Introduction to Photon Science

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DESY Summer School 2025

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  - History of X-ray Sources
  - Principle of Synchrotrons
- **PART II:**
  - Principle of Free-Electron Lasers
- **PART III:**
  - Examples of Science at Synchrotrons & FELs

Introduction to Photon Science

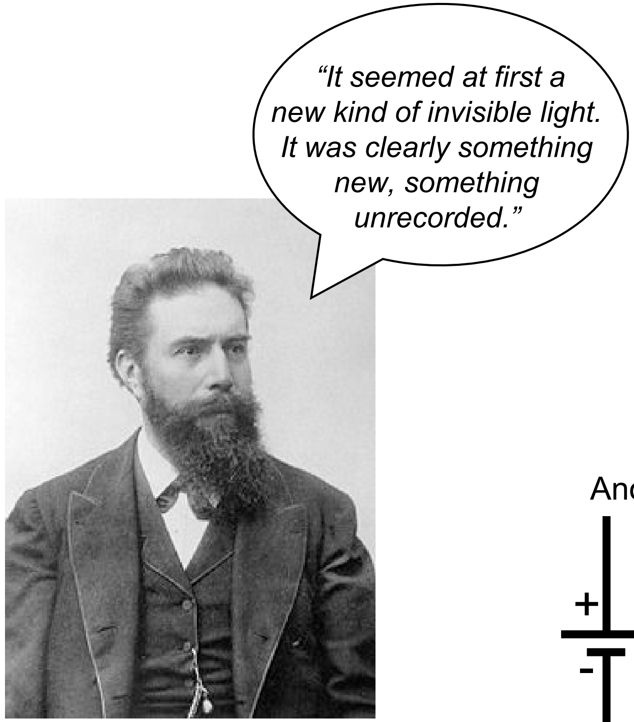
Part I: Basics of synchrotrons

A short history of X-ray sources

Generation of X-rays: X-ray tube

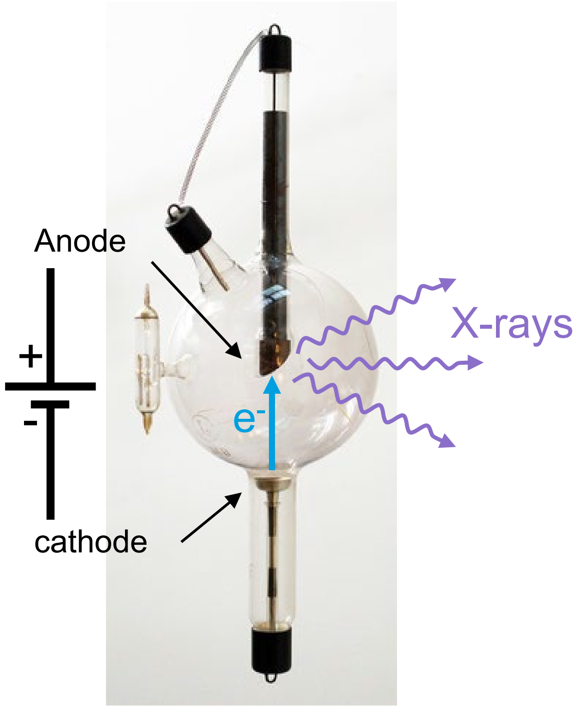
From discovery to first application

1895: Discovery of X-rays by Wilhelm Conrad Röntgen

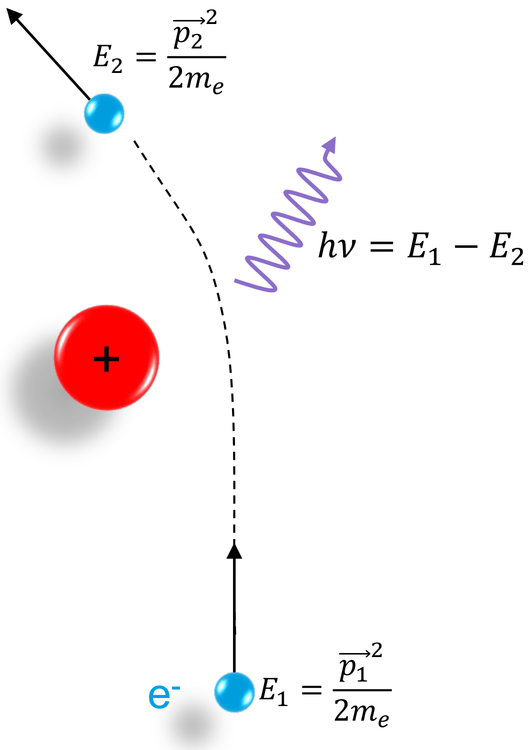


Wilhelm Conrad Röntgen
(1845 – 1923)
Nobel Prize 1901

Crookes tube



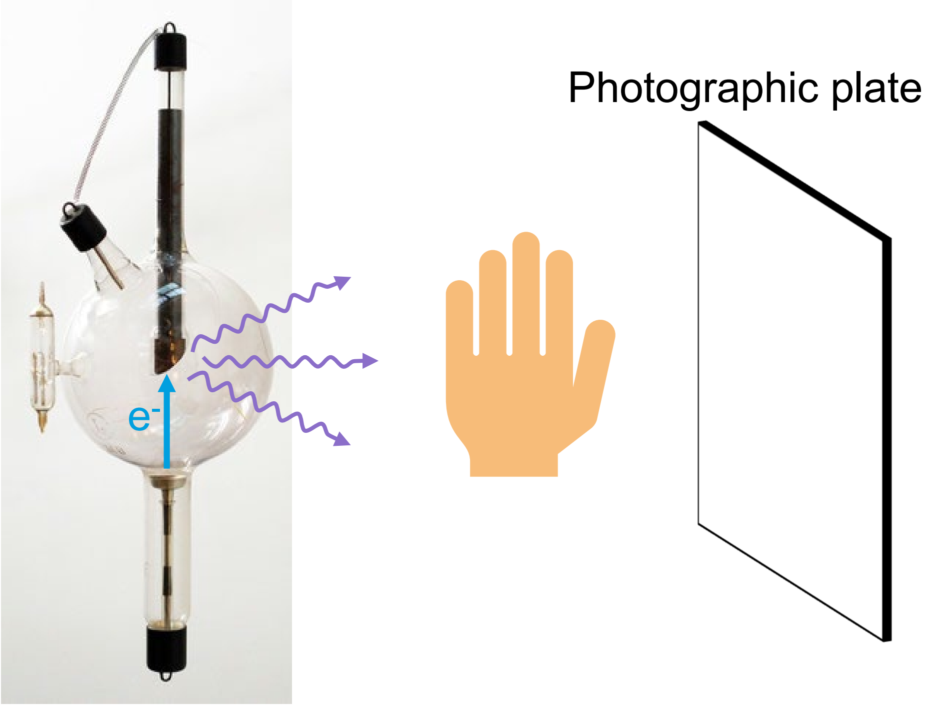
General principle for generation of X-rays: Bremsstrahlung



Generation of X-rays: X-ray tube

From discovery to first application

1 month later: first X-ray image



30-150 kV

25 min exposure time

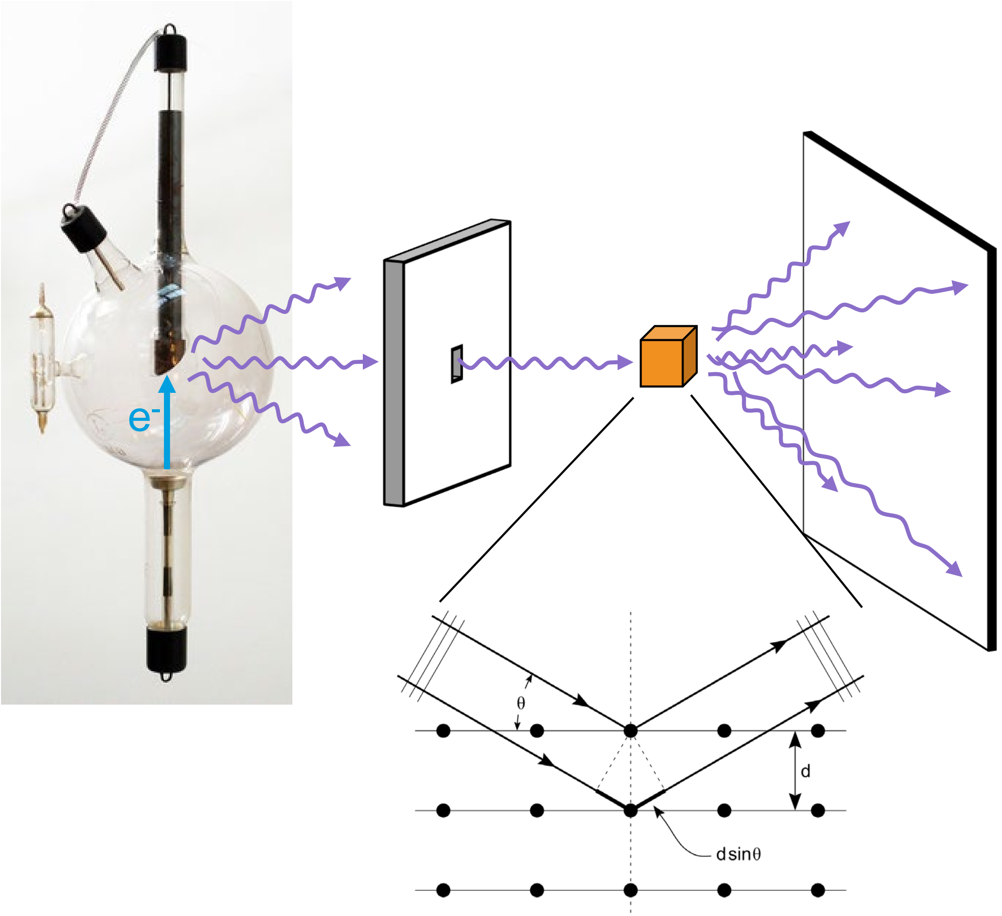
Röntgen’s wife hand

Generation of X-rays: X-ray tubes

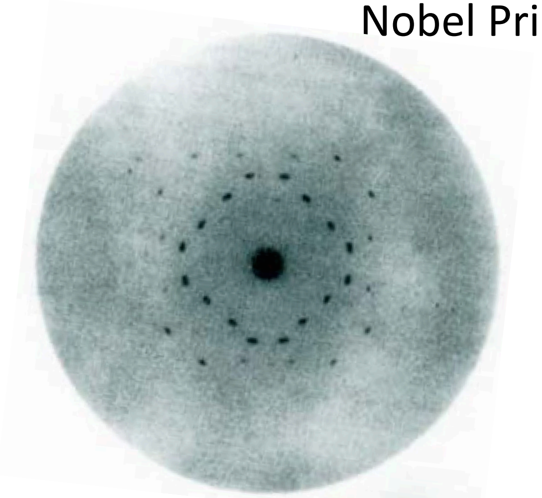
X-ray diffraction from crystalline structures

First diffraction patterns obtained by Max von Laue in 1912

W. Friedrich *et al. Annalen der Physik* **346**, 971–988 (1913)



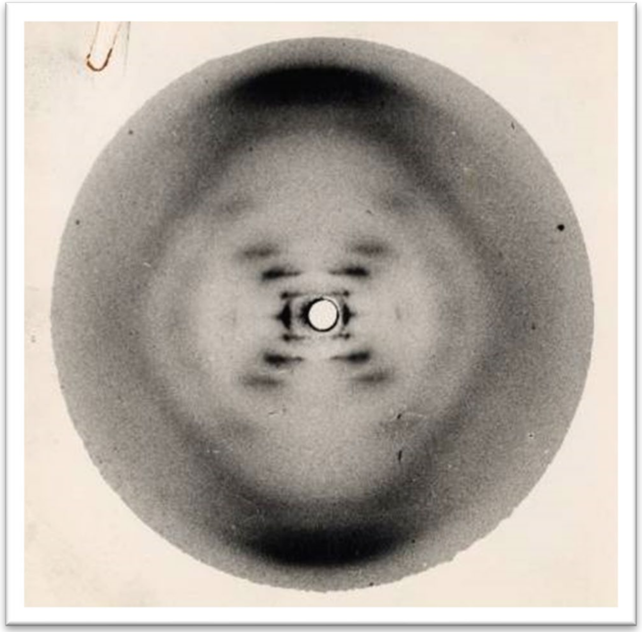
Max von Laue
(1879 – 1960)
Nobel Prize 1914



ZnS crystal

Generation of X-rays: X-ray tubes

X-ray diffraction from crystalline structures



1952: The first X-ray diffraction pattern of DNA
62 hours exposure time !

Rosalind Franklin
(1920 – 1958)
~~Nobel Prize 1962~~

The **Nobel Prize in Physiology or Medicine 1962 was awarded** jointly to Francis Harry Compton Crick, James Dewey Watson and Maurice Hugh Frederick Wilkins **"for their discoveries concerning the molecular structure of nucleic acids and its significance for information transfer in living material"**

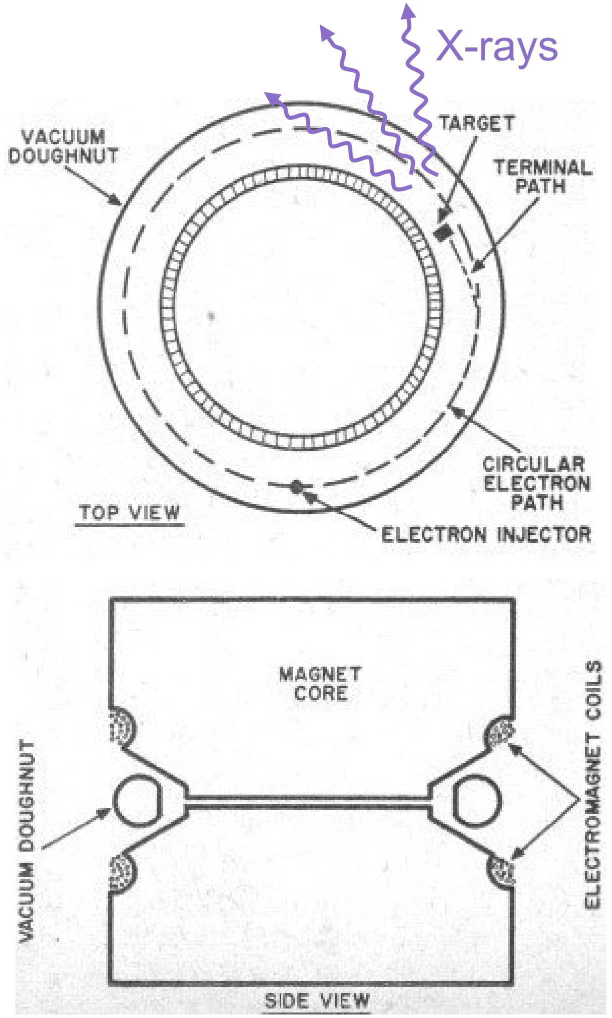
Generation of X-rays: Betatron

Acceleration in a magnetic field

The Betatron

World's Most Powerful X-Ray Machine Holds Vast Possibilities for Medicine, Industry, Research

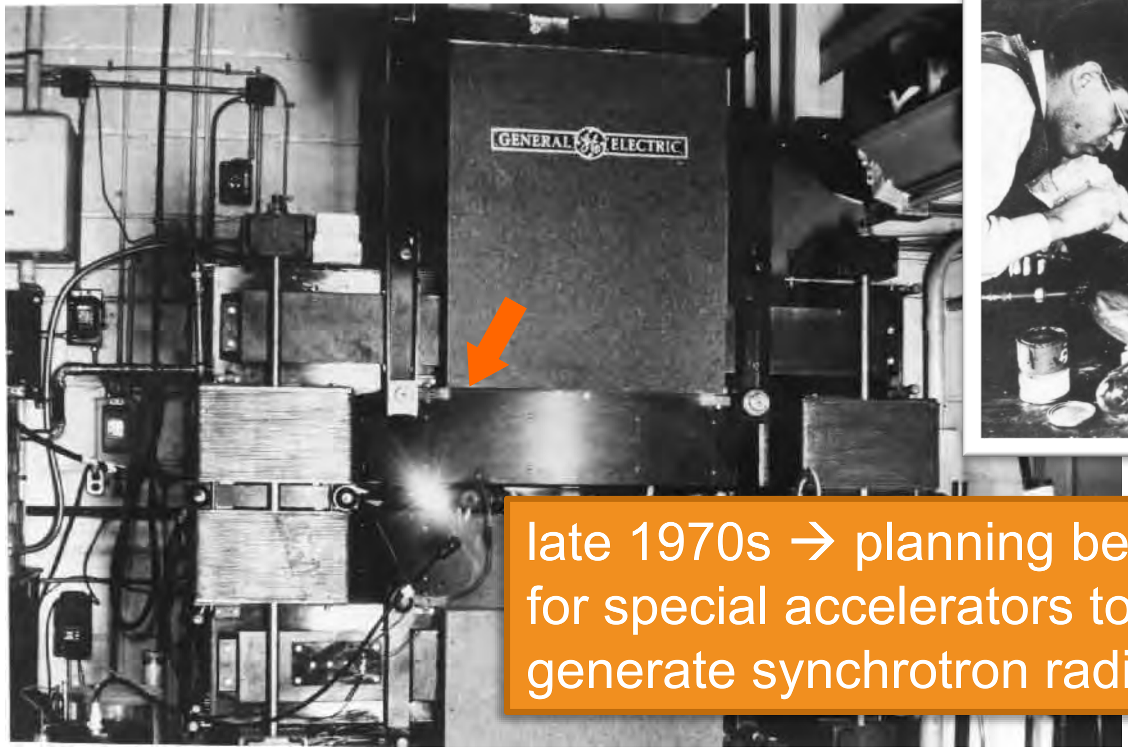
Professor Donald W. Kerst with the first betatron, having 2.3-million volts output energy, on the table and the 20-million-volt machine alongside. The circular vacuum tube of the large unit can be seen in place in the center of the betatron, between the pole faces of the 3½-ton magnet. The larger betatron is only three feet high



Scientific American, Vol. 168, No. 5 (MAY · 1943), pp. 207-209

Generation of X-rays : Synchrotron

First observation of synchrotron radiation



late 1970s → planning began for special accelerators to generate synchrotron radiation

April 24, 1947: First observation of SR at General Electric 70 MeV synchrotron (Langmuir, Elder, Gurewitch, Charlton, Pollock)

→ relativistic speed

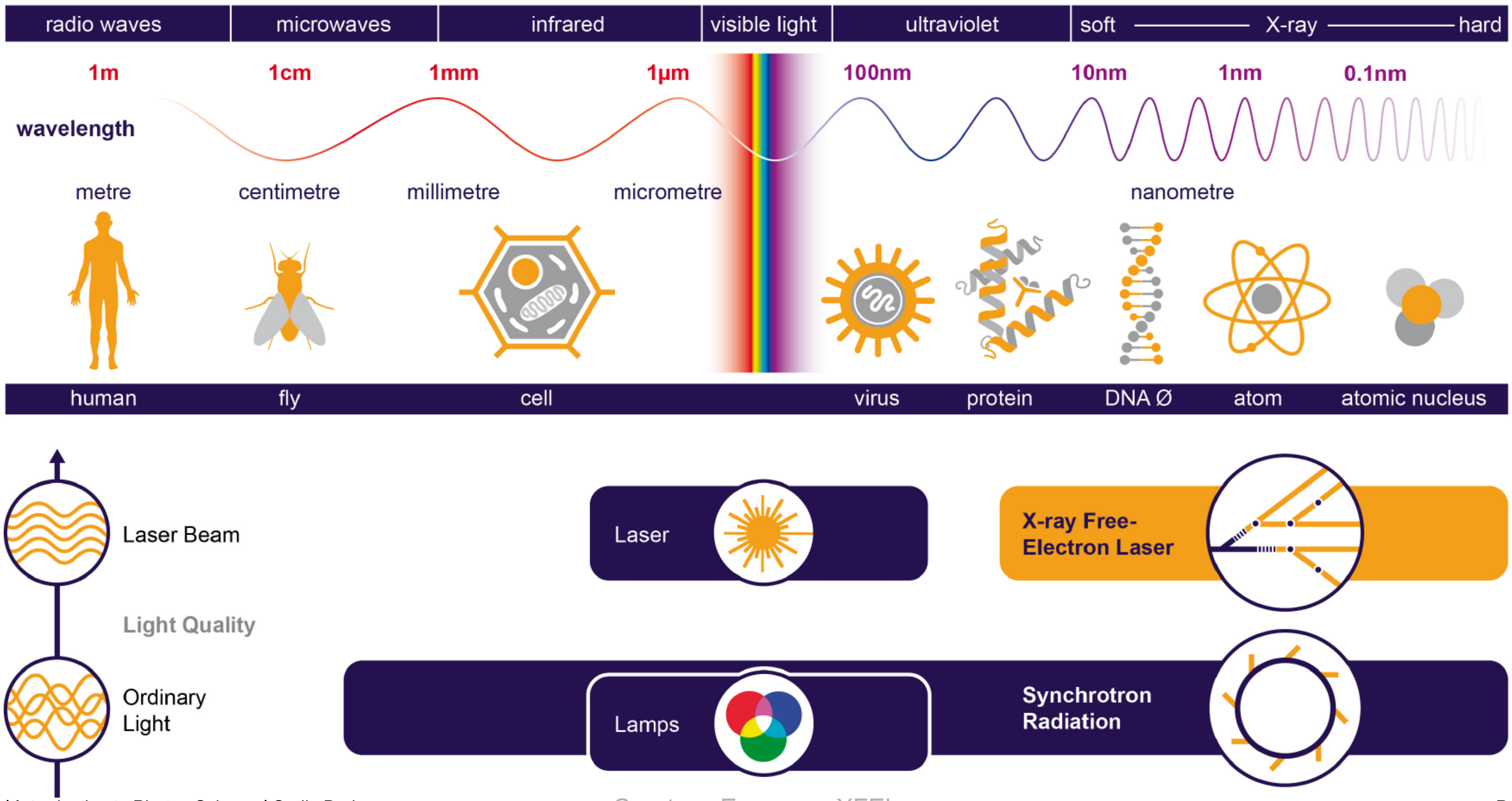
Generation of X-rays : and now?

Linac and 3rd generation synchrotron

few MeV radiotherapy linac

ESRF (Grenoble, FR), 6 GeV synchrotron

Big facilities for studying tiny objects…



Courtesy European XFEL

Source: https://lightsources.org/

Synchrotron radiation facilities worldwide

More than 50 light sources

Free-electron lasers

Synchrotron radiation facilities in Europe

DESY machine history

3000 employees, 3000 international guests per year (from more than 40 nations)
(130 apprentices, 500 PhD students and postdocs)
Annual budget: 349 M€

DESY founded 1959 as an Electron Synchrotron Facility for Elementary Particle Research

1964	DESY (Synchrotron)		e-	7.4 GeV
1974	DORIS (Storage Ring)	300m	e+/e-	3.5 GeV (later 5 GeV)

1980 HASYLAB@DORIS
1984 Upgrade with 7 Wiggler/Undulator Beamlines
1993 Dedicated SR Source at 4.5 GeV

1978 PETRA (Storage Ring) 2.3km e+/e- 19 GeV

1990 HERA (Storage Ring) 6.3km p+/e- 920 GeV / 27.5 GeV (using PETRA as Booster)

1997 FLASH (Free-Electron Laser)
2005 Dedicated User Facility

2007 Shutdown of HERA and Reconstruction of PETRA → PETRA III

2009 PETRA III Dedicated SR Source at 6 GeV (one of the most brilliant synchrotron sources worldwide)

2012 Shutdown of DORIS
2014 FLASH II (Extension of FLASH)

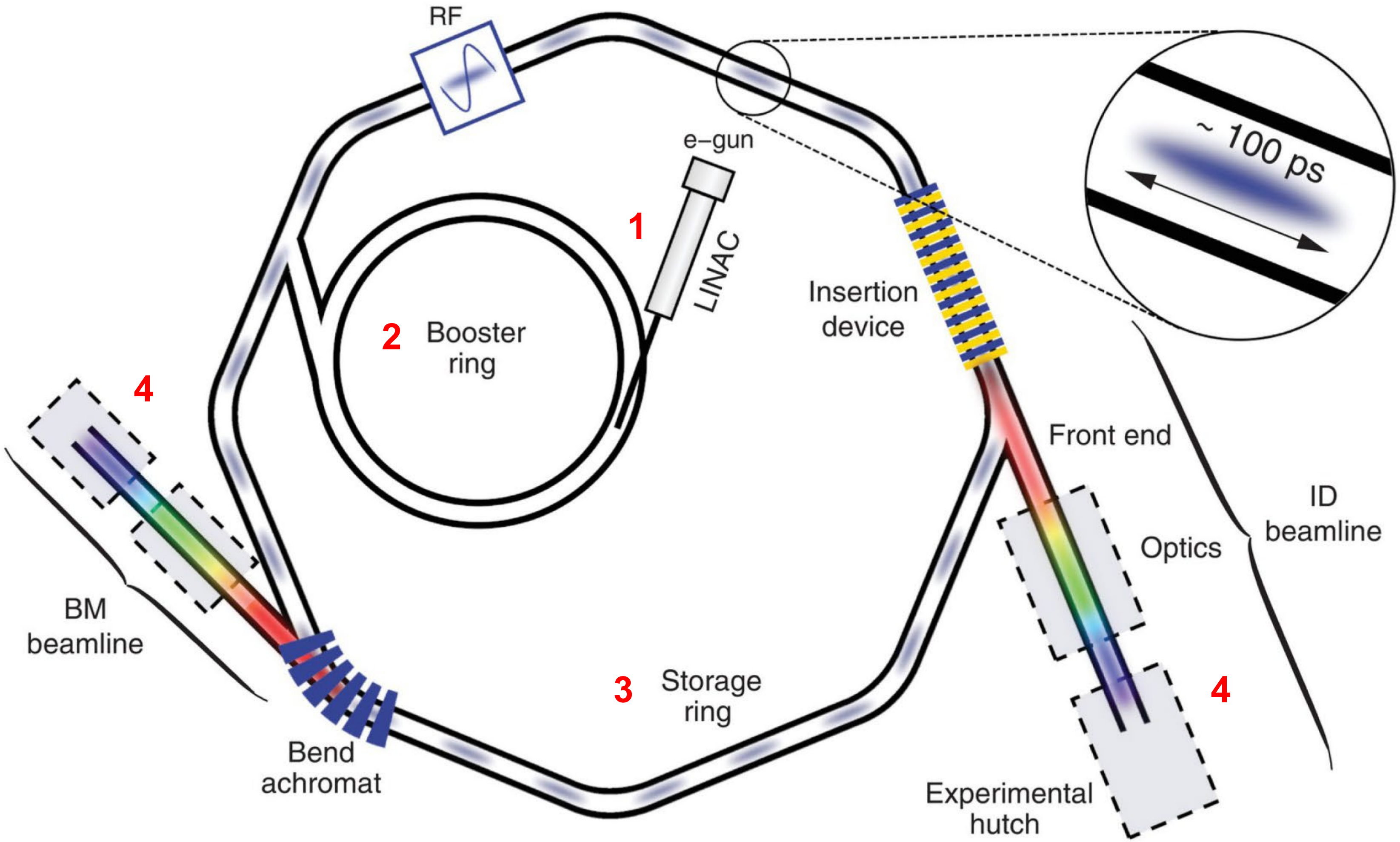
Participation in the European XFEL project (operation since 2017)

Basics of Synchrotrons

Synchrotron

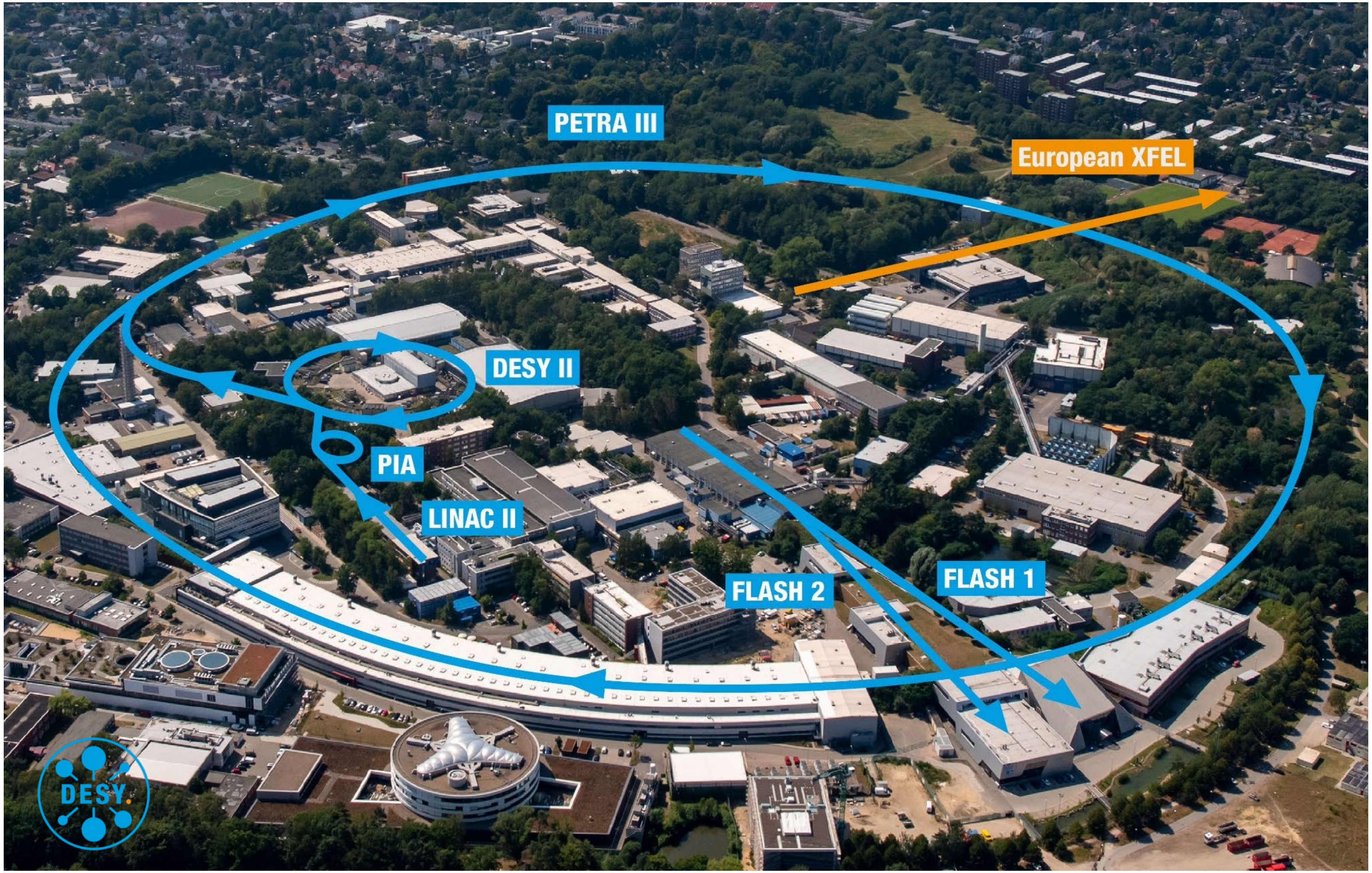
Principal structures

1. e^- are produced and accelerated in a LINAC
2. e^- are accelerated to nominal energy (GeV) in the booster accelerator
3. e^- bunches travel in the storage ring in a wide circular path, emitting light as they change directions
4. X-ray light, emitted towards “beamlines”
   → experiments



An Introduction to Synchrotron Radiation: Techniques and Applications, 2nd edition, P. Willmott, 2019, Wiley

Synchrotron at DESY



4 eV – 200 keV

Radiation by acceleration of a charged particle

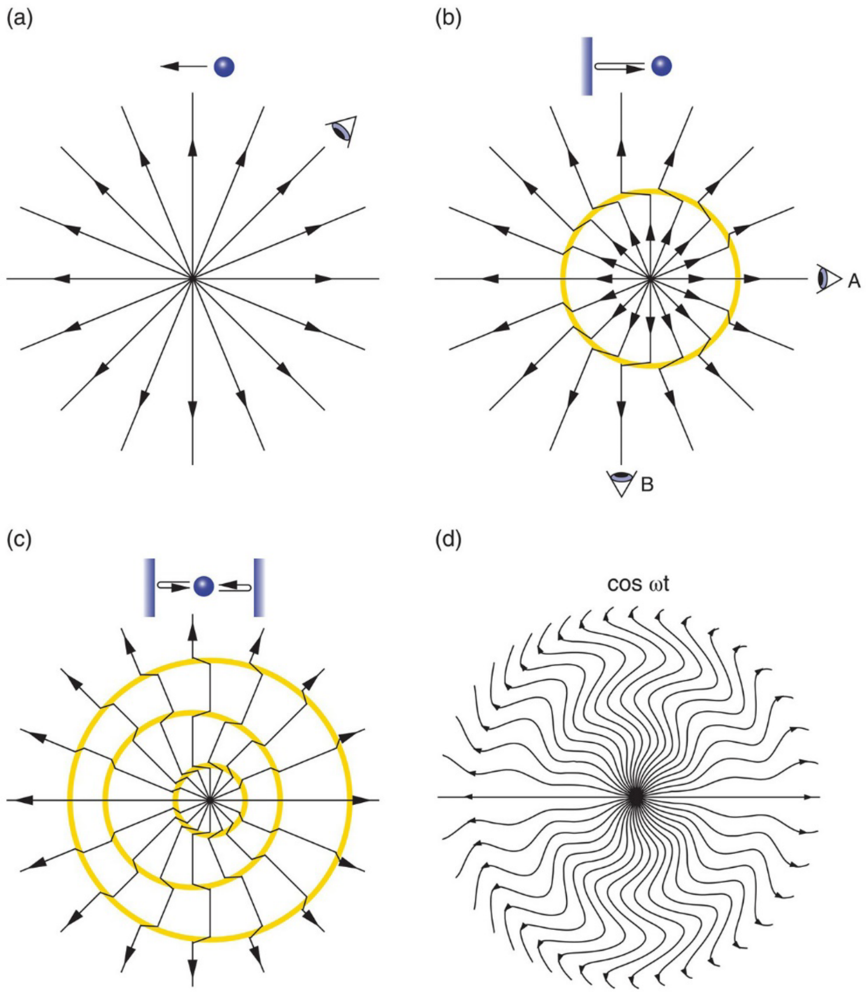
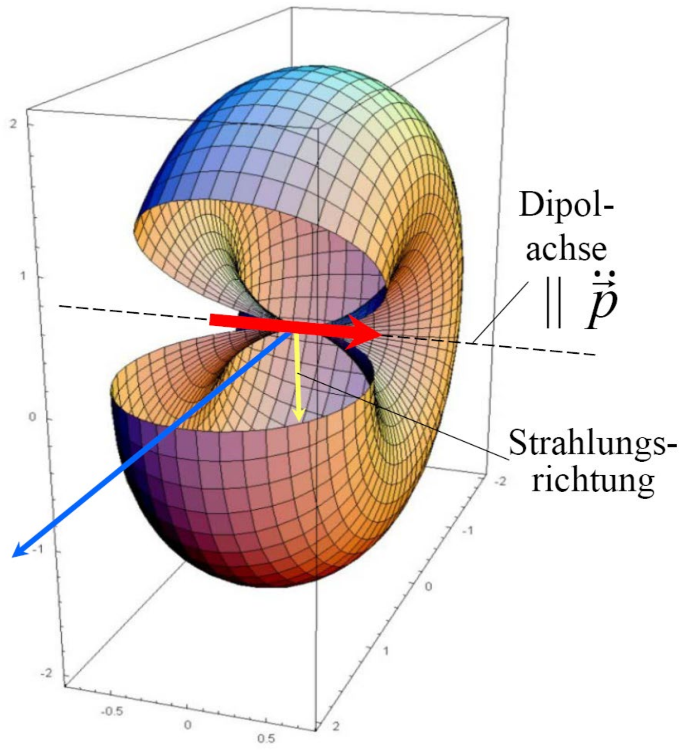


Figure 3.3 Generation of electromagnetic radiation by acceleration of a charged particle. (a) A charged particle at rest or moving at uniform speed will not emit light, as any observer of the particle detects no lateral component of the electric-field lines. (b) If, however, the particle undergoes acceleration, an observer positioned anywhere other than along the axis of that acceleration (position A), will see a shift in the position and direction of the electric-field lines as the event horizon washes over them at the speed of light (for example, at position B). (c) A charged particle bouncing between two boundaries will generate a corresponding set of pulses of electromagnetic radiation at regular intervals. (d) A simple-harmonic driving force will generate radiation at the same frequency.

An Introduction to Synchrotron Radiation: Techniques and Applications, 2nd edition, P. Willmott, 2019, Wiley

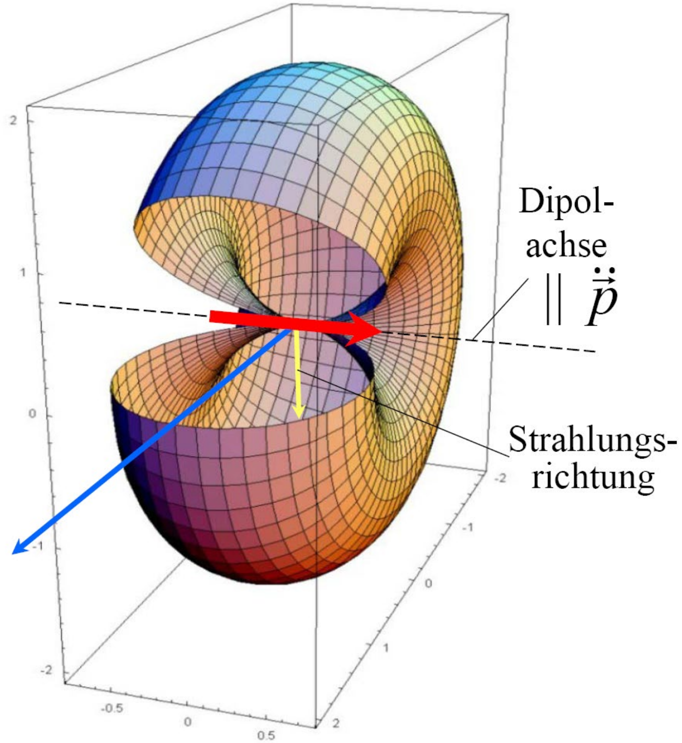
Emission pattern for circular accelaration



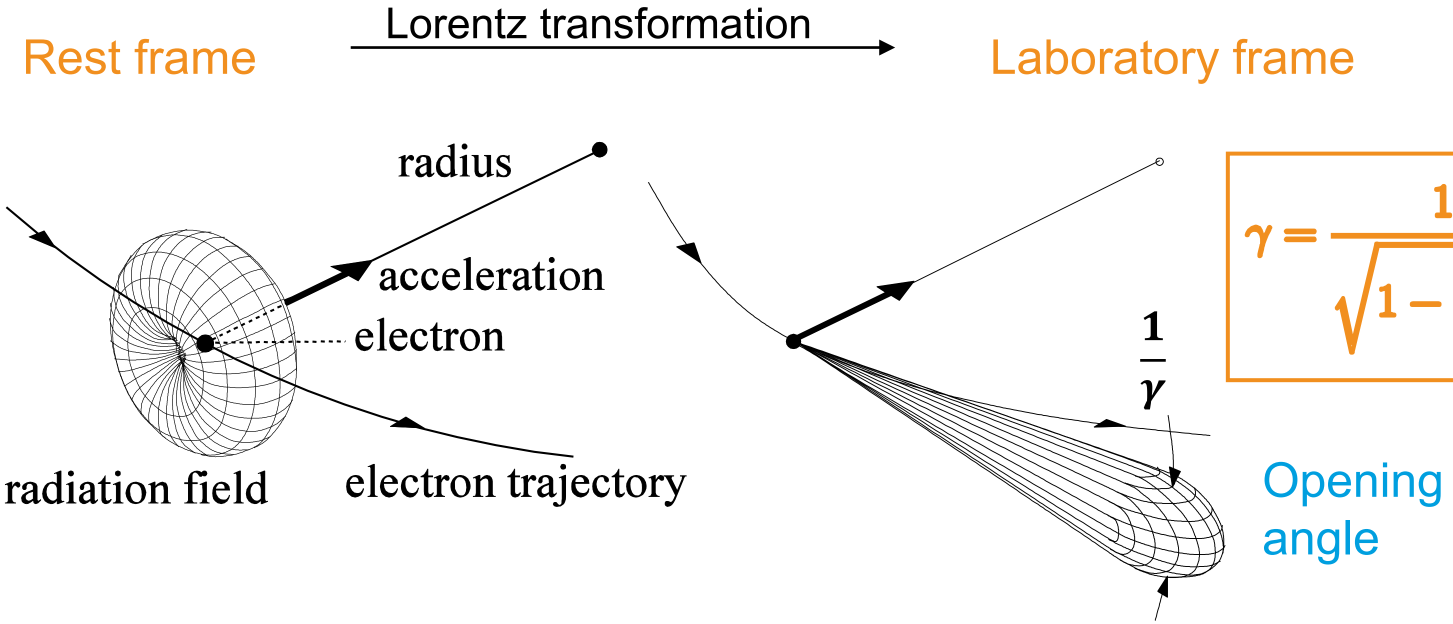
Hertzian Dipole

- Every accelerated charge radiates electromagnetic waves
- Oscillatory motion: No radiation in direction of the oscillation
- The maximum radiated power is observed perpendicular to the oscillation direction

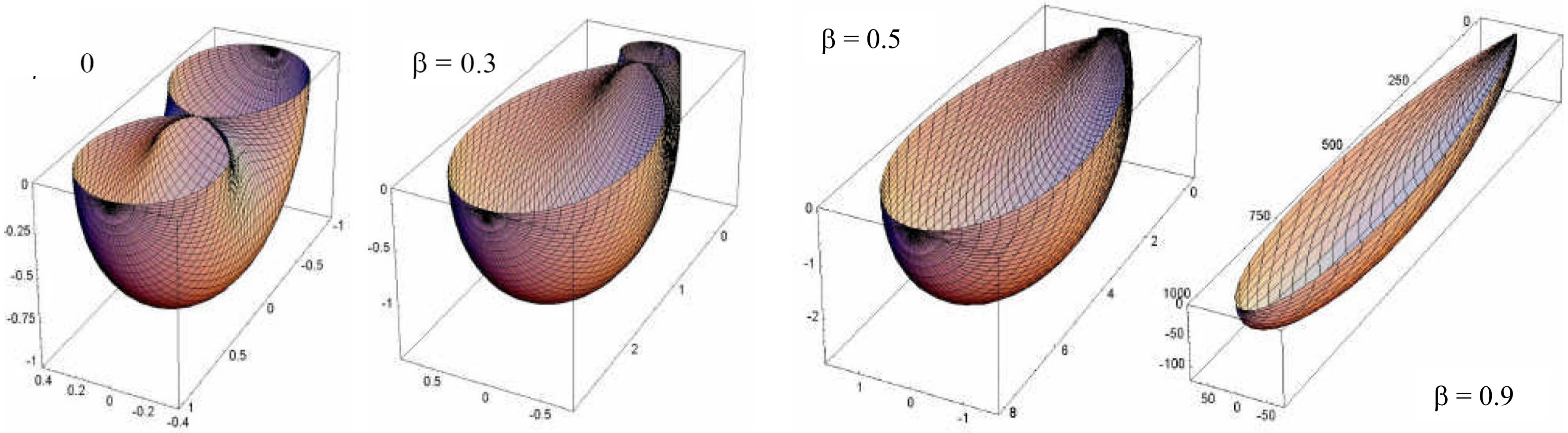
Emission pattern for circular acceleration



Hertzian Dipole

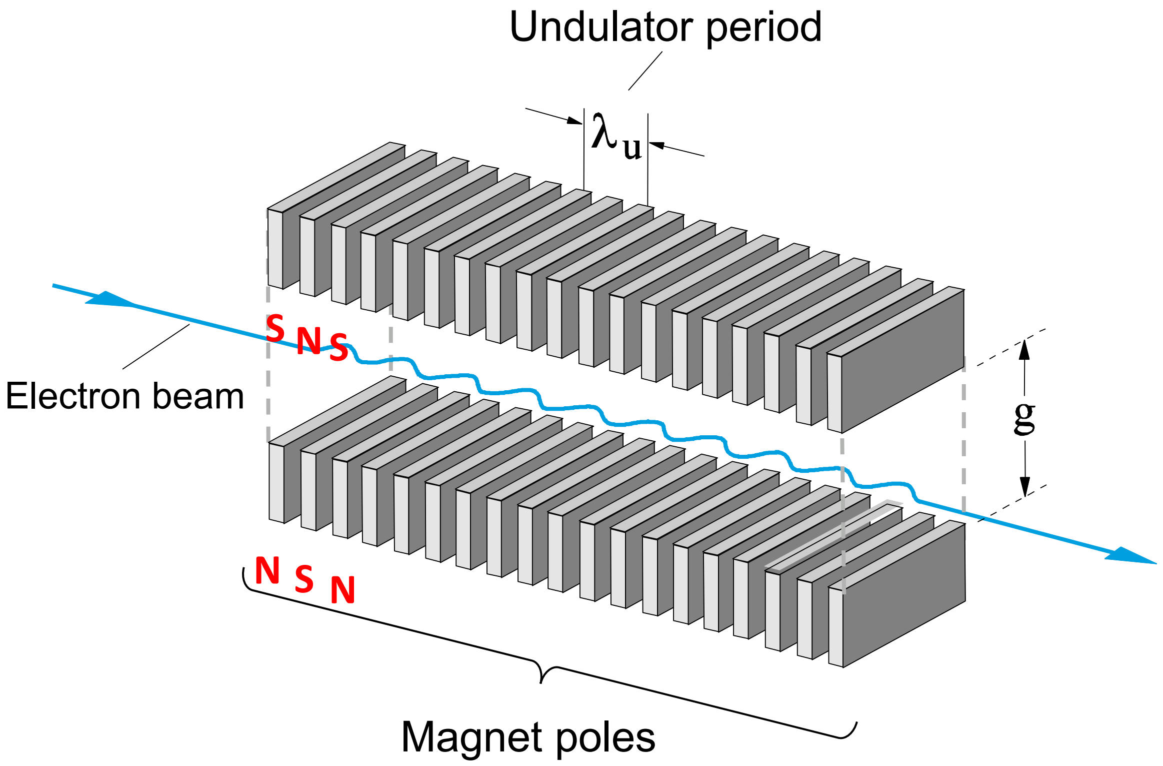


$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{E}{m_0c^2}$$



Insertion devices: Wigglers and Undulators

Undulation motion



Synchrotron Radiation (SR) is a relativistic effect

γ the relativistic Lorentz factor

Many features can be understood in terms of two processes:

- Lorentz contraction
- Doppler shift

When a relativistic charged particle is travelling through a periodic magnetic field, in the particles rest frame it sees a magnetic field rushing towards it.

In our rest frame the magnet period is λ_u

$$\gamma = \frac{E}{E_0}$$

$$\beta = \frac{v}{c}$$

$$\beta = \sqrt{1 - \frac{1}{\gamma^2}}$$

c is the velocity of light in free space
v is the velocity of the electron
β is the relative velocity of the electron
E is the electron energy
E_0 is the electron rest energy (0.511 MeV)

This γ factor turns up again and again in SR !

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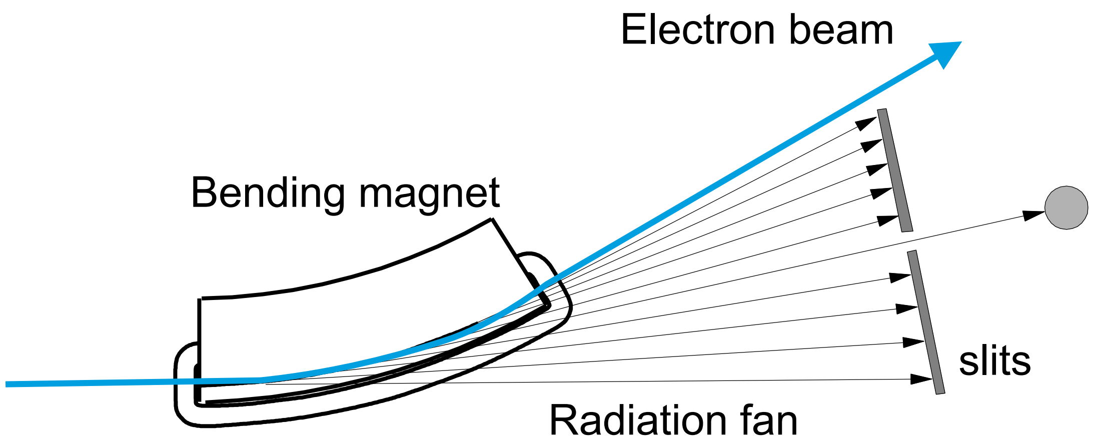
This γ factor turns up again and again in SR !

- What is γ at PETRA III ?
- What wavelength does the particle emit?
- What wavelength do we observe?

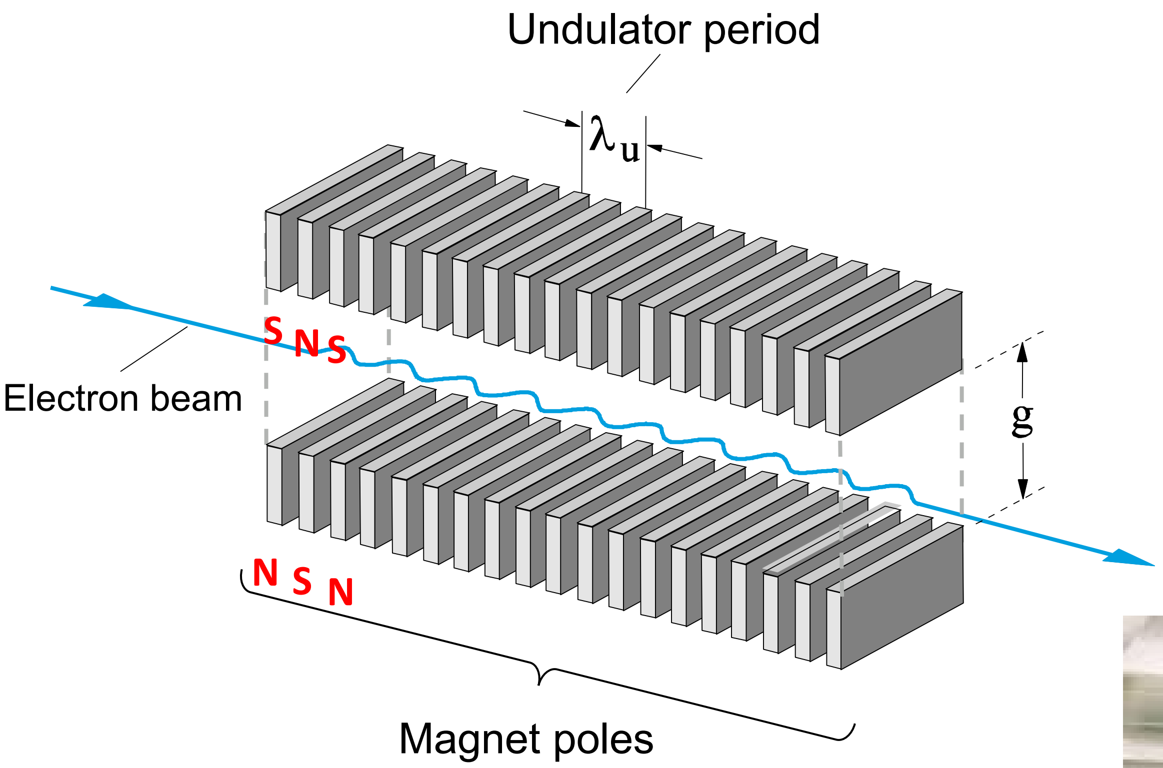
Bending magnet



- The radiation is emitted in the plane of the orbiting particles
- The radiation is linearly polarized in the orbit plane

Insertion devices: Wigglers and Undulators

Undulation motion

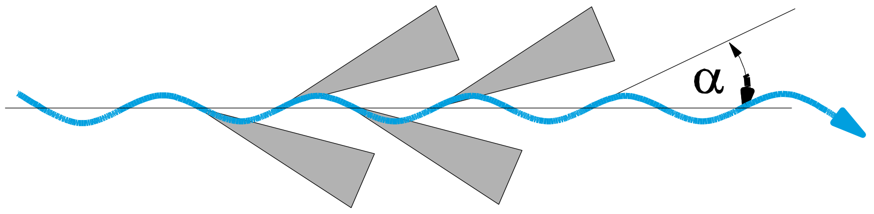


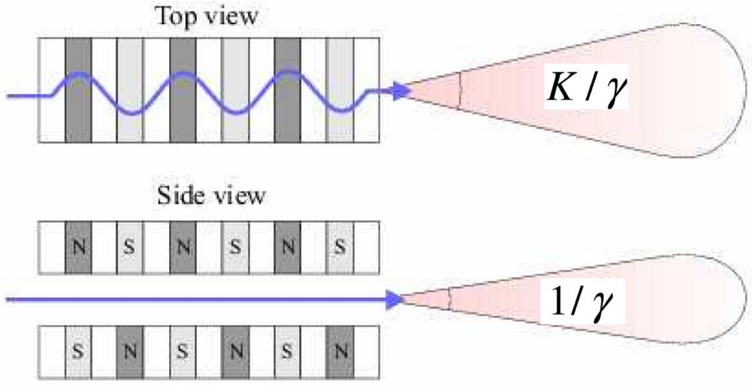
- Multiplication of the radiation intensity by periodically repeated magnet structures

Undulator strength parameter $K = \frac{eB\lambda_u}{2\pi m_e c}$

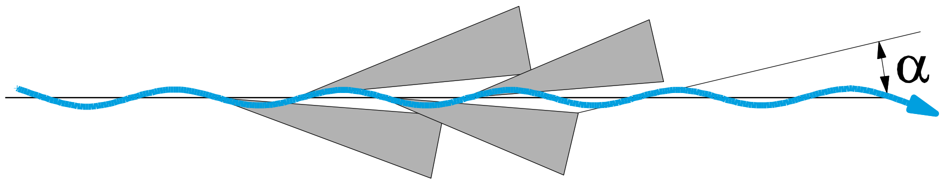
Insertion devices: Wigglers and Undulators

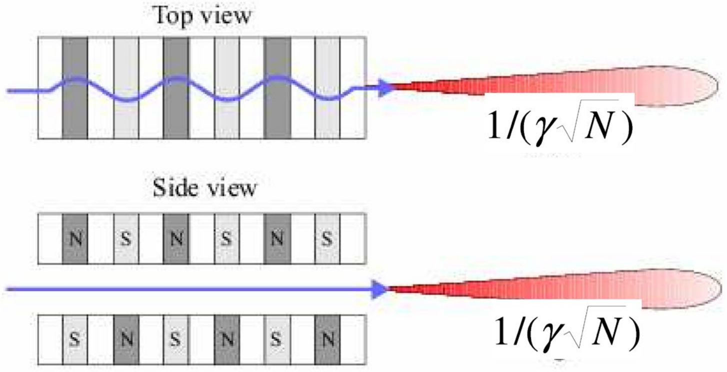
$K \gg 1$ ➔ Wiggler regime: $\alpha > 1/\gamma$





$K \leq 1$ ➔ Undulator regime: $\alpha < 1/\gamma$





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

and $\frac{\Delta\lambda}{\lambda} \approx \frac{1}{N}$ with N= # periods of undulator

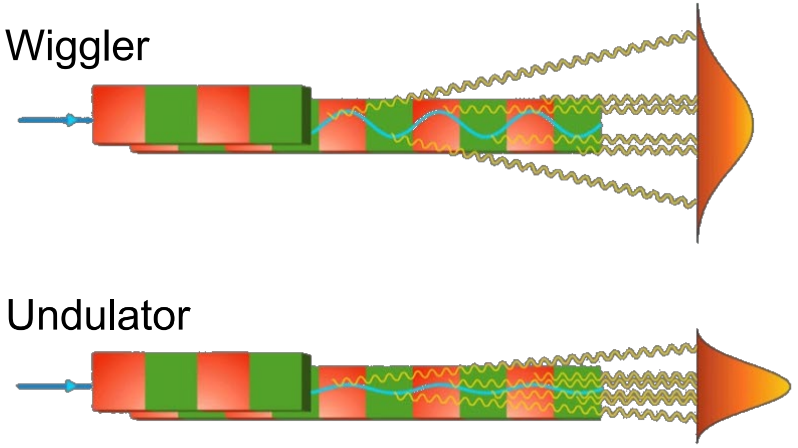
- In the undulator regime the radiation cones overlap and the wave trains can interfere constructively → increase of intensity

Insertion devices: Wigglers and Undulators

Intensity of the emitted radiation

N_p = Number of magnet poles

N_e = Number of electrons/bunch



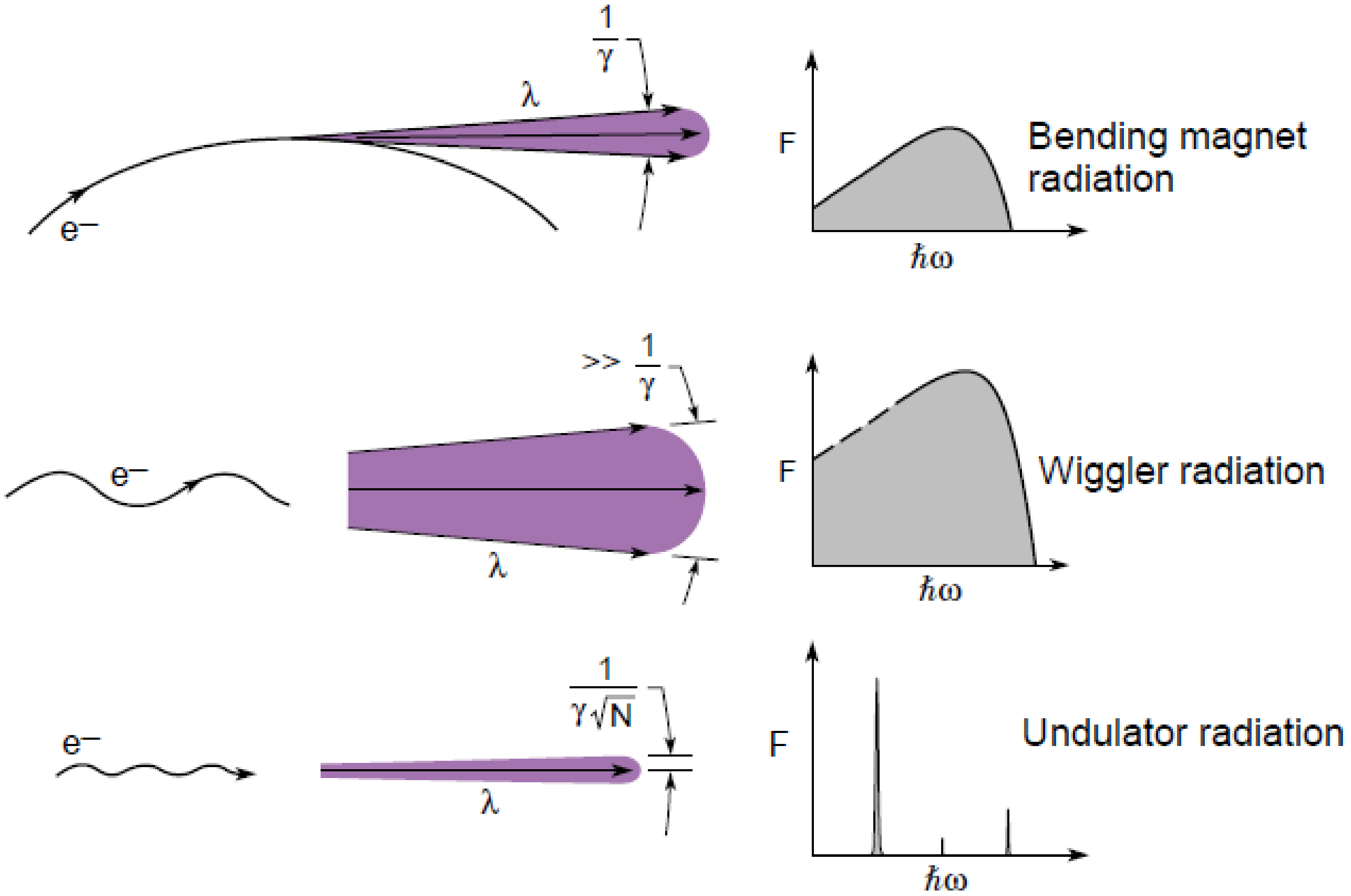
Incoherent superposition

$$I \sim N_e N_p$$

Partially coherent superposition

$$I \sim N_e N_p^2$$

Radiation from the different insertion devices



Photon intensities delivered by different insertion devices

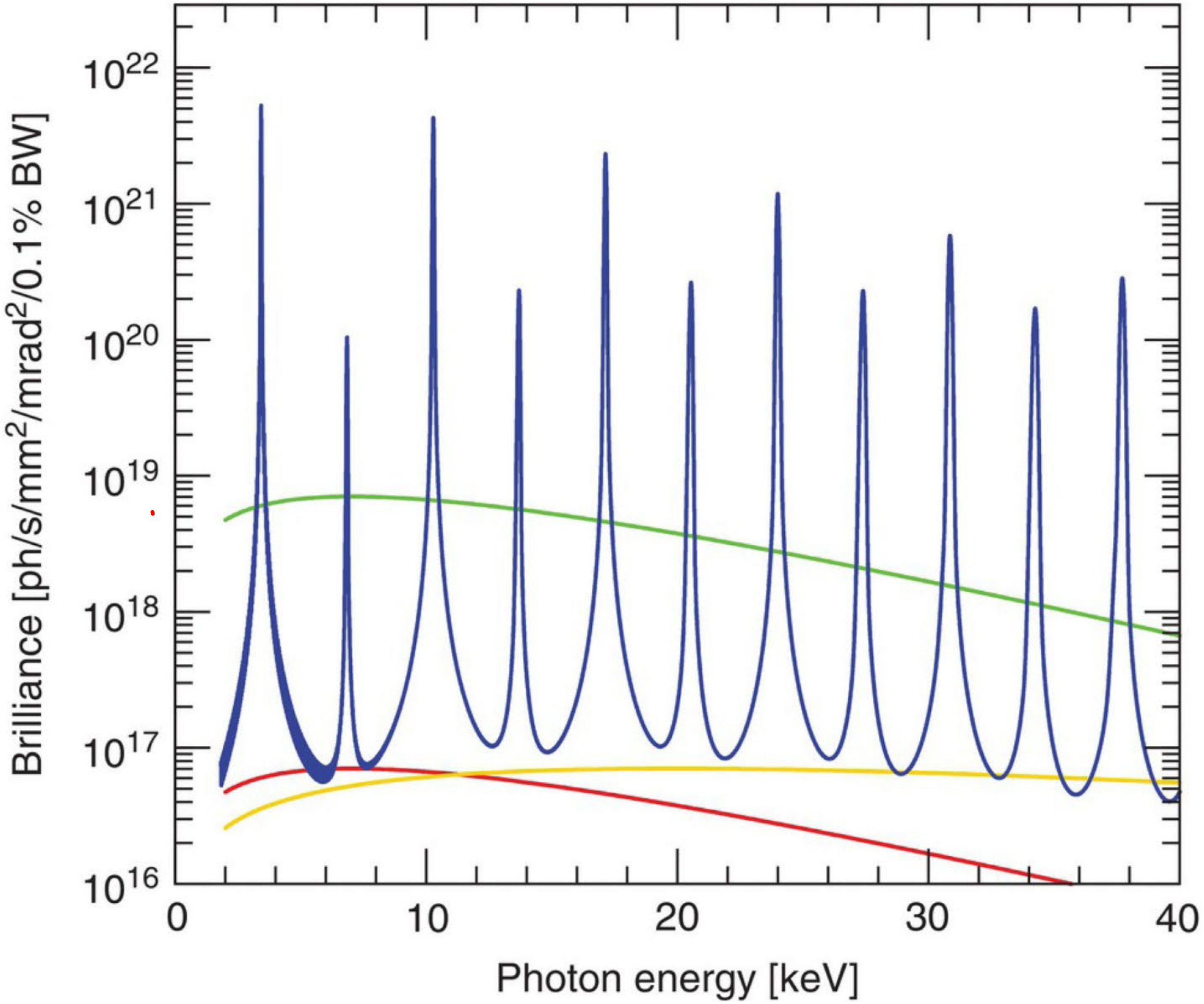


Figure 3.35 Comparison of brilliances at a 3 GeV DLSR running at 400 mA between a U14 undulator with $K = 1.6$ (blue), a bending magnet with $B = 1.41$ T (red), a superbend with $B = 4$ T (yellow), and a wiggler with the same field strength as the bending magnet and 100 periods (green).

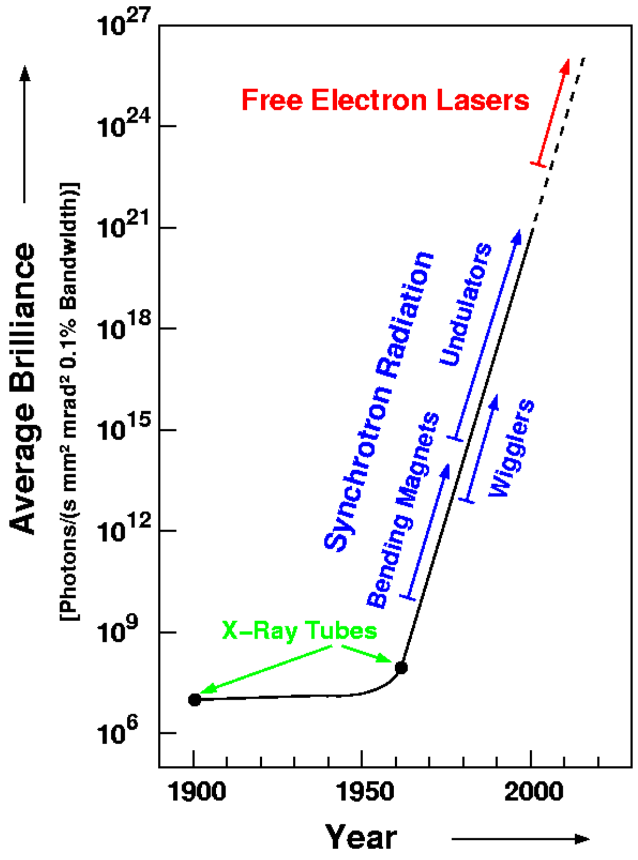
An Introduction to Synchrotron Radiation: Techniques and Applications, 2nd edition, P. Willmott, 2019, Wiley

Evolution of synchrotron radiation sources

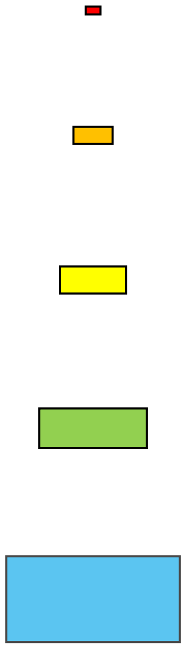
Smaller, brighter!

$$\text{brilliance} = \frac{Photon\ flux}{\sigma_x \sigma_y \sigma'_x \sigma'_y\ BW}$$

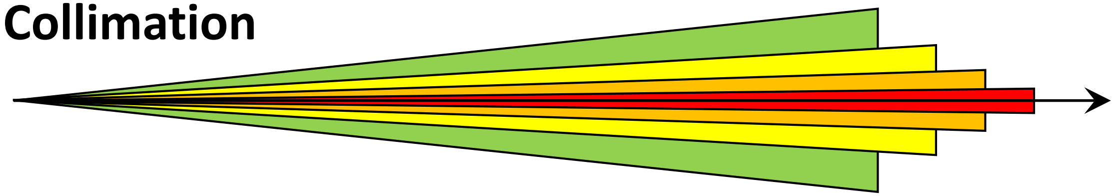
Photon flux	= photons/s
σ_x, σ_y	= transverse area from which SR is emitted
σ'_x, σ'_y	= solid angle into which the SR is emitted
BW	= bandwidth of the monochromator



Source size

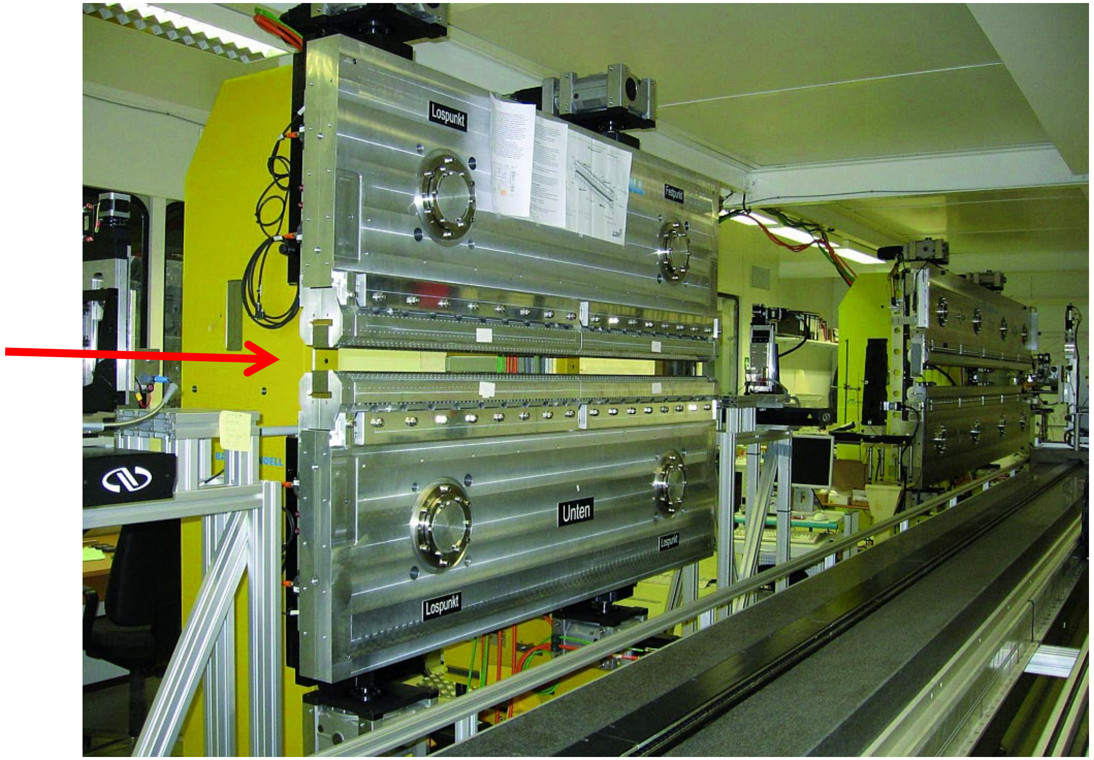


Collimation



PETRA III @ DESY

Characteristic parameters



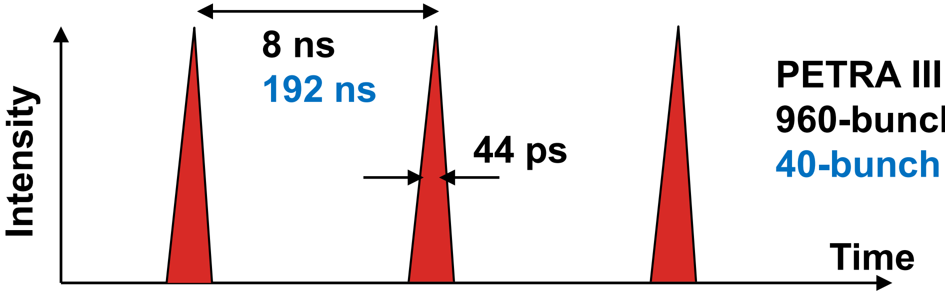
Vertical aperture of vacuum chamber: 7 mm

PETRA III machine parameters

Electron energy: **6 GeV**
Circumference: 2304 m
Revolution time: 7.685 μs
Number of bunches: 960, 480, 40
Bunch separation: 8, 16, 192 ns
Bunch length: 13.2 mm, **44 ps**
Total beam current: **100 mA** (top-up mode)

Horizontal emittance: **1.2 nm rad**
Vertical emittance: **0.012 nm rad**

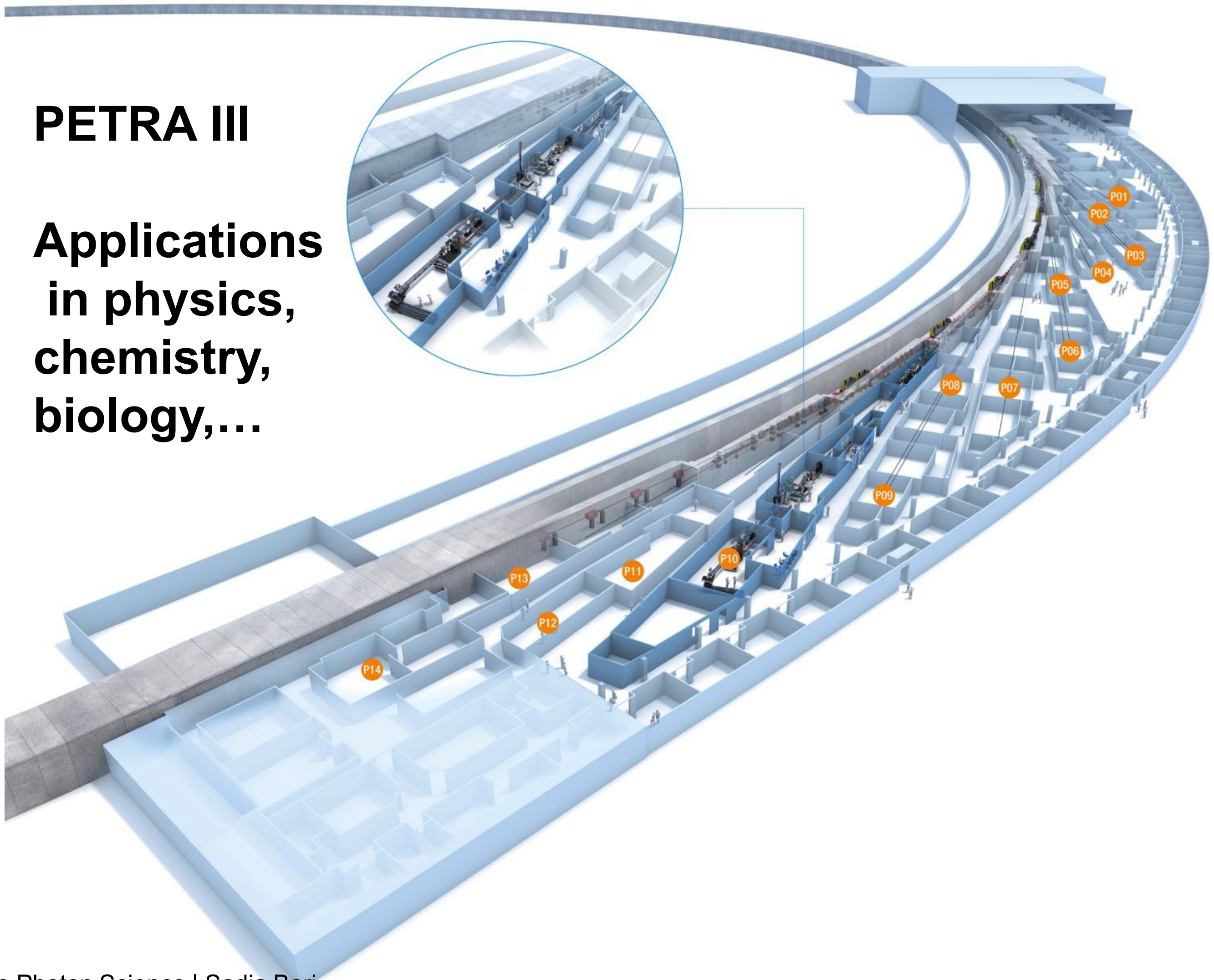
Bending magnet field: 0.873 T
Bending magnet radius: 22.92 m
Critical photon energy: **20.9 keV**

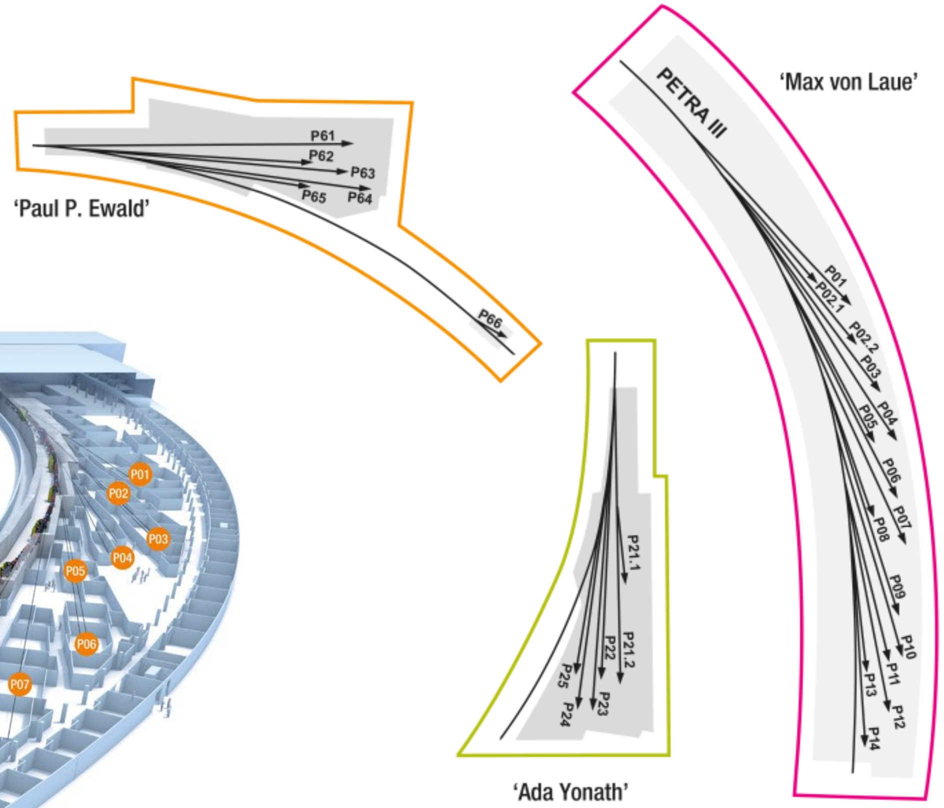


PETRA III
960-bunch mode
40-bunch (timing) mode

PETRA III

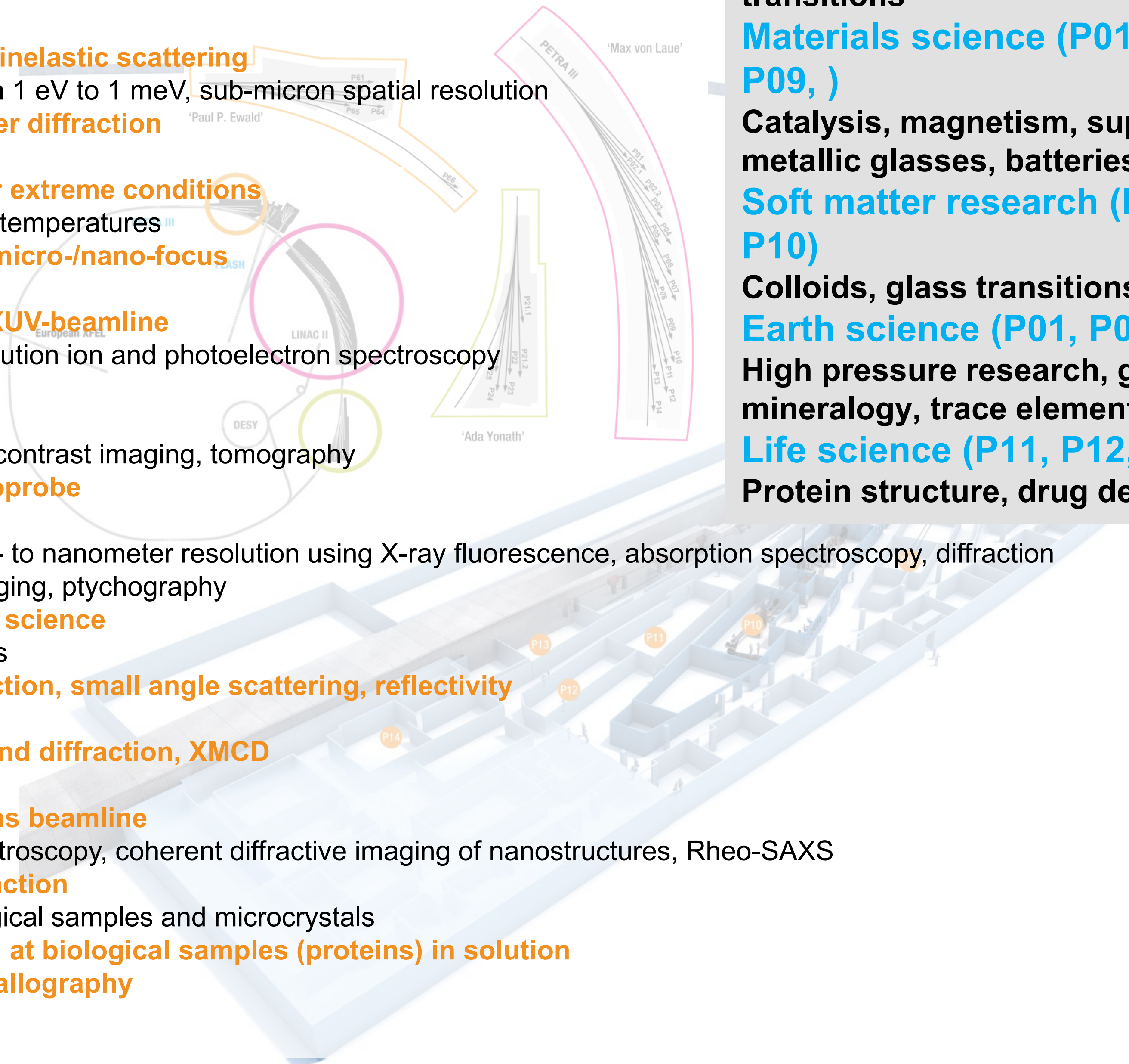
Applications in physics, chemistry, biology,…





PETRA III Facilities

P01: **Nuclear resonant and inelastic scattering**
2.5 - 80 keV, Resolution 1 eV to 1 meV, sub-micron spatial resolution
P02.1: **High-resolution powder diffraction**
60 keV, Resolution
P02.2: **Microdiffraction under extreme conditions**
25 - 60 keV, high pressure, high/low temperatures
P03: **X-ray scattering with micro-/nano-focus**
9 – 23 keV
P04: **Variable polarization XUV-beamline**
250 - 3000 eV High-resolution ion and photoelectron spectroscopy
P05: **Imaging beamline**
5- 50 keV
Phase- and absorption contrast imaging, tomography
P06: **Hard X-ray micro/nanoprobe**
5 - 21 keV
Visualization with micro- to nanometer resolution using X-ray fluorescence, absorption spectroscopy, diffraction coherent diffraction imaging, ptychography
P07: **High energy materials science**
30 - 200 keV, Microfocus
P08: **High resolution diffraction, small angle scattering, reflectivity**
5 - 29 keV, Microfocus
P09: **Resonant scattering and diffraction, XMCD**
2.7 - 50 keV
P10: **Coherence applications beamline**
5 - 25 keV Photon correlation spectroscopy, coherent diffractive imaging of nanostructures, Rheo-SAXS
P11: **Bio-Imaging and diffraction**
5 - 30 keV, Micro/nanobeam, biological samples and microcrystals
P12: **Small angle scattering at biological samples (proteins) in solution**
P13/P14: **Macromolecular crystallography**



Atomic and molecular science (P04)
Surface science (P01, P03, P08, P10)
Thin films, wetting phenomena, phase transitions
Materials science (P01, P02, P04, P07, P09,)
Catalysis, magnetism, superconductivity, metallic glasses, batteries
Soft matter research (P01, P03, P08, P09, P10)
Colloids, glass transitions
Earth science (P01, P02, P08, P09)
High pressure research, geophysics, mineralogy, trace element analysis
Life science (P11, P12, P13, P14)
Protein structure, drug development