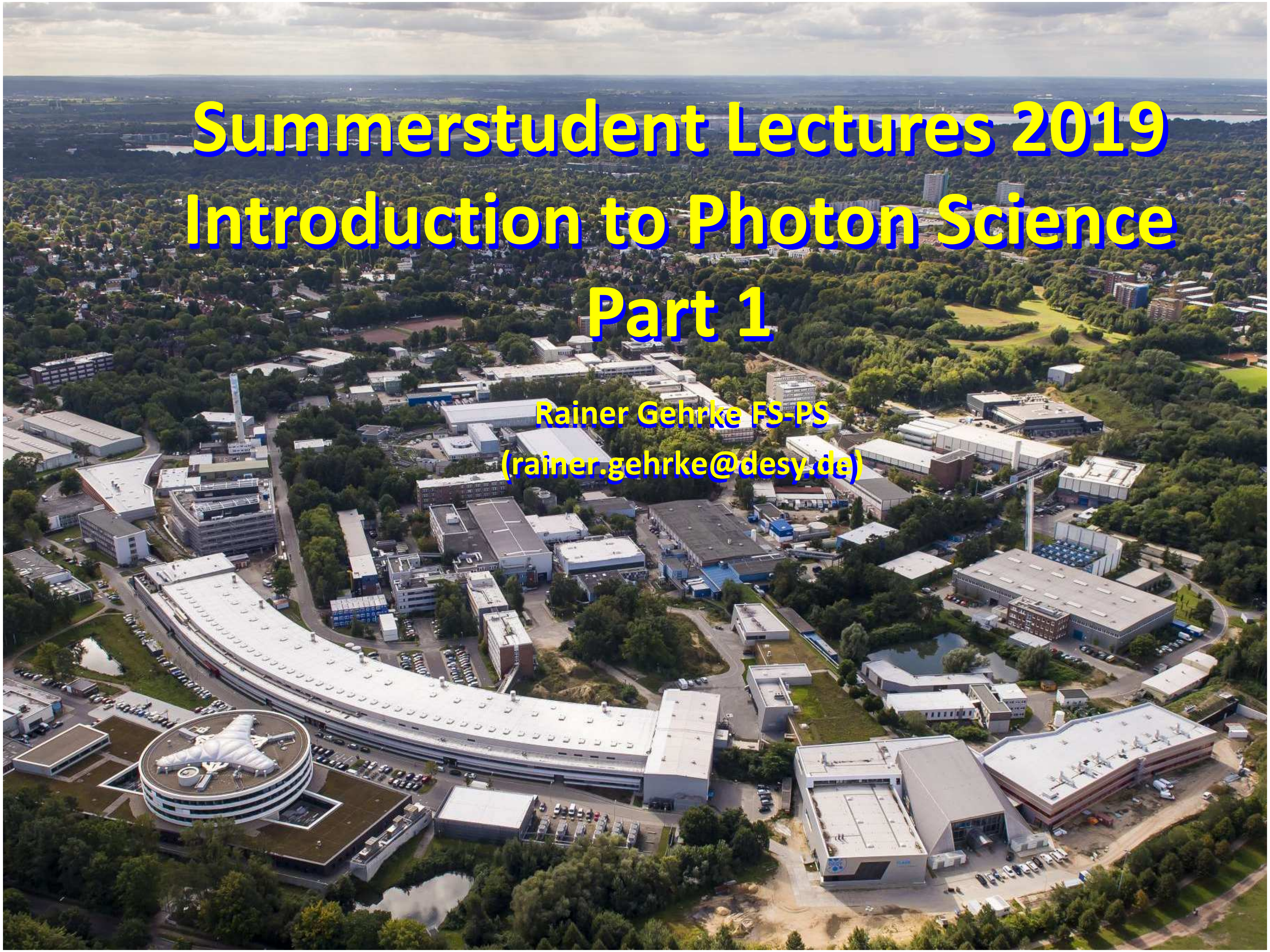

Summerstudent Lectures 2019
Introduction to Photon Science
Part 1

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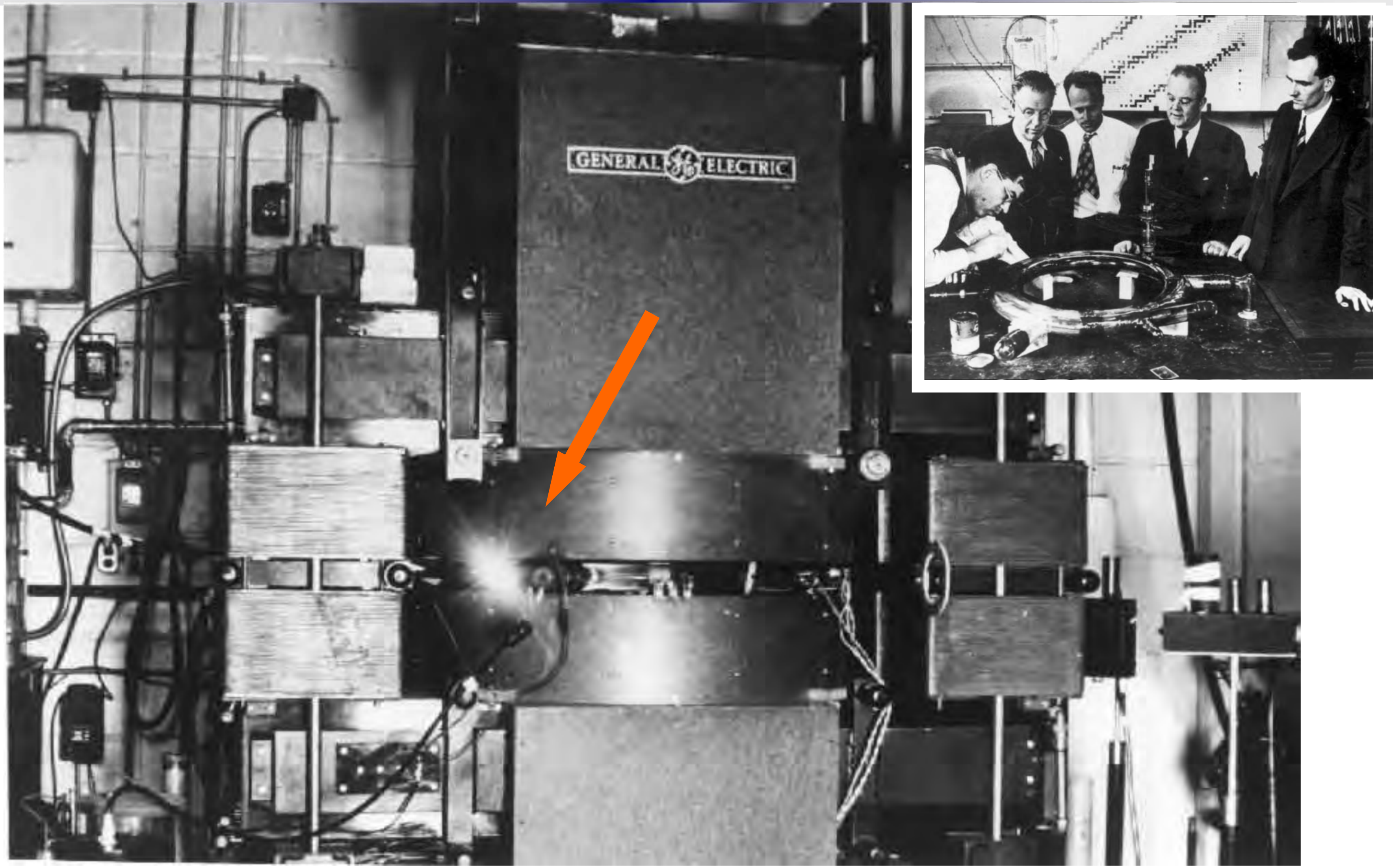
(rainer.gehrke@desy.de)

Outline

1. Synchrotron Radiation – Production and Properties
2. SR Instrumentation – Optics and Detectors
3. Scientific Experiments Using SR – Examples
    a. Scattering and Diffraction
    b. Spectroscopy
    c. Imaging
4. Experiments at Free Electron Lasers

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)

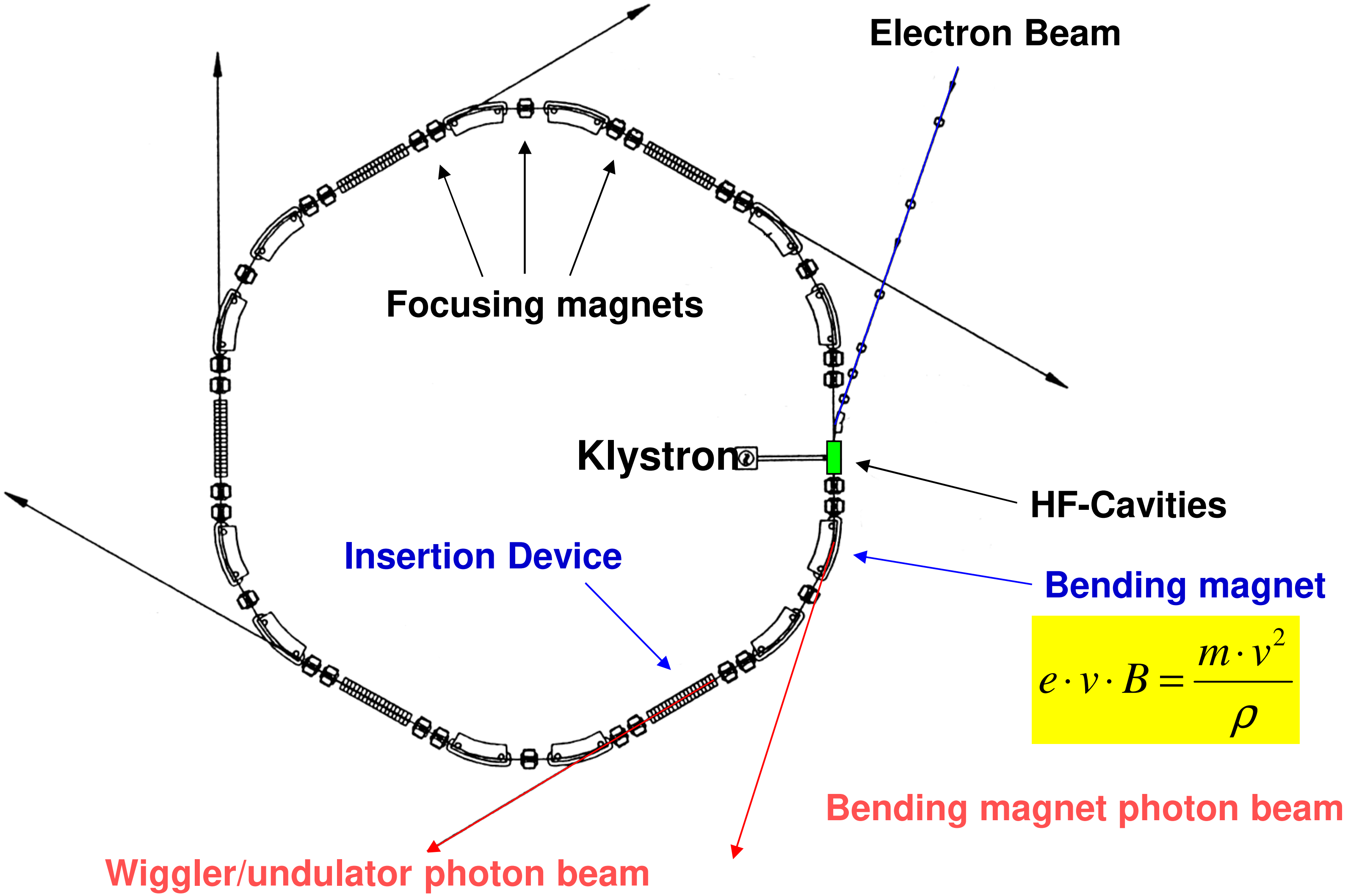
DESY Machine History

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

Synchrotron Radiation from Storage Rings



$$e \cdot v \cdot B = \frac{m \cdot v^2}{\rho}$$

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

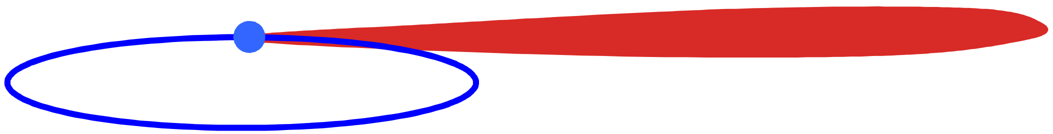
1. High photon flux

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

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)

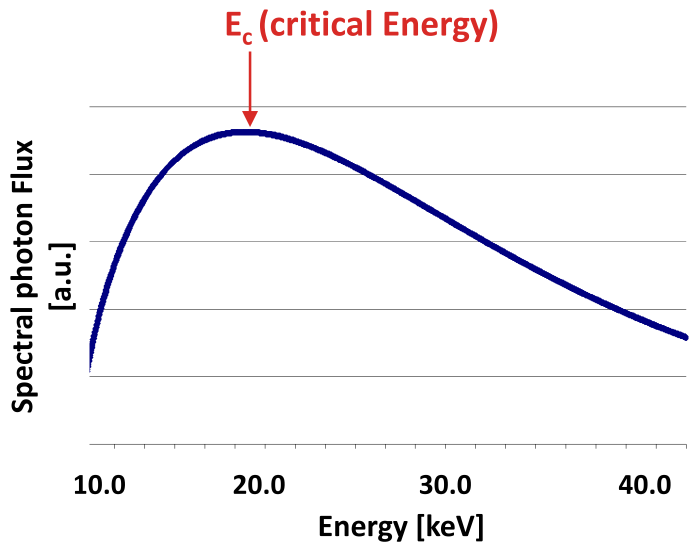
$\Theta = 2/\gamma$ = 0.0085 mrad at 6 GeV ($\gamma = E / m_e c^2$)



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

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

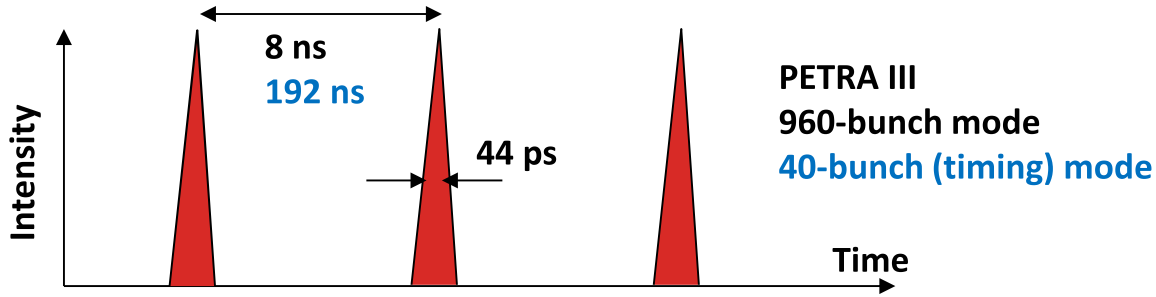
Example PETRA III → E_c = 21 keV



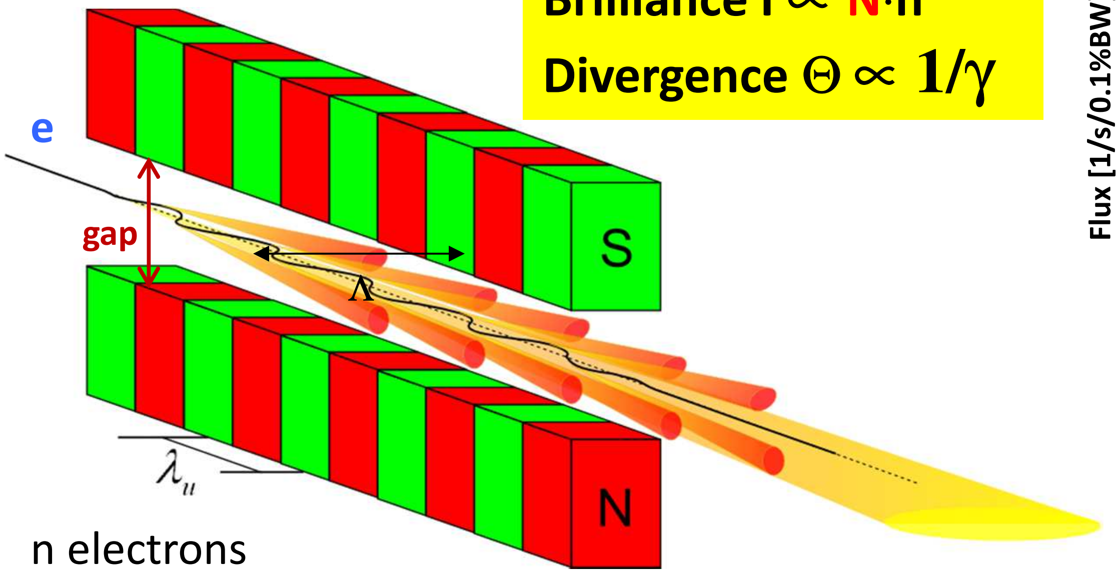
4. Polarization (linear in ring plane, circular above and below)

5. Time structure

6. Clean light pulses



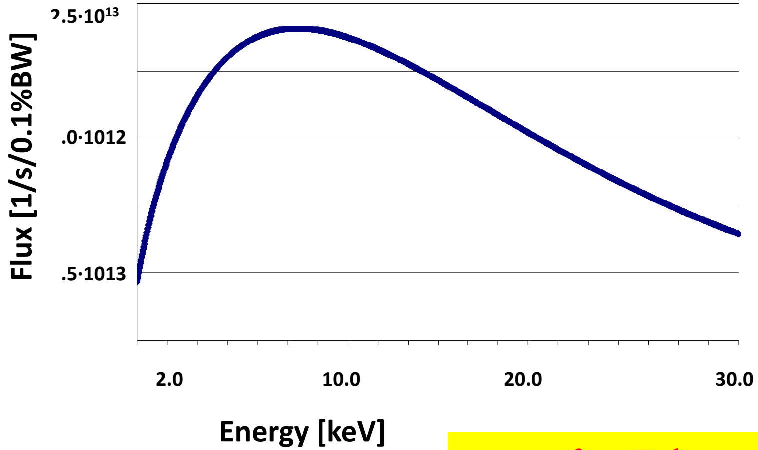
Wiggler (N poles)



n electrons

Brilliance I ∝ N·n

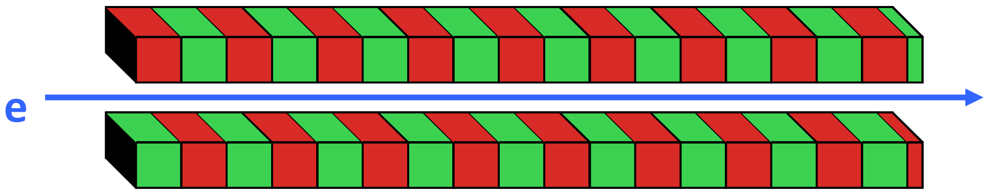
Divergence Θ ∝ 1/γ



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

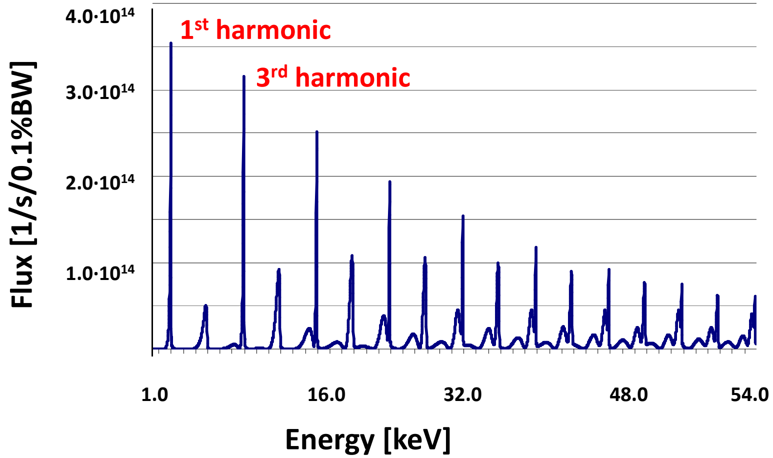
$$\lambda_{photon} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Undulator (N poles)



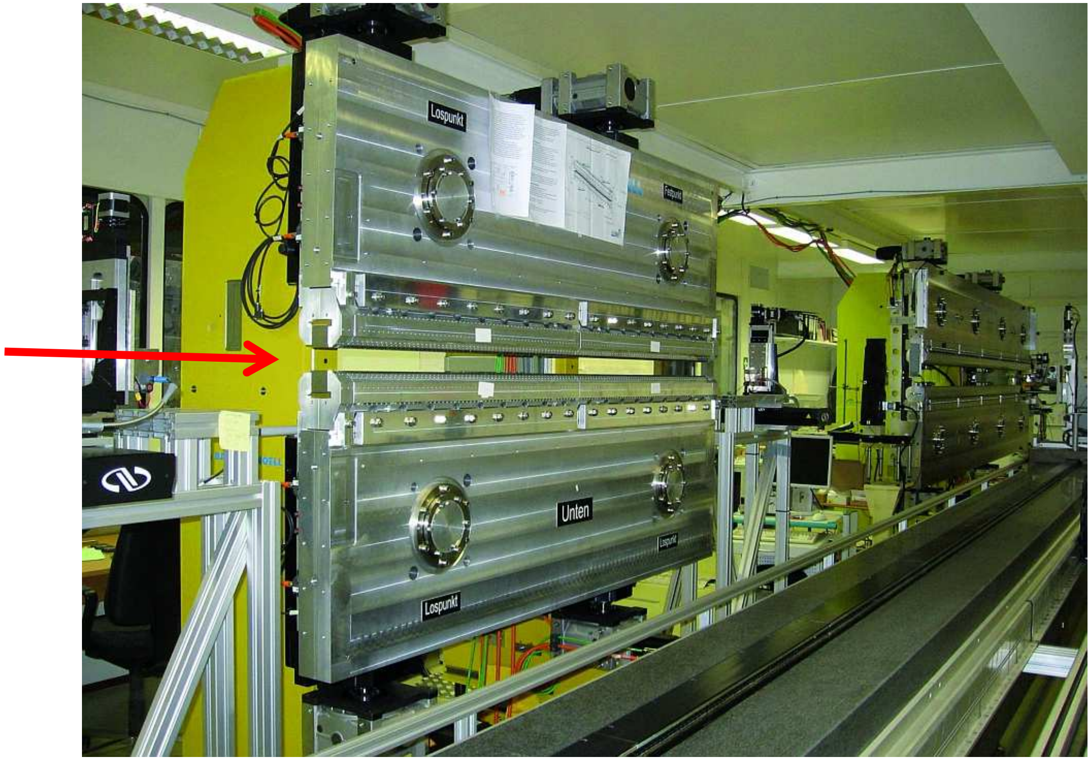
Brilliance I ∝ N² · n

Divergence Θ ∝ $1/\sqrt{\gamma^2 \cdot N}$



PETRA III Undulator

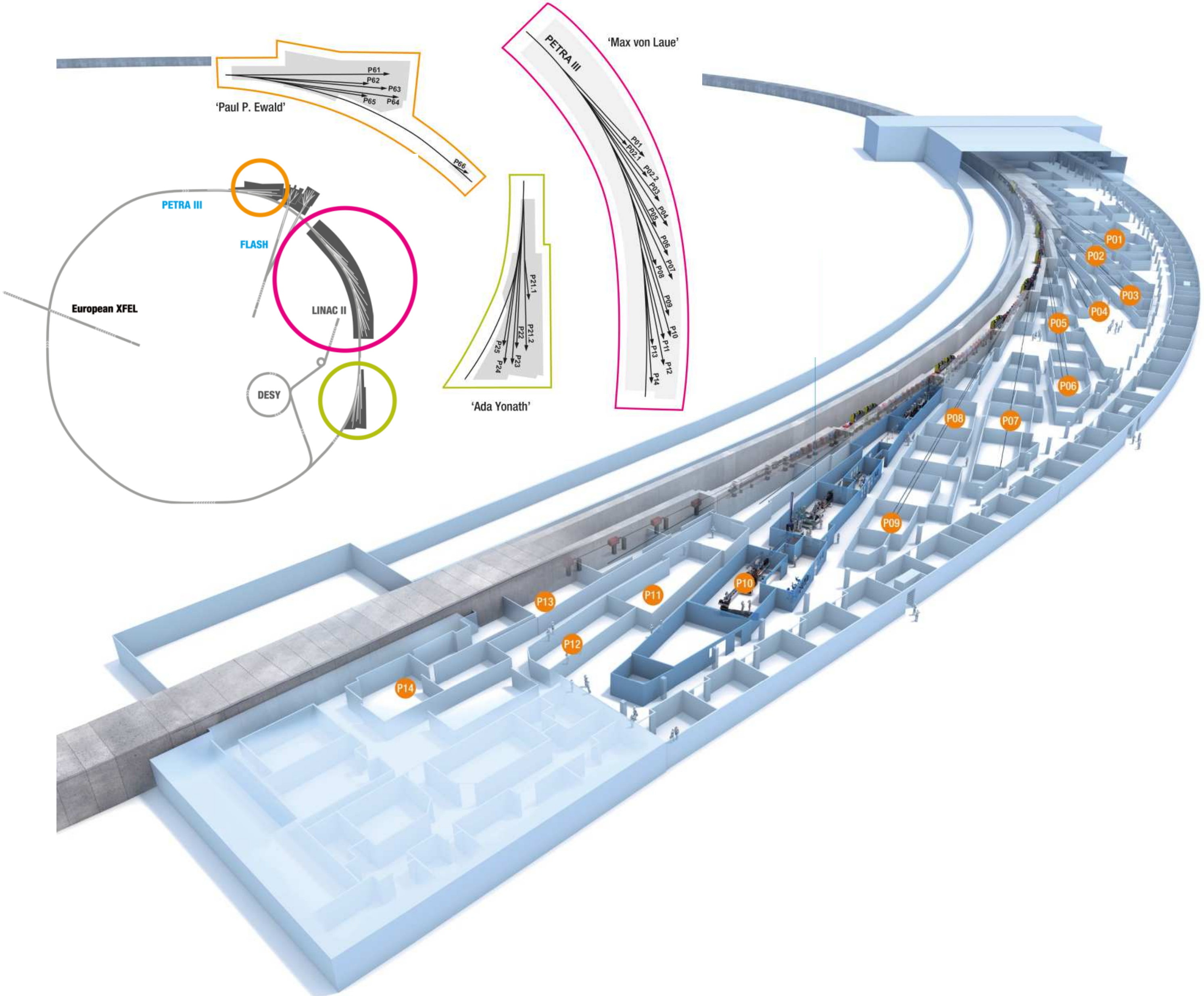
Vertical aperture of vacuum chamber: 7 mm



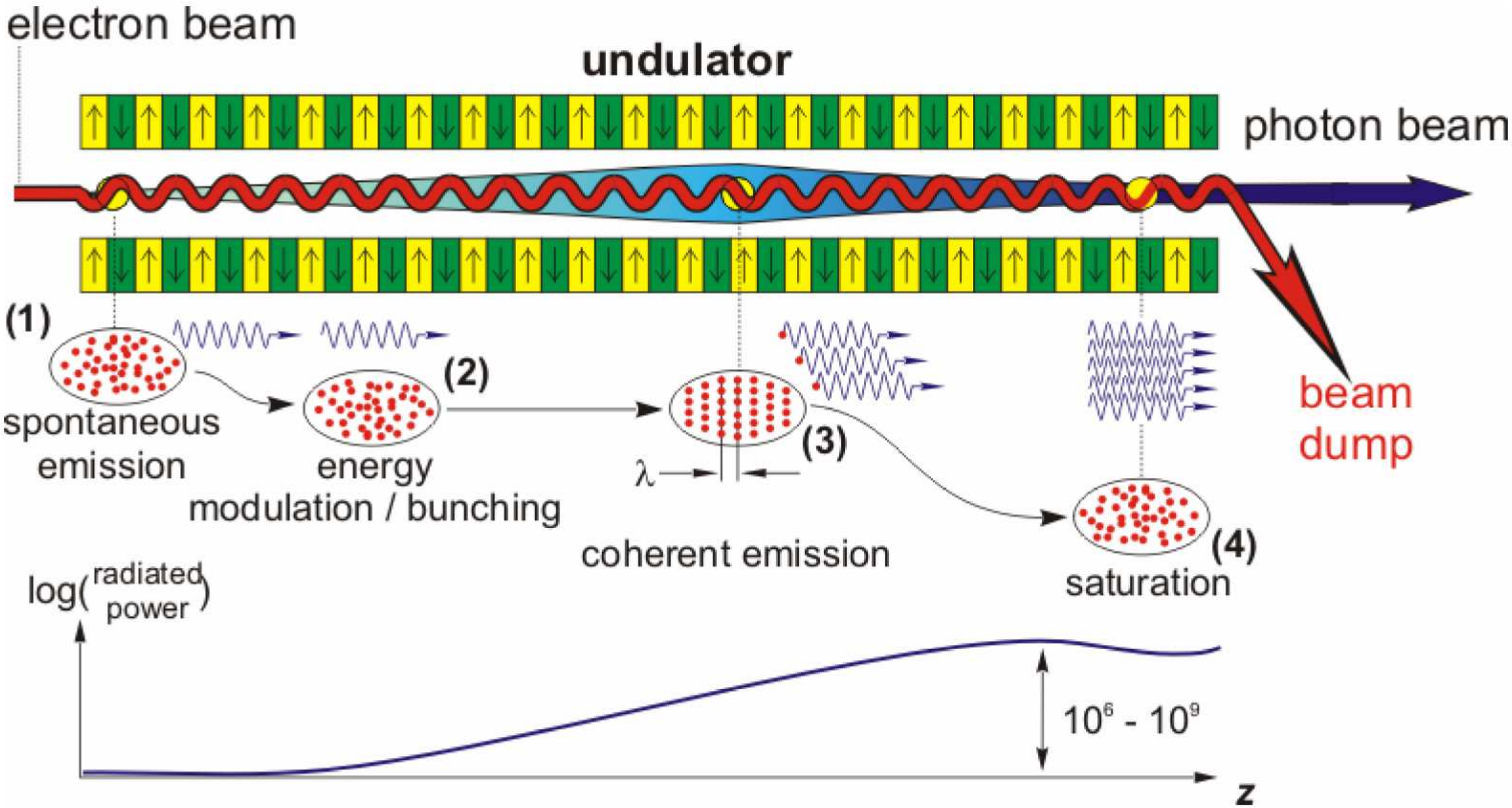
PETRA III machine parameters

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



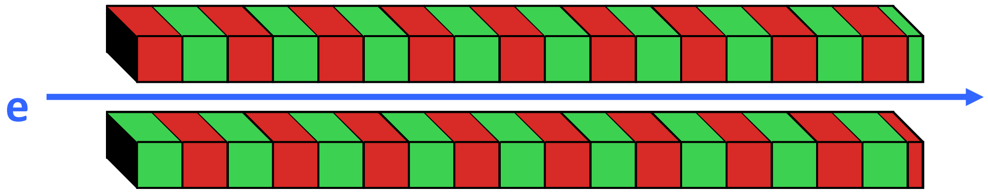
Self-Amplified Stimulated Emission (SASE)



Low gain	Exponential gain	Saturation

SASE undulators (Free Electron Laser)

SASE – Undulator (Free Electron Laser)



n electrons
N poles

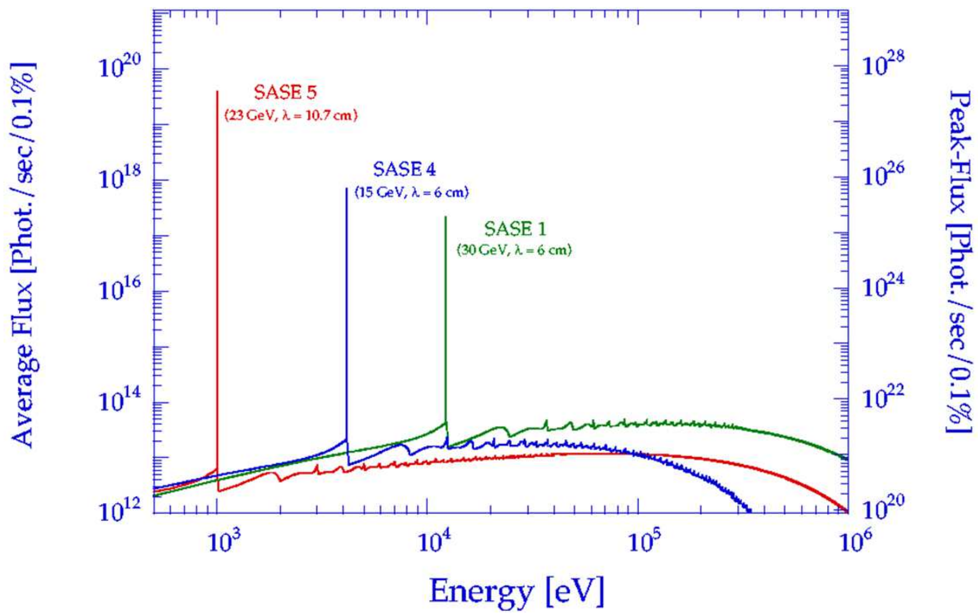
Brilliance I $\propto$ N^2 · n^2

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

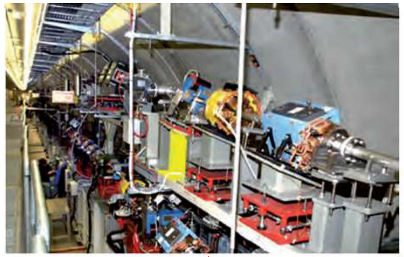


The FLASH free electron laser

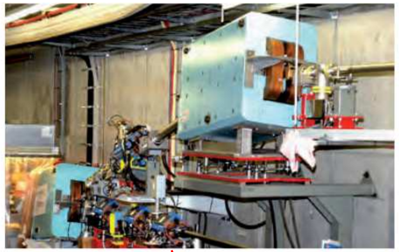
Accelerator modules

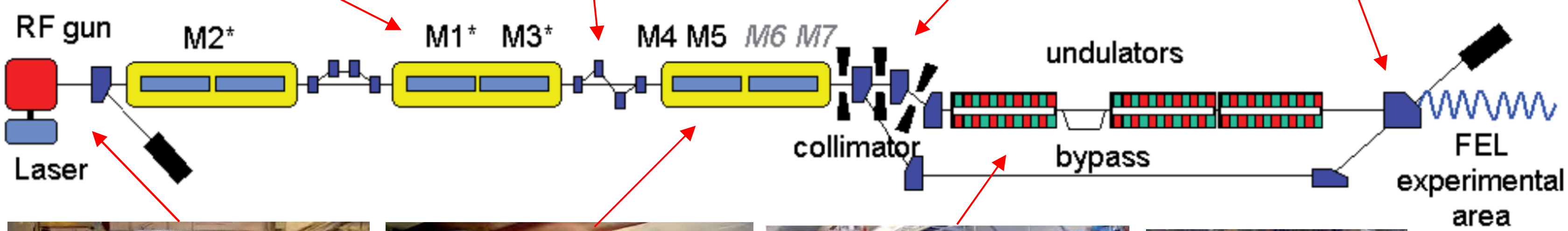
Bunch compressors
50 A → 2 kA

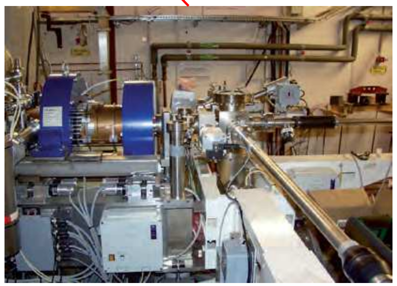
Collimators



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

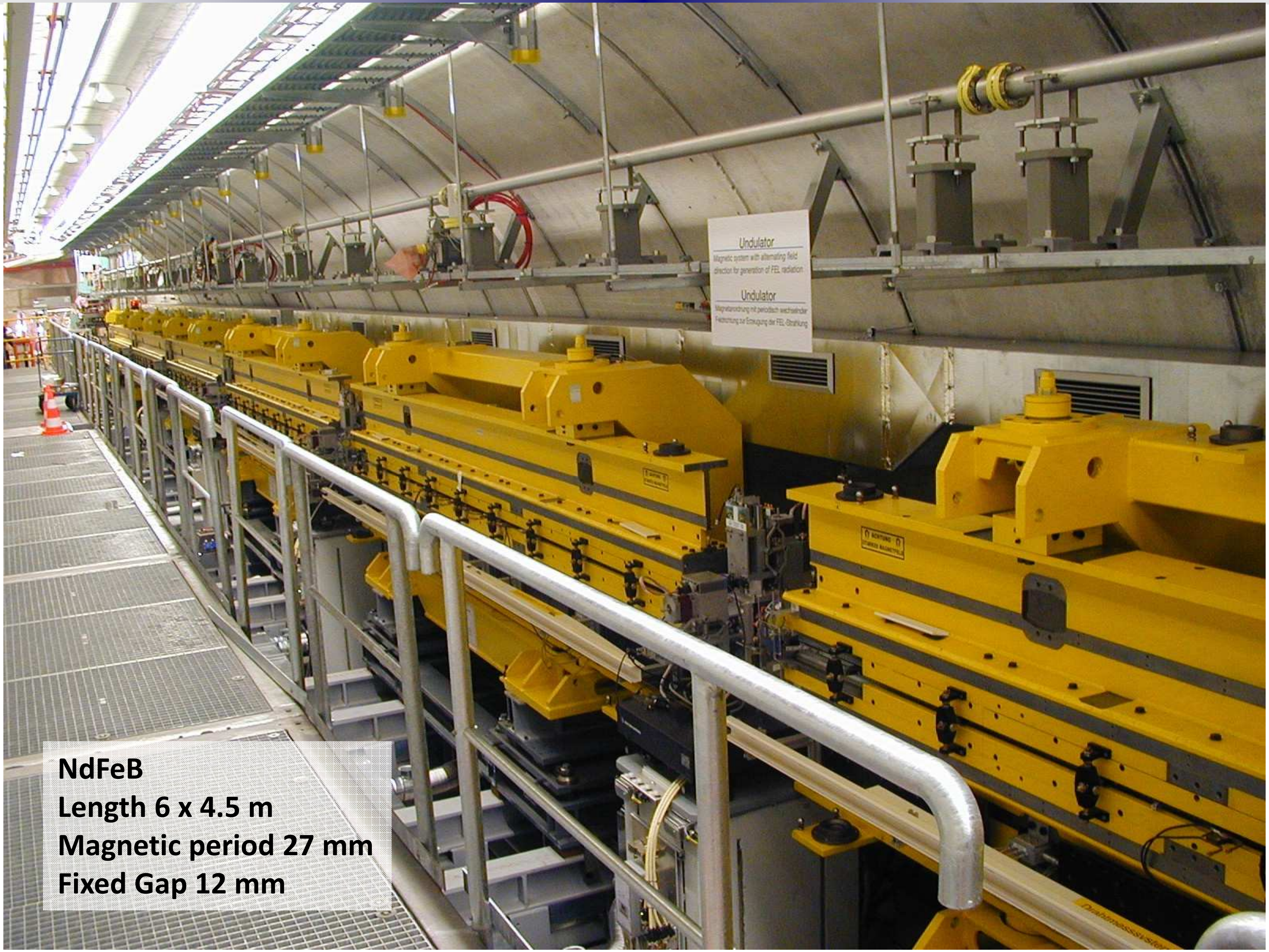
Total length about 320 m
Wavelength 51 nm – 4.2 nm – 1.7 (3rd harmonic)
Energy 24 eV – 295 eV
Pulse duration

Tuned by electron energy (undulator gap fixed)

FLASH Linear Accelerator Modules

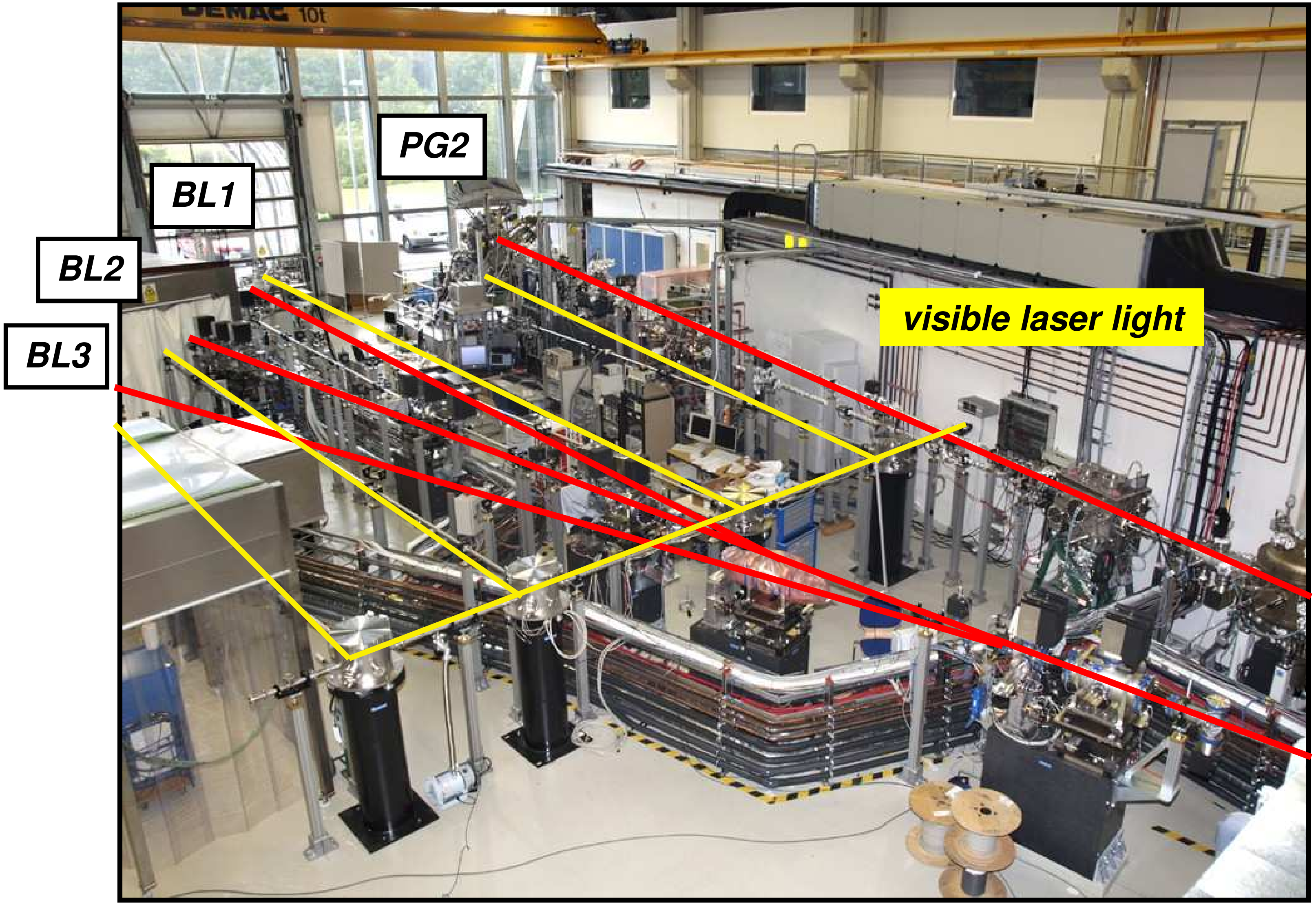
Superconducting Niobium cavities: 15 MV/m

FLASH Undulator Assembly

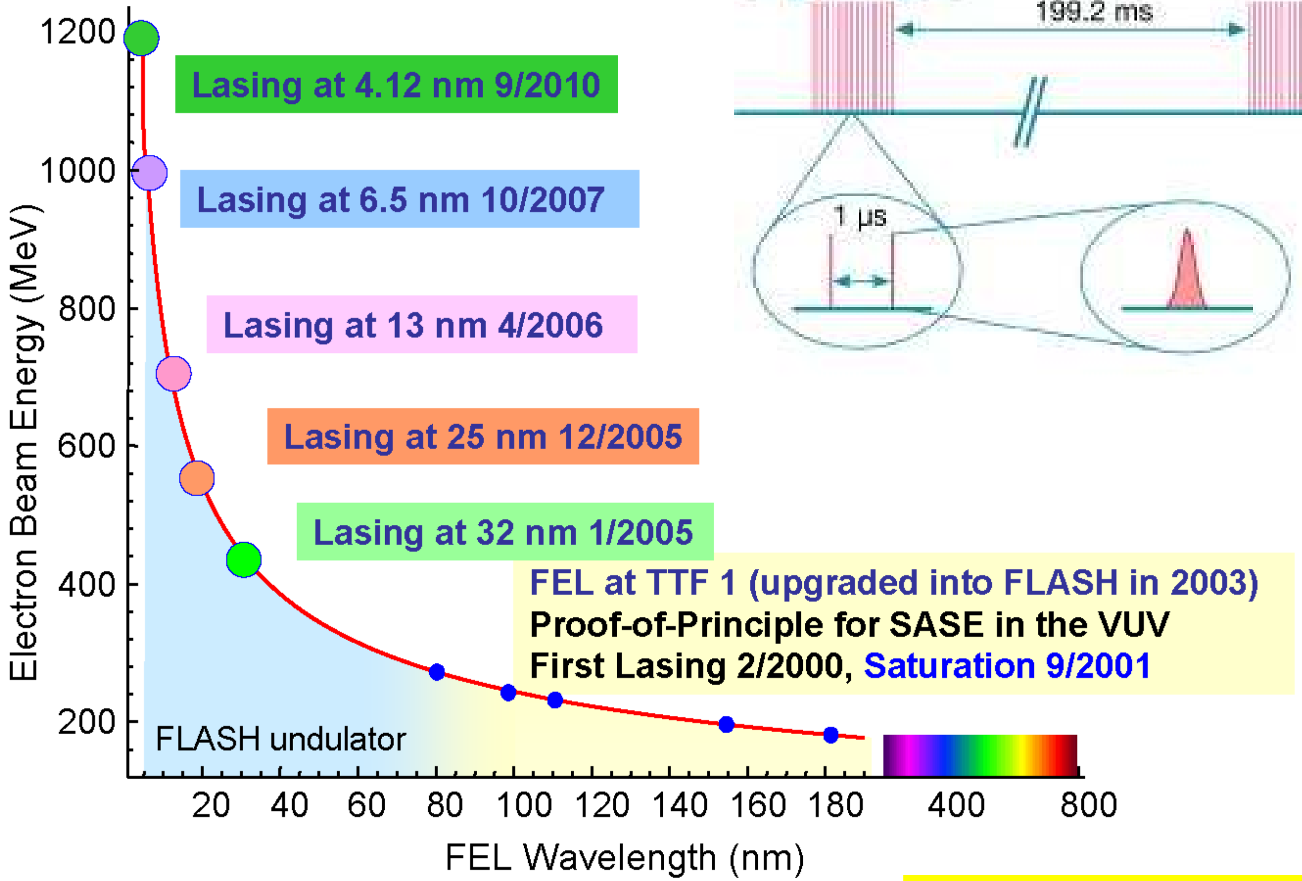


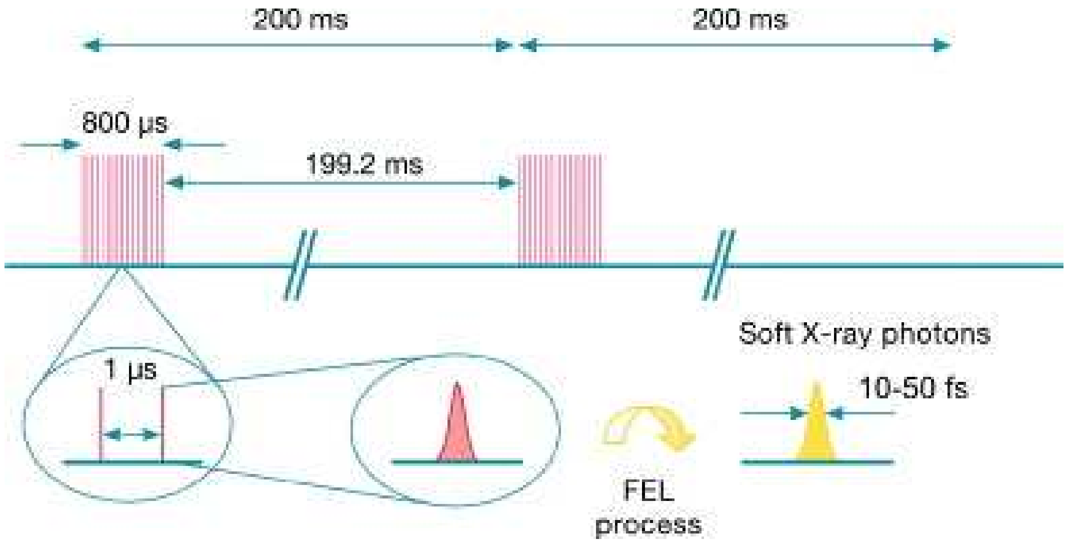
NdFeB
Length 6 x 4.5 m
Magnetic period 27 mm
Fixed Gap 12 mm

FLASH I experimental hall



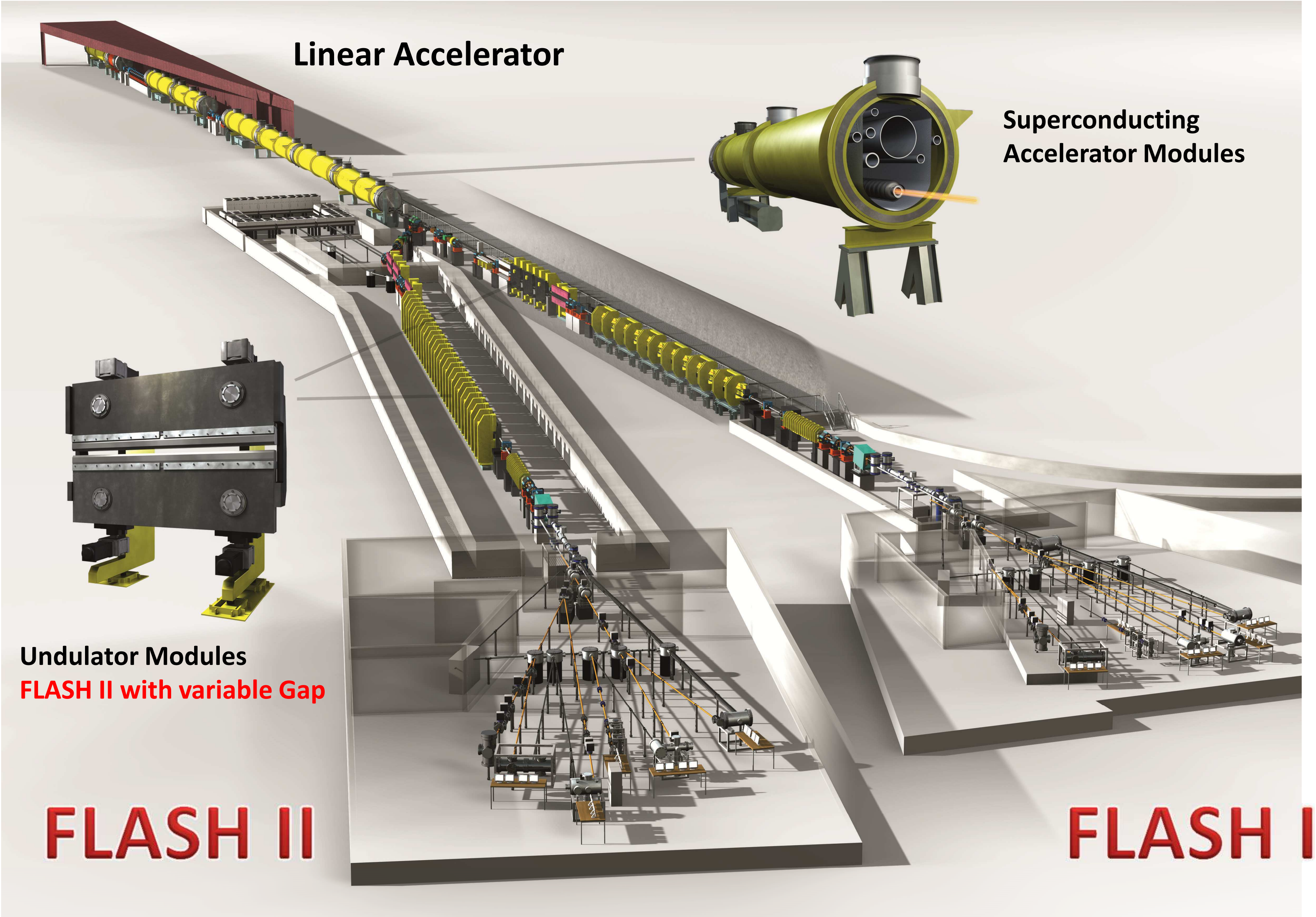
FLASH Development of maximum photon Energy



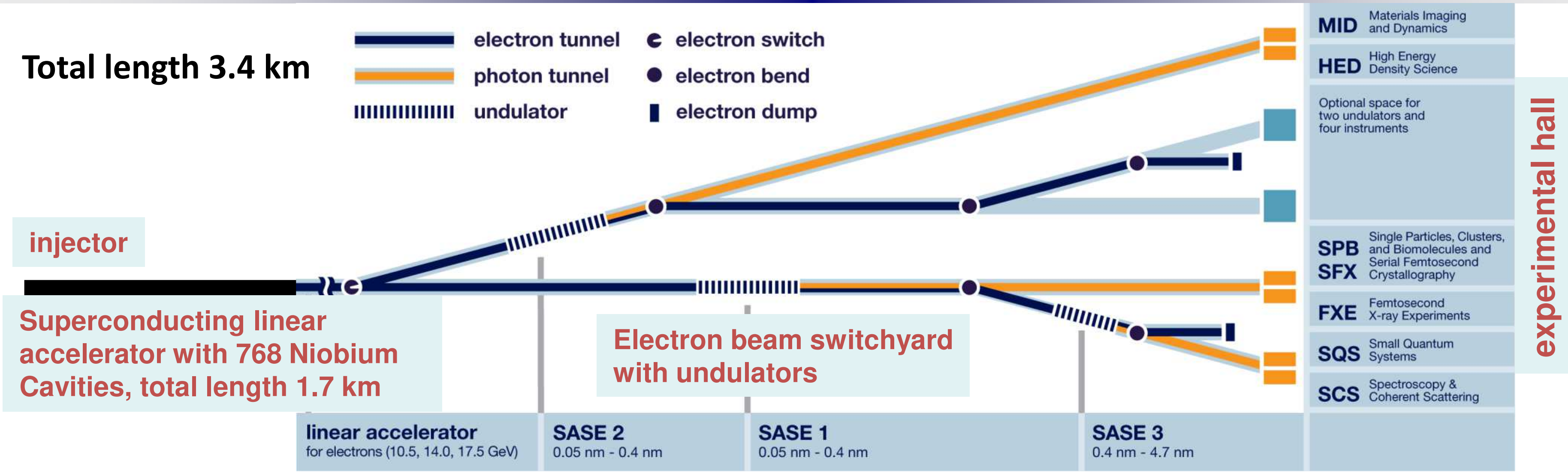


$$\lambda_{photon} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

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

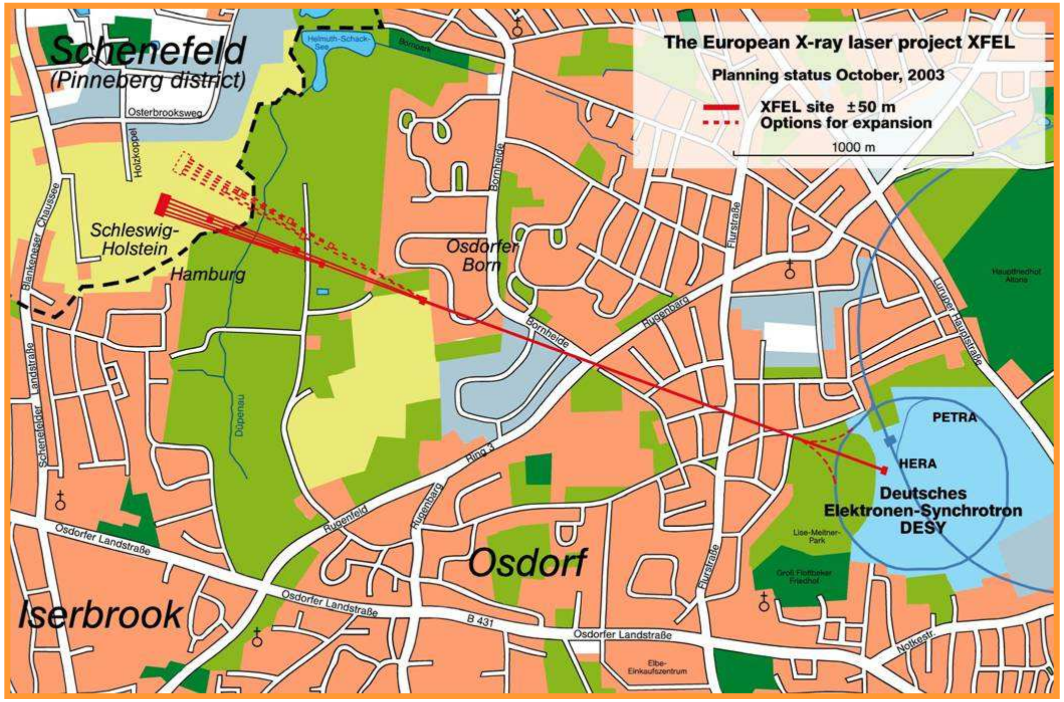
Photon Energies: 0.2 – 3 – 26 keV

Average Brilliance: ~10^{25}

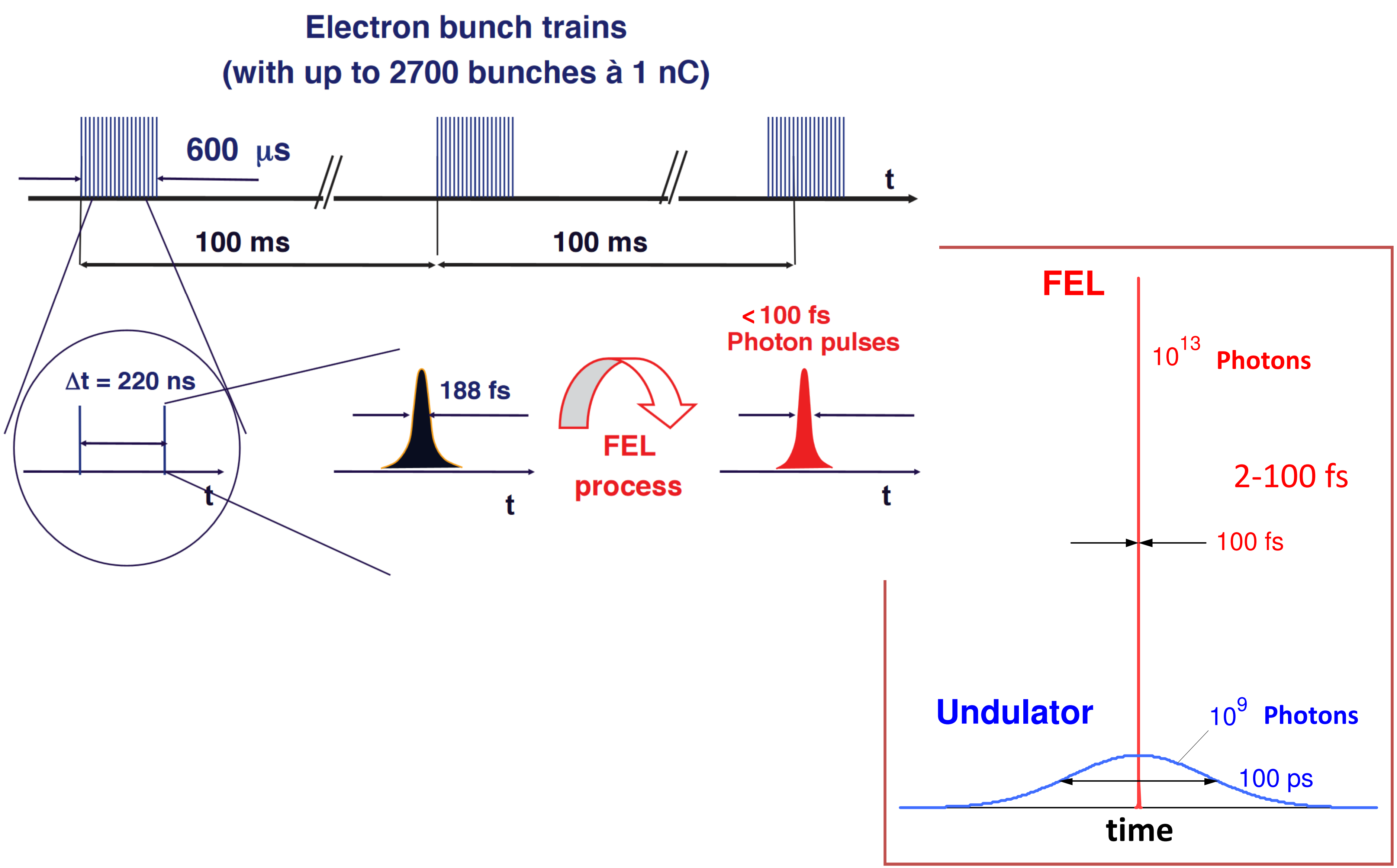
$1/(s \cdot mm^2 \cdot mrad^2 \cdot 0.1\%BW)$

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

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

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

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

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

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

Emittance $=$ $\boldsymbol{size \cdot divergence}$

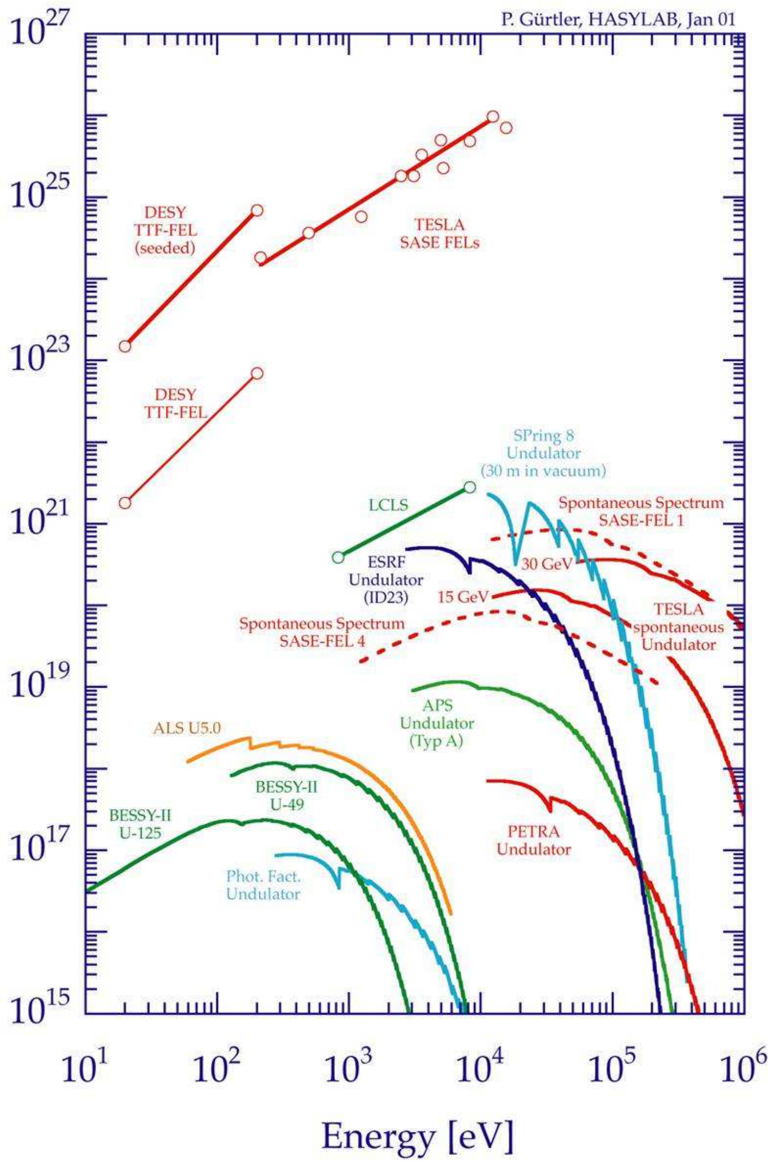
$$\boldsymbol{B = \frac{F}{Emittance}}$$

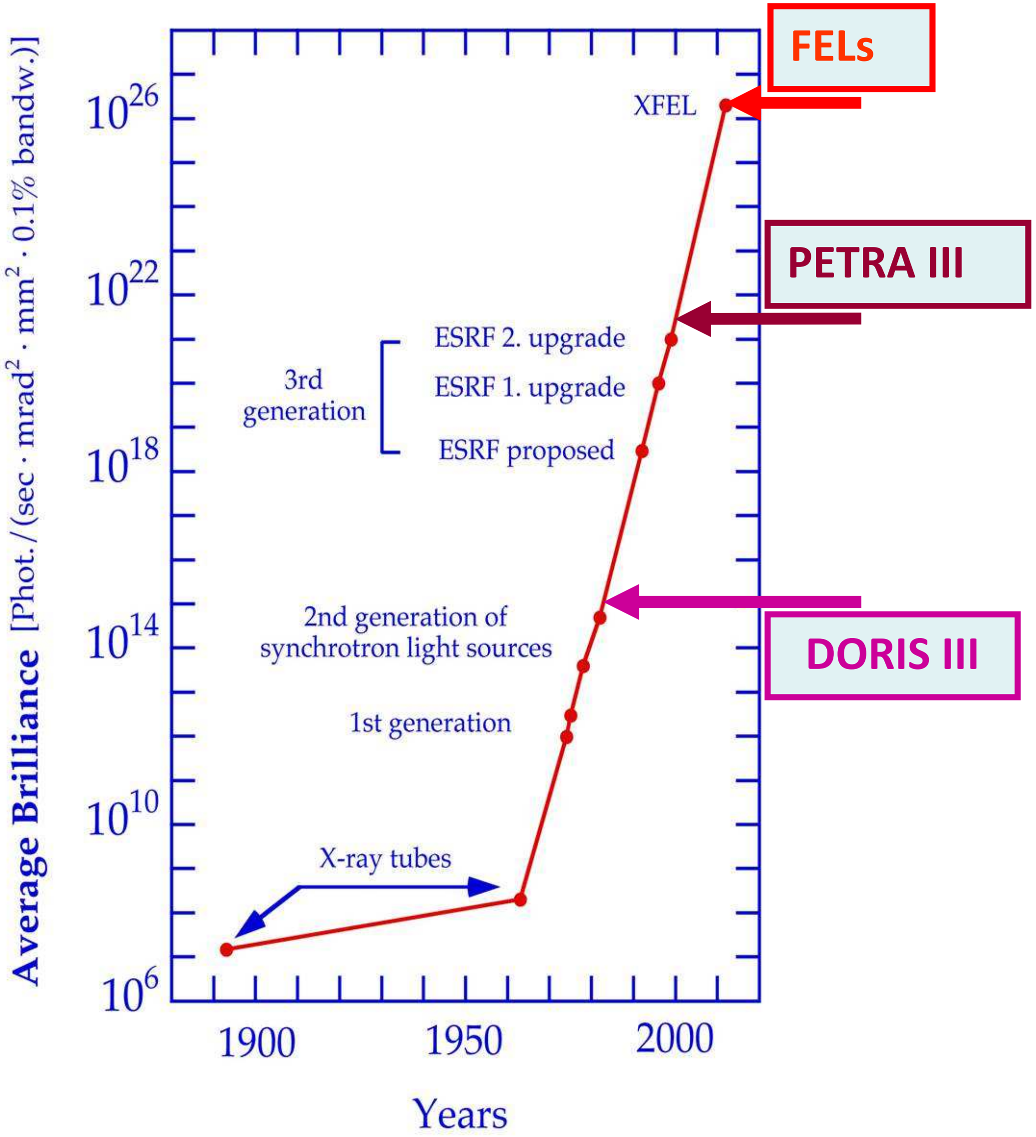
Degree (fraction) of lateral **coherence**

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

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

Evolution of Brilliance





Synchrotron Radiation Facilities Worldwide

DESY

HELMHOLTZ GEMEINSCHAFT

HZB Helmholtz Zentrum Berlin

ALBA

MAX IV

PAUL SCHERRER INSTITUT PSI

diamond

DESY.

Elettra Sincrotrone Trieste

SOLEIL SYNCHROTRON

ESRF The European Synchrotron

NSRRC

PAL POHANG ACCELERATOR LABORATORY

SPring-8

PF Photon Factory Institute of Materials Structure Science High Energy Accelerator Research Organization,KEK

SYNCHROTRON THAILAND

Canadian Light Source

Argonne NATIONAL LABORATORY

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

DESY

Synchrotron Radiation Facilities in Europe

HELMHOLTZ GEMEINSCHAFT

PETRA III 6 GeV

DIAMOND 3.0 GeV

SOLEIL 2.7 GeV

ESRF 6 GeV

ALBA 3 GeV

MAX IV 3.0 GeV

Diffraction limited

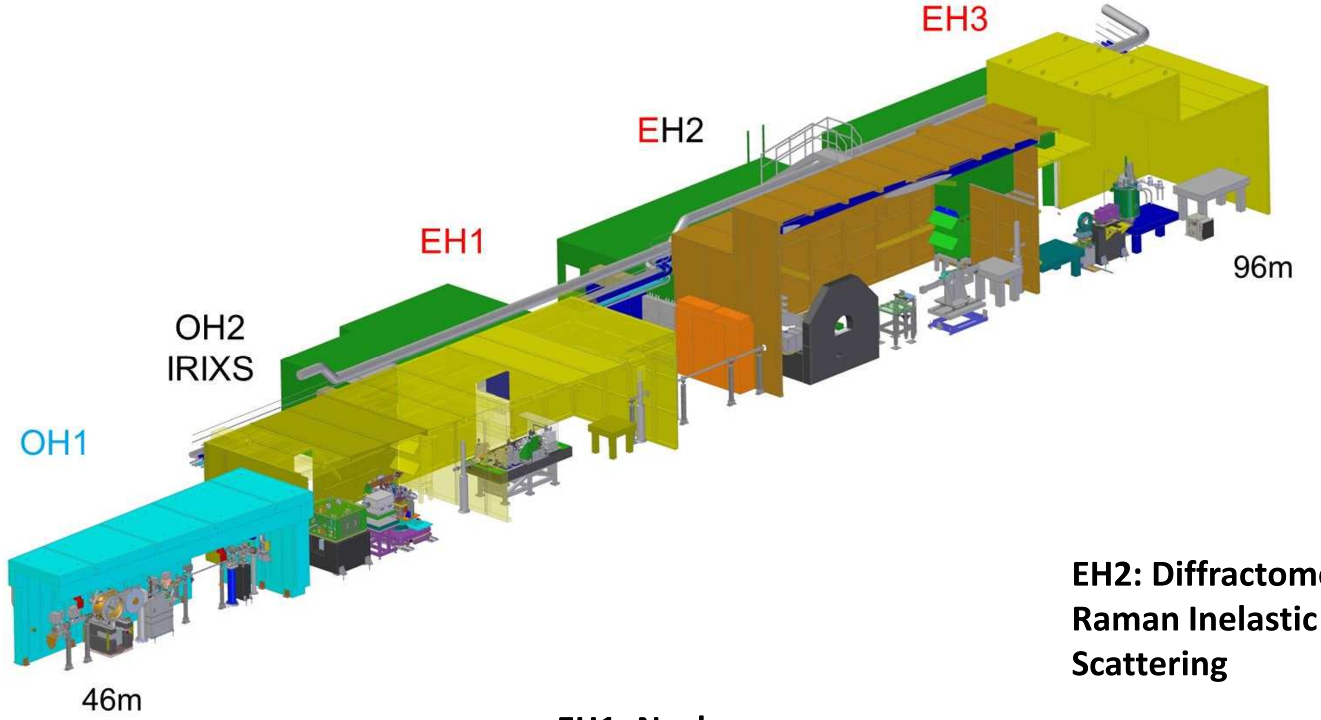
BESSY 1.7 GeV

SLS 2.4 GeV

Elettra 2.4 GeV

Optics and Detectors

PETRA III Beamline Layout Example: P01

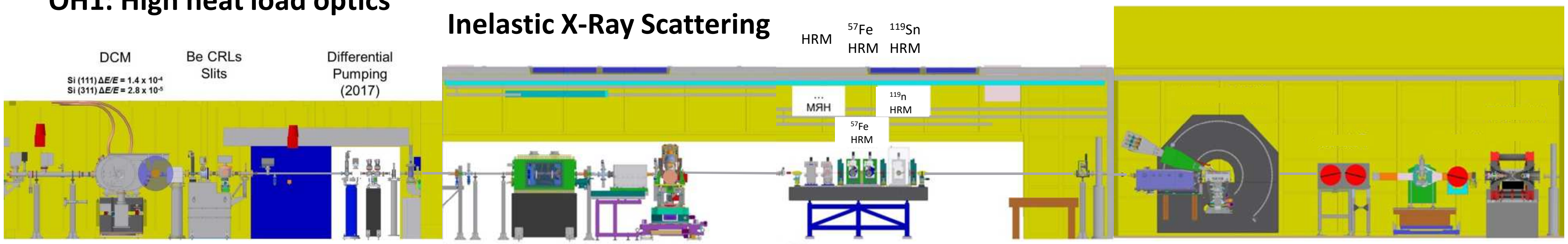


EH2: Diffractometer for Raman Inelastic X-Ray Scattering

EH1: Nuclear Resonant Scattering

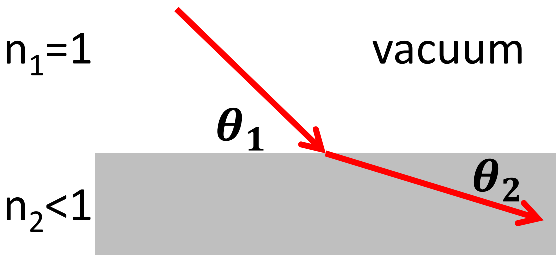
OH1: High heat load optics

OH2: Resonant Inelastic X-Ray Scattering



Beam

X-Ray Mirrors



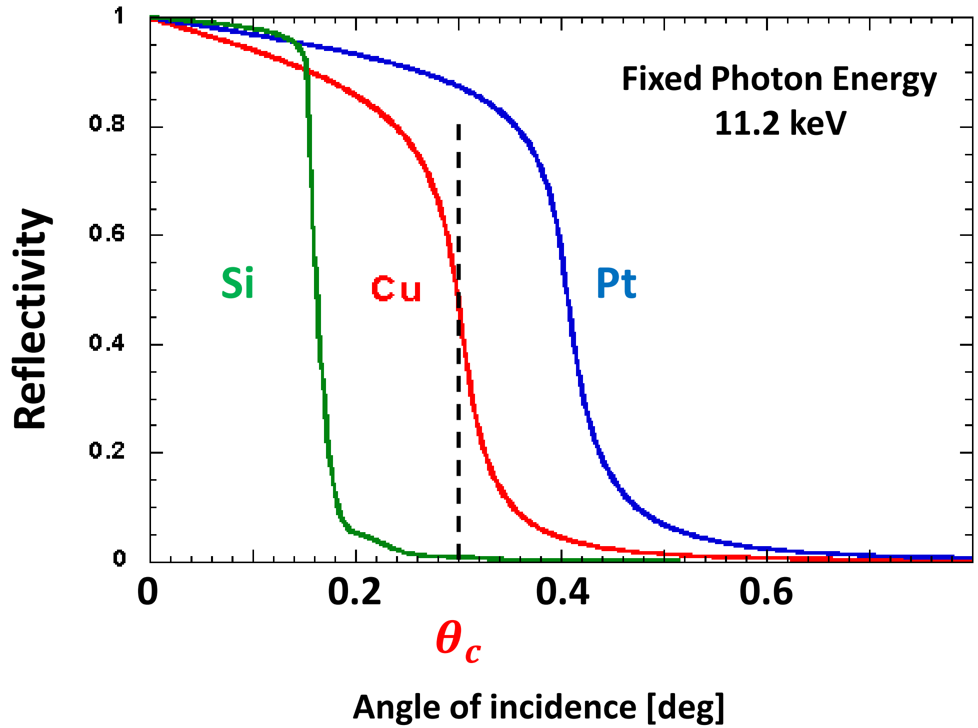
Snell's Law:

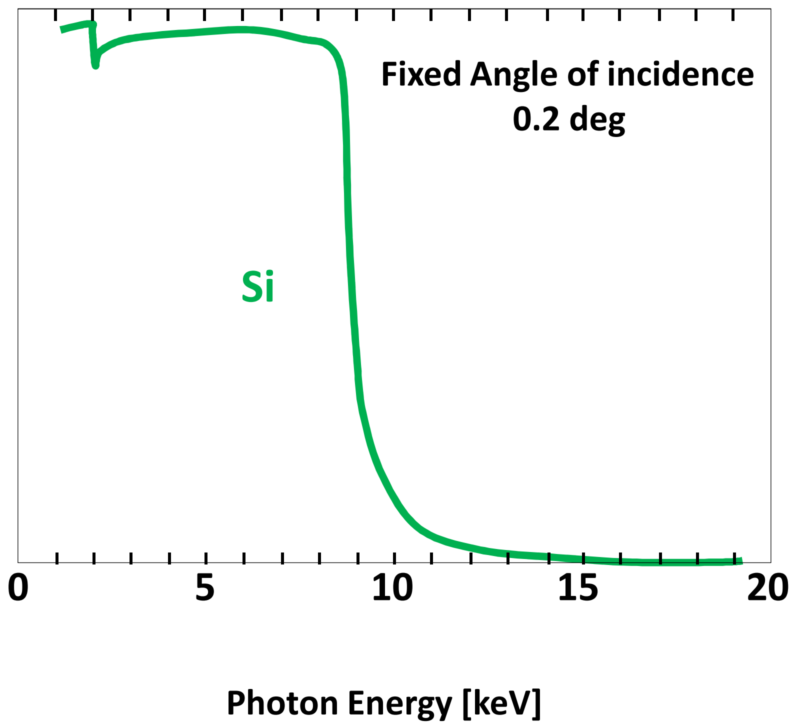
$$\frac{\sin\left(\frac{\pi}{2}-\theta_1\right)}{\sin\left(\frac{\pi}{2}-\theta_2\right)} = \frac{n_2}{n_1} = n_2$$

$\boldsymbol{\theta_2 = 0}$

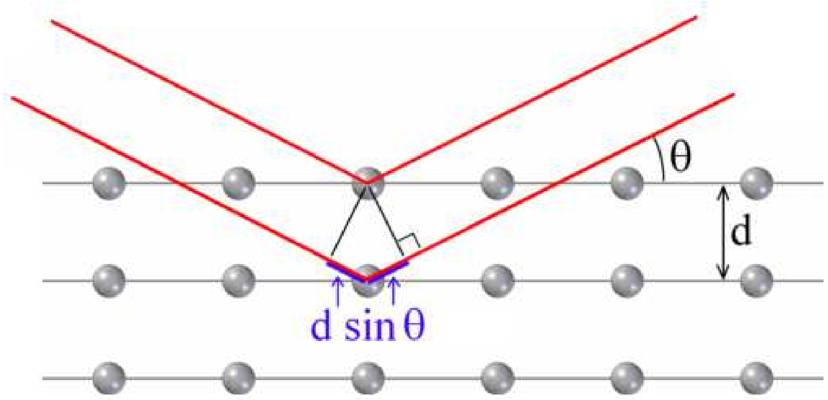
$\boldsymbol{\theta_1 = \theta_c}$

$$\theta_c \sim \sqrt{2(1-n_2)}$$

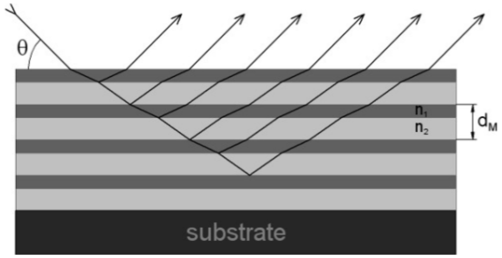




Crystal X-Ray Monochromators



Crystal



Multilayer

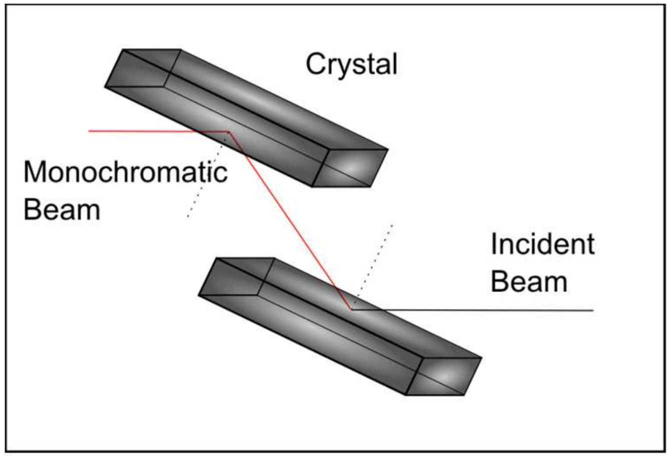
E.g.

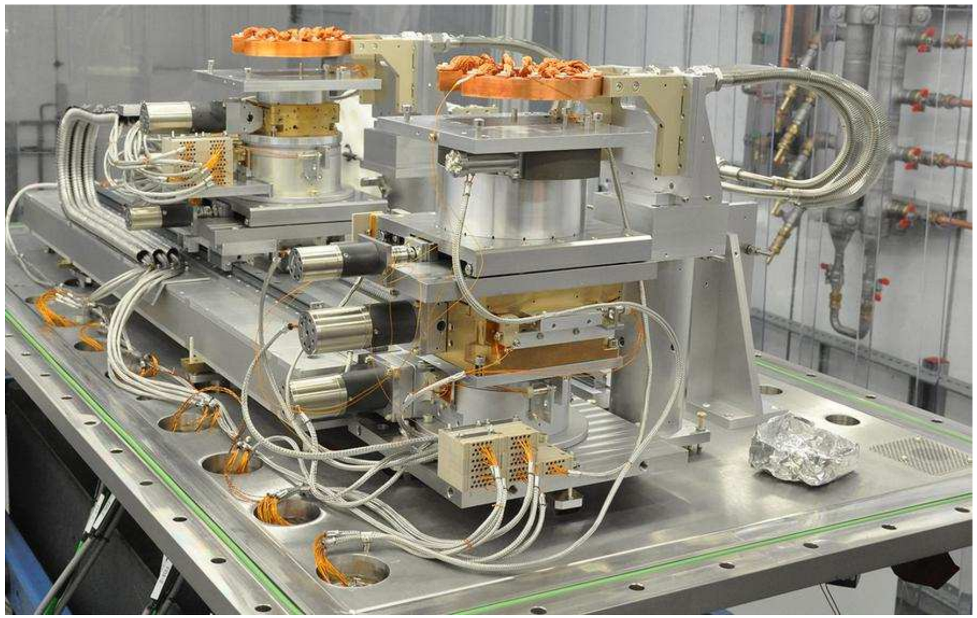
SiC/W

$$n \cdot \lambda = \frac{2d}{n} \cdot \sin\theta \qquad , n \epsilon N$$

Fixed exit double crystal monochromator arrangement

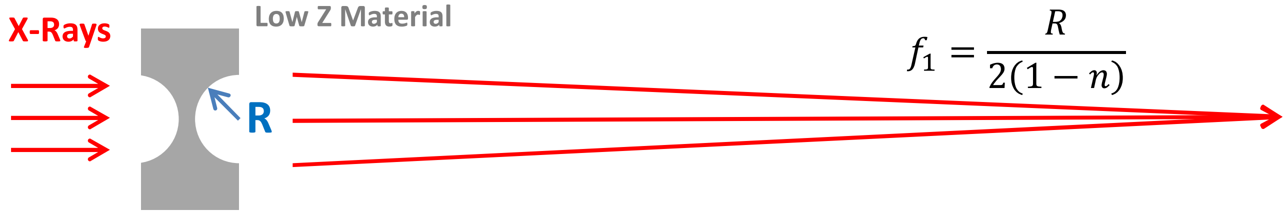
Example:
Silicon (111)
Energy resolution
$\Delta E/E \approx 10^{-4}$





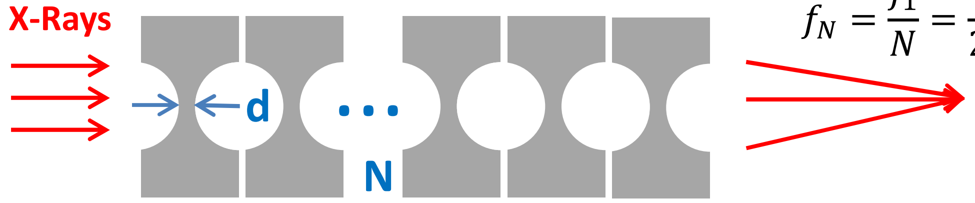
Cryogenically cooled double Laue monochromator at a PETRA III beamline (vacuum vessel removed).

Compound Refractive X-Ray Lenses



$$f_1 = \frac{R}{2(1-n)}$$

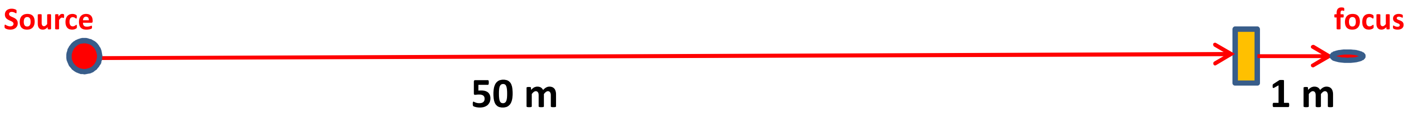
n<1



$$f_N = \frac{f_1}{N} = \frac{R}{2N(1-n)}$$

Example:
Material: Beryllium
R = 0.25 mm
f_N = 1 m
d = 20 µm

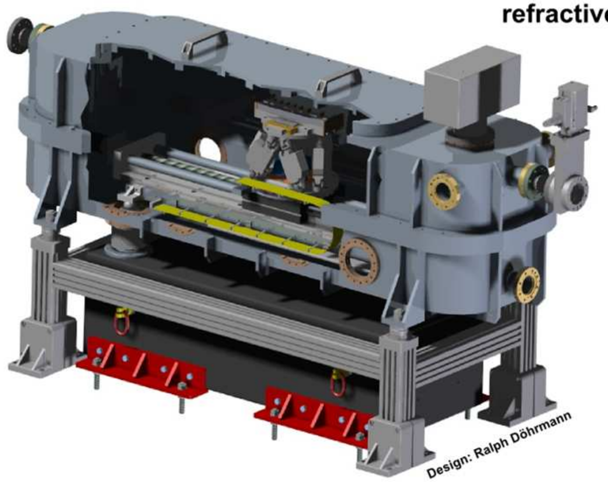
E [keV]	1-n [10^{-6}]	N
8	5.26	24
20	0.85	147
40	0.21	587



Source demagnification 1:50

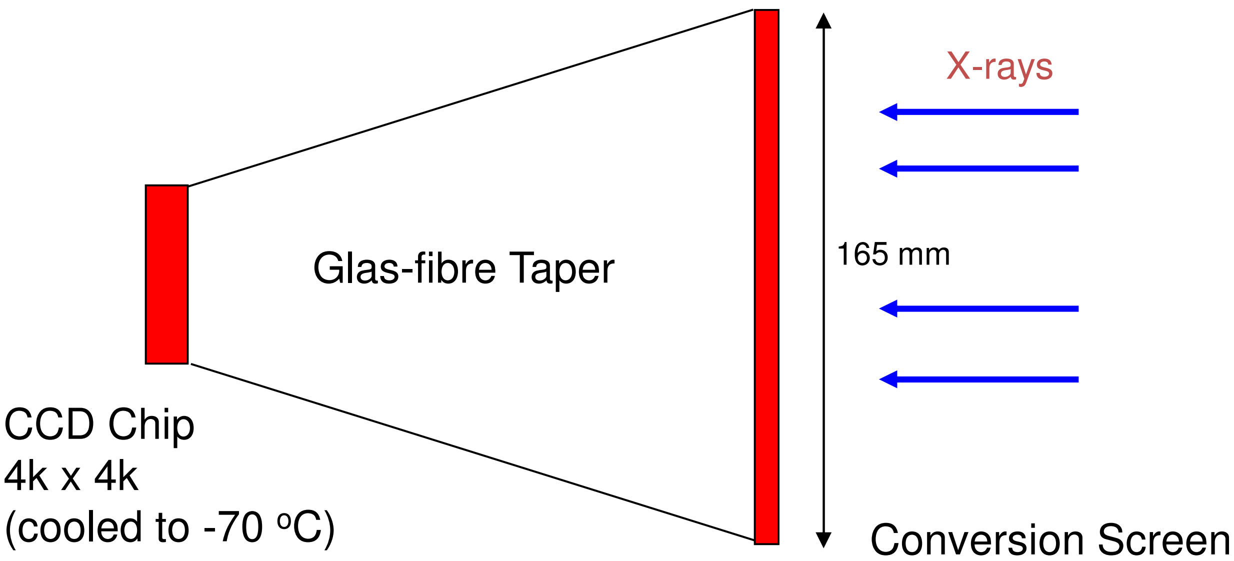
Stack of 2D Beryllium lenses

Housing for beryllium compound refractive lenses



Beamline Components: Detectors

Integrating pixel detector
Readout time 2.5 s
Dark current 0.01 e^-/pixel/s
Readout noise 10 per pixel
Dynamic range 10^4
(limited by dark current and
pixel saturation)

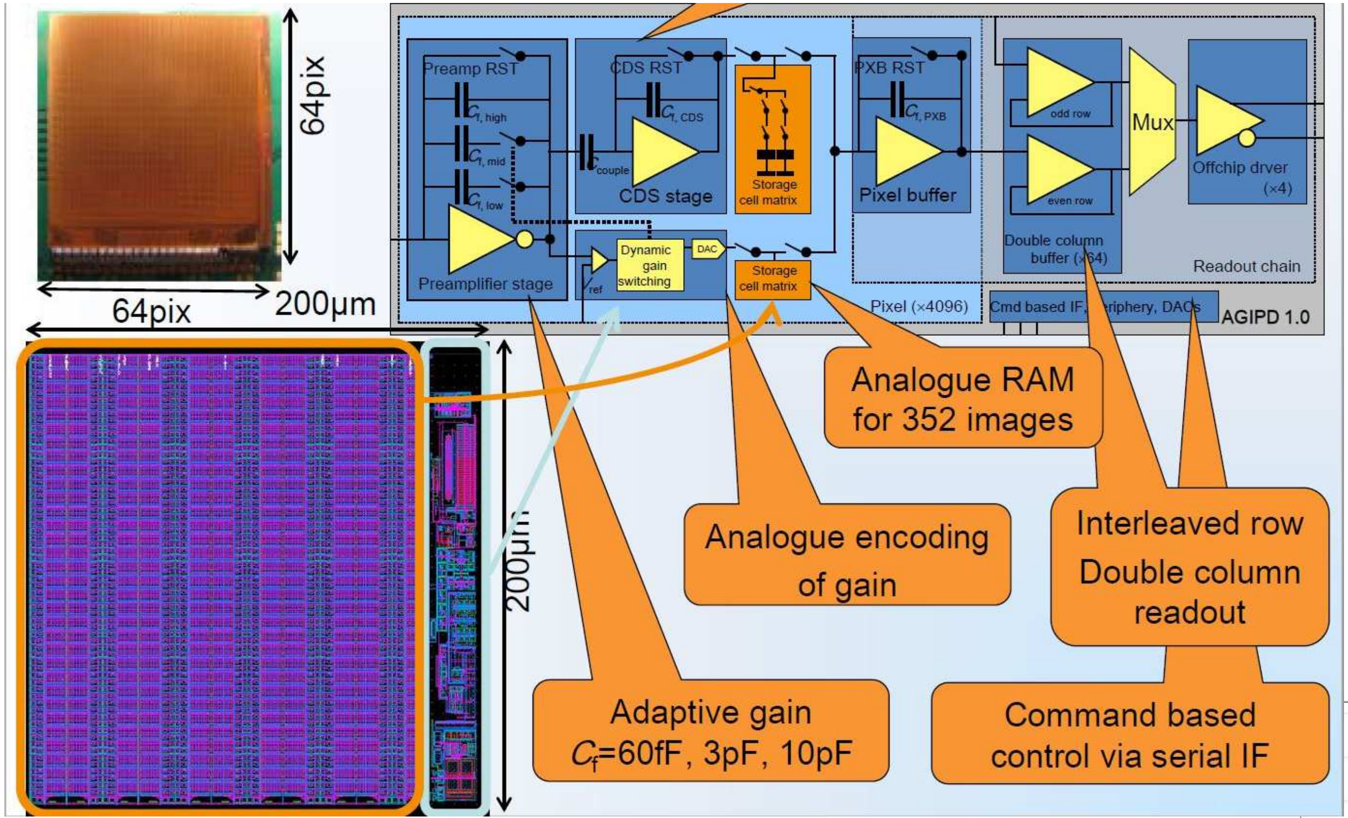


Adaptive Gain Integrating Pixel Detector (AGIPD)

4096 pixel Module

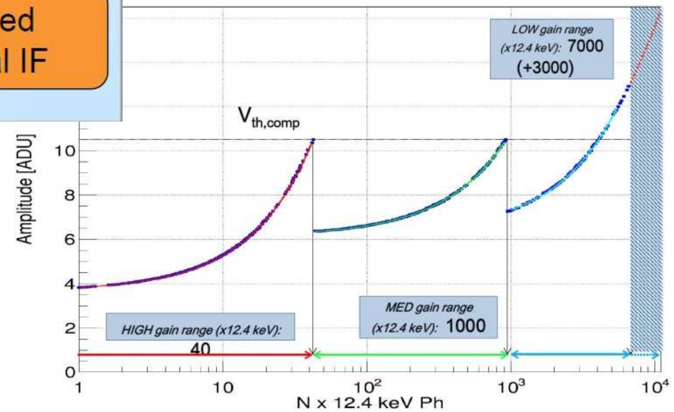
AGIPD ASIC

- 1 to 10^4 photons/pixel and pulse (three gain stages)
- at 12 keV
- 4.5 MHz frame rate
- Capable to store 352 frames Prior to readout

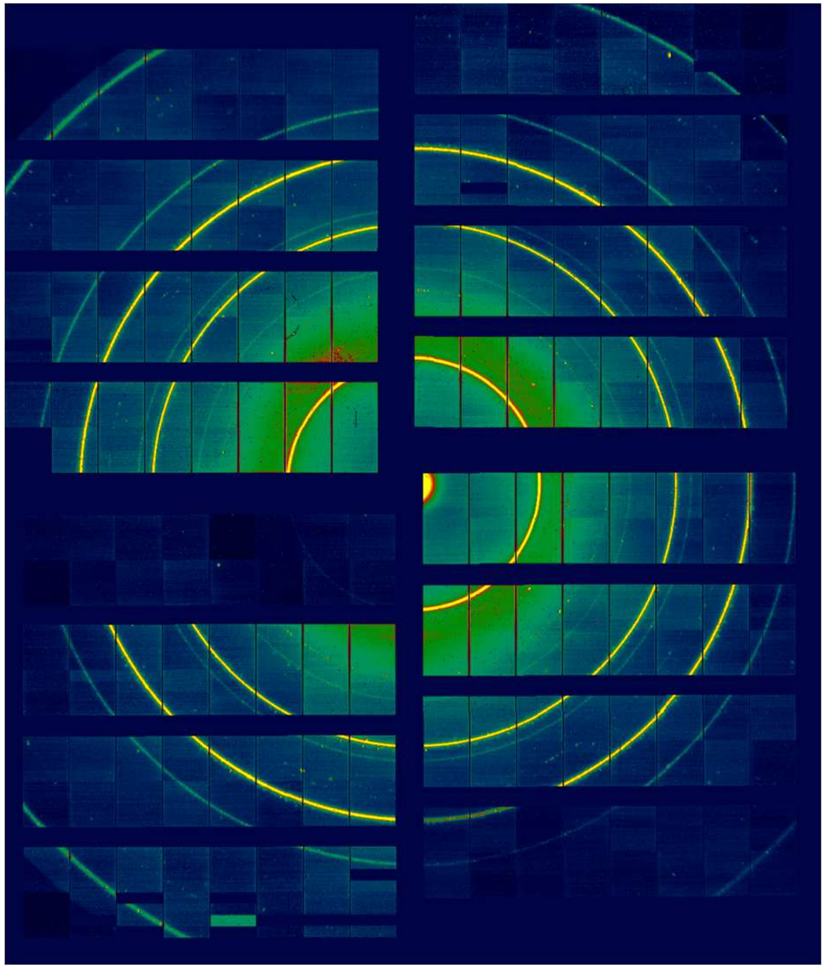


Single Pixel

size 200 x 200 µm²



The AGIPD



Four movable Quadrants, each with four stripes of
2 x 8 modules in each stripe → 1024 x 2024 pixel (1 Mpix)
Housing under vacuum
Optimize coverage of scattering plane, guide primary beam alongside the sensitive area