical emittance}
Time structure of synchrotron radiation (1)

Example: European Synchrotron Radiation Facility (ESRF)

\[
Circumference = 844 \text{ m}
\]

rf-cavities in the ring provide the electric field to accelerate the electrons to compensate for the radiation losses

\[V_{\text{rf}} = 352 \text{ MHz}\]

This means:

992 buckets of stable phase for the electrons, separated by 2.84 ns

A bucket filled with electrons is called a bunch.
Time structure of synchrotron radiation (2)

Various filling modi can be realized depending on the experimental needs:

- **single-bunch**
  - $I_{\text{max}} = 16 \text{ mA}$
  - lifetime = 8 h
  - 2.81 $\mu$s gaps

- **16-bunch**
  - $I_{\text{max}} = 90 \text{ mA}$
  - lifetime = 10 h
  - 176 ns gaps

- **uniform**
  - $I_{\text{max}} = 200 \text{ mA}$
  - lifetime = 60 h
  - 2.839 ns gaps

- **$2 \cdot \frac{1}{3}$**
  - $I_{\text{max}} = 200 \text{ mA}$
  - lifetime = 55 h
  - 2.839 ns & 0.94 $\mu$s

- **hybrid**
  - $I_{\text{max}} = 193 + 7 \text{ mA}$
  - lifetime = 40 / 7 h
  - 2.839 ns & 0.47 $\mu$s

**Time-resolved measurements**
Storage ring and beamlines

- Klystron
- Focusing magnets
- Undulator
- Wiggler
- Magnet
- Bending
- Injection
- Cavity
- Electrons from booster
- Acceleration
- Beamline
- Photon beam profile @ 10 m distance

Sample
- High-resolution monochromator
- Pre-monochromator

Power density
- @ 10 m
- Vertical
- Horizontal

Photon beam profile @ 10 m distance
- 4 mm
- 4 mm

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RR-Lecture-1
Synchrotron radiation facilities around the world

Parameters of selected facilities

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European Synchrotron Radiation Facility (ESRF), Grenoble, France
PETRA-III Upgrade

http://petra3.desy.de/
Experiments with Synchrotron Radiation
(a selection)
Protein crystallography

X-rays

Protein crystal

Diffraction pattern
Imaging of magnetic domains

Circularly polarized SR, E = 778 eV

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Lensless imaging of magnetic nanostructures by X-ray spectro-holography


1BESSY mbH, Albert-Einstein-Straße 15, 12489 Berlin, Germany
2SSRL, Stanford Linear Accelerator Center, 2575 Sand Hill Road, Menlo Park, California 94025, USA
3Department of Applied Physics, 316 Via Pueblo Mall, Stanford University, Stanford, California 94305-4090, USA
4San Jose Research Center, Hitachi Global Storage Technologies, 650 Harry Road, San Jose, California 95120, USA

Grain mapping of metals and alloys

How does the microstructure of a material change upon mechanical load and deformations?

H. F. Poulsen et al.
Microtomography using Synchrotron Radiation

FRELON = Fast REadout, LOw Noise

Monochromatic and parallel beam
Rotation from 0 to 180 °, ~900 radiographs, step ~0.2 °
SPECIFICITY of SYNCHROTRON RADIATION for MICROTOMOGRAPHY

- parallel and coherent beam
- monochromatic beam
- high flux beam
  - High spatial resolution
  - High temporal resolution
  - Quantitative measurements
  - In-situ, real-time, images
Microstructure of bones: Development during Osteoporosis disease

33 years  
55 years  
63 years

Microstructure of ice crystals in snow

Structure of wet snow
Demands on detectors for current and future experiments with synchrotron radiation:

Improvement of:  
Spatial resolution  
Energy resolution  
Time resolution

Most of present-day experiments are dealing with equilibrium properties of condensed matter. In the future, non-equilibrium properties will be of great interest:

Dynamics of phase transformations, magnetic switching phenomena, chemical reactions, etc.

Reveal the underlying mechanisms by taking snapshots on ultrashort time scales!
Time Scales in Magnetism

- Spin Precession
- Spin-Lattice Relaxation
- Domain Propagation
- Spin-Orbital Exchange

- FEL
- Synchrotron Radiation

Time (s)

- $10^{-15}$
- $10^{-12}$
- $10^{-9}$
- $10^{-6}$
New radiation sources - New detectors
Limits of Storage - Ring Based Sources

Beam properties reflect the equilibrium dynamics of particles in the ring, resulting from averaging over all revolutions

Particles are re-cycled

Development of New Radiation Sources

Radiation is generated by single bunches passing through an undulator

Energy - Recovery Linear Accelerator (ERL)

Sub-Picosecond Pulsed Source (SPPS)

X-ray Free Electron Laser (XFEL)
Generation of ultrashort, coherent light pulses via the process of Self-Amplified Stimulated Emission (SASE)

1. Ultrarelativistic electrons (monoenergetic, small emittance, high charge density) are traveling through a very long undulator.
2. The emitted radiation overtakes the electrons flying ahead of them.
3. The electric field of the radiation interacts with these electrons.
4. Some are accelerated, some are slowed down.
5. Along the flight path, the electrons gradually organize themselves into a multitude of thin disks, separated by a distance equal to the wavelength of the emitted radiation.
Electron bunch modulation in the SASE process

**GENESIS** - simulation for TTF parameters
Courtesy - Sven Reiche (UCLA)
SASE exponential growth and saturation

low gain | exponential gain | non-linear
(high-gain linear regime)

\[ P(z) = P_0 \exp\left(\frac{z}{L_{\text{gain}}}\right) \]

gain \sim 10^5

saturation length \sim 10 L_{\text{gain}}
duration, length
Time structure of the XFEL radiation

Electron bunch trains
(with up to 4000 bunches à 1 nC)

\[ \Delta t = 200 \text{ ns} \]

Photon pulses

FEL process

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Generation of ultrashort coherent x-ray pulses

\[ N_p = \text{Number of magnet poles} \]
\[ N_e = \text{Number of electrons/bunch} \]

**Incoherent superposition**
\[ I \sim N_e N_p \]

**Partially coherent superposition**
\[ I \sim N_e N_p^2 \]

**Fully coherent superposition**
\[ I \sim N_e^2 N_p^2 \]

Self-Amplified Stimulated Emission (SASE)
The European XFEL at the DESY site

http://xfel.desy.de
Potential for biomolecular imaging with femtosecond X-ray pulses

Richard Neutze*, Remco Wouts*, David van der Spoel*, Edgar Weckert†‡ & Janos Hajdu*

* Department of Biochemistry, Biomedical Centre, Box 576, Uppsala University, S-75123 Uppsala, Sweden
† Institut für Kristallographie, Universität Karlsruhe, Kaiserstrasse 12, D-76128, Germany

Explosion of a biomolecule (T4 lysozyme) after exposure to a 2-fs XFEL pulse (E = 12 keV)

Detector challenges for experiments with XFEL radiation

Time resolution $\Delta t$ significantly below 1 ps

Existing technology:
- Fast photodiodes (X-ray and laser sensitive): $\sim 50 - 100$ ps
- X-ray streak cameras: $\sim 500$ fs, very low sensitivity, no 2D

Fast read-out for single exposures of detectors

Synchronization of excitation and detection

Invention of completely new detection techniques