Summerstudent Lectures 2018
Introduction to Photon Science
Part 1

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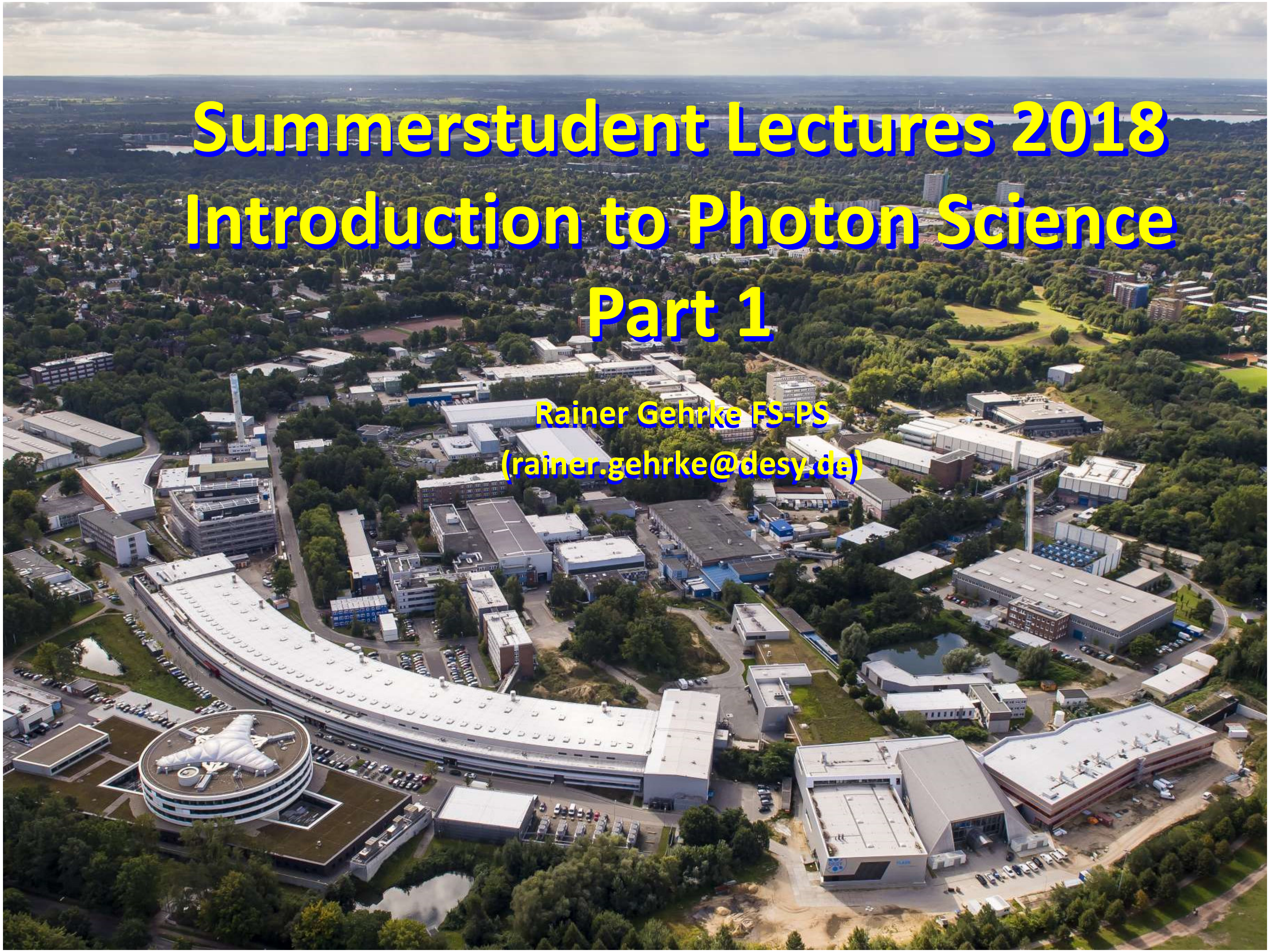
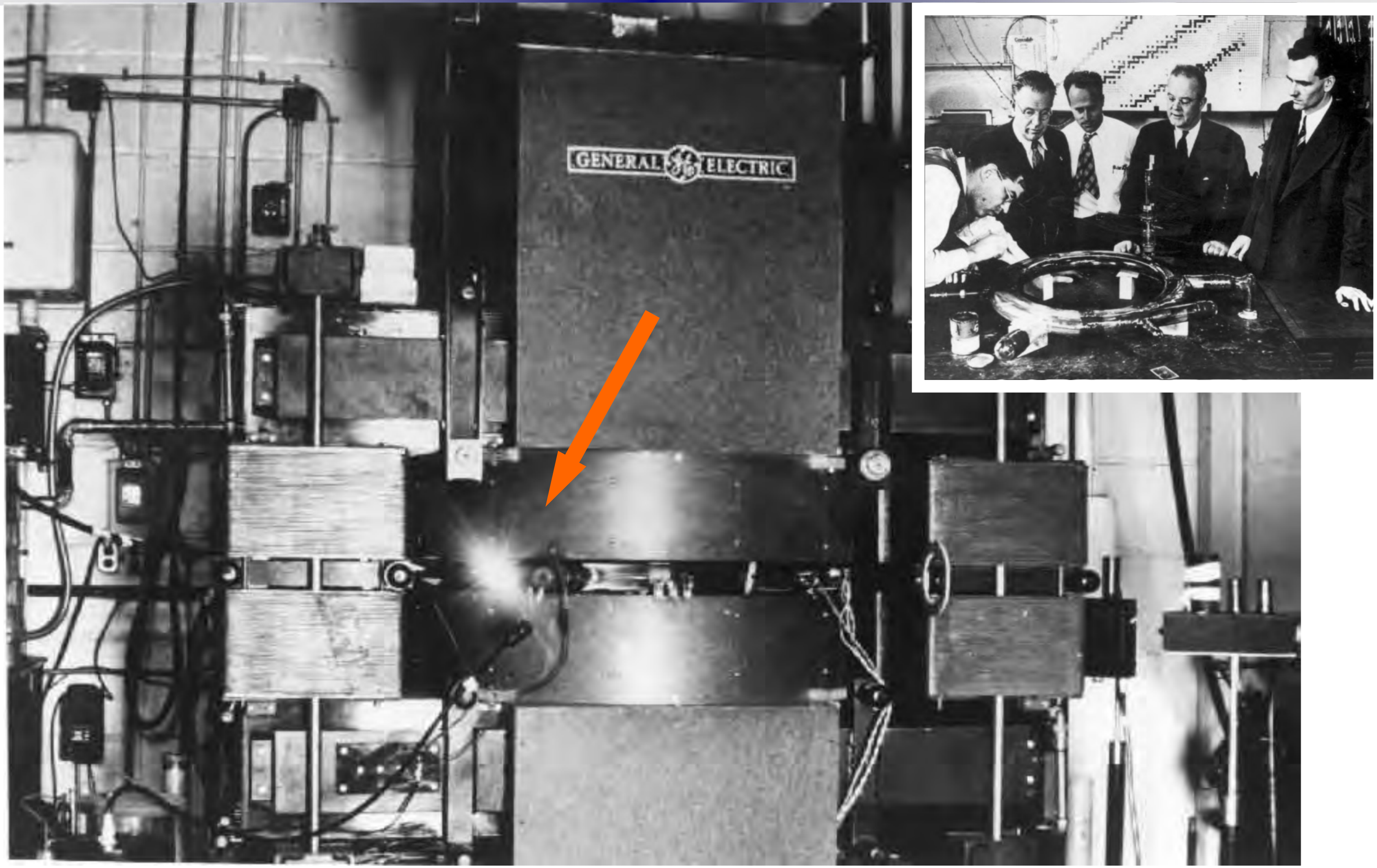


Synchrotron Radiation
Production and Properties

First observation of Synchrotron Radiation



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

DESY Machine History

2000 Employees, 3000 International Guests
(100 apprentice, 100 undergraduate, 350 PHD, 300 Postdoc)
Annual Budget: 230 M€

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

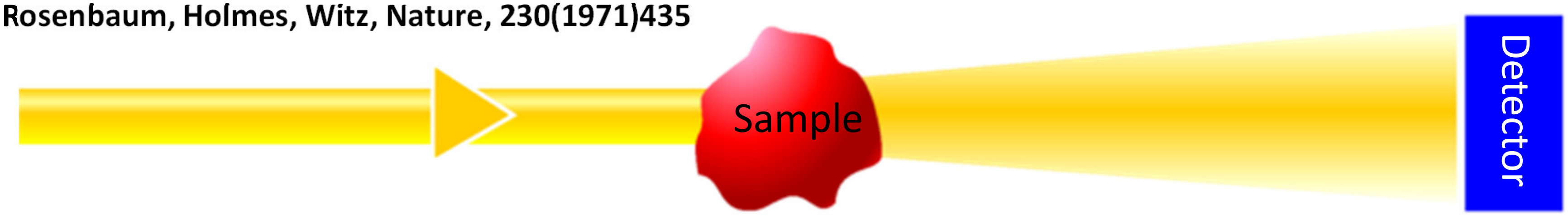
1964	DESY (Synchrotron)		e-	7.4 GeV
1974	DORIS (Storage Ring)	300m	e+/e-	3.5 GeV (later 5 GeV)
1980	HASYLAB@DORIS			
1984	Upgrade with 7 Wiggler/Undulator Beamlines			
1993	Dedicated SR Source at 4.5 GeV			
1978	PETRA (Storage Ring)	2.3km	e+/e-	19 GeV
1990	HERA (Storage Ring)	6.3km	p+/e-	920 GeV / 27.5 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			(presently most brilliant SR source worldwide)
2012	Shutdown of DORIS			
2014	FLASH II (Extension of FLASH)			

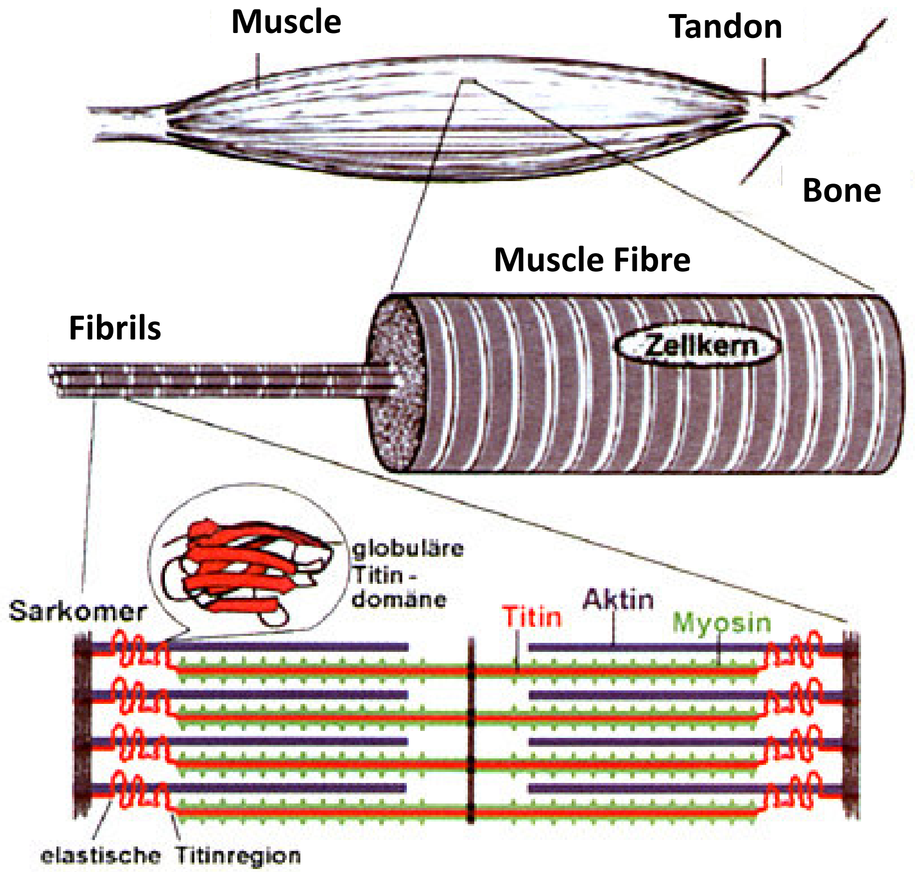
Participation in the European XFEL project

First Experiments Using Synchrotron Radiation (1964 – 1975)

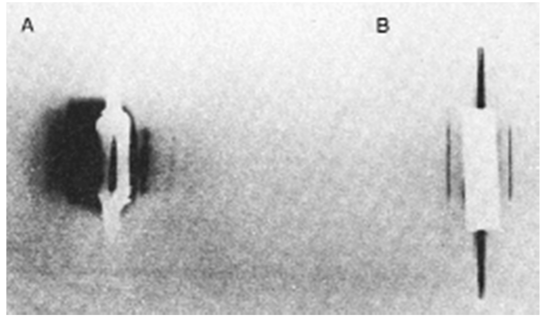
- **1970: Small angle X-ray scattering on muscle fibres**

Rosenbaum, Holmes, Witz, Nature, 230(1971)435

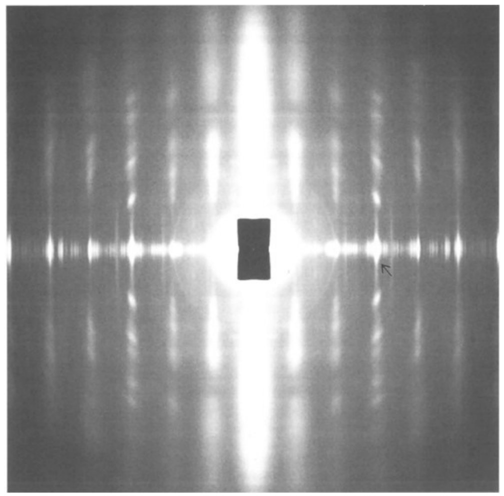




1970



1996



Key Properties of Radiation Emitted by Relativistic Electrons on a Curved Path in a magnetic field

1. High photon flux

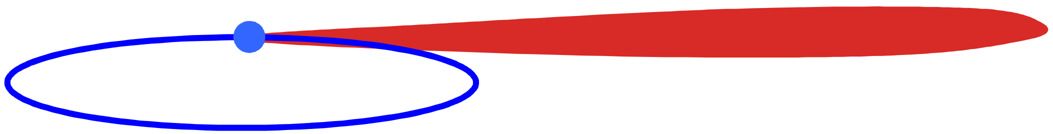
$$P_c = \frac{2q_e^2}{3m_e^4c^7} \cdot \frac{E^4}{R^2}$$

Example PETRA III bending magnet:
E = 6 GeV, B = 0.87 T (R = 22.9 m) → P_c = 62 kW @ 100mA

2. High degree of collimation (brilliance)

$\Theta = 2/\gamma$ = 0.0085 mrad at 6 GeV

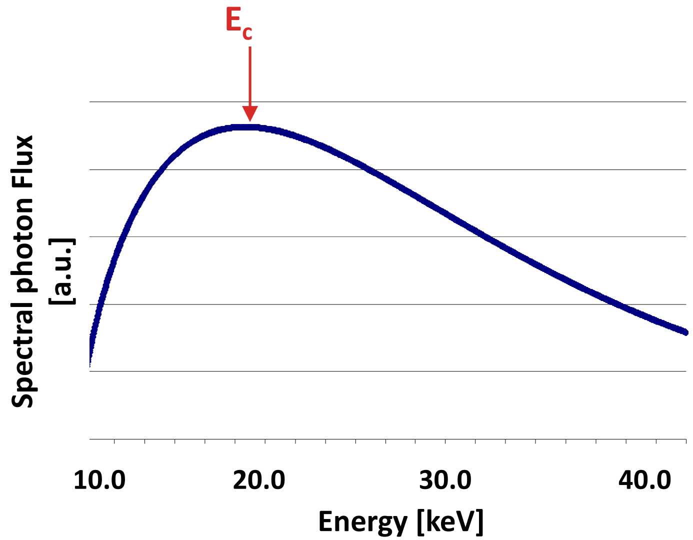
($\gamma = E / m_e c^2$)



3. Continuous spectrum (IR to hard X-rays)

$$E_c[keV] = 0.665 \cdot E^2[GeV] \cdot B[T]$$

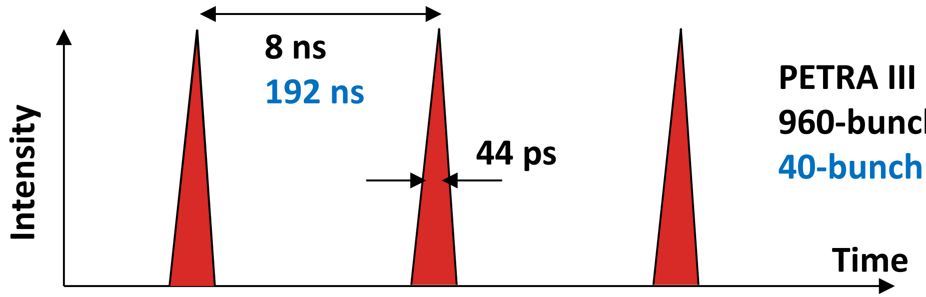
Example PETRA III → E_c = 21 keV



4. Polarization (linear in ring plane, circular above and below)

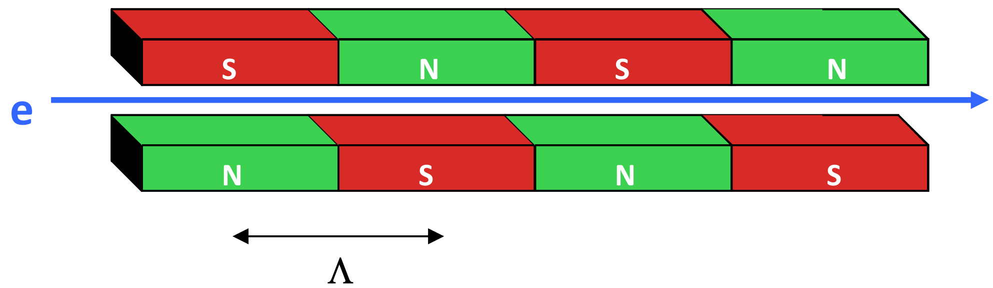
5. Time structure

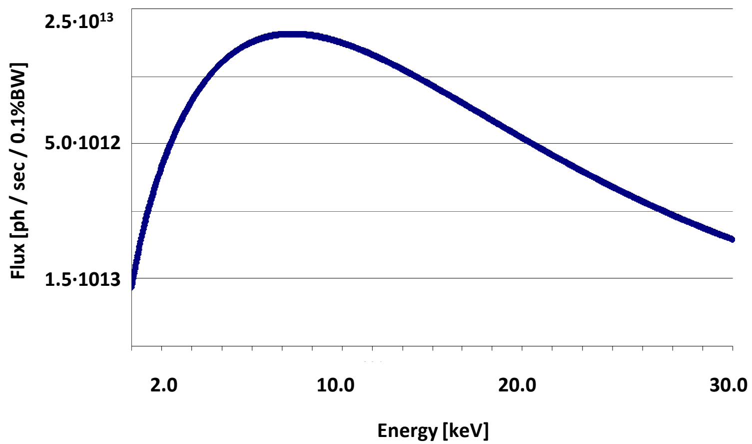
6. Clean light pulses



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

Wiggler (N poles)





n electrons

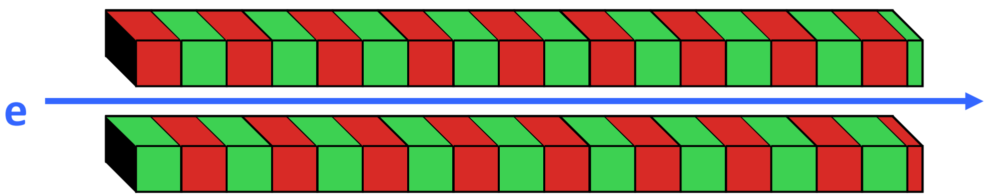
Brilliance I $\propto$ N·n

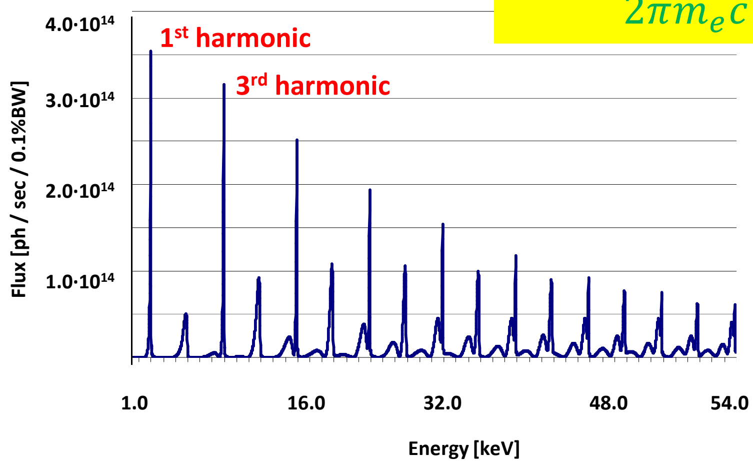
Divergence $\Theta \propto 1/\gamma$

$$\lambda_{photon} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$K = \frac{\lambda_u e B}{2\pi m_e c}$$

Undulator (N poles)



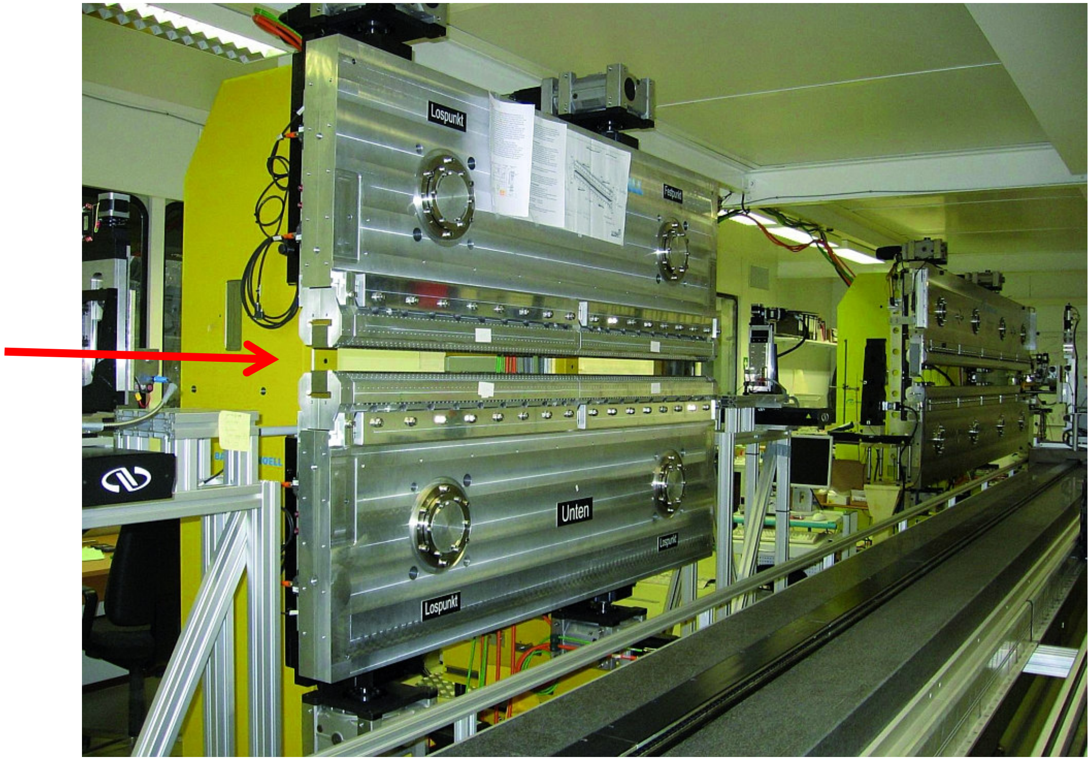


Brilliance I $\propto$ N^2 · n

Divergence $\Theta \propto 1/\sqrt{\gamma^2 \cdot N}$

PETRA III Undulator

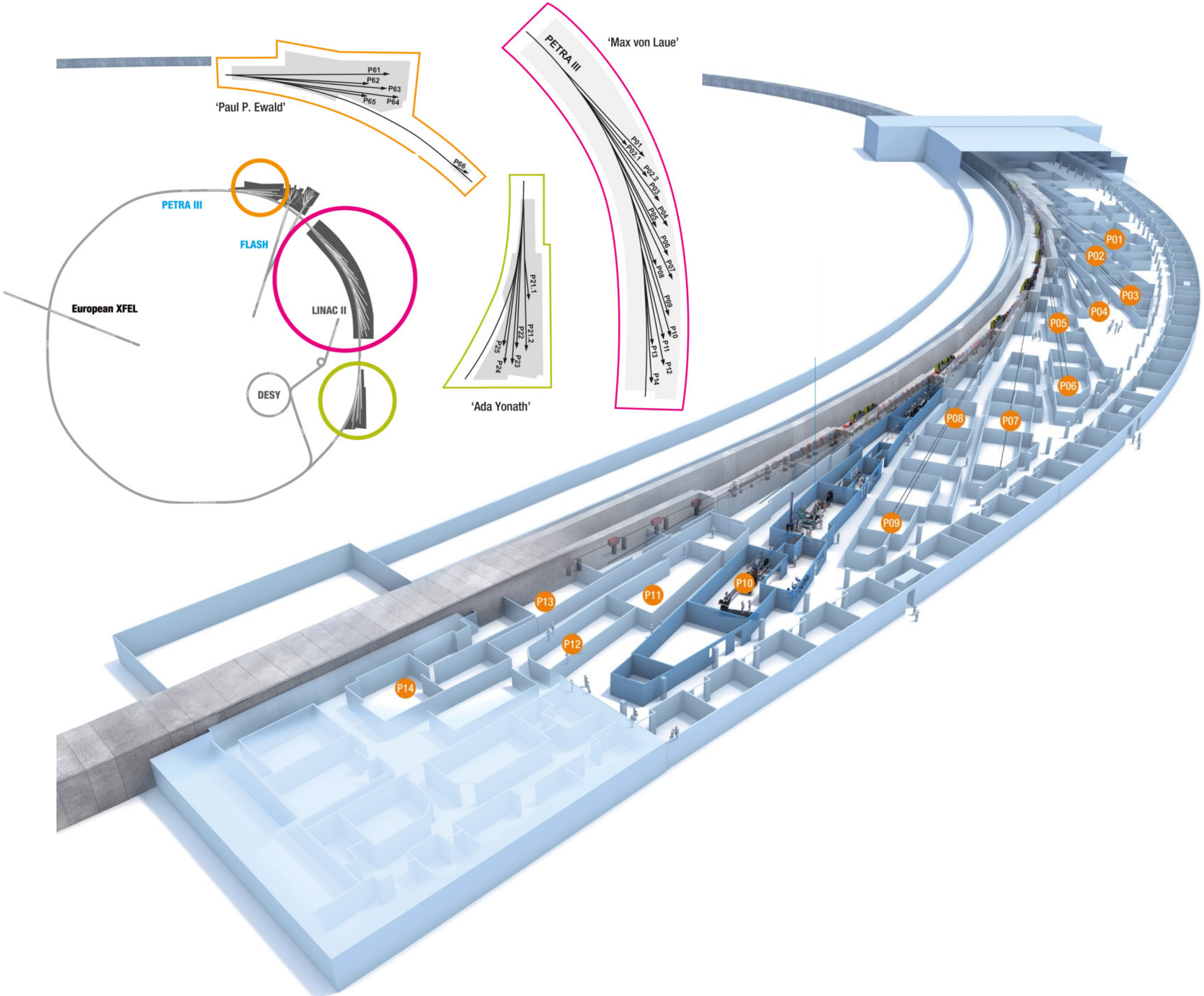
Vertical aperture of vacuum chamber: 7 mm



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**
Coupling factor:	1%
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 Facilities



Scientific Experiments with photons at PETRA III

24 Undulator Beamlines
About 2000 Scientists from about 400 Institutes
about 4000 hours of user beamtime per year

Physics, Chemistry, Biology, Medicine

Scattering and Diffraction

- **Small Angle X-Ray Scattering** **(SAXS, USAXS, GISAXS, ASAXS)**
- **Diffraction and Crystallography** **(General, Powders, Proteins, High Pressure, Surfaces)**

Spectroscopy

- **XUV Fluorescence Spectroscopy**
- **X-Ray Absorption Spectroscopy**
- **X-Ray Photoemission Spectroscopy**
- **Inelastic X-Ray Scattering** **(Nuclear Resonant Scattering)**

Imaging

- **Microtomography**
- **X-Ray Micro Fluorescence**

Weak Signals
e.g. High Collimation
e.g. Small Samples
Time resolved measurements
Tunable wavelength
Time Structure

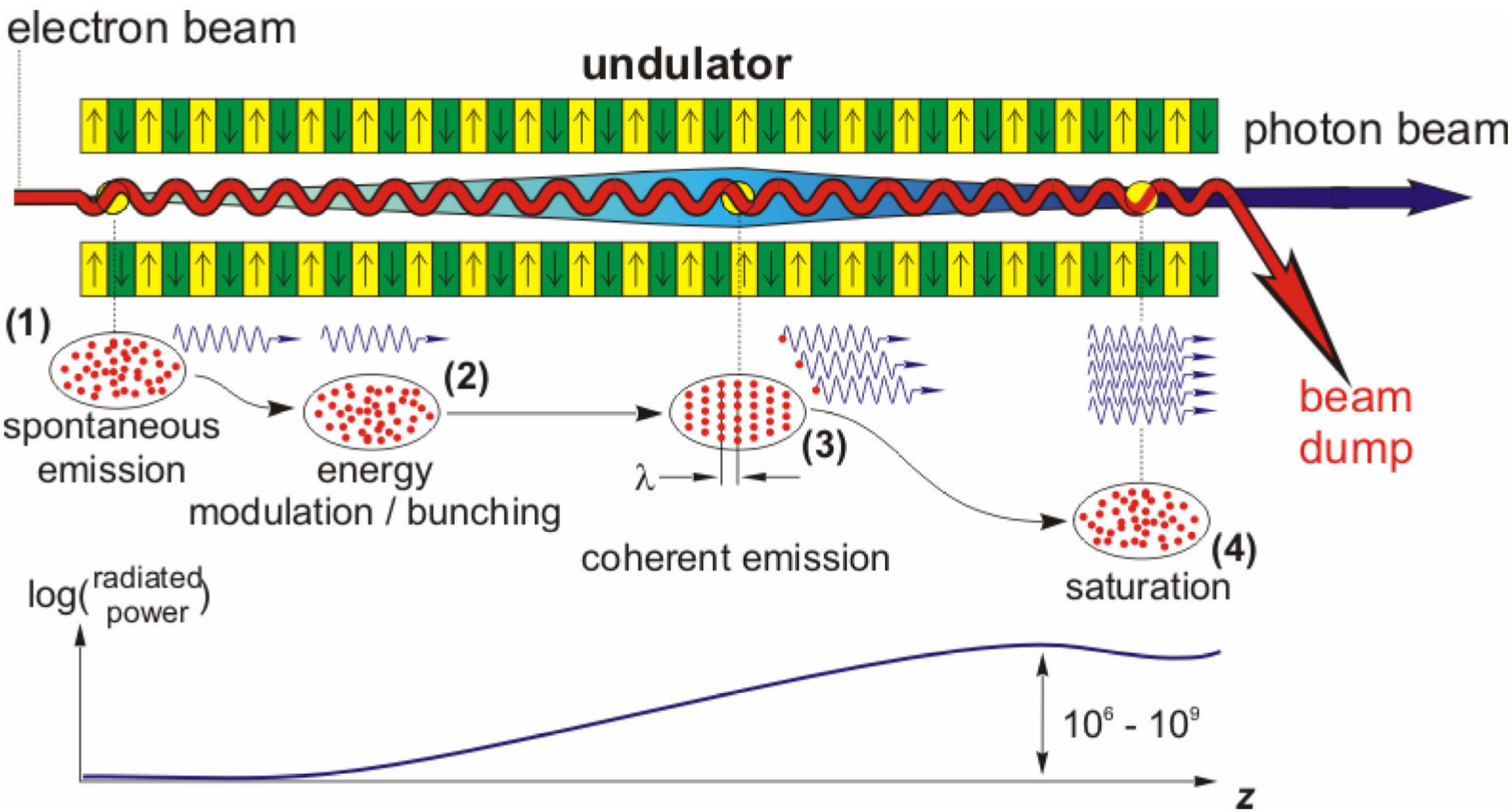
Experiments concentrate on experiments with small focus primary beams ($\mu m, nm$)

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 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**

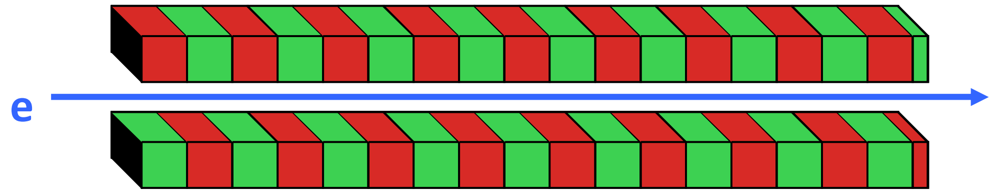
Surface Science (P01, P03, P08, P10)
Thin films, Wetting phenomena, Phase transitions
Materials Science (P01, P02, P04, P07, P09,)
Catalysis, Magnetism, Superconductivity, Metallic Glasses, Batteries
Soft Matter Research (P01, P03, P08, P09, P10)
Colloids, Glass Transitions
Earth Science (P01, P02, P08, P09)
High Pressure Research, Geophysics, Mineralogy, Trace Element Analysis
Life Science (P11, P12, P13, P14)
Protein Structure, Drug Development

Self-Amplified Stimulated Emission (SASE)



Low gain | Exponential gain | Saturation

SASE – Undulator (Free Electron Laser)



n electrons
N poles

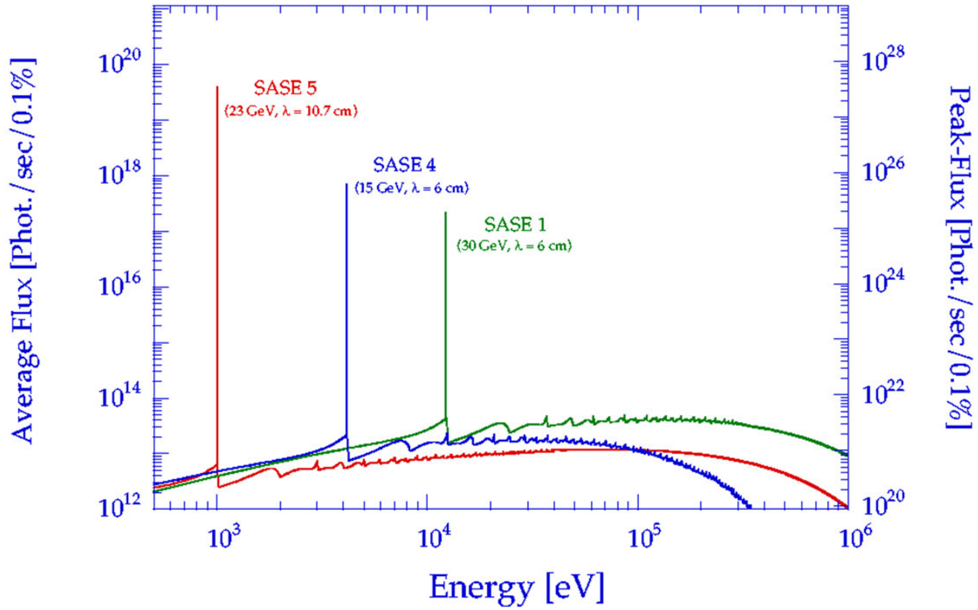
Brilliance I $\propto N^2 \cdot n^2$

Divergence $\Theta \propto 1/\sqrt{\gamma^2 \cdot N \cdot n}$

$$\lambda_{photon} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Plus:

- Extreme short pulses (< 100 fsec)
- $10^{12} – 10^{13}$ photons/puls
- Up to 40000 pulses/sec
- 0.1% intrinsic energy resolution
- Full coherence

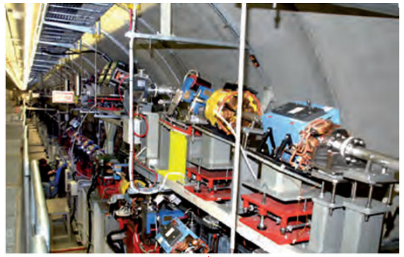


The FLASH free electron laser

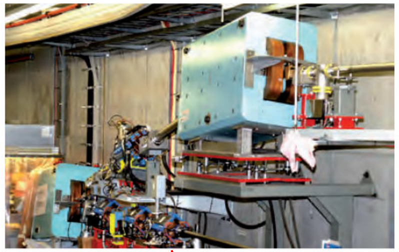
Accelerator modules

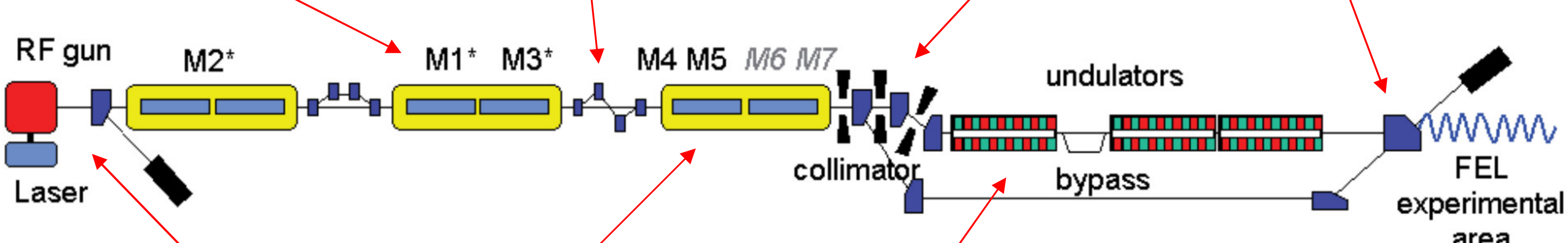
Bunch compressors
50 A → 2 kA

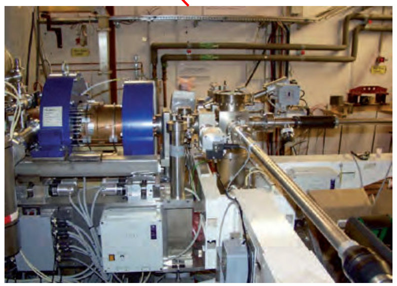
Collimators



Electron dump







RF electron gun
5 MeV

Accelerator modules
150 – 450 – 1250 MeV

Undulator Assembly
NdFeB, Length 6 x 4.5 m
Magnetic period 27 mm
Fixed Gap 12 mm

Experimental hall

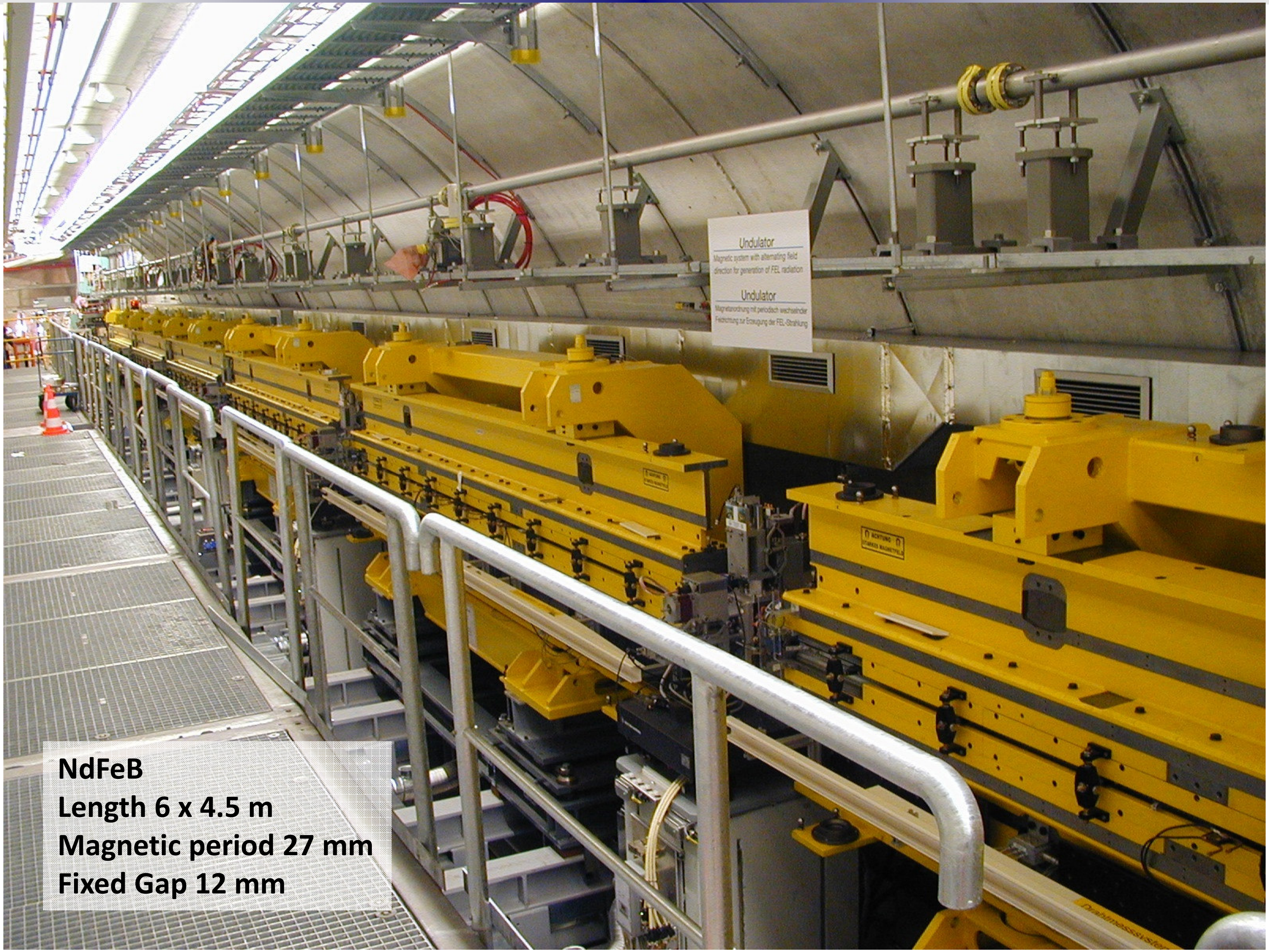
Total length about 320 m
Wavelength 51 nm – 4.2 nm – 1.7 (3rd harmonic)
Energy 24 eV – 295 eV
Pulse duration

Tuned by electron energy (undulator gap fixed)

FLASH Linear Accelerator Modules

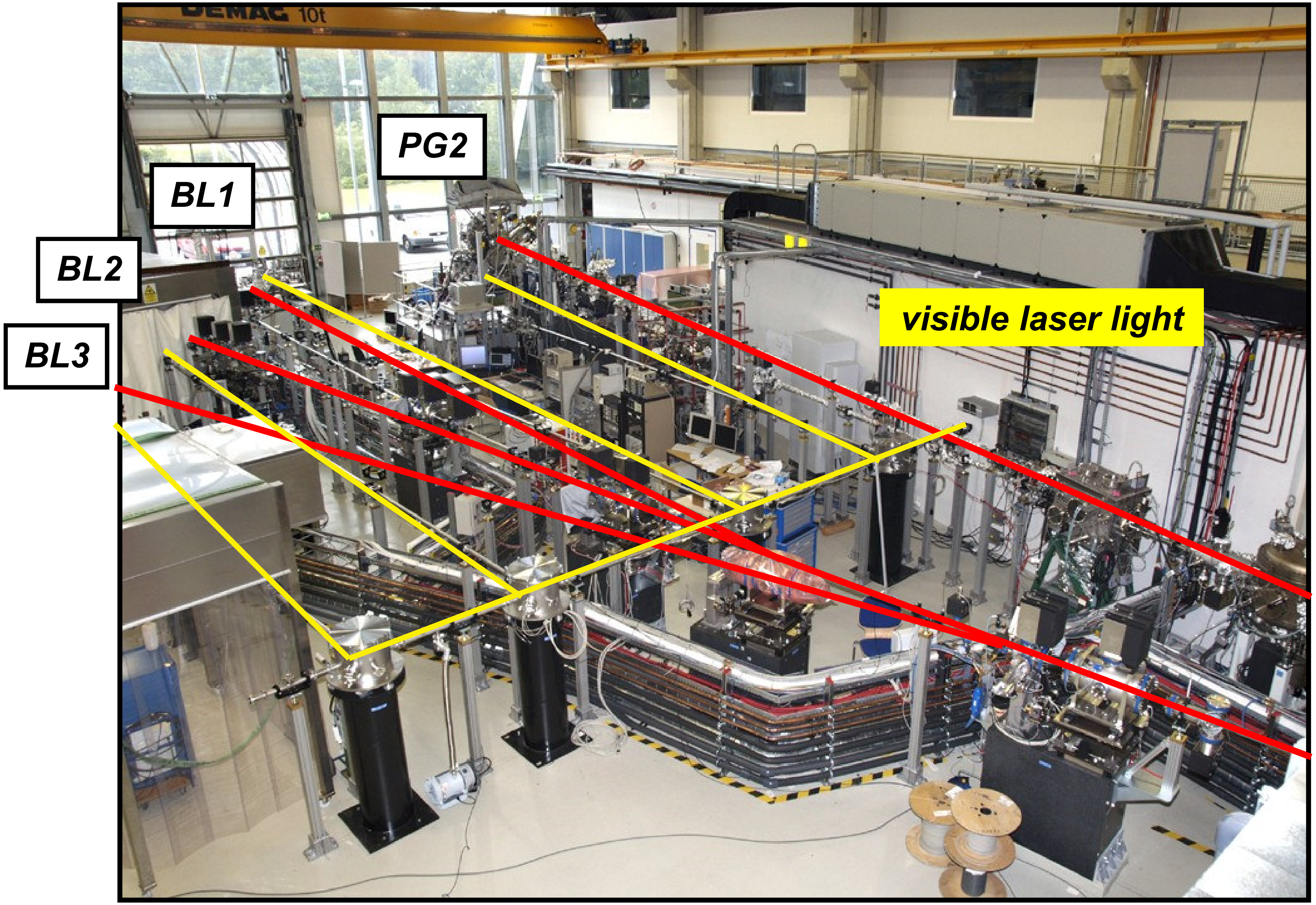
Superconducting Niobium cavities: 15 MV/m

FLASH Undulator Assembly

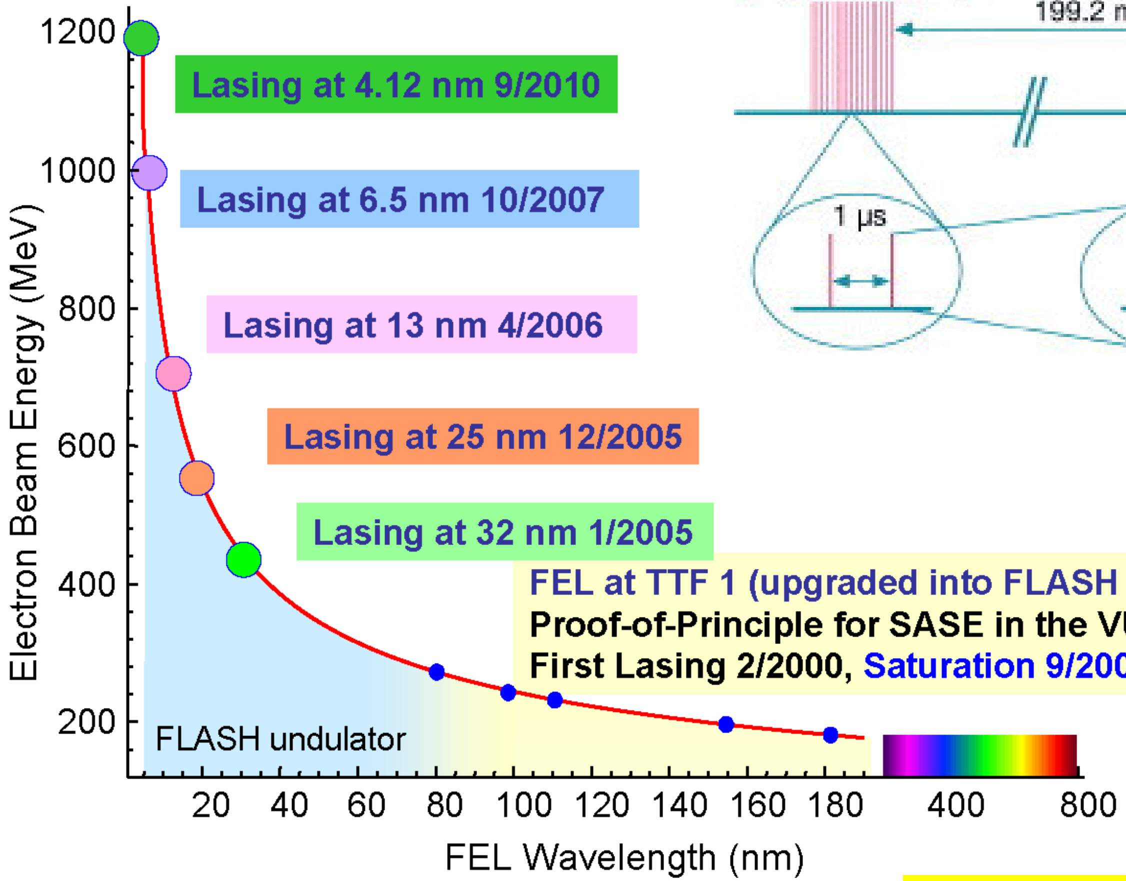


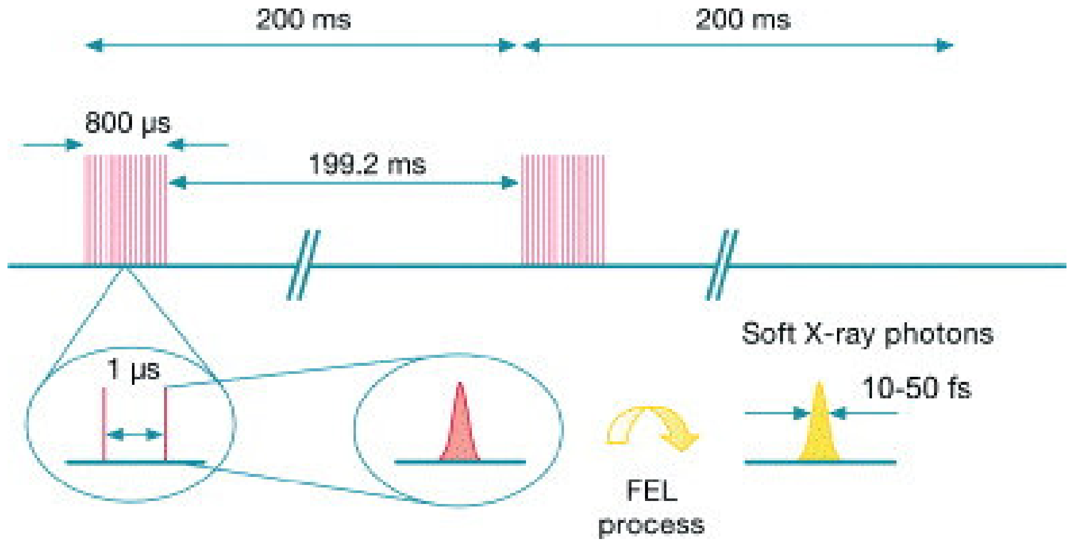
NdFeB
Length 6 x 4.5 m
Magnetic period 27 mm
Fixed Gap 12 mm

FLASH I experimental hall



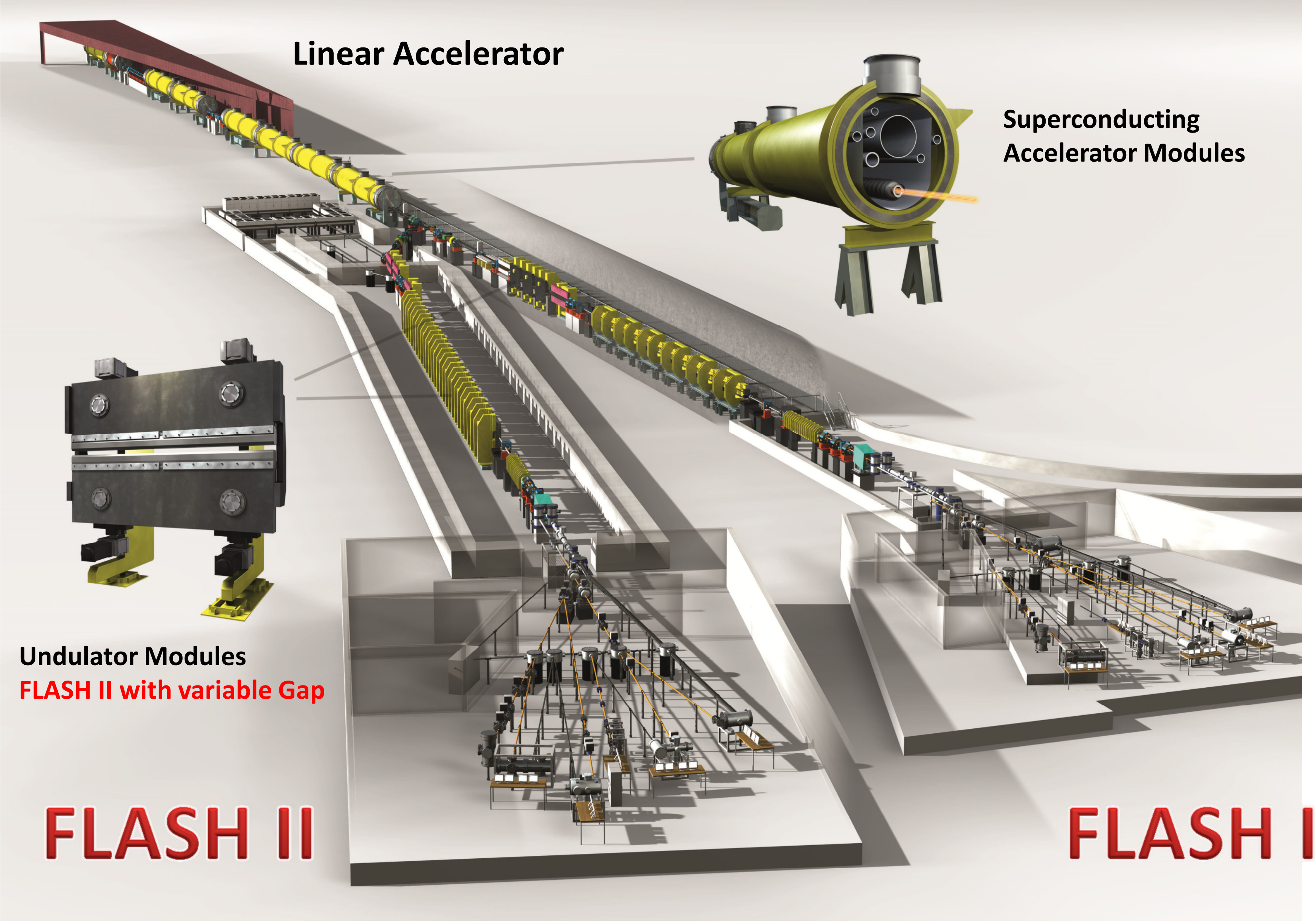
FLASH Development of maximum photon Energy



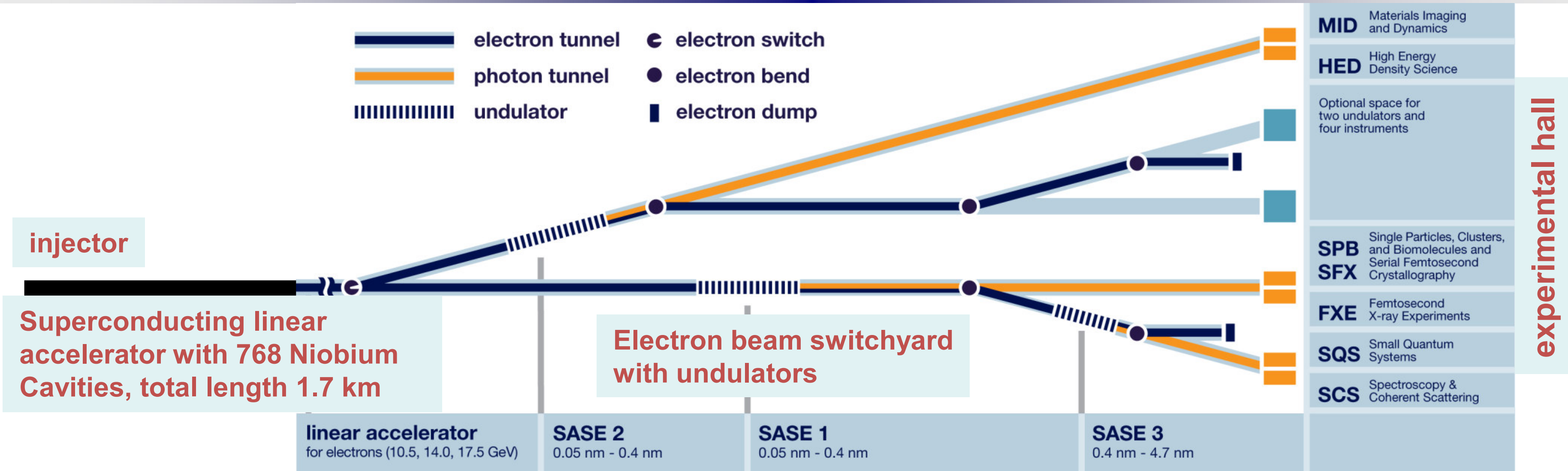


$$\lambda_{photon} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

FLASH Facilities



European XFEL: Schematic Layout



Supercond. Linac: up to 17.5 GeV

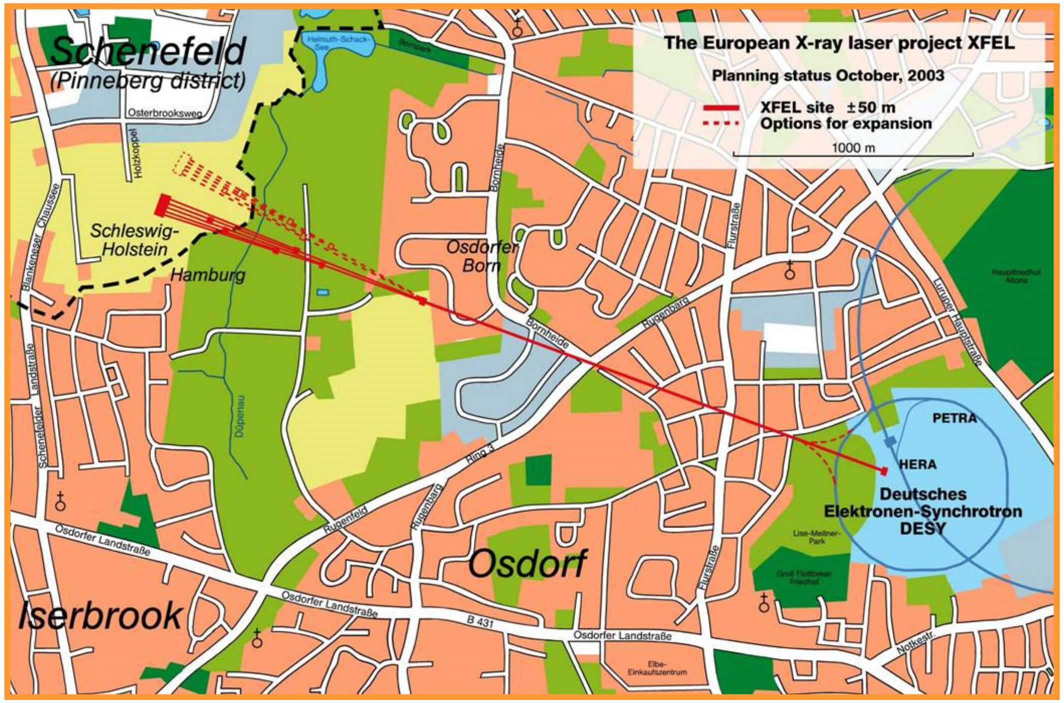
Undulators:

SASE1/2: 34 Modules, 212 m total length
SASE 3 : 20 Modules, 125 m total length

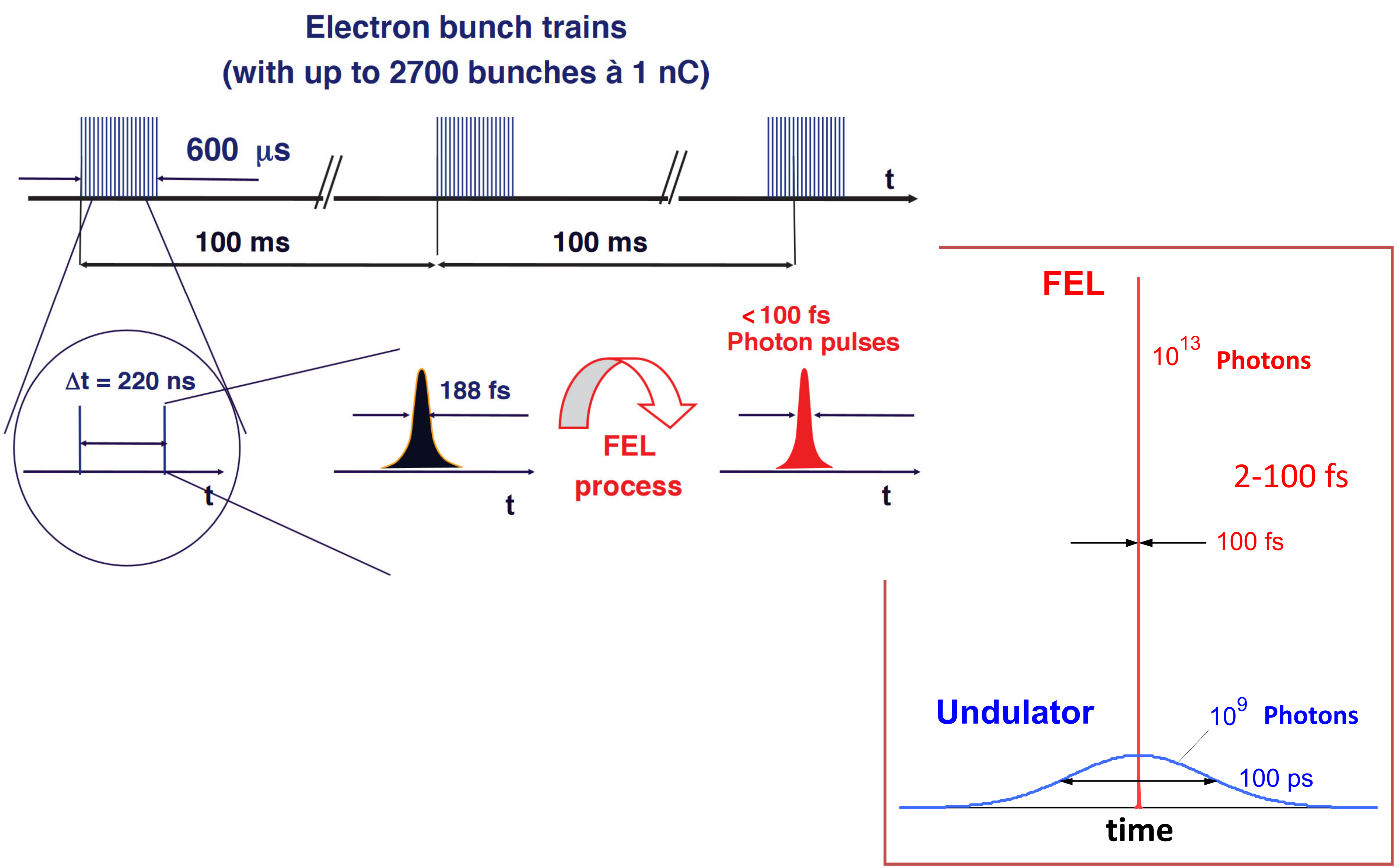
Photon Energies: 0.2 – 3 – 26 keV
Average Brilliance: ~10^{25}
1/(s·mm²·mrad²·0.1%BW)

Peak Brilliance: ~10^{33}

pulse length: <100 fs



European XFEL: Pulse Time Structure



Different quantities to describe photon intensity

Total Flux *F*
number of photons
per time and energy interval

$$[F_{tot}] = \frac{Number\ of\ photons}{s}$$

Emittance $=$ $size \cdot divergence$

Spectral Flux
number of photons
per time, and energy band

$$[F] = \frac{Number\ of\ photons}{s \cdot 0.1\%BW}$$

Brilliance *B*
number of photons
per time, energy band, solid angle,
and source area

$$[B] = \frac{Number\ of\ photons}{s \cdot mm^2 \cdot mrad^2 \cdot 0.1\%BW}$$

$$B = \frac{F}{Emittance}$$

Peak brilliance B^{peak}
brilliance scaled to pulse duration

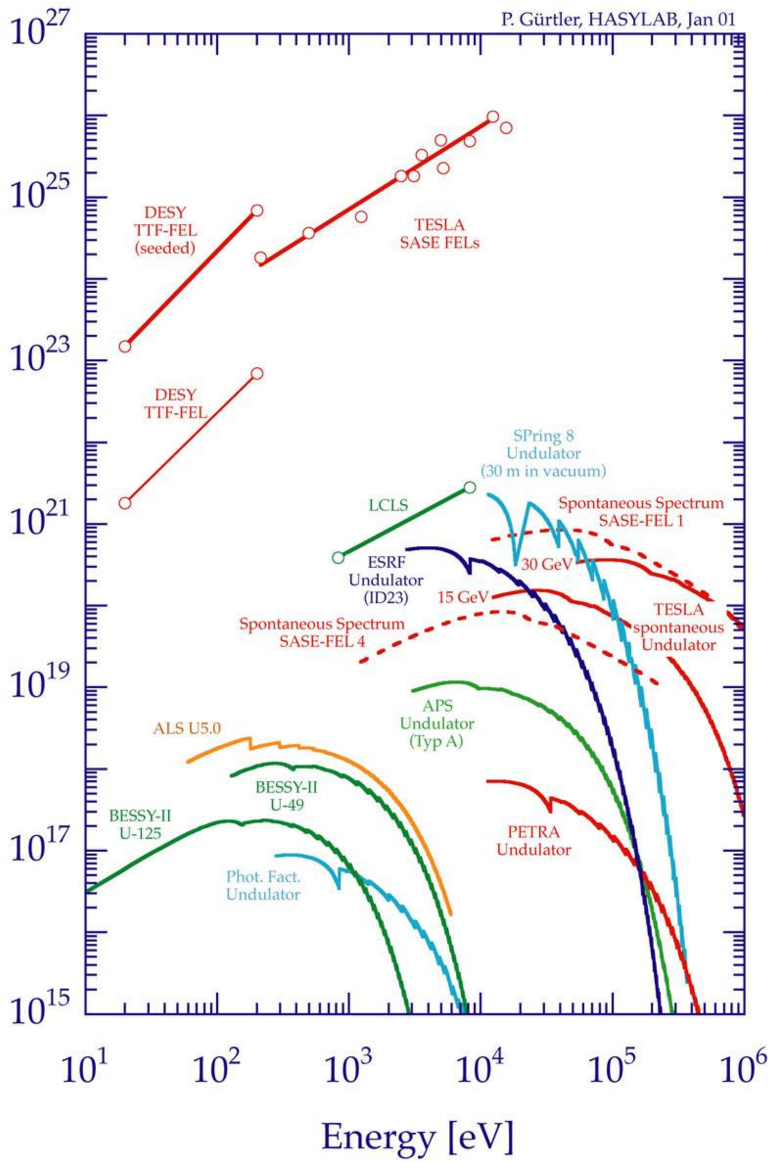
$$B^{peak} = \frac{B}{\tau \times f}$$

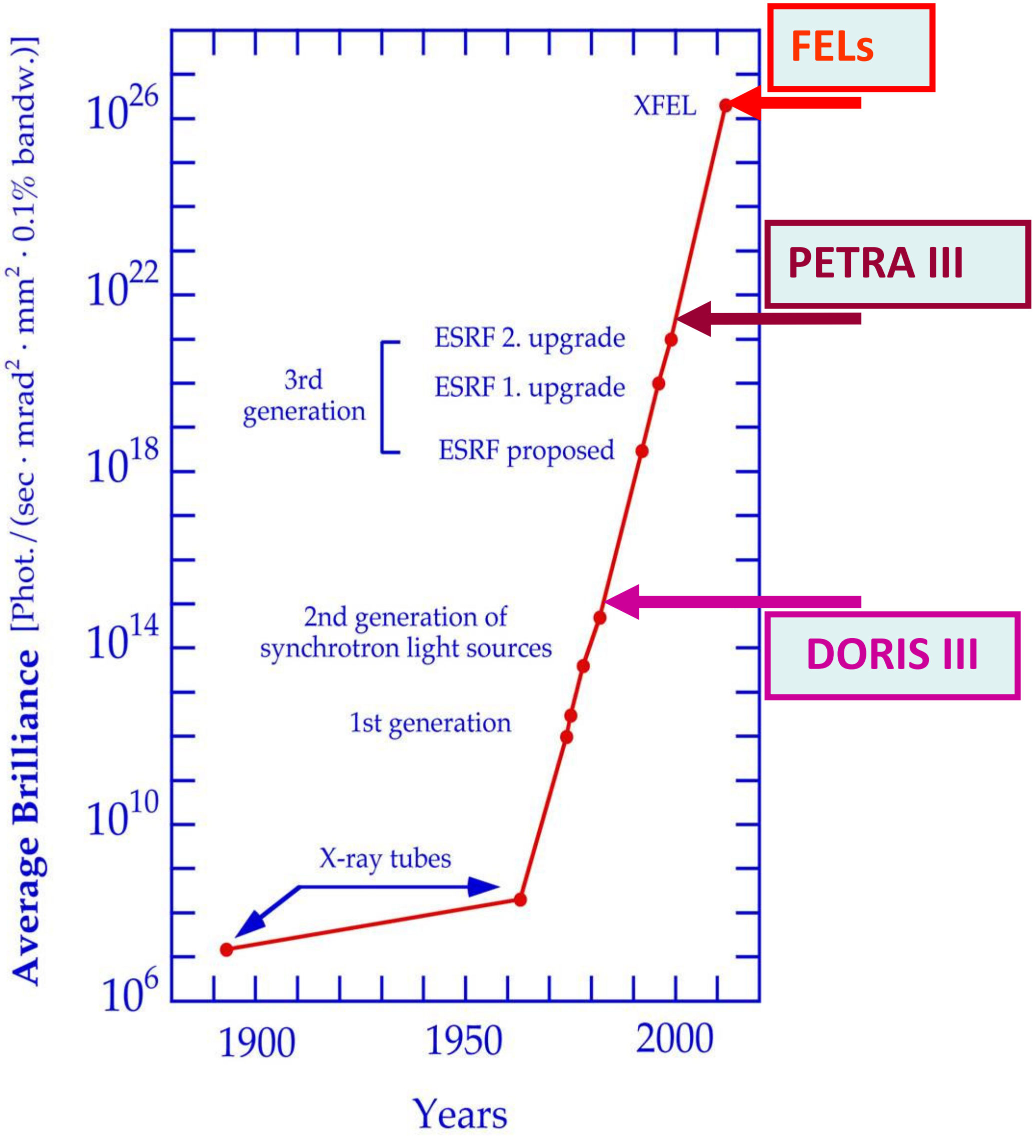
Degree (fraction) of lateral **coherence**

$$\frac{4\lambda^2}{Emittance} \leq 1 \Rightarrow$$

Emittance has a lower (diffraction) limit, at which the source becomes fully laterally coherent

Evolution of Brilliance





Synchrotron Radiation Facilities Worldwide

DESY
HELMHOLTZ GEMEINSCHAFT

PAL POHANG ACCELERATOR LABORATORY
NSRRC
SPring-8
Photon Factory
Institute of Materials Structure Science
High Energy Accelerator Research Organization,KEK
SYNCHROTRON THAILAND
Canadian Light Source
Argonne NATIONAL LABORATORY

HZB Helmholtz Zentrum Berlin
ALBA
MAX IV
PAUL SCHERRER INSTITUT PSI
diamond
DESY.
Elettra Sincrotrone Trieste
SOLEIL SYNCHROTRON
ESRF The European Synchrotron

ALS ADVANCED LIGHT SOURCE
BROOKHAVEN NATIONAL LABORATORY
SLAC NATIONAL ACCELERATOR LABORATORY
CHESS CORNELL HIGH ENERGY SYNCHROTRON SOURCE
LNLS

SESAME
Australian Synchrotron

European XFEL
SLAC NATIONAL ACCELERATOR LABORATORY
PAL POHANG ACCELERATOR LABORATORY
PAUL SCHERRER INSTITUT PSI
Elettra Sincrotrone Trieste
SPring-8

Synchrotron Radiation Facilities in Europe

ISA

FELIX