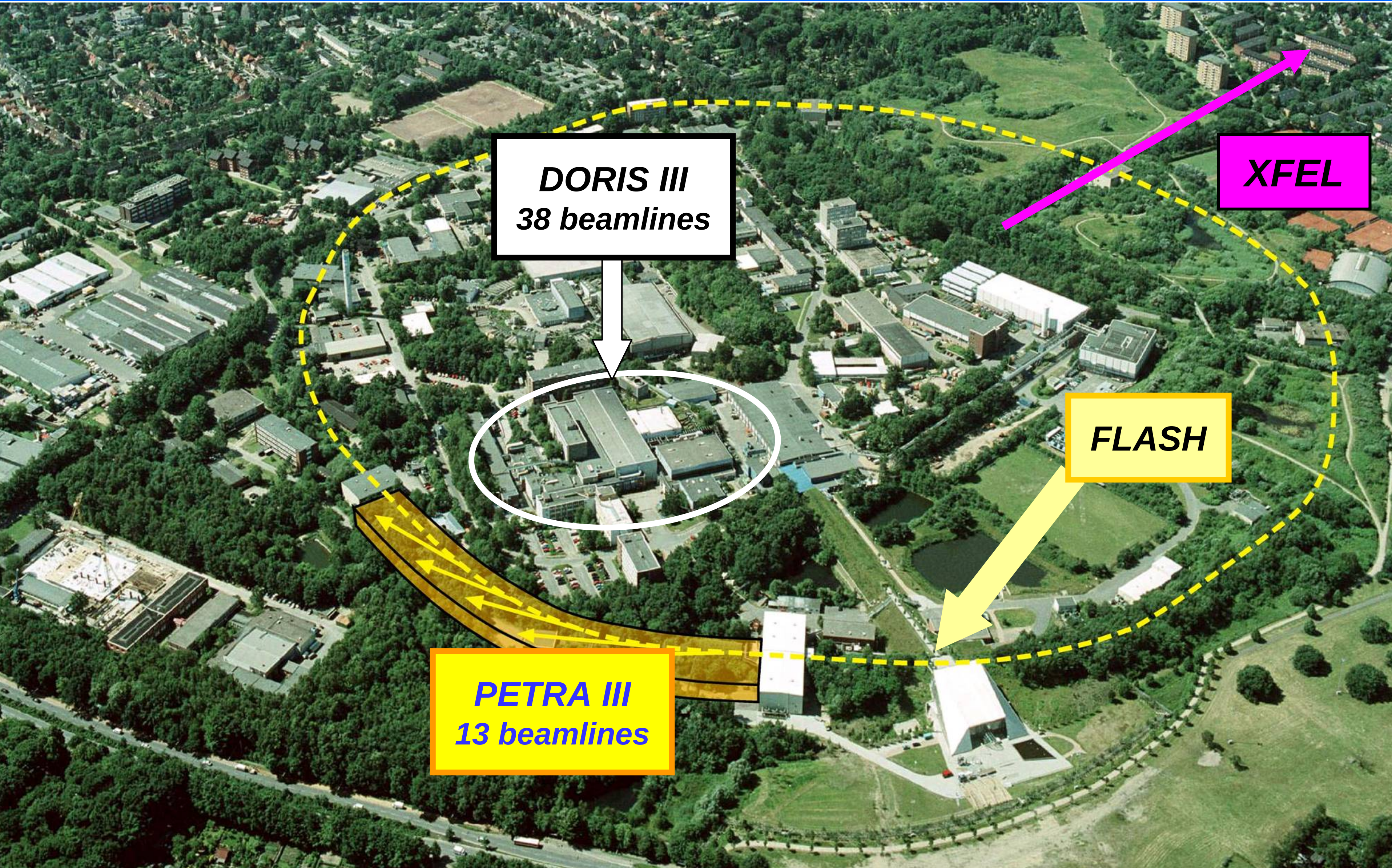
Research with Synchrotron Radiation

Part I

Ralf Röhlsberger

- Generation and properties of synchrotron radiation
- Radiation sources at DESY

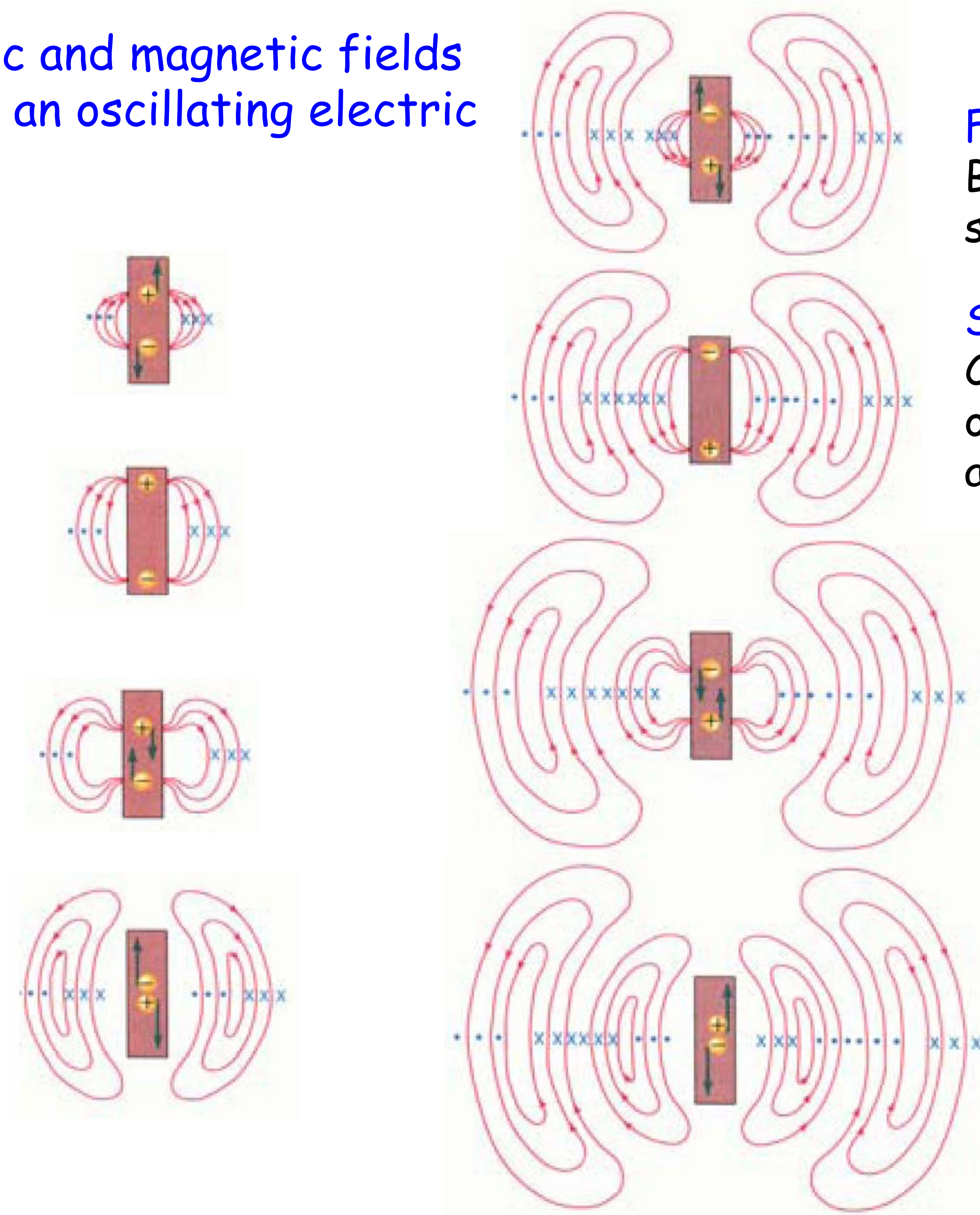
Synchrotron Radiation Sources at DESY



How to generate synchrotron radiation ?

Generation of electromagnetic waves

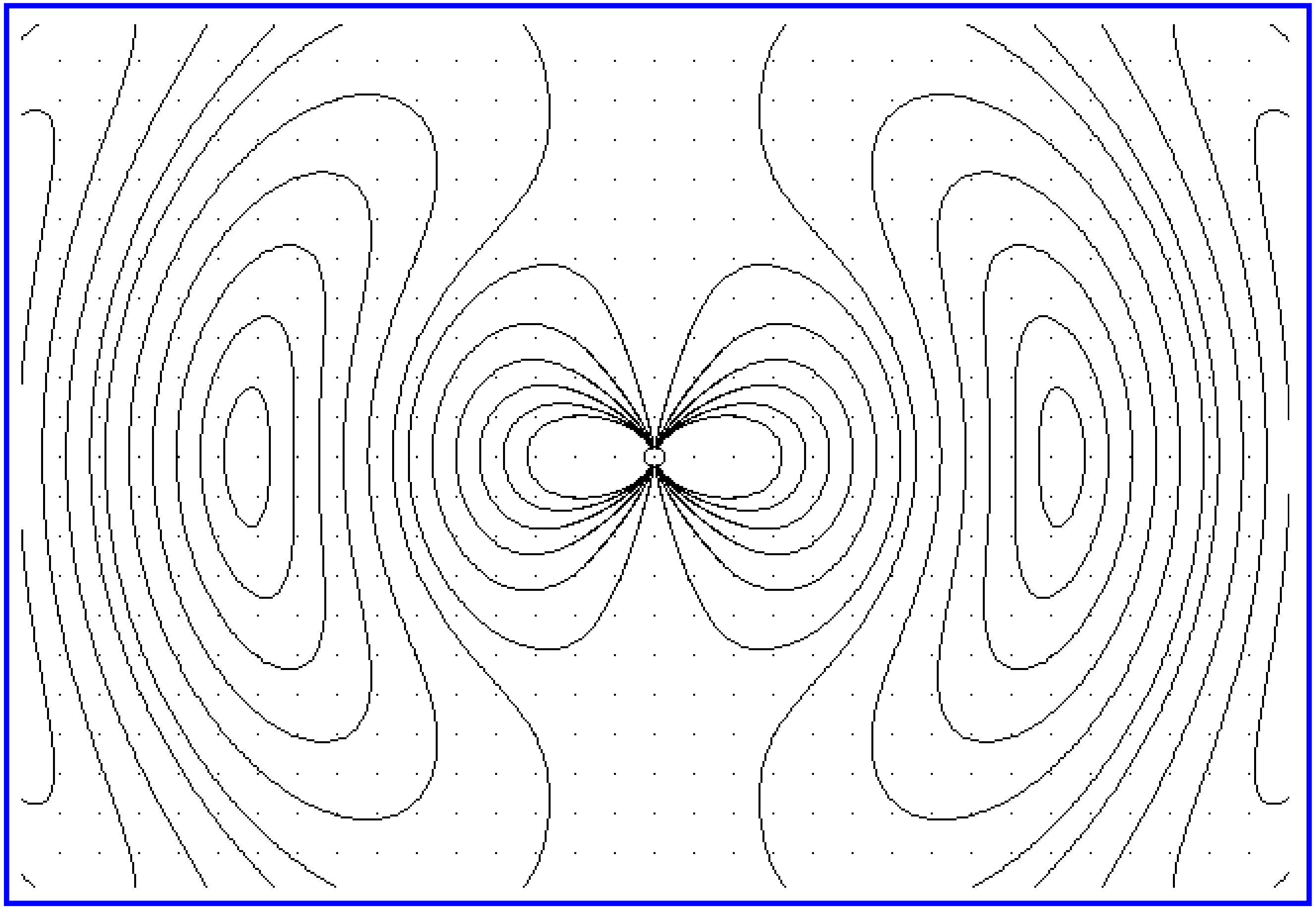
Electric and magnetic fields around an oscillating electric dipole



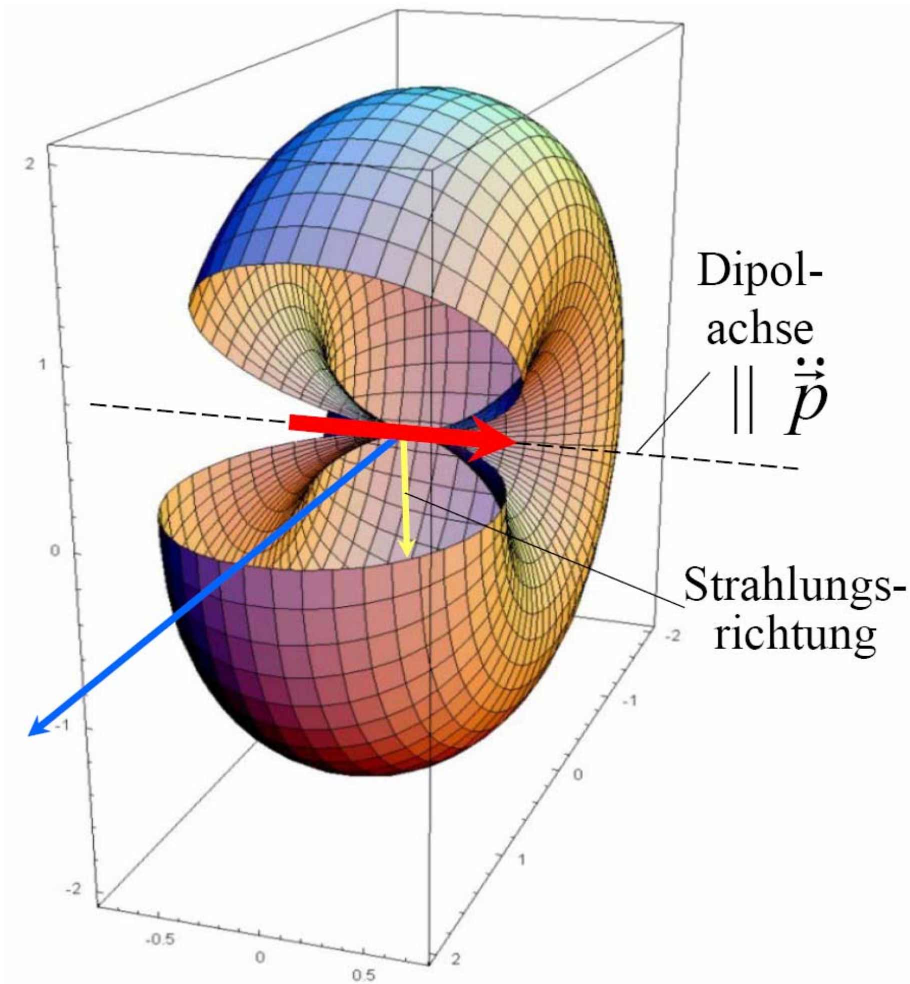
First Halfperiod: E- and B-fields propagate into space

Second Halfperiod: Change of sign, the outer fields decouple and propagate freely.

Field lines around an oscillating electric dipole



Radiation characteristic of a Hertz dipole



Every accelerated charge radiates electromagnetic waves

Radiated power

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

Larmor formula

Oscillatory motion:
No radiation in direction of the oscillation.

Maximum radiated power perpendicular to the oscillation direction:

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:

$$P_S = \frac{e^2 c}{6\pi\,\epsilon_0}\frac{1}{(m_0c^2)^4}\frac{E^4}{R^2}$$

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

Dependence on particle mass:

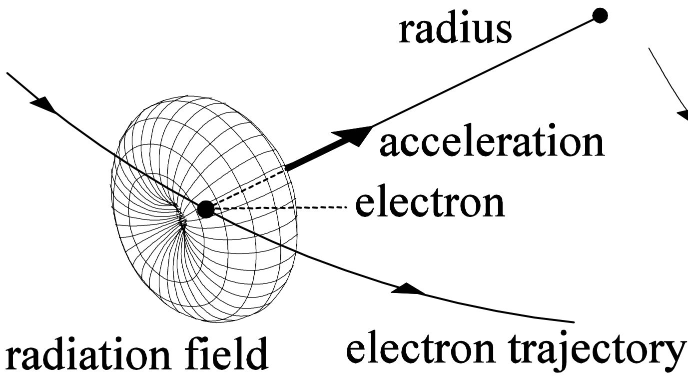
$$\frac{P_{S,e}}{P_{S,p}} = \left(\frac{m_p}{m_e}\right)^4 \approx 10^{13}$$

Synchrotron radiation is only for electrons/positrons
sufficiently intense

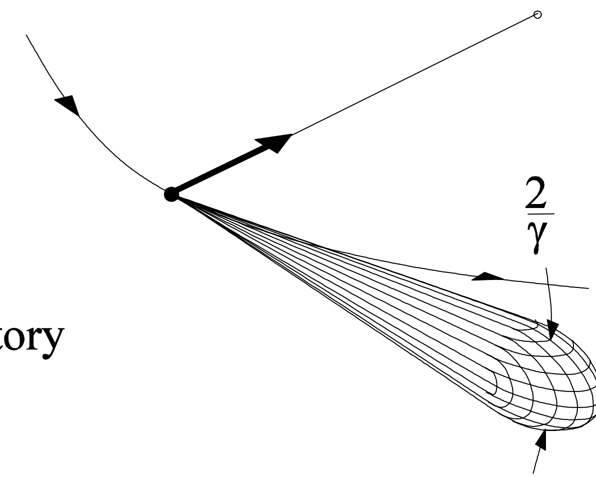
Emission pattern for circular accelaration

Lorentz transformation →

Rest frame

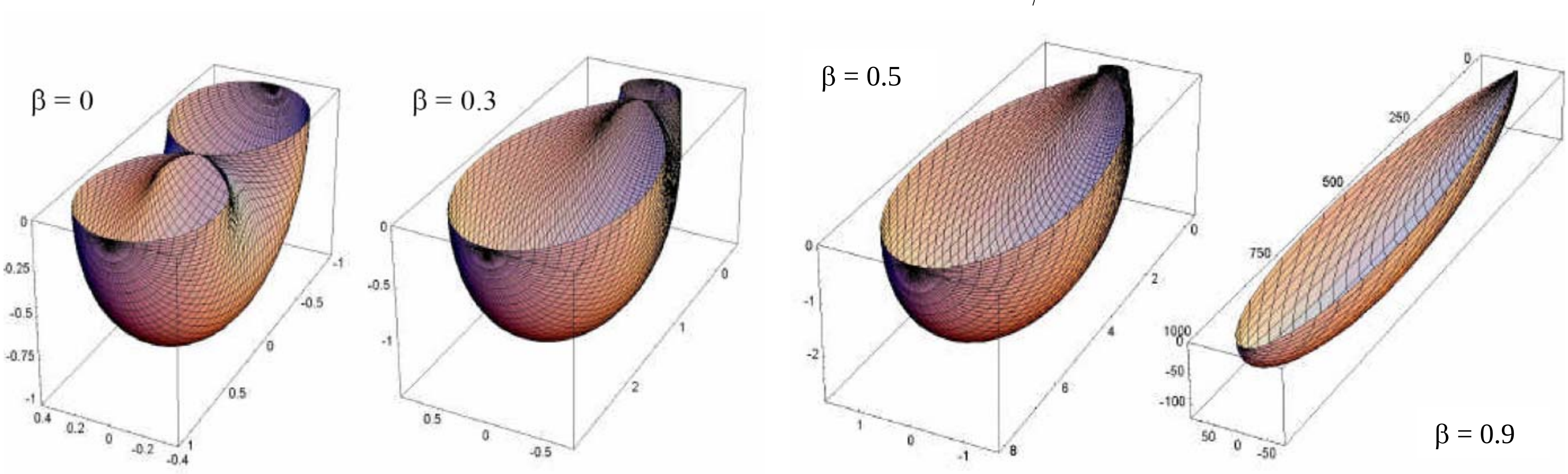


Laboratory frame



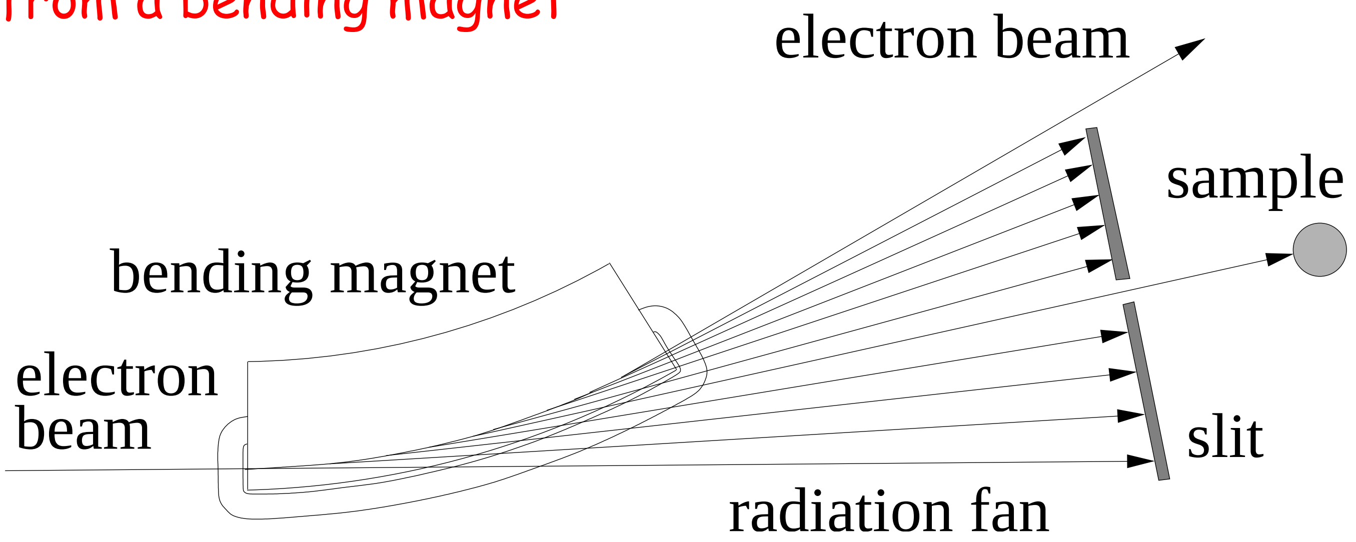
$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{E}{m_0 c^2}$$

Opening angle



Emission pattern

Radiation from a bending magnet

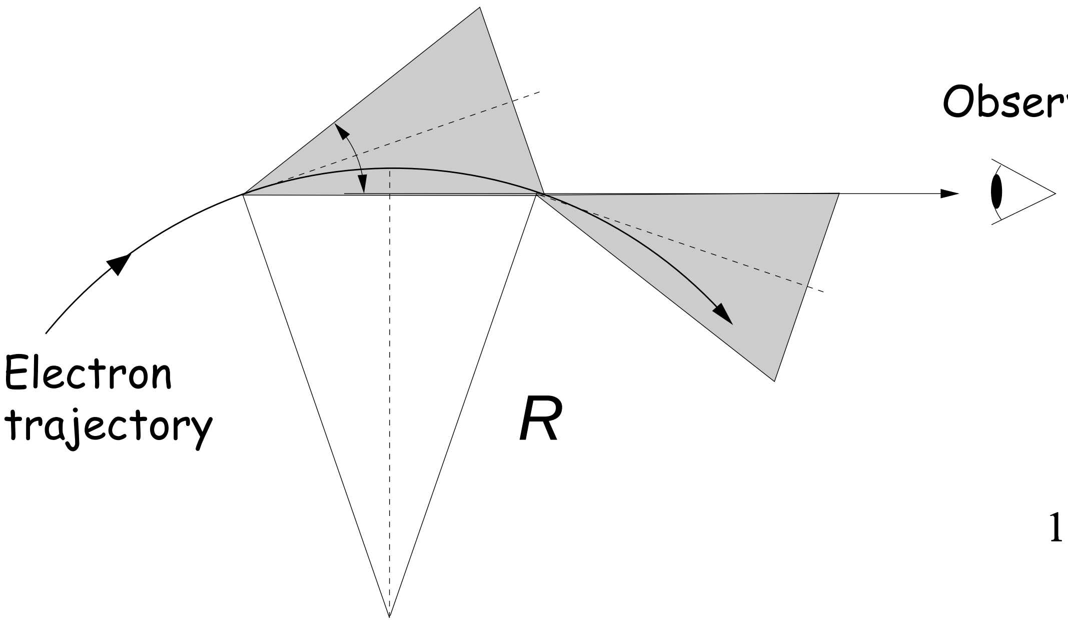


$$E = 5\,\mathrm{GeV}$$
$$\Longrightarrow \gamma = 10^4$$
$$\Longrightarrow \Delta\Theta = \frac{2}{\gamma} = 0.2\,\mathrm{mrad} \approx 40''$$

The radiation is emitted in the plane of the orbiting particles

The radiation is linearly polarized in the orbit plane

Pulse duration and energy spectrum



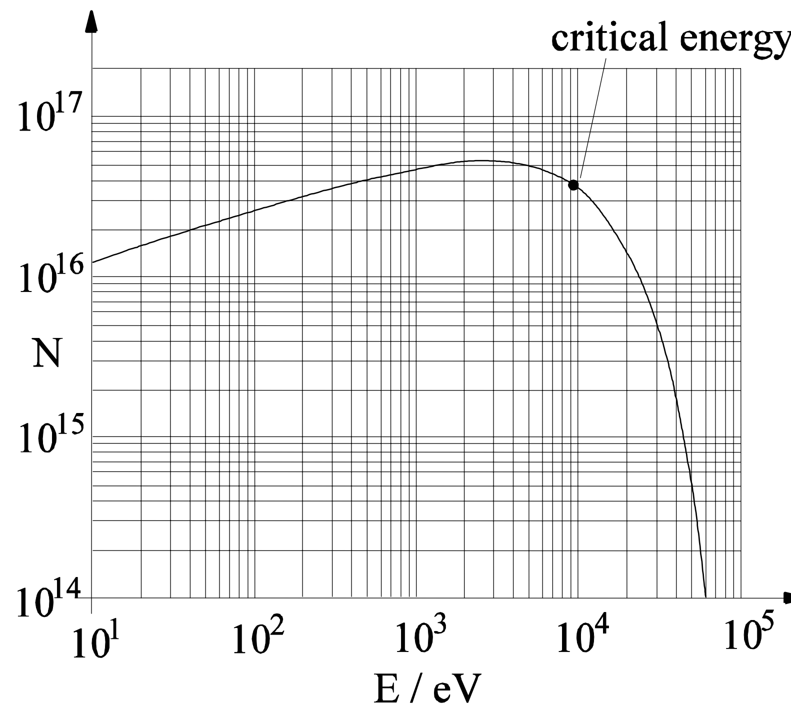
Duration of radiation flash (single electron)

$$\Delta t = \frac{4R}{3\,c\,\gamma^3}$$

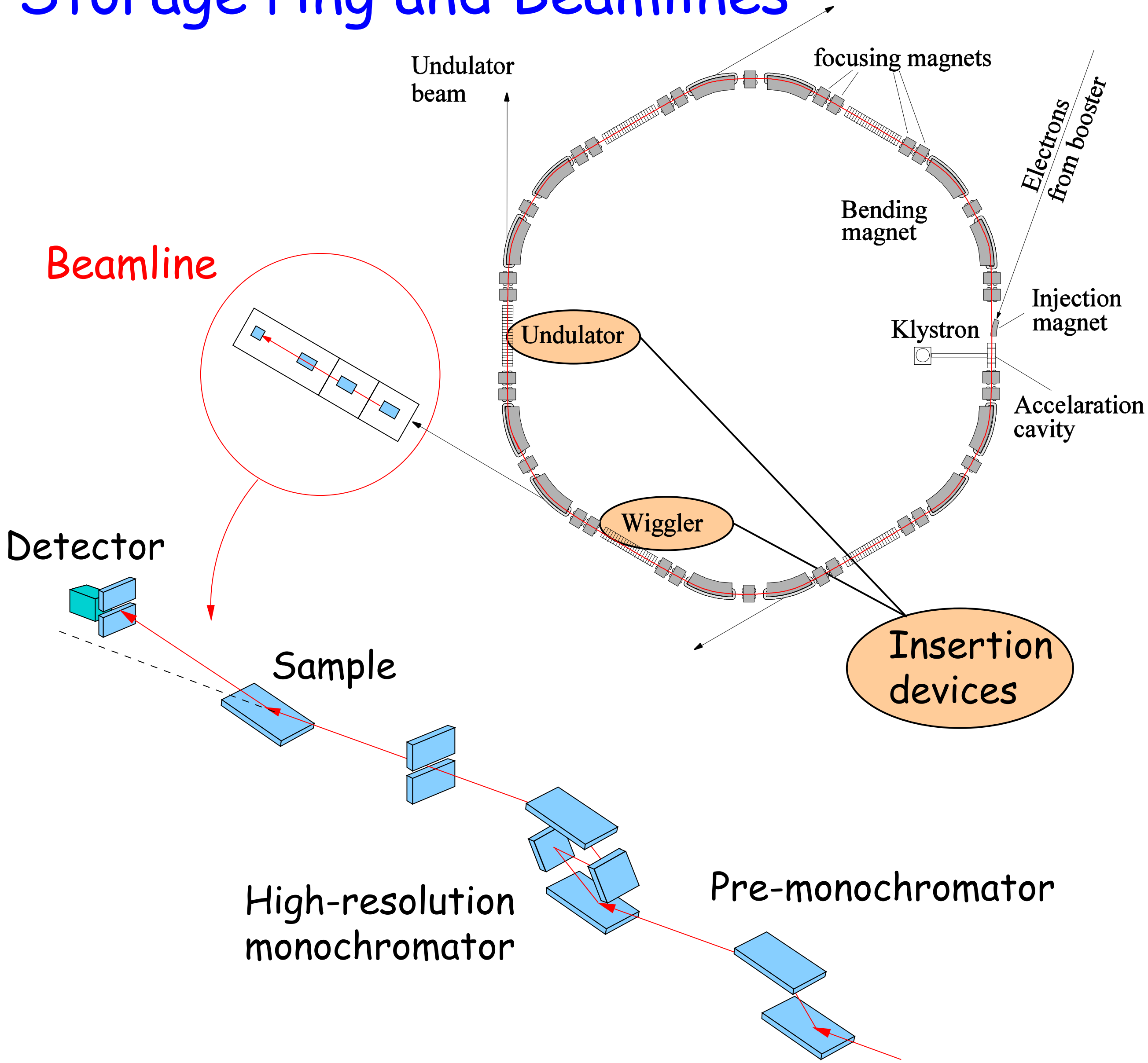
$$R = 30\,\mathrm{m} \qquad \gamma = 10^4$$

$$\Longrightarrow \quad \Delta t = 10^{-19}\,\mathrm{s}$$

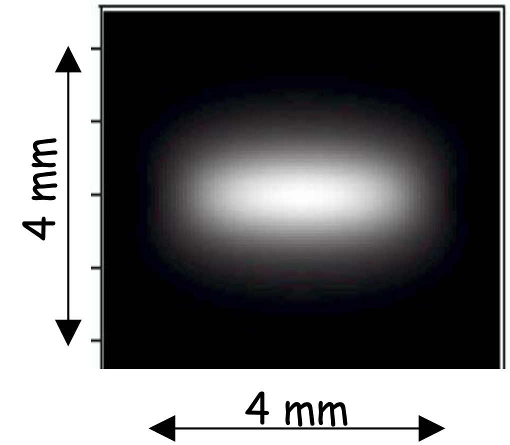
$$\Longrightarrow \quad E_c = \frac{h}{\Delta t} \approx 40\,\mathrm{keV}$$



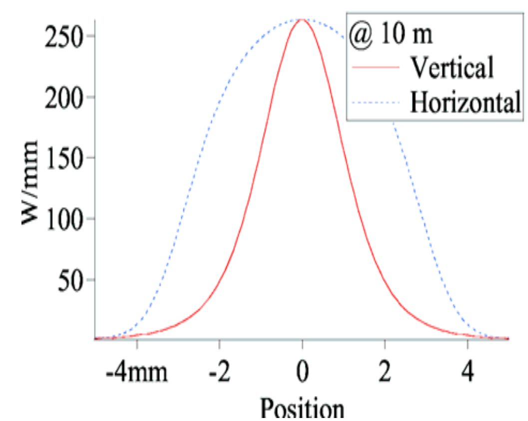
Storage ring and Beamlines



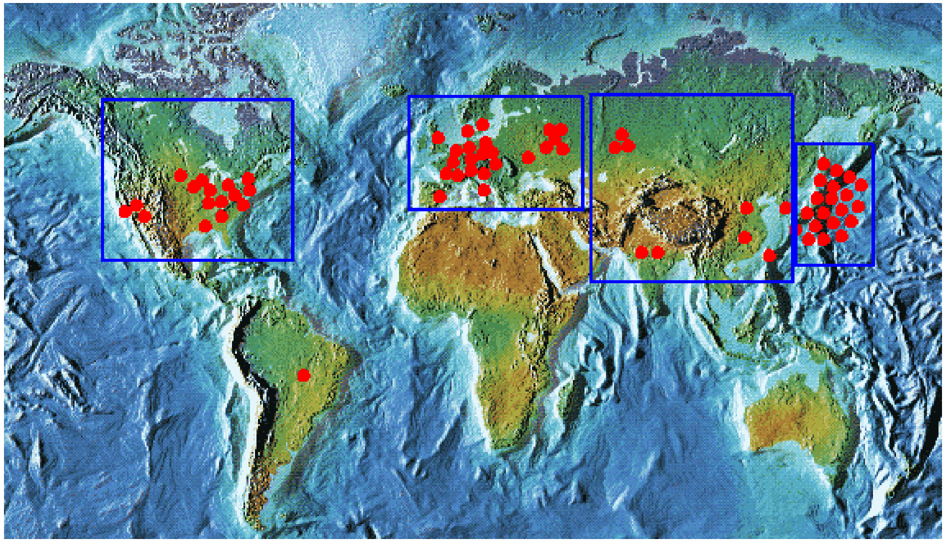
Photon beam profile @ 10 m distance



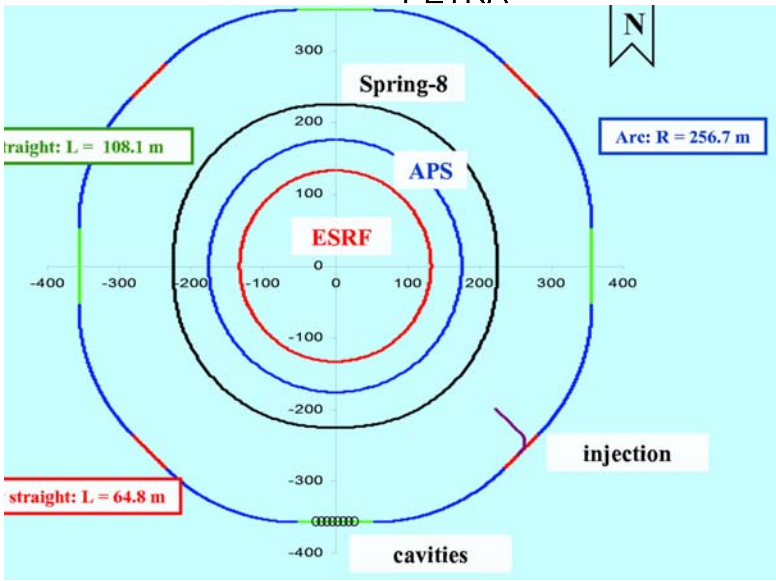
Power density



Synchrotron radiation facilities around the world



PETRA



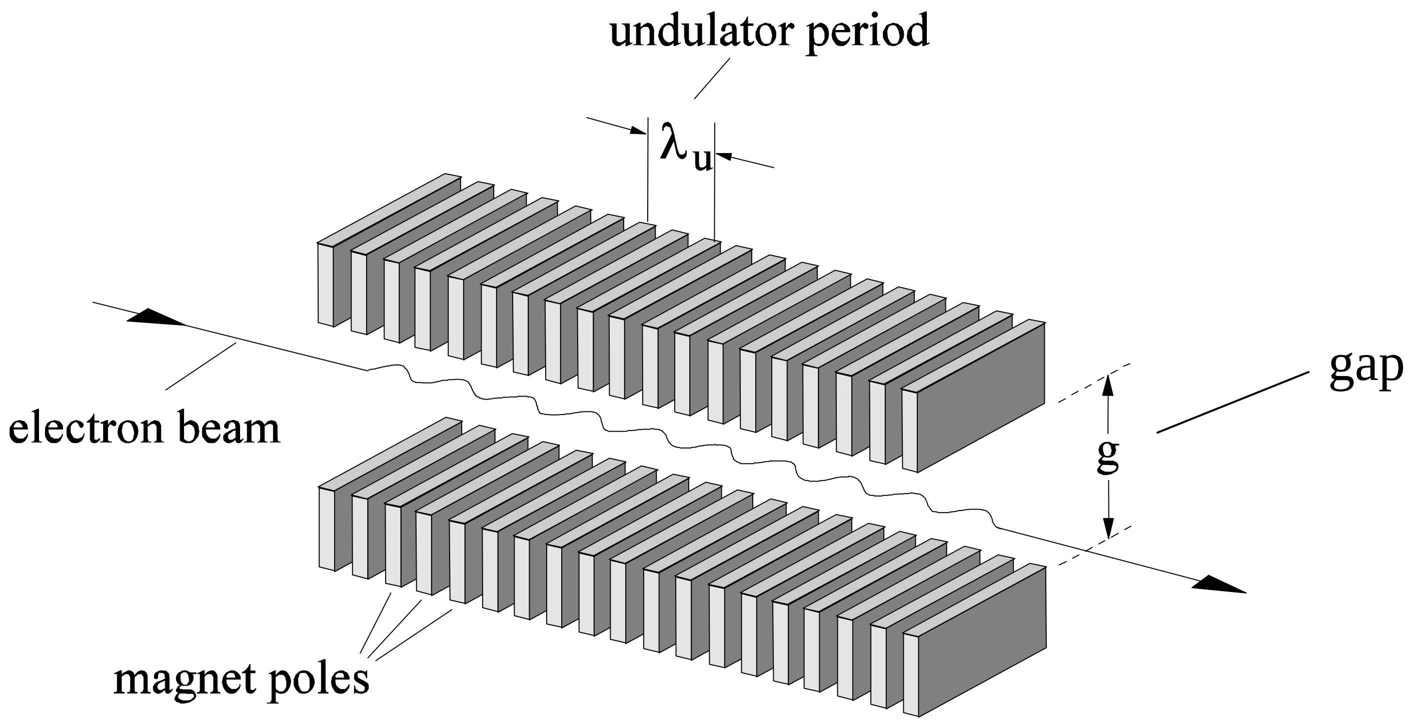
Parameters of selected facilities

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 II, Hamburg	12.0	2304	7.680	2.00	100

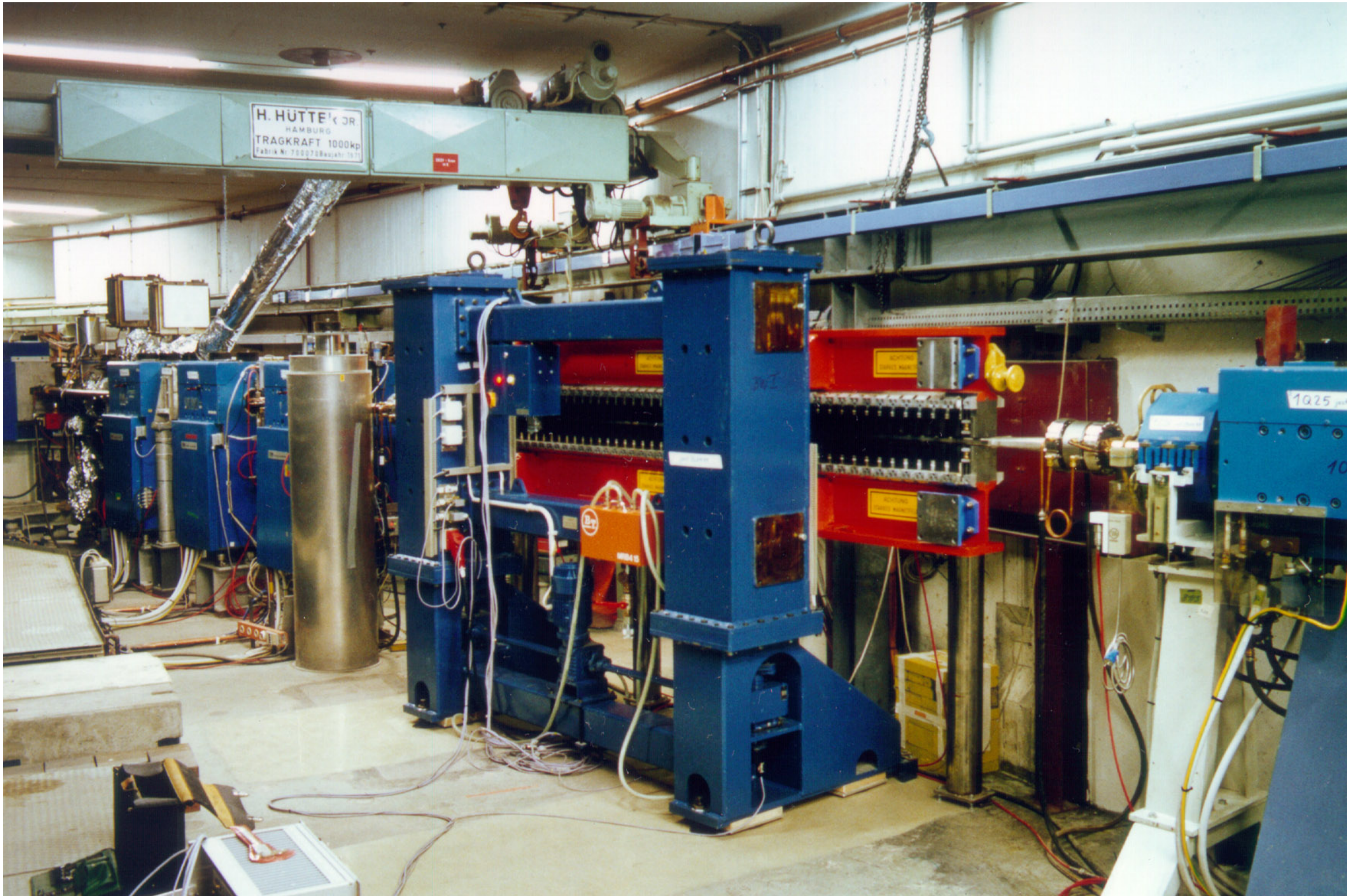
European Synchrotron Radiation Facility (ESRF), Grenoble,France

Insertion devices: Wigglers and undulators

Electrons travelling through periodic magnet structures (insertion devices) :

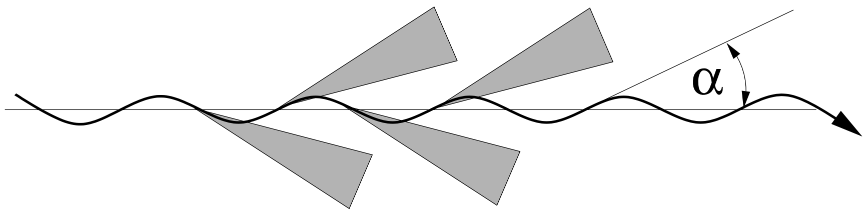


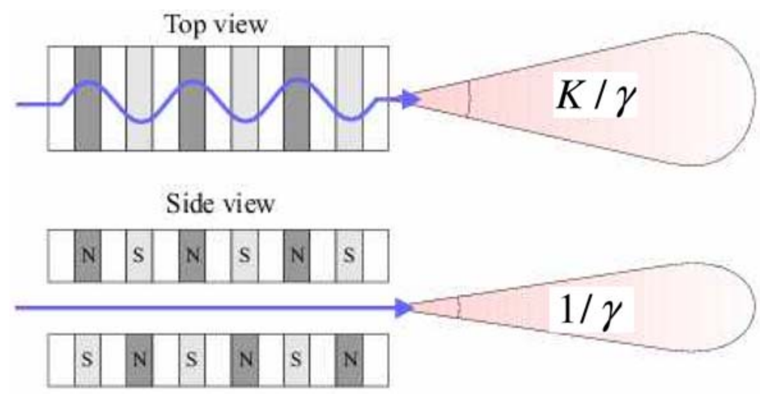
Wiggler at DORIS III



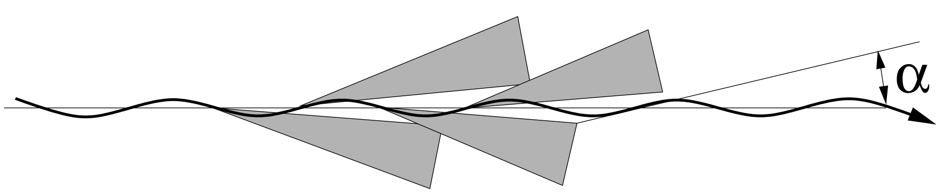
Insertion devices: Wigglers and Undulators (1)

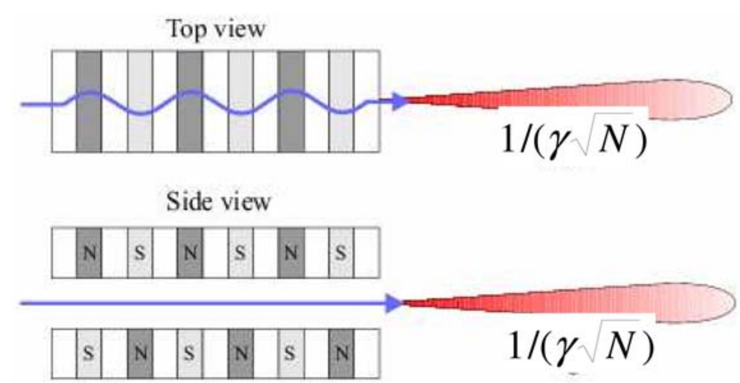
Wiggler regime: $\alpha > 1/\gamma$





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





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

Insertion devices: Wigglers and Undulators (2)

$$\alpha = \frac{K}{\gamma}$$

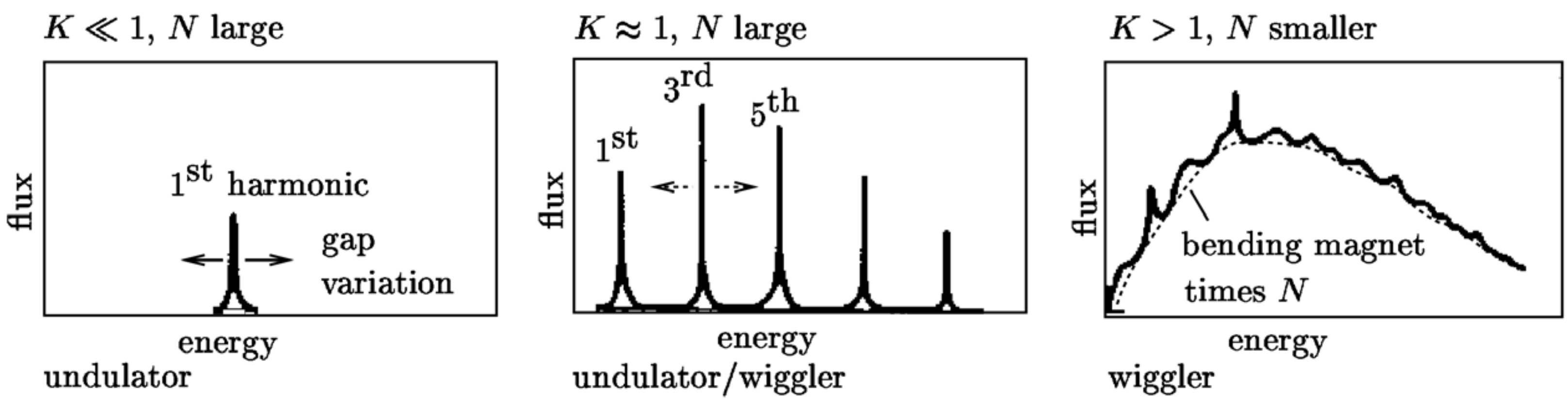
K : deflection parameter

$$K = 0.934\,\lambda_u(\mathrm{cm})\,B_0(\mathrm{T})$$

λ_u : magnetic period

B_0 : magnetic field at orbit

K determines the shape of the energy spectrum of an insertion device:



Energy of the n^{th} harmonic:

$$E_n(\mathrm{keV}) = n\,\frac{0.95\,E^2(\mathrm{GeV})}{\lambda_u(\mathrm{cm})(1+K^2/2)}$$

Angular width of n^{th} harmonic:

$$\sigma = \frac{1}{\gamma}\sqrt{\frac{1+\frac{1}{2}K^2}{2Nn}}$$

How to characterize the properties of a synchrotron radiation source ?

$$\text{Total flux} \equiv \frac{\text{Photons}}{\text{s}}$$

$$\text{Spectral flux} = \frac{\text{Total flux}}{0.1\%\text{bandwidth}} \quad \left[\frac{\text{Photons/s}}{0.1\%\text{bandwidth}}\right]$$

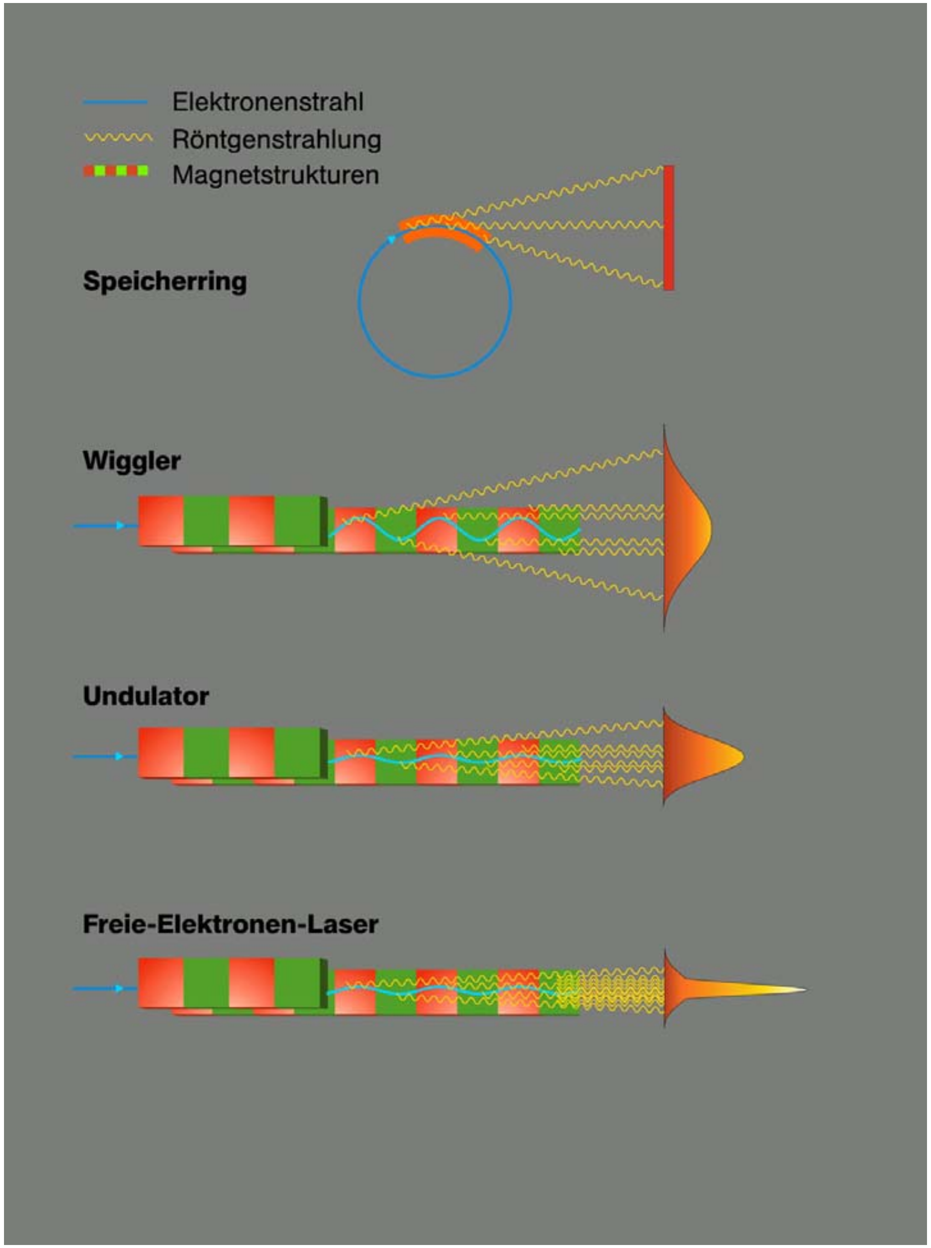
$$\text{Brightness} = \frac{\text{Total flux}}{\text{solid angle} \cdot 0.1\%\text{bandwidth}} \quad \left[\frac{\text{Photons/s}}{\text{mrad}^2 \cdot 0.1\%\text{bandwidth}}\right]$$

$$\text{Brilliance} = \frac{\text{Total flux}}{\text{solid angle} \cdot \text{source area} \cdot 0.1\%\text{bandwidth}}$$

$$\left[\frac{\text{Photons/s}}{\text{mrad}^2 \cdot \text{mm}^2 \cdot 0.1\%\text{bandwidth}}\right]$$

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

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

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

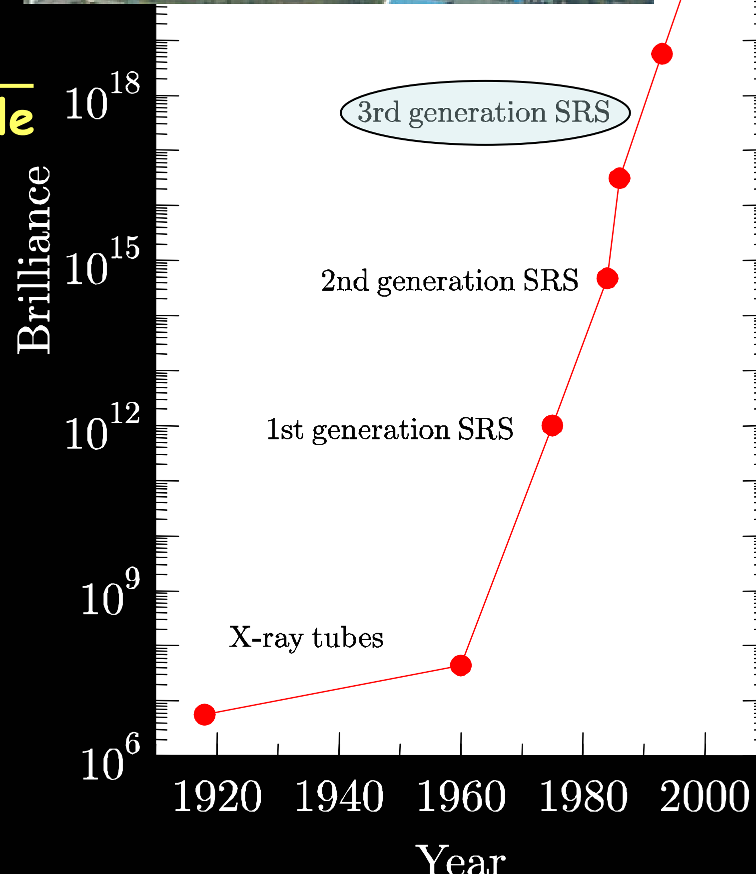
Fully coherent superposition

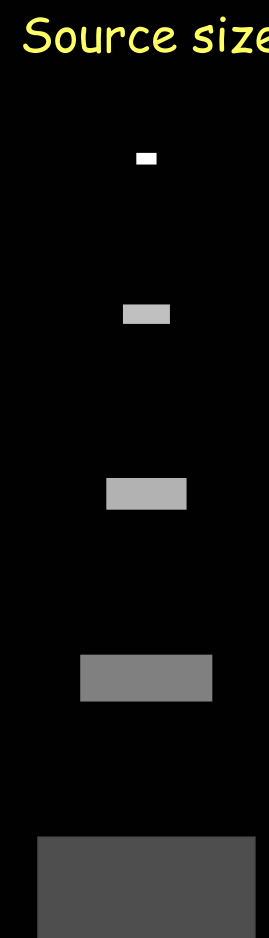
$$I \sim N_e^2 \, N_p^2$$

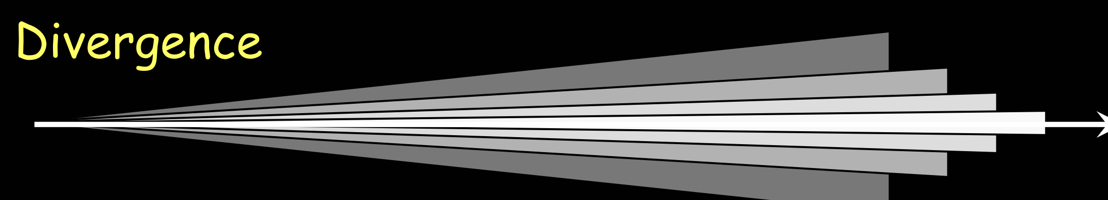
Self-Amplified Stimulated Emission (SASE)

Evolution of Source Brilliance

Brilliance = $\dfrac{\text{Spectral flux}}{\text{source area} \times \text{solid angle}}$

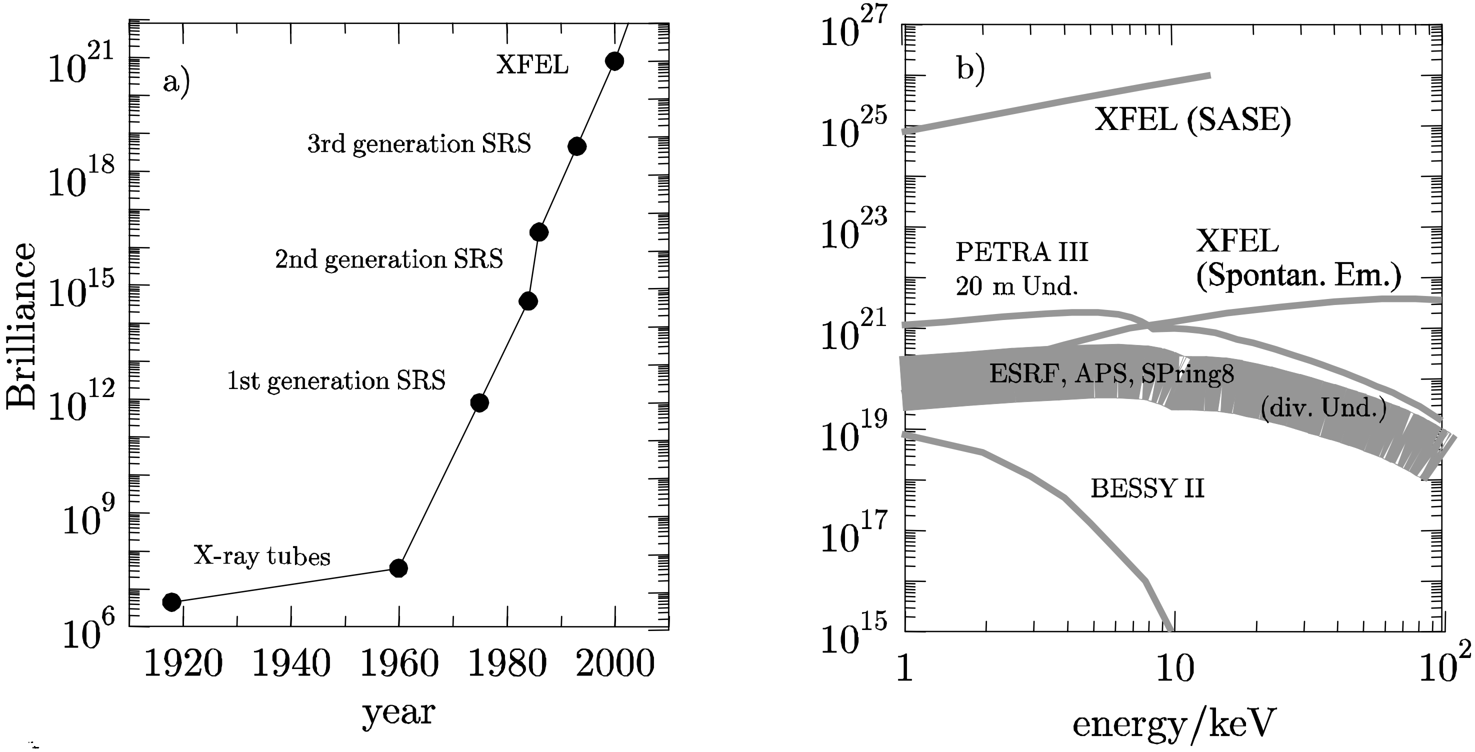






Evolution of Brilliance

(SRS = Synchrotron Radiation Source)



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

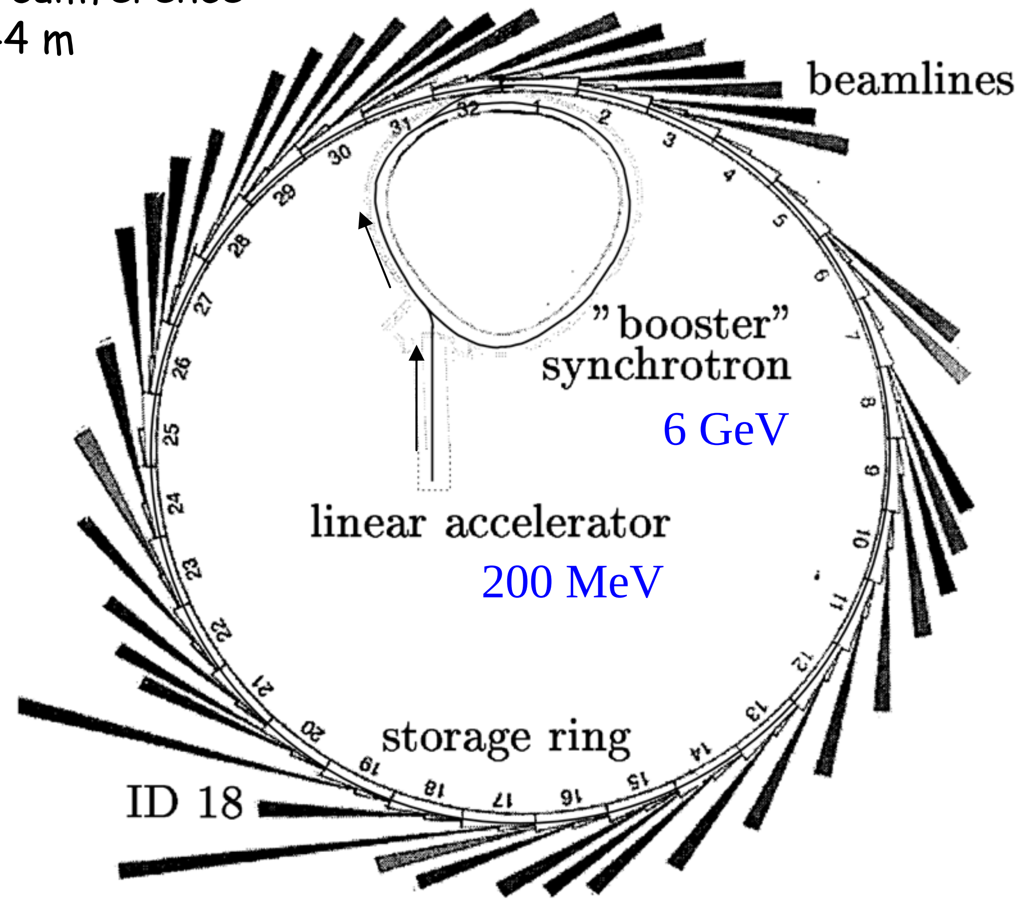
2nd generation: Radiation from bending magnets and introduction of first insertion devices, lower e-beam emittance, optimization of light extraction

3rd generation: dedicated storage rings, very low e-beam emittance, brilliance is figure of merit, mainly undulators, long straight sections

Time structure of synchrotron radiation (1)

Example: European Synchrotron Radiation Facility (ESRF)

Circumference
844 m



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

ν_{rf} = 352 MHz

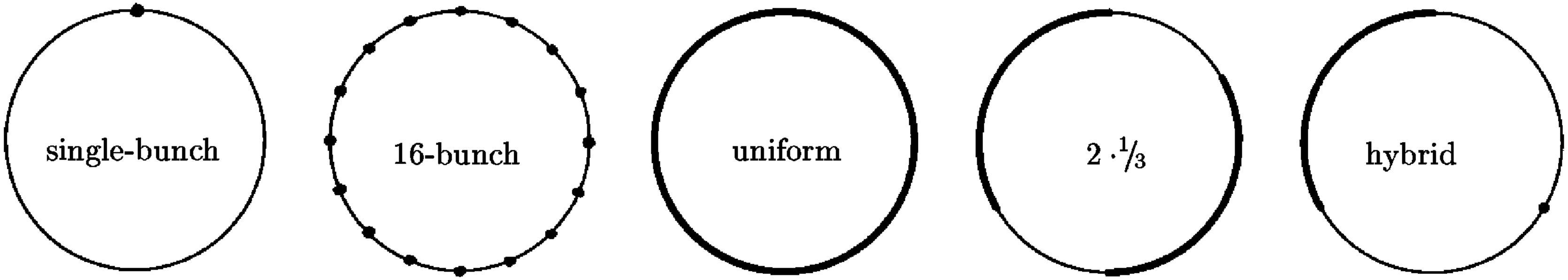
This means:

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

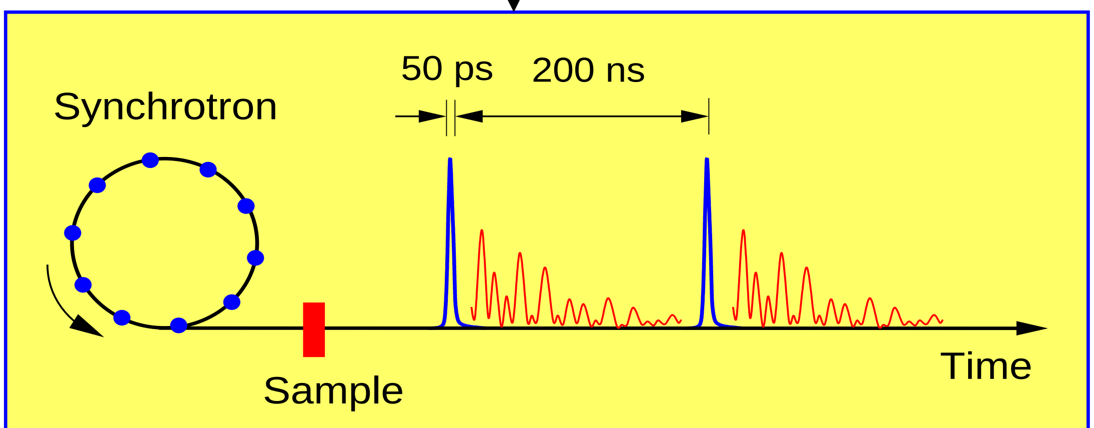
A bucket filled with electrons is called a bunch

Time structure of synchrotron radiation (2)

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

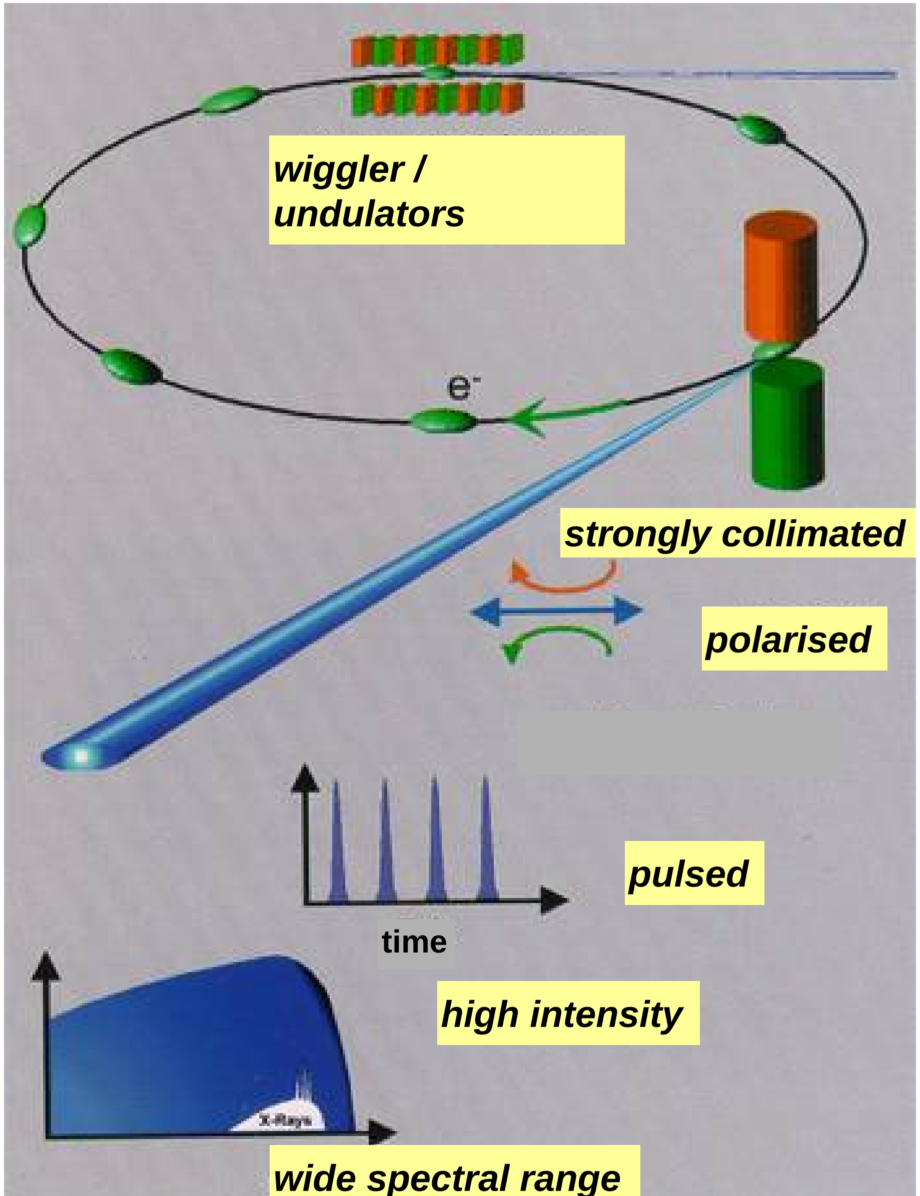


single-bunch	16-bunch	uniform	$2 \cdot \frac{1}{3}$	hybrid
$I_{max} = 16\,\mathrm{mA}$	$I_{max} = 90\,\mathrm{mA}$	$I_{max} = 200\,\mathrm{mA}$	$I_{max} = 200\,\mathrm{mA}$	$I_{max} = 193 + 7\,\mathrm{mA}$
lifetime = 8 h	lifetime = 10 h	lifetime = 60 h	lifetime = 55 h	lifetime = 40 / 7 h
2.81 μs gaps	176 ns gaps	2.839 ns gaps	2.839 ns & 0.94 μs	2.839 ns & 0.47 μs



Time-resolved measurements

Summary: Properties of synchrotron radiation



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

Applications:
- spectroscopy
- diffraction/scattering
- imaging

Fields:
- solid state physics
- crystallography
- structural biology
- chemistry/catalysis
- geo-/environmental science
- materials science, nano science
- medical science
- atoms, molecules and clusters
- magnetism
- engineering science

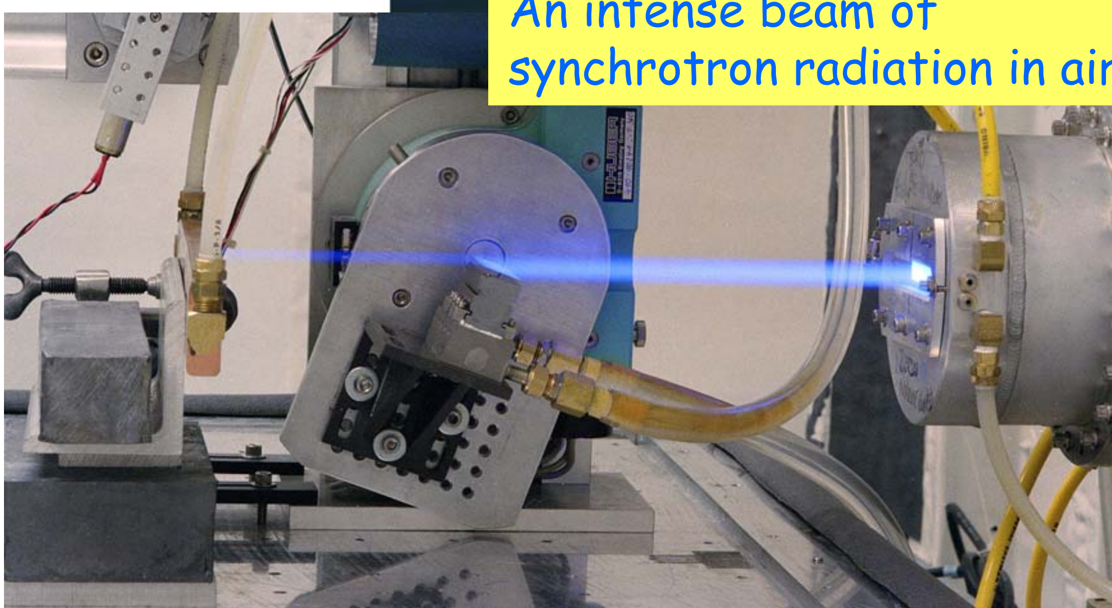
Comparison of power densities

Sunlight on earth:

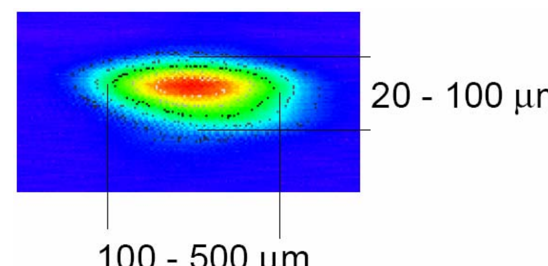
P_{sol} = 1 kW/m²

Synchrotron radiation behind undulator:

P_{SR} = 8000 MW/m²

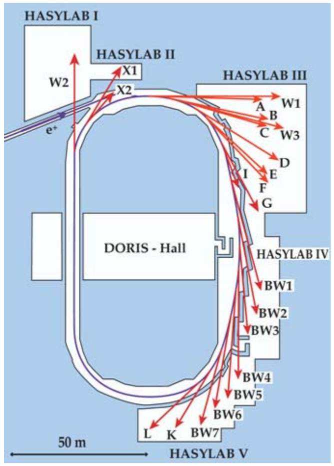


An intense beam of synchrotron radiation in air



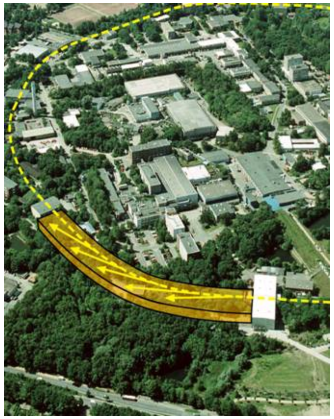
Photon Facilities at DESY

DORIS III

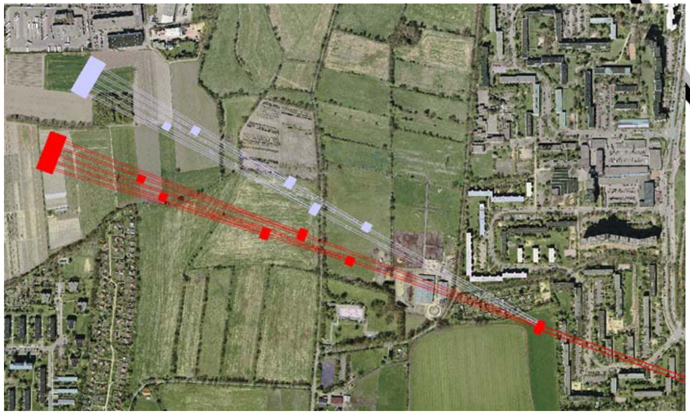


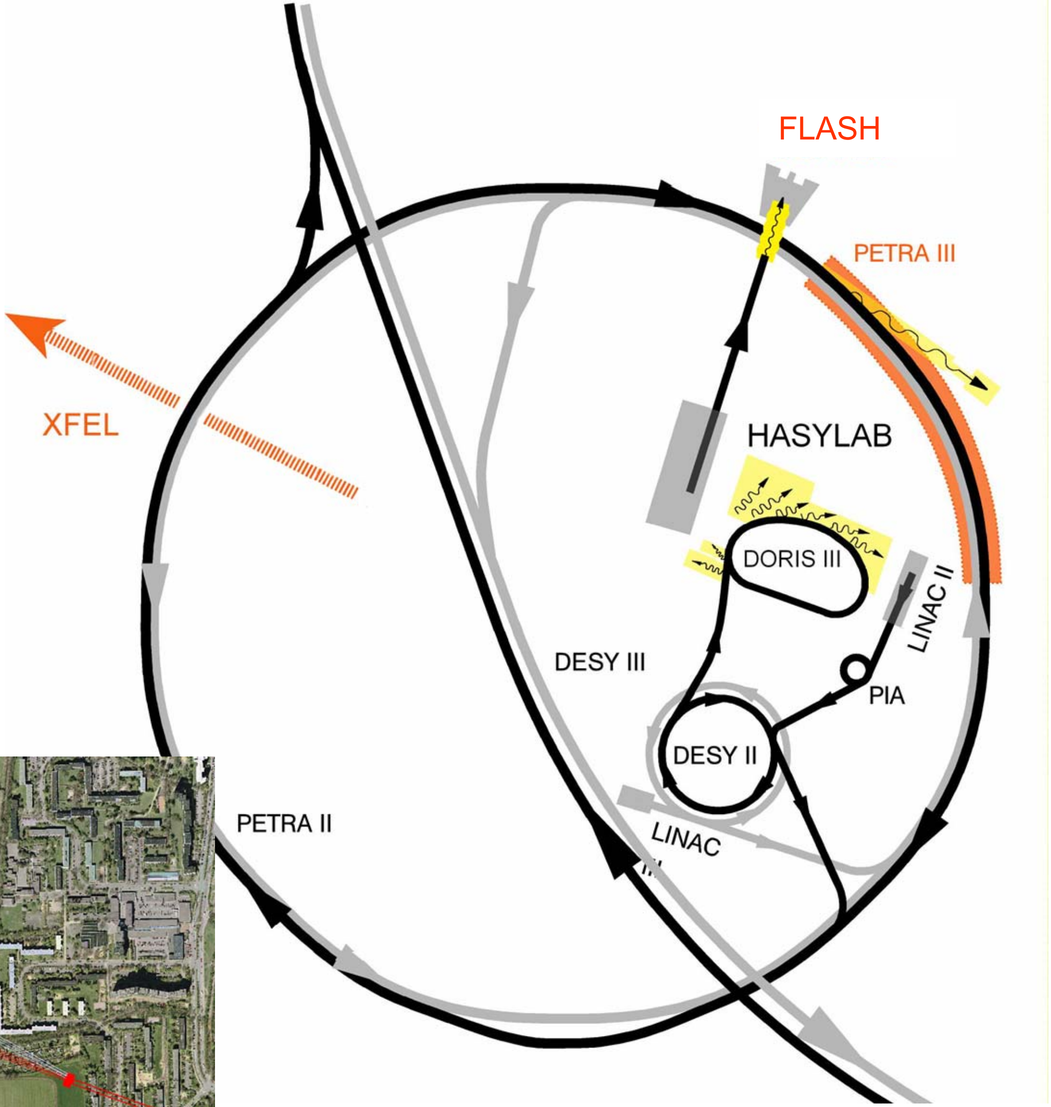
FLASH

PETRA II/III



XFEL





DORIS III

38 beamlines, 70 experimental stations

11 Stations operated by external organizations:
- **EMBL: 7**
- **MPG: 1**
- **GKSS: 1**
- **GFZ: 2**

16 stations operated with support from external institutions:
- **BMBF-Verbundforschung**
- **FZ Jülich**
- **University Hamburg**
- **University Kiel**
- **University Aachen**
- **Debye Inst. Utrecht**
- **RISØ**
- **MPI Golm**

PETRA-III

http://petra3.desy.de

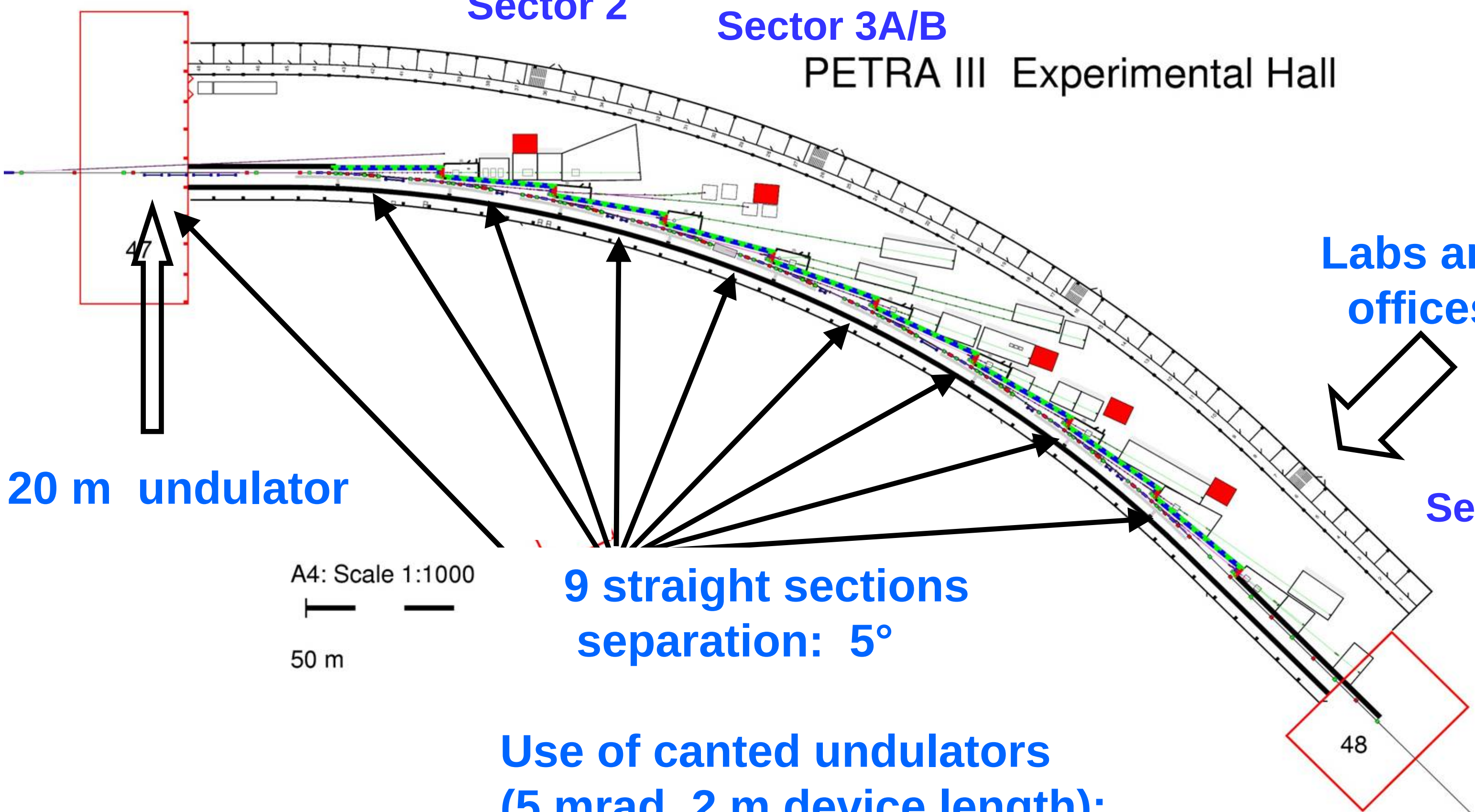
PETRA III construction site, 2.8.2007, 9:52

ID-sectors

Sector 1

Sector 2

Sector 3A/B



Labs and offices

Sector 9A/B

20 m undulator

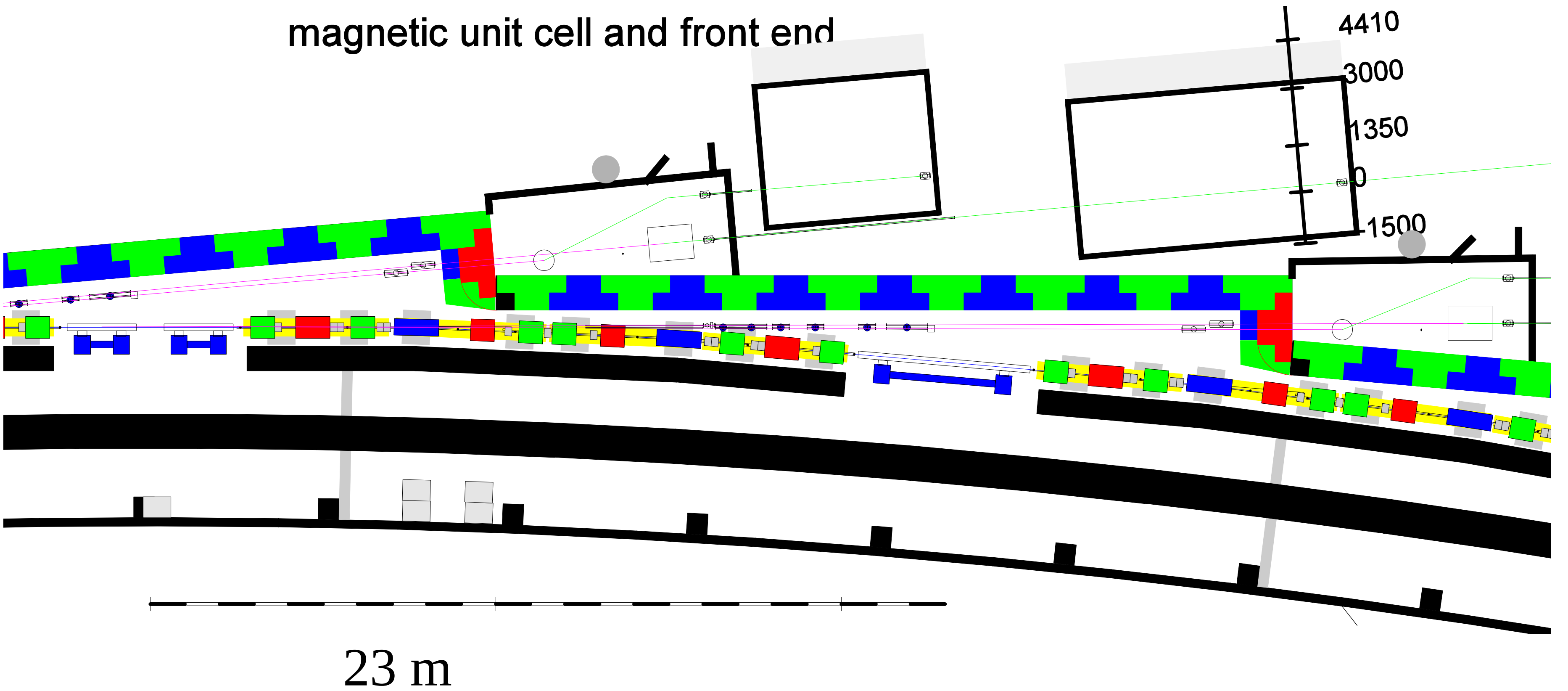
9 straight sections
separation: 5°

Use of canted undulators
(5 mrad, 2 m device length):

→ 14 separate undulator BLs

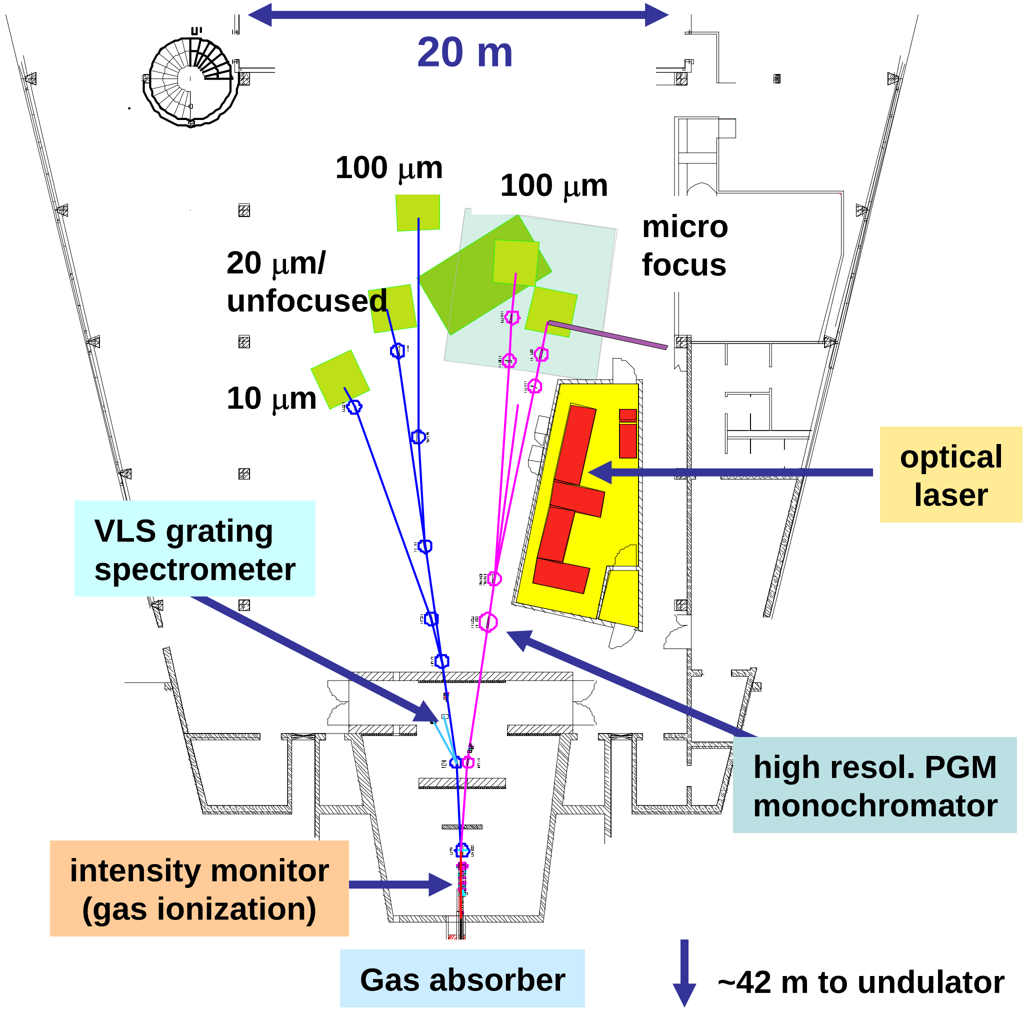
max. BL-length 103 m (from the source)

magnetic unit cell and front end



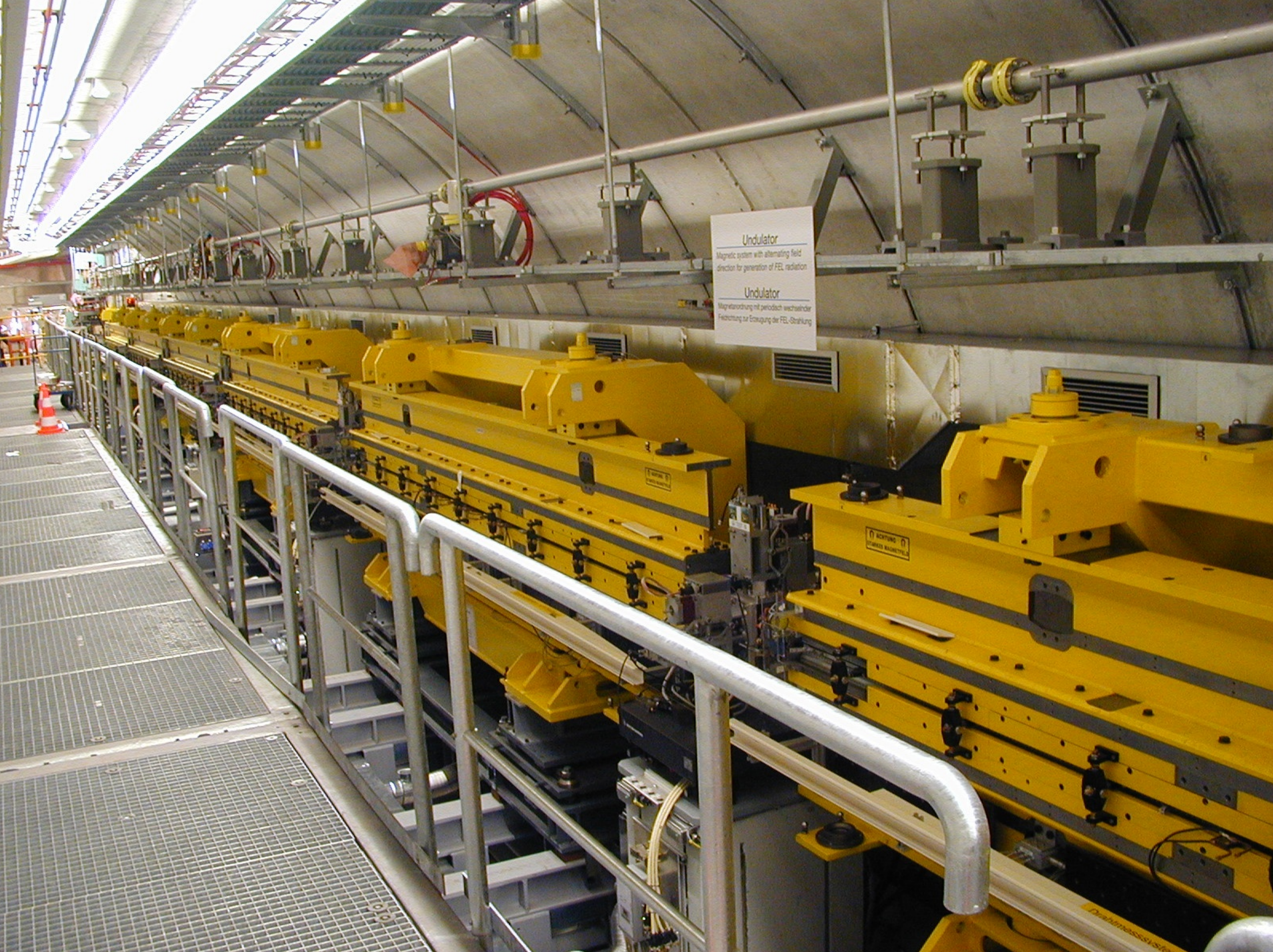
Canted undulators beam separation 5 mrad

FLASH (Free-electron Laser in Hamburg)

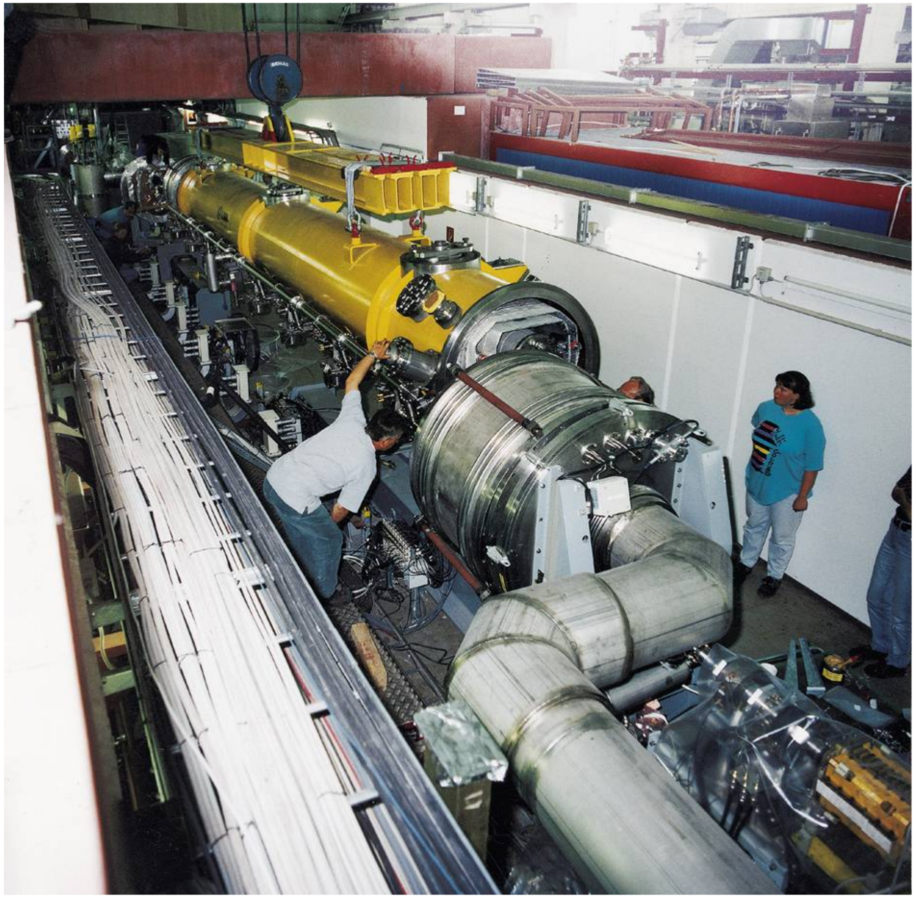


Start of user Operation: 2005

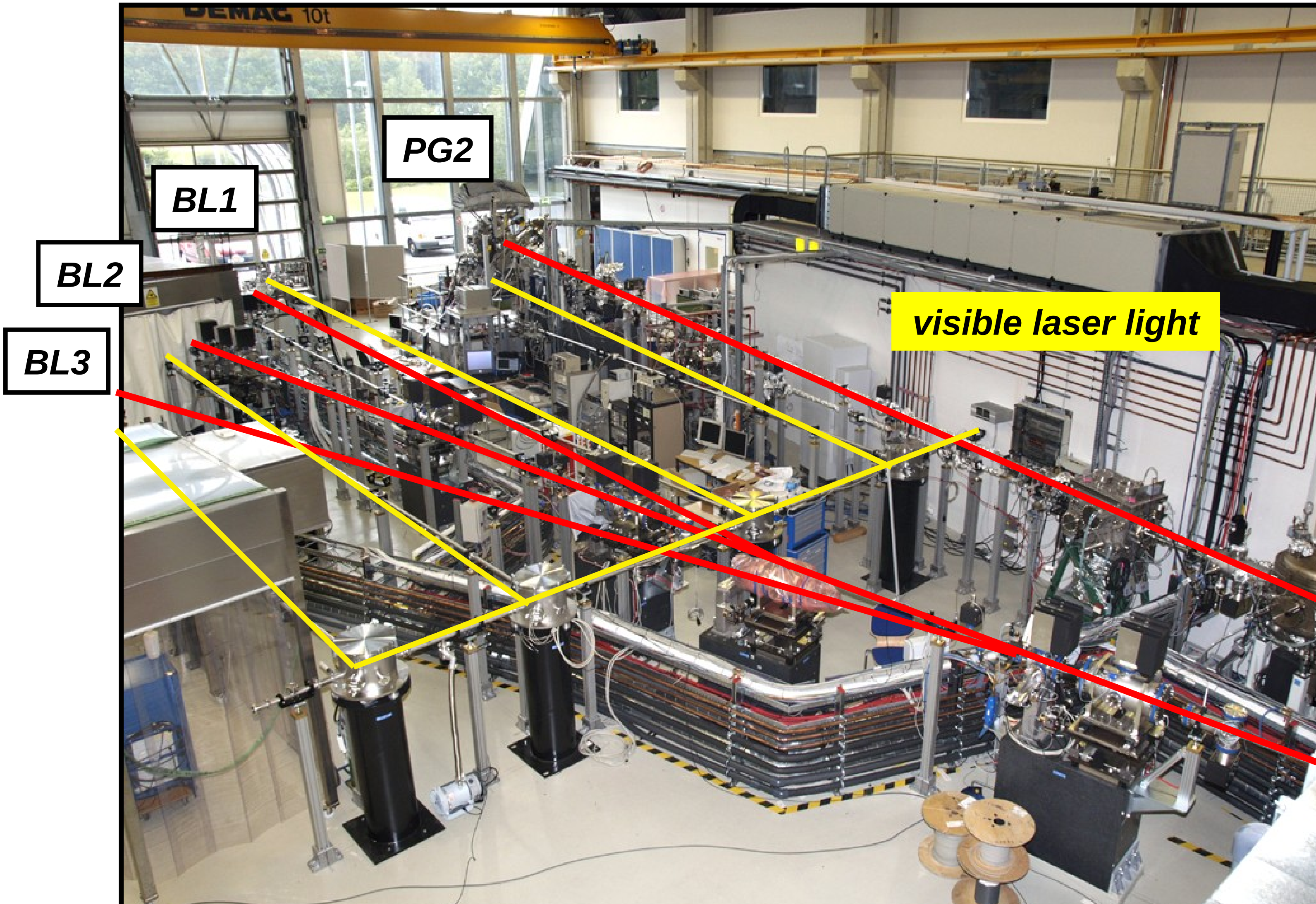
superconducting linac: 1 GeV
minimal wavelength: 6nm
five experimental platforms with different focal spots/optics


Undulator
Magnetic system with alternating field direction for generation of FEL radiation
Undulator
Magnetanordnung mit periodisch wechselnder Feldrichtung zur Erzeugung der FEL-Strahlung

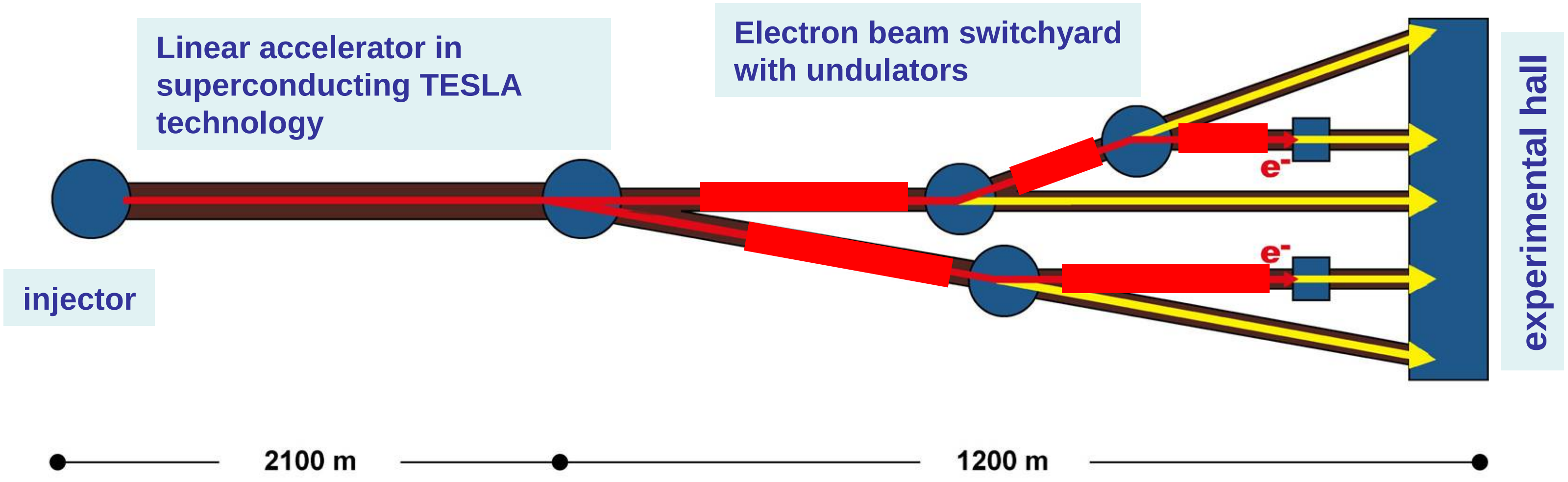
Production and assembly of superconducting cavities for FLASH



FLASH experimental hall

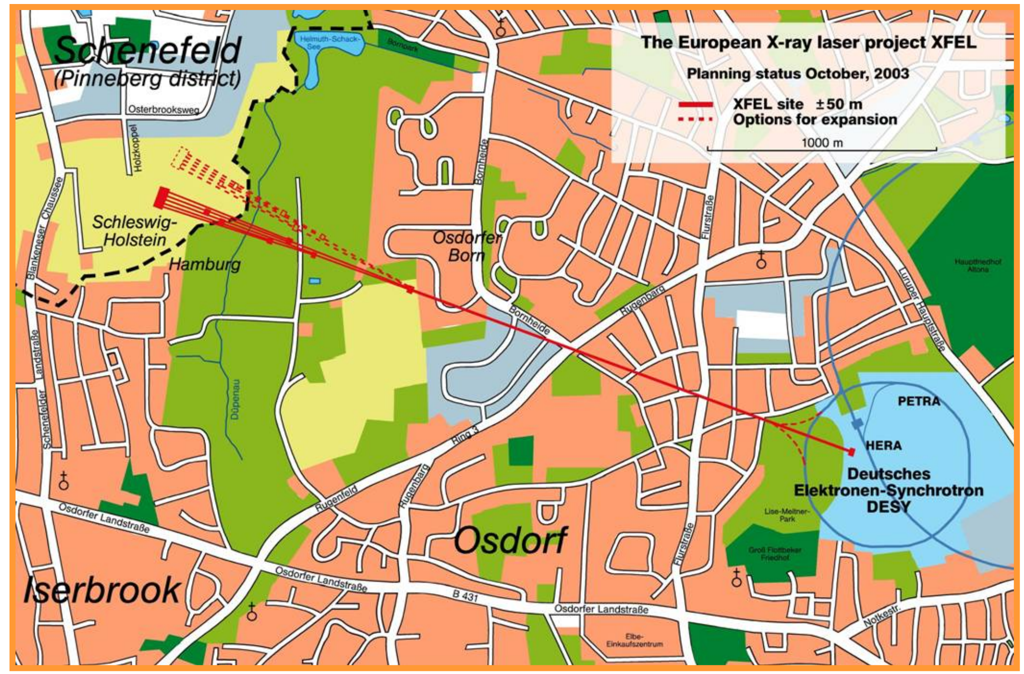


XFEL: The European X-ray Free-Electron Laser

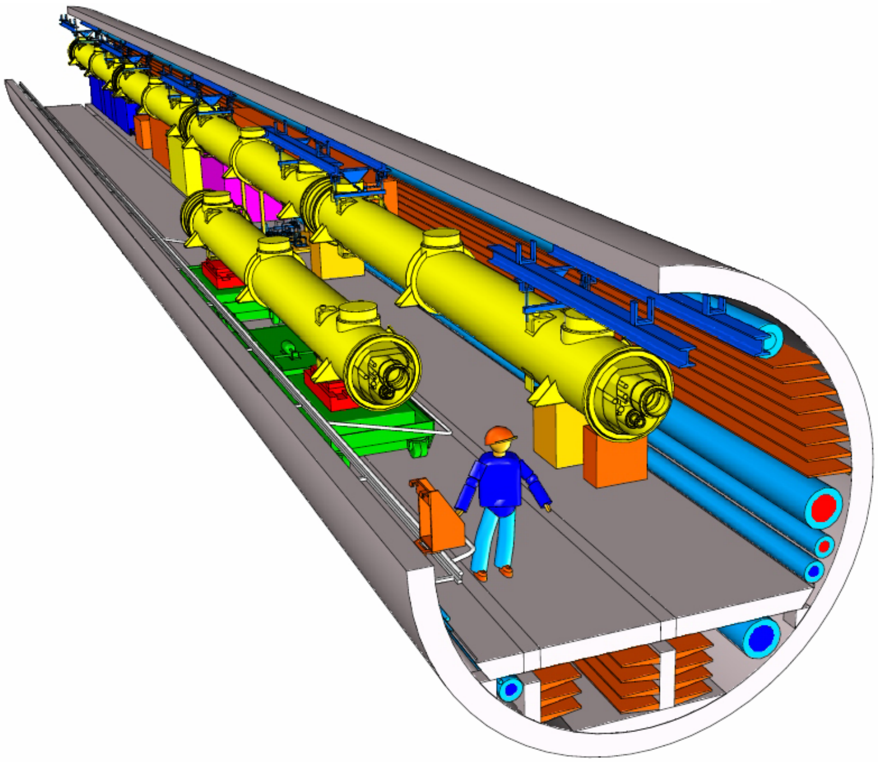


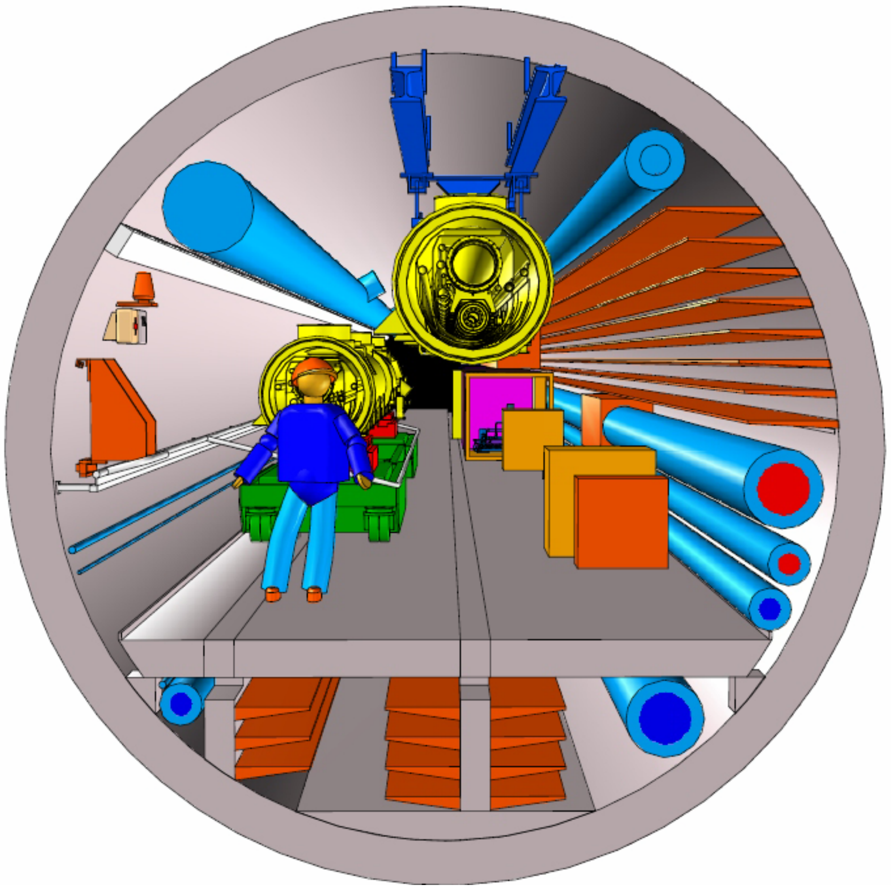
Linac: 20GeV
min. wavelength: ~1Å
photons per pulse: ~10^{12}
pulse length: ~100fs

2 X-ray SASE FELs,
1 SASE XUV-FELs, and
2 beamlines for short pulse physics using spontaneous radiation
10 experimental stations

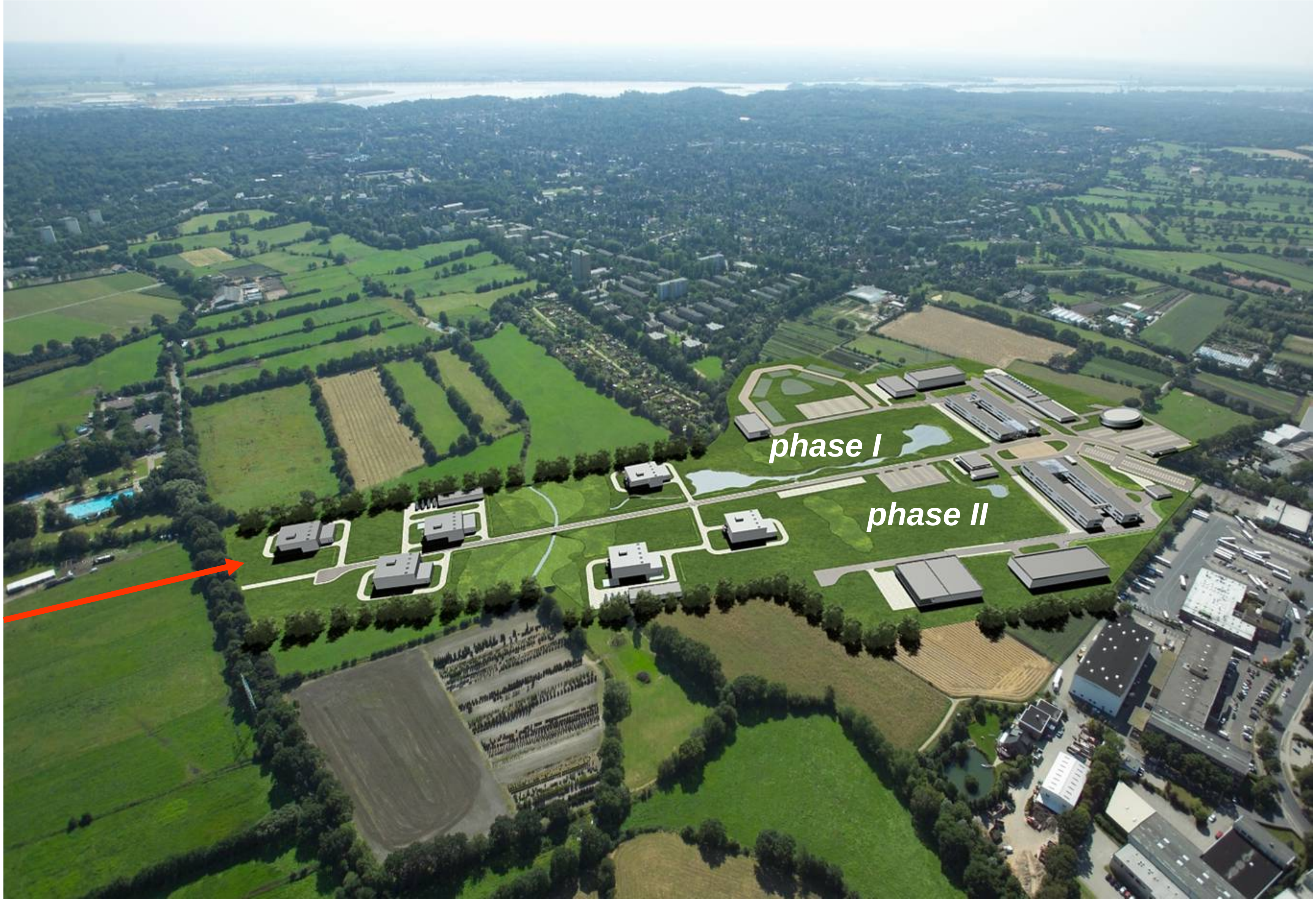


XFEL Accelerator Tunnel

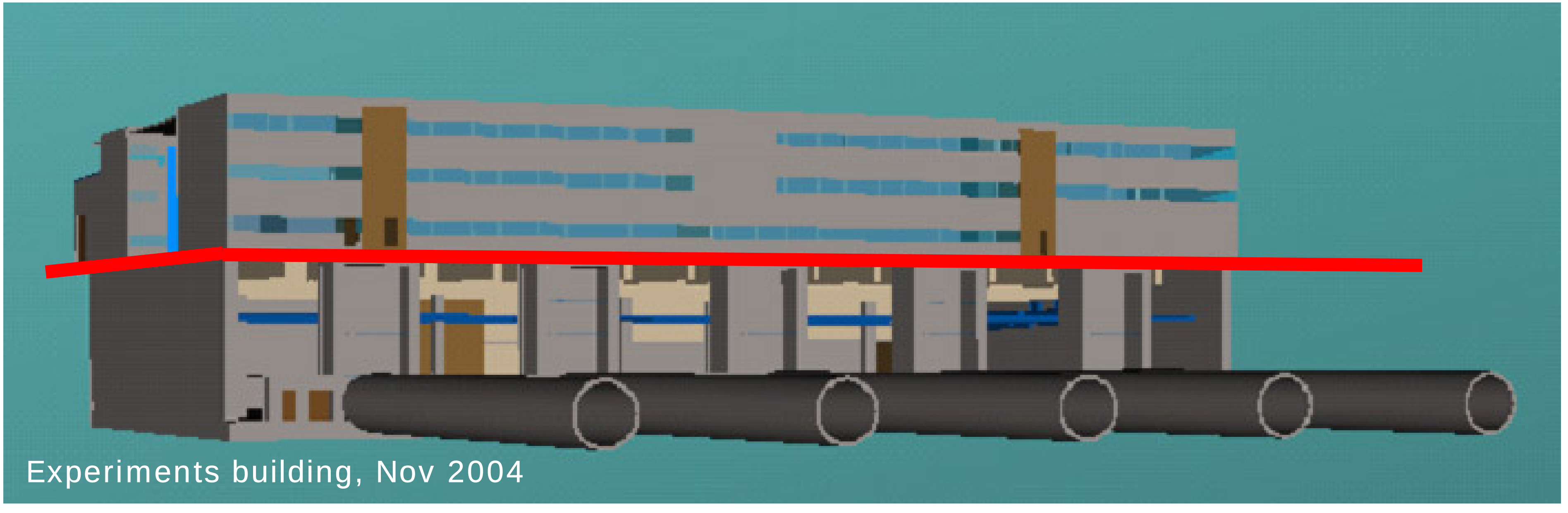




XFEL Site Schenefeld



Experimental hall of the European X-ray FEL Project



DESY site: Injector complex, infra-structure