PIER Graduate Week 2014
6 – 9 Oct 2014

Essentials of X-ray Physics
Scattering, Imaging, Spectroscopy and beyond

Part I

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Introduction: Generation of X-rays

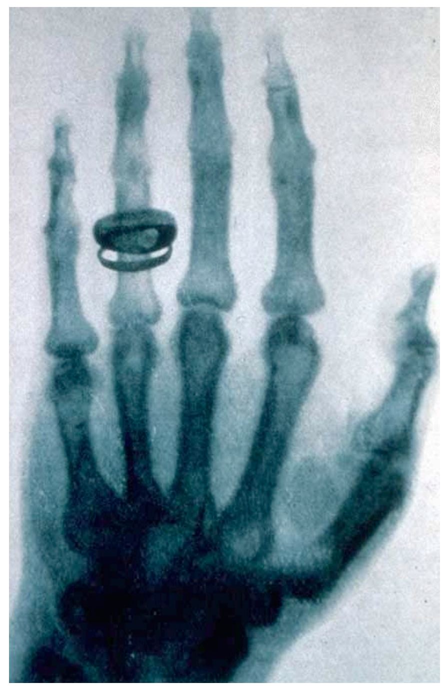
What are X-rays good for ? **Reveal structure and dynamics of matter with highest spatial and temporal resolution**

(Answer 2014)

1895: Discovery of X-rays by Wilhelm Conrad Röntgen

First commercial X-ray tube

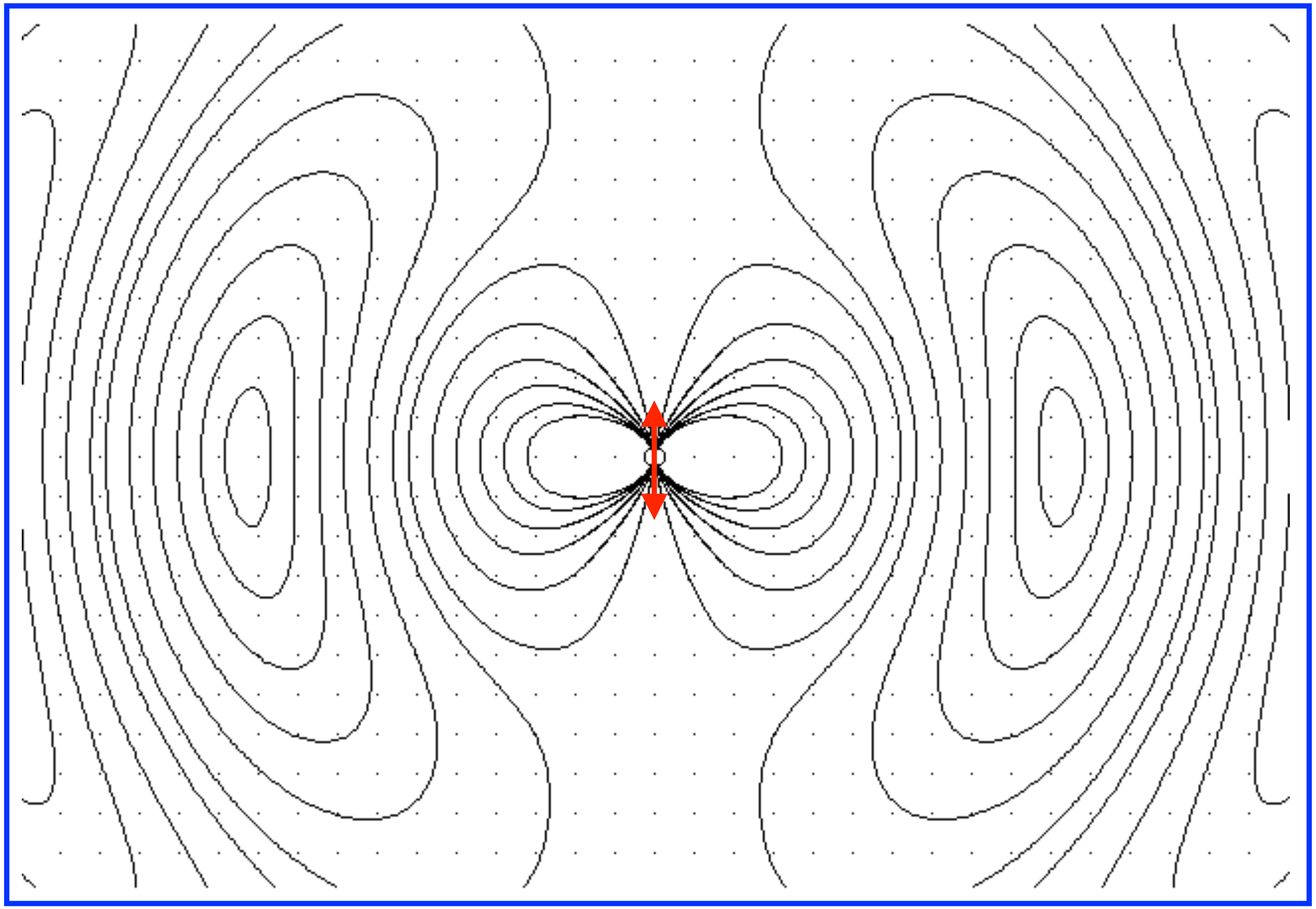
First X-ray images (1986)



Wilhelm Conrad Röntgen
(1845 – 1923)
Nobel Prize 1901

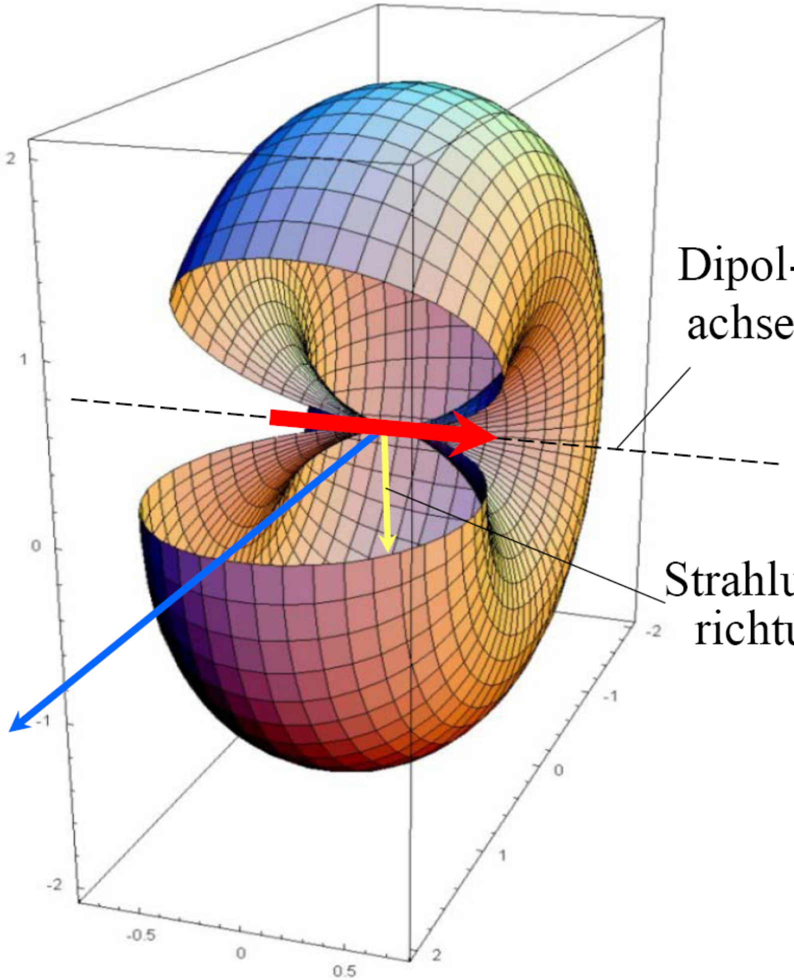
General principle for generation of x-rays: Bremsstrahlung

Field lines around an oscillating electric dipole



Heinrich Hertz
(1857 – 1894)

Radiation Pattern of a Hertzian Dipole



Every accelerated charge radiates electromagnetic waves

Larmor formula for the radiated power

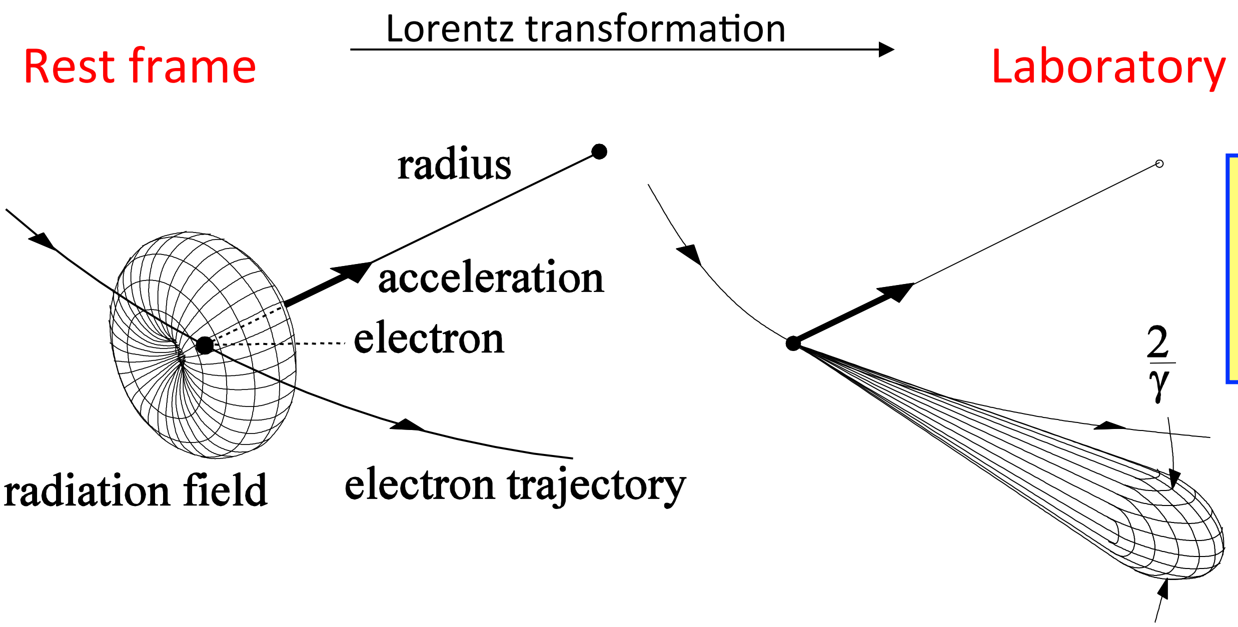
$$P = \frac{e^2}{6\pi\varepsilon_0 m^2 c^3}\left(\frac{d\vec{p}}{dt}\right)^2$$

$\vec{p} \equiv$ momentum

Oscillatory motion:
No radiation in direction of the oscillation.

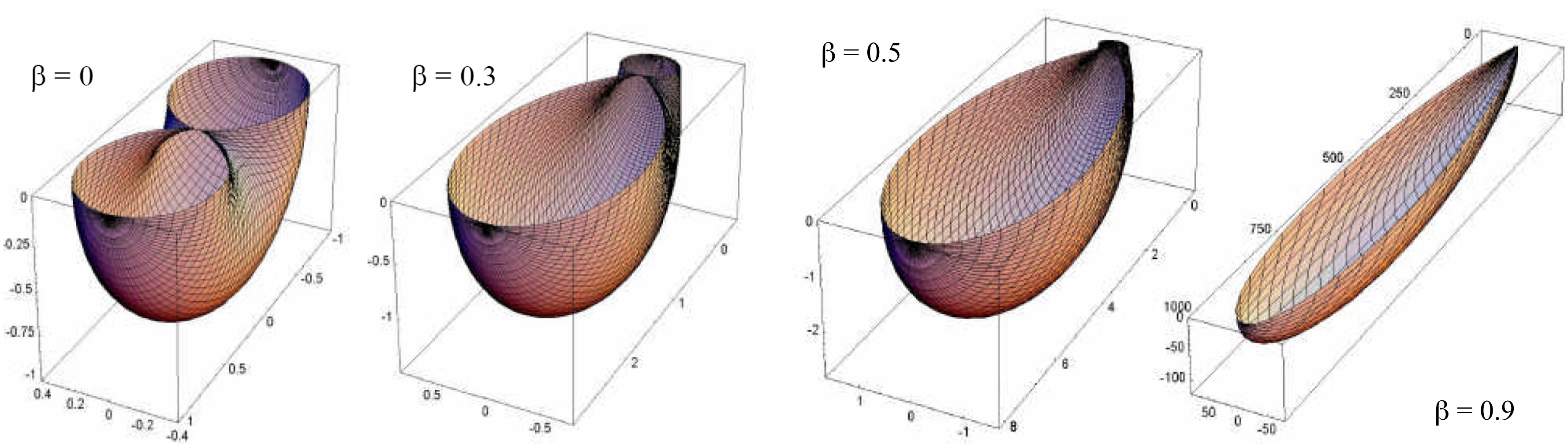
The maximum radiated power is observed perpendicular to the oscillation direction

Emission Pattern of an Accelerated Dipole



$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{E}{m_0 c^2}$$

Opening angle



Circular acceleration: Generation of Synchrotron Radiation

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

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

Lorentz transformation and application to circular acceleration:

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

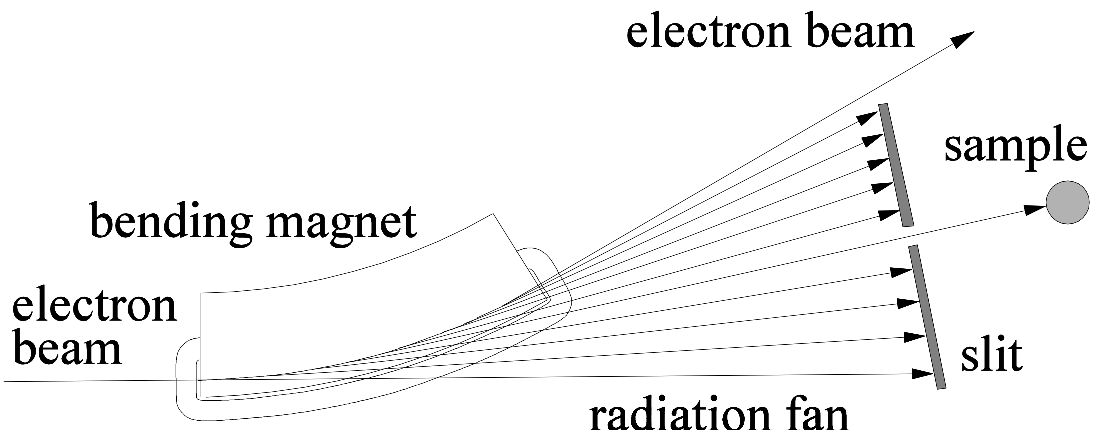
E = particle energy
R = radius of curvature
m_0 = particle mass

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

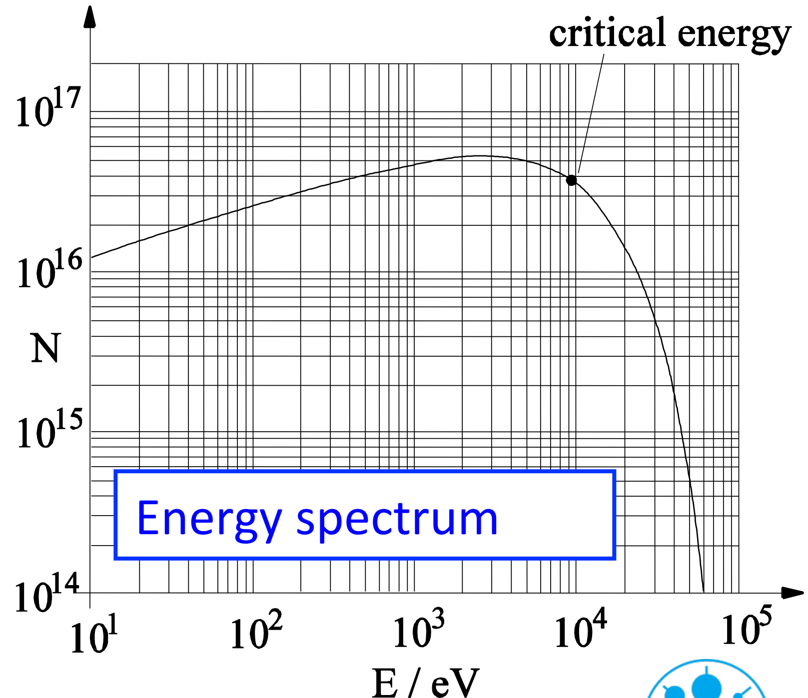
Radiation from a bending magnet



$$E = 5\,\mathrm{GeV}$$

$$\Longrightarrow \gamma = 10^4$$

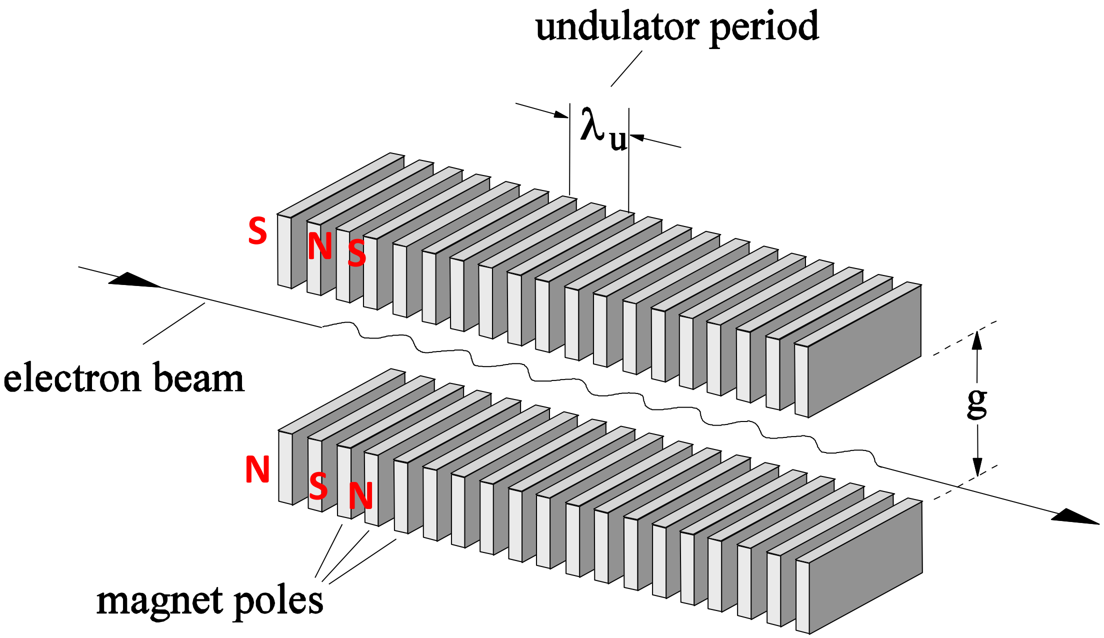
$$\Longrightarrow \Delta\Theta = \frac{2}{\gamma} = 0.2\,\mathrm{mrad} \approx 40''$$

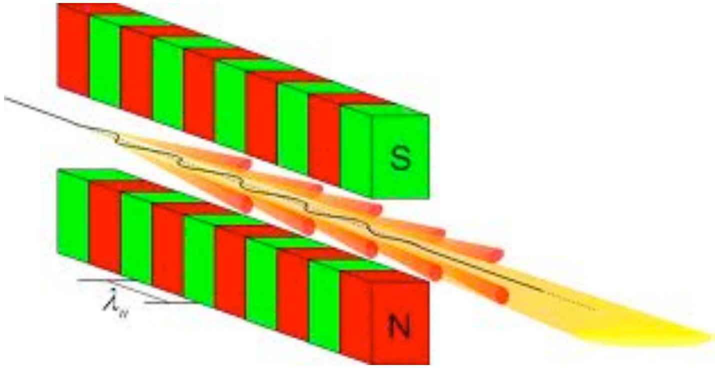


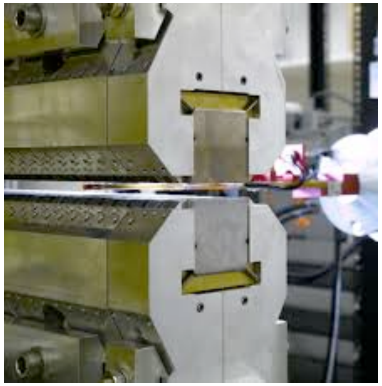
- The radiation is emitted in the plane of the orbiting particles
- The radiation is linearly polarized in the orbit plane

Wiggler and Undulators

Multiplication of the radiation intensity by periodically repeated magnet structures

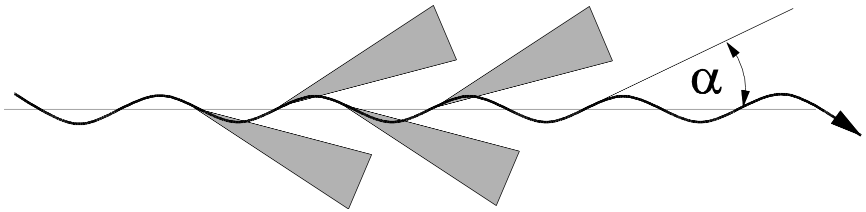


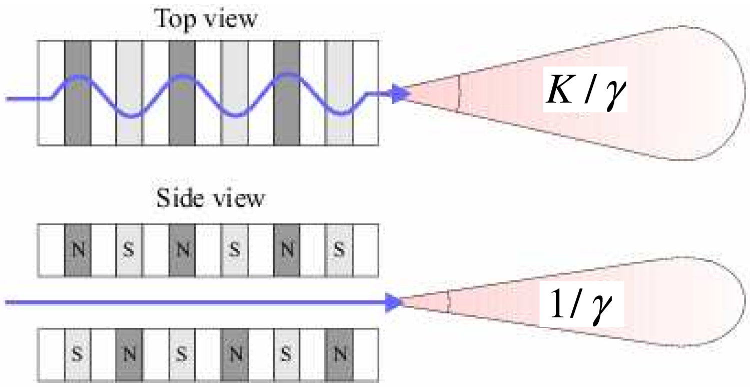




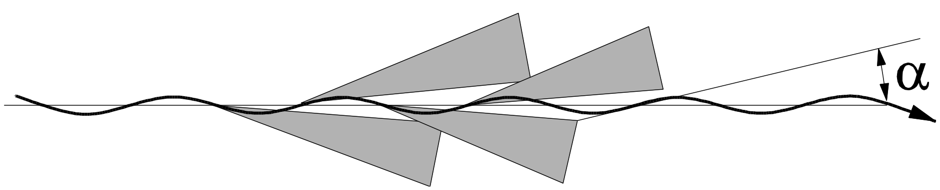
Insertion devices: Wigglers and Undulators

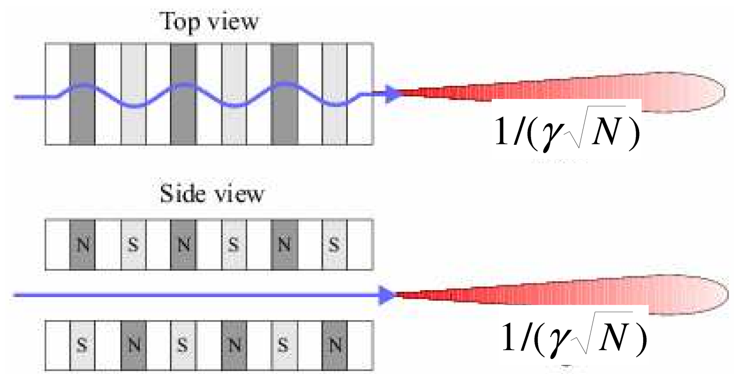
Wiggler regime: $\alpha > 1/\gamma$





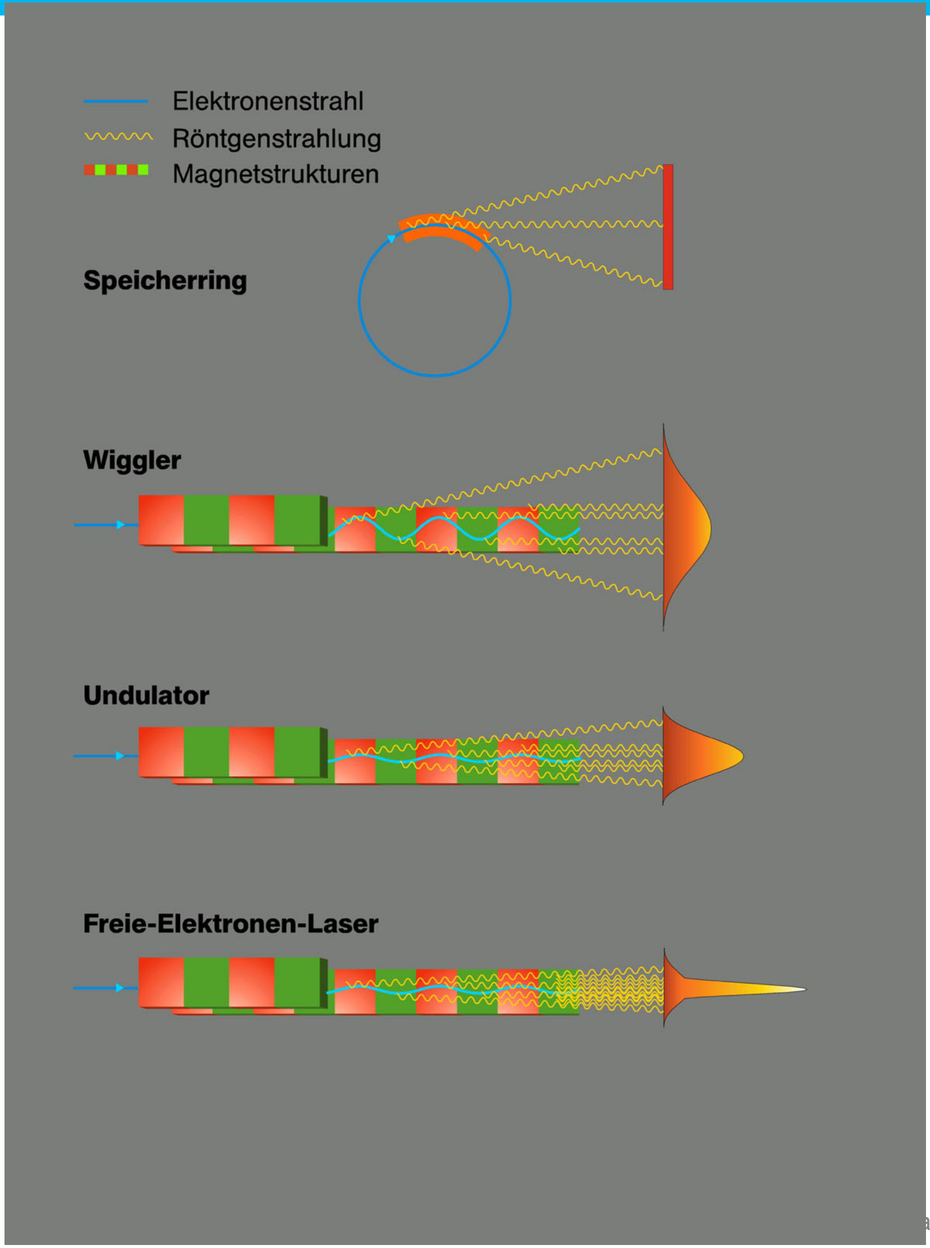
Undulator regime: $\alpha < 1/\gamma$





In the undulator regime the radiation cones overlap and the wave trains can interfere constructively

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

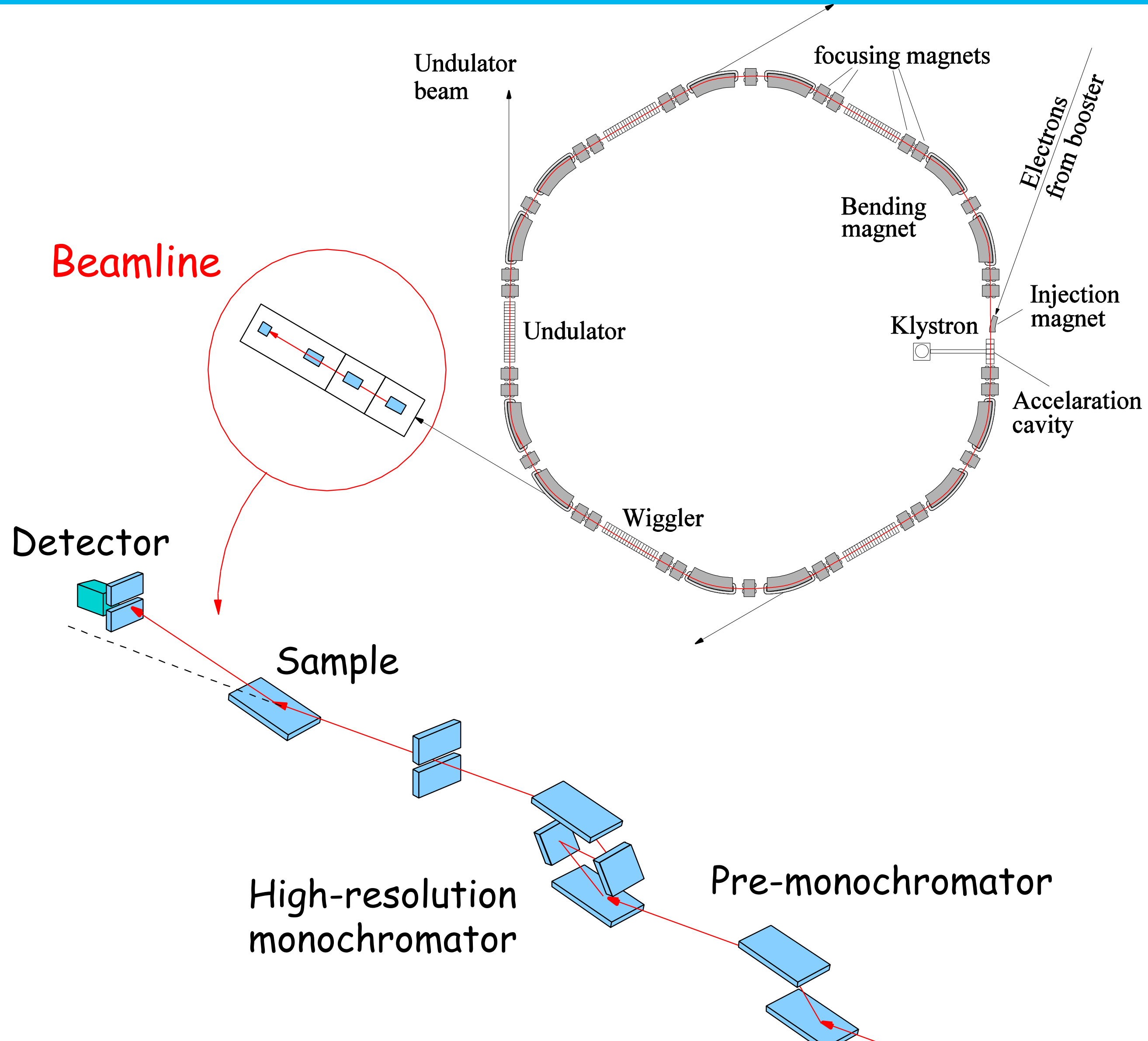
$$I \sim N_e N_p^2$$

Fully coherent superposition

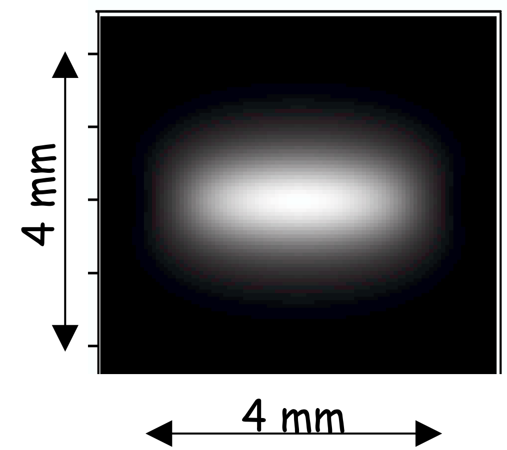
$$I \sim N_e^2 N_p^2$$

Self-Amplified Stimulated Emission (SASE)

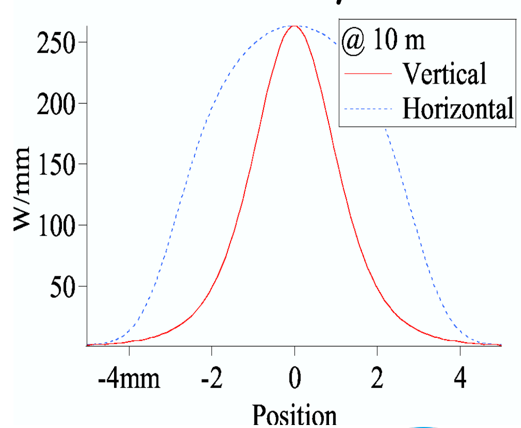
Getting the Radiation to the Experiment: Storage Ring and Beamlines



Photon beam profile @ 10 m distance



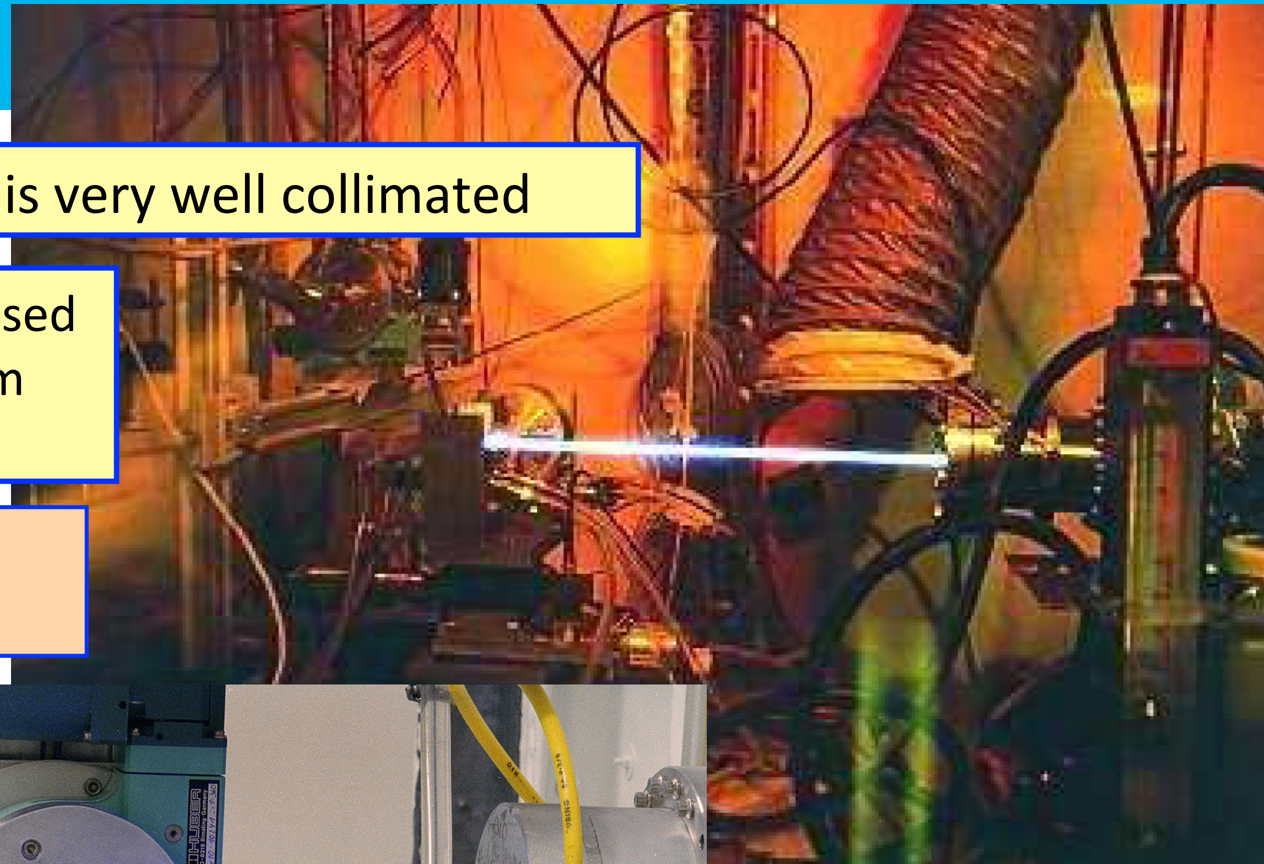
Power density

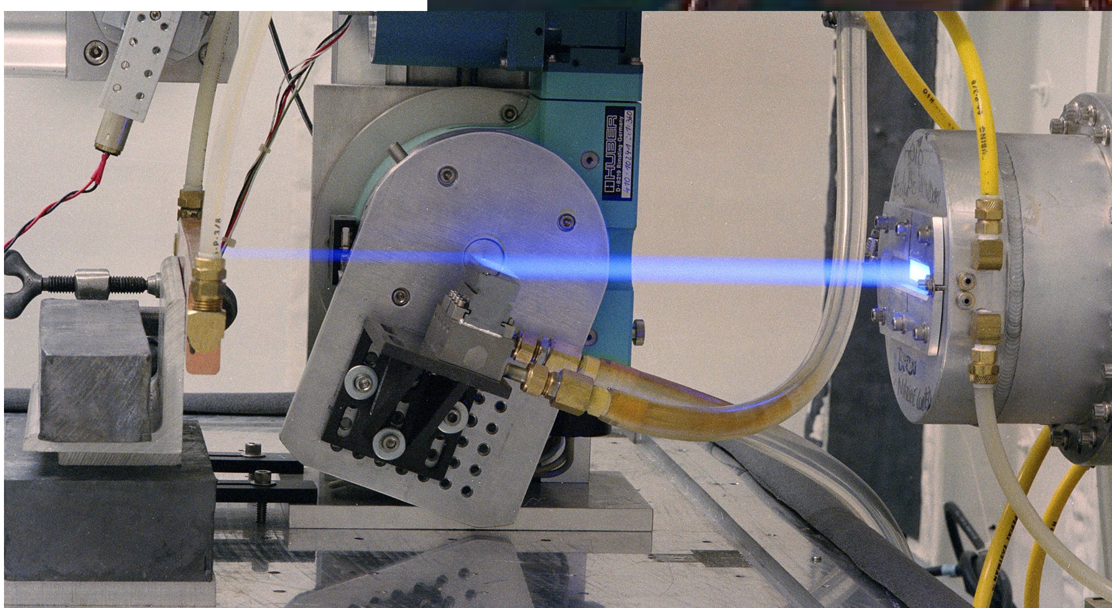


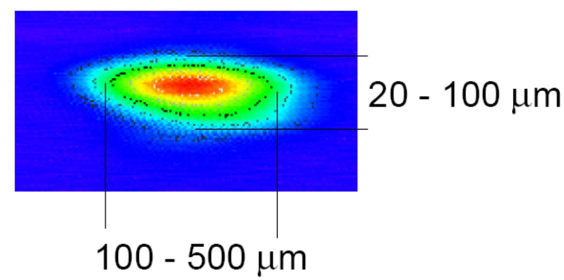
Synchrotron radiation is very well collimated

With collimated and focused radiation one can perform high-resolution studies

Applications in physics, biology, chemistry, ...

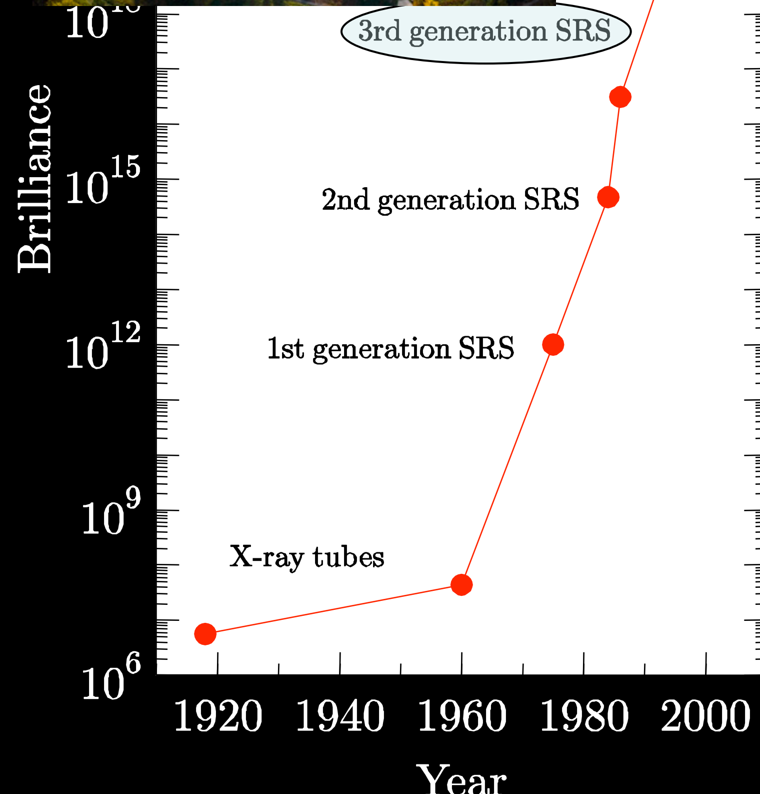




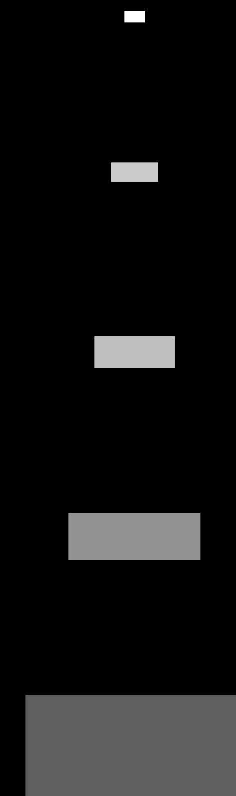


Evolution of synchrotron radiation sources

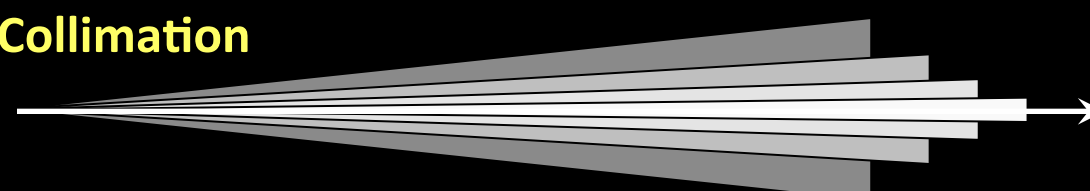
$$B = \frac{\text{Number of Photons/s}}{\text{Solid angle} \cdot \text{Source size} \cdot \Delta E}$$



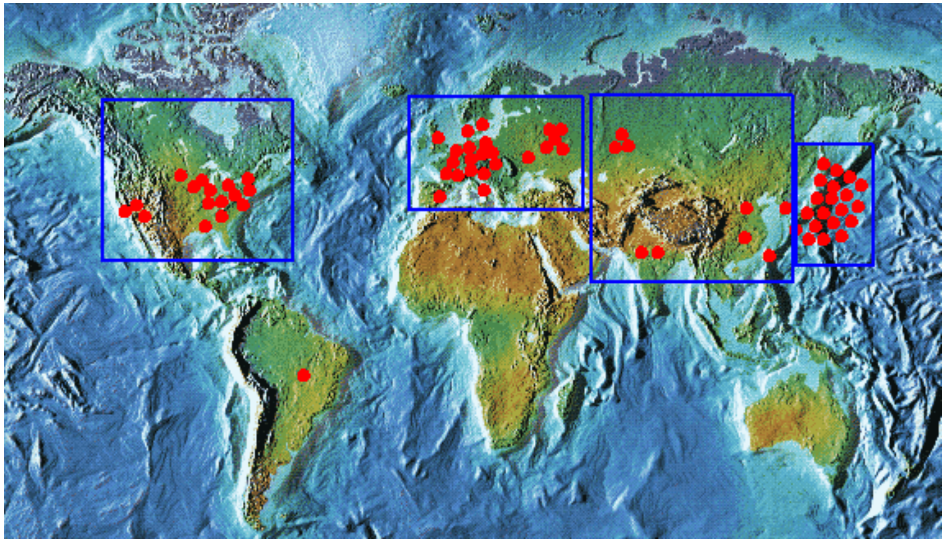
Source size

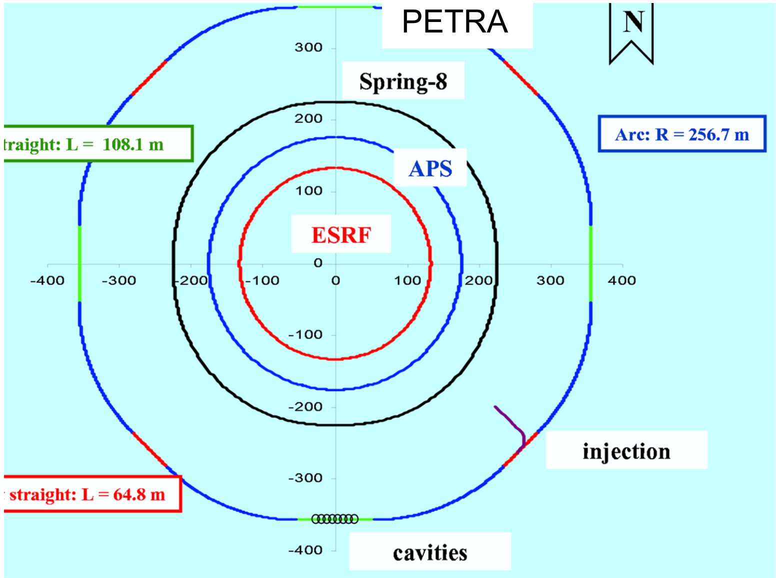


Collimation



Synchrotron Radiation Facilities around the World

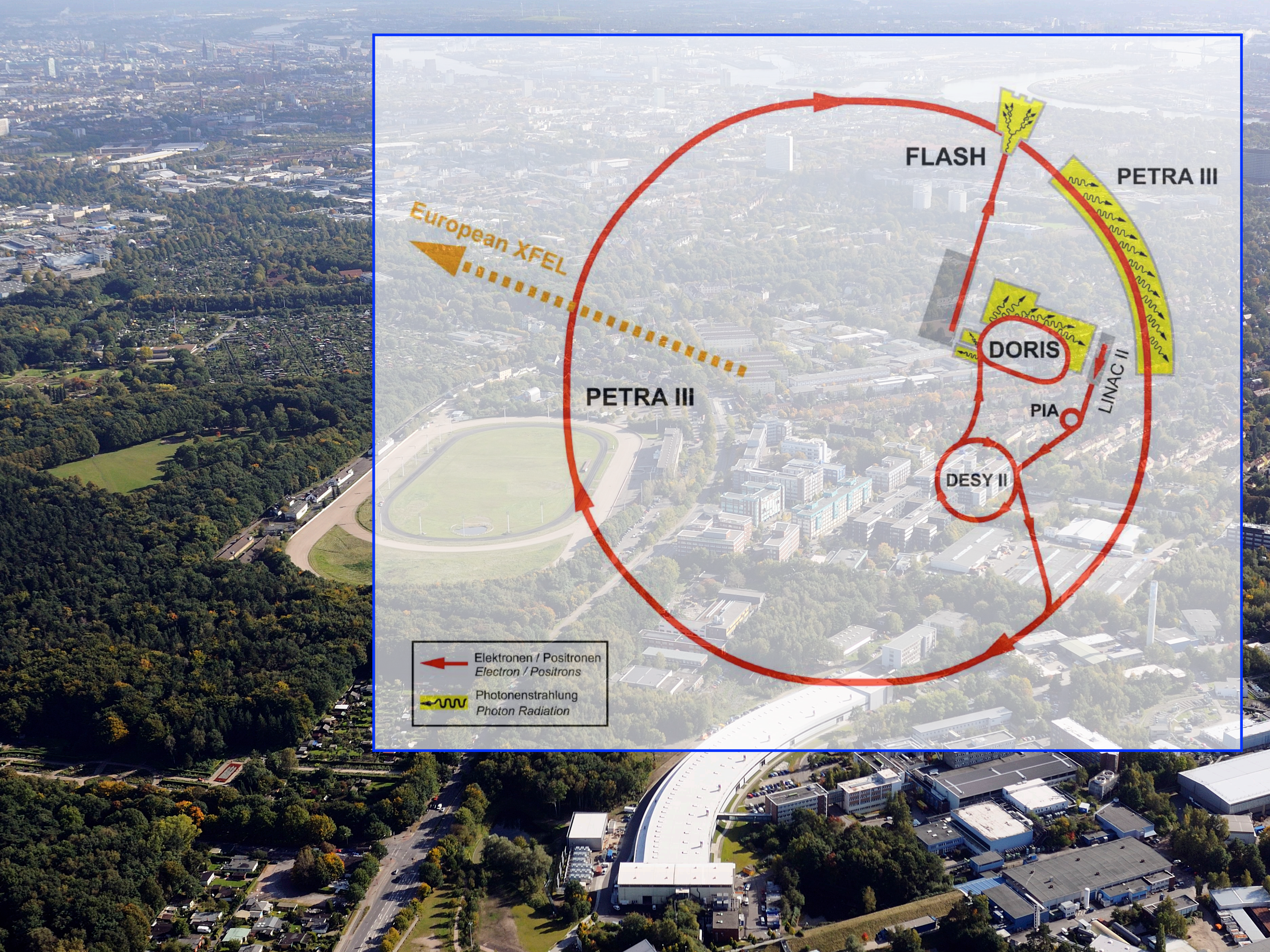




Parameters of selected facilities

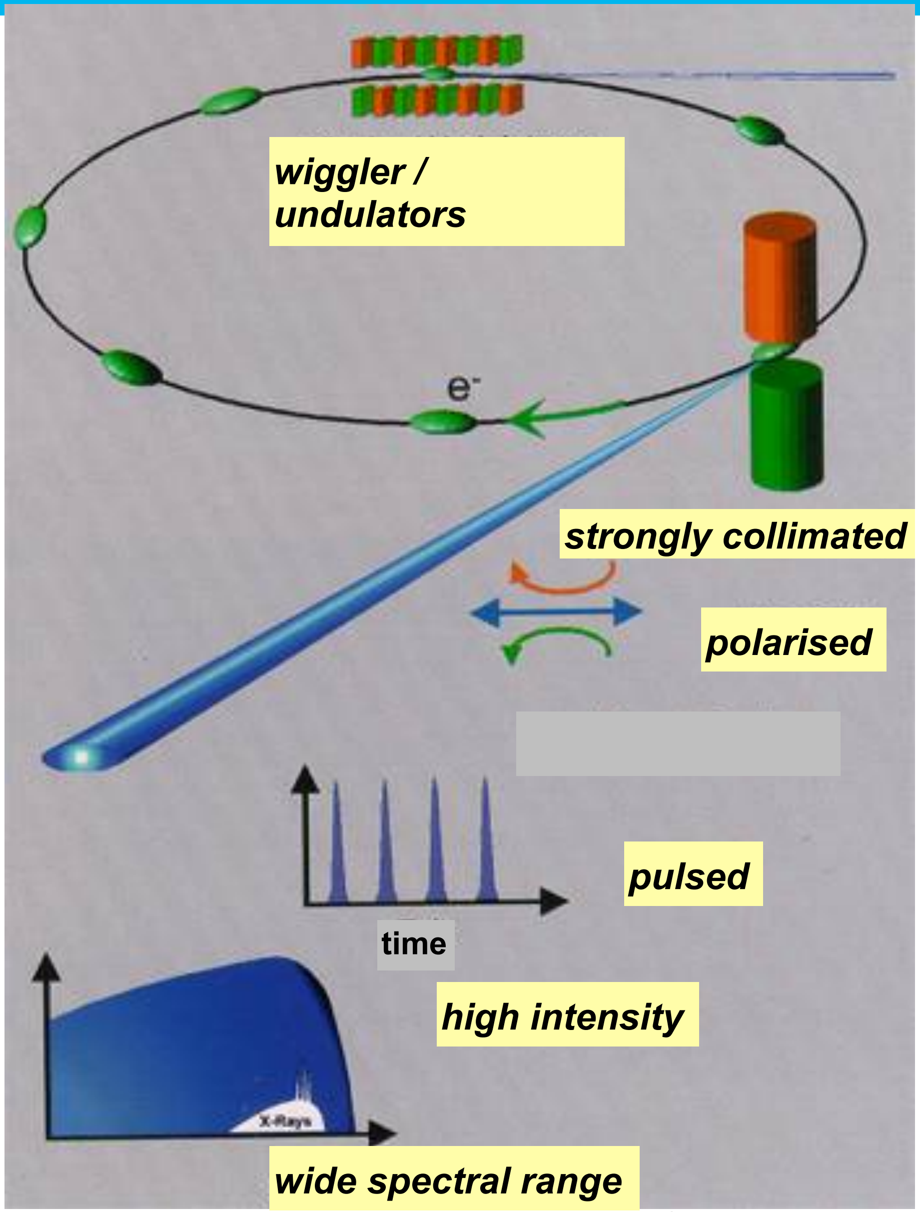
Storage Ring, Location	Particle Energy [GeV]	Circum-ference [m]	Orbit Period [µs]	Bucket Separat. [ns]	Bunch Length [ps]
ESRF, Grenoble, France	6.0	844	2.816	2.84	70
APS, Argonne, USA	7.0	1104	3.683	2.84	60
SPring8, Japan	8.0	1436	4.790	1.97	100
PETRA III, Hamburg	6.0	2304	7.680	8.00	100

PETRA III, DESY, Hamburg, Germany



FLASH
PETRA III
European XFEL
DORIS
LINAC II
PETRA III
PIA
DESY II
Elektronen / Positronen
Electron / Positrons
Photonenstrahlung
Photon Radiation

Summary: Properties of Synchrotron Radiation



Properties:

- **high brilliance and flux**
- **infrared up to hard X-rays (>100keV)**
- **polarization**
- **time structure**