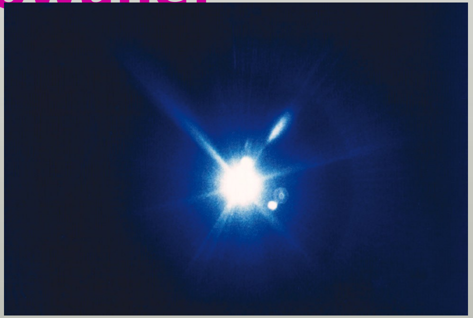
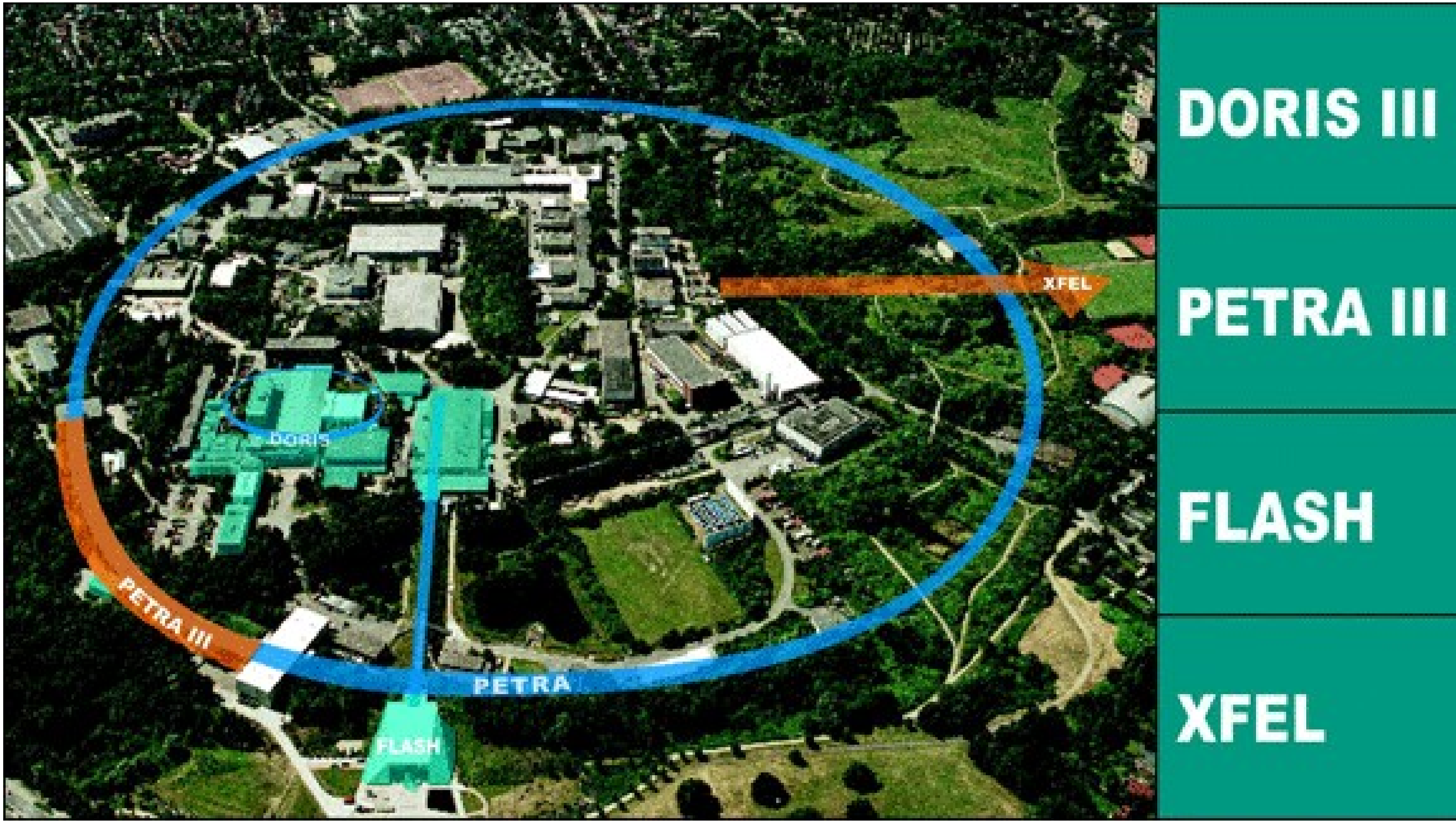
AKADEMIA GÓRNICZO-HUTNICZA
IM. STANISŁAWA STASZICA W KRAKOWIE

Laser rentgenowski na swobodnych elektronach- nowe źródła promieniowania X w DESY-HASYLAB

Marek Lankosz

Wydział Fizyki i Informatyki Stosowanej



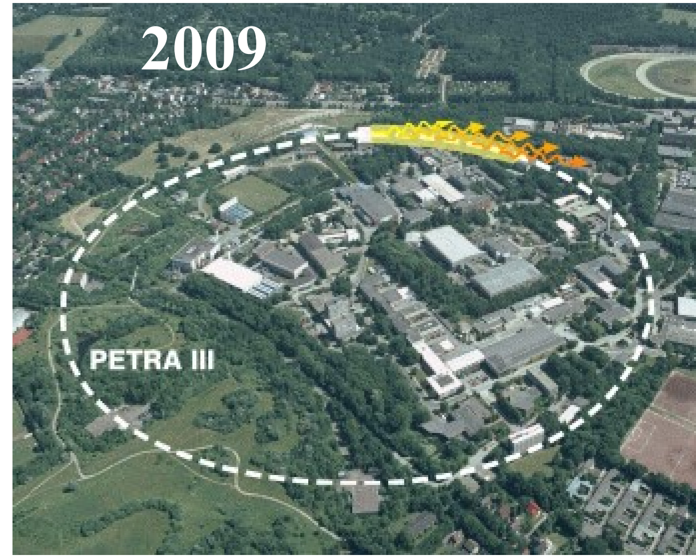


Light sources for research with photons at DESY

Source: DESY, Hamburg

Total project construction cost - 1,081.6 M€

Source: DESY, Hamburg

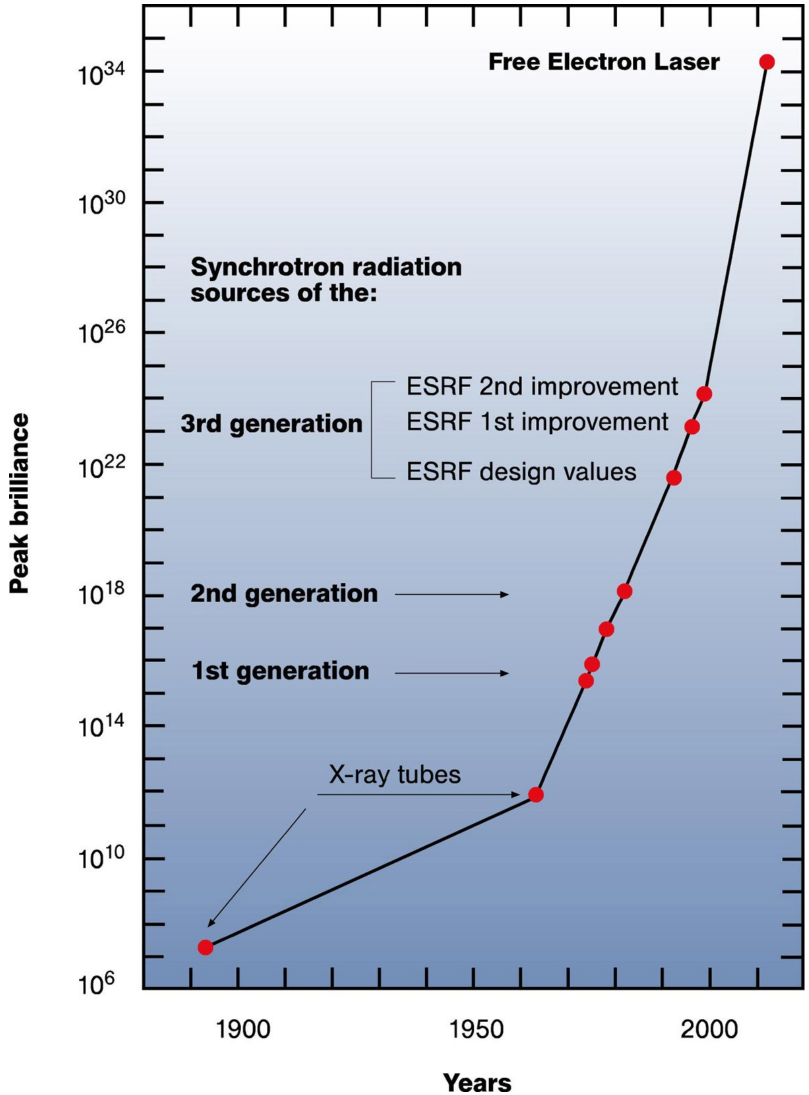


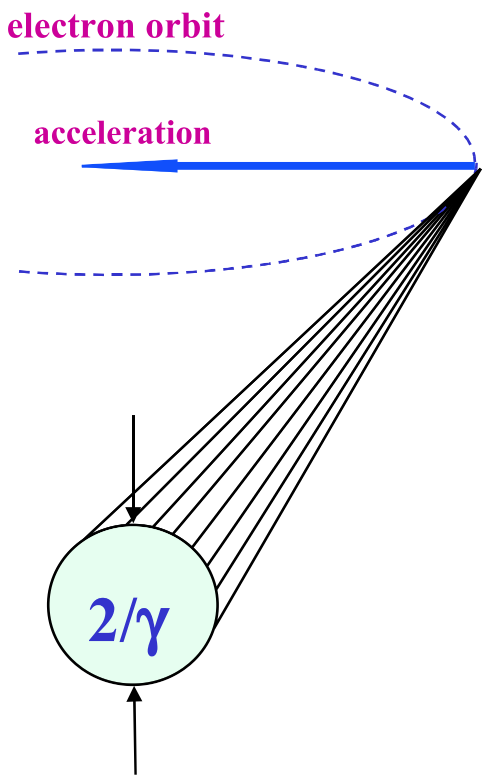
Petra III Facilities

a total investment of 225 million €

PETRA and HERA accelerators

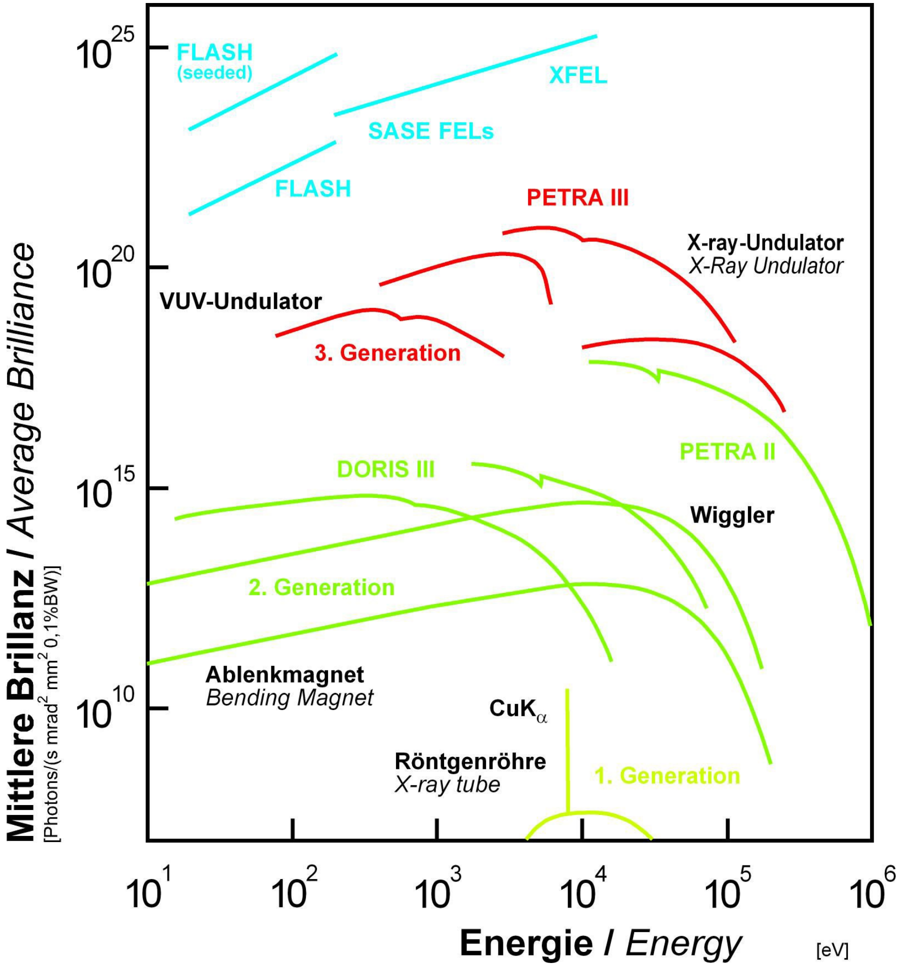
Source: DESY, Hamburg

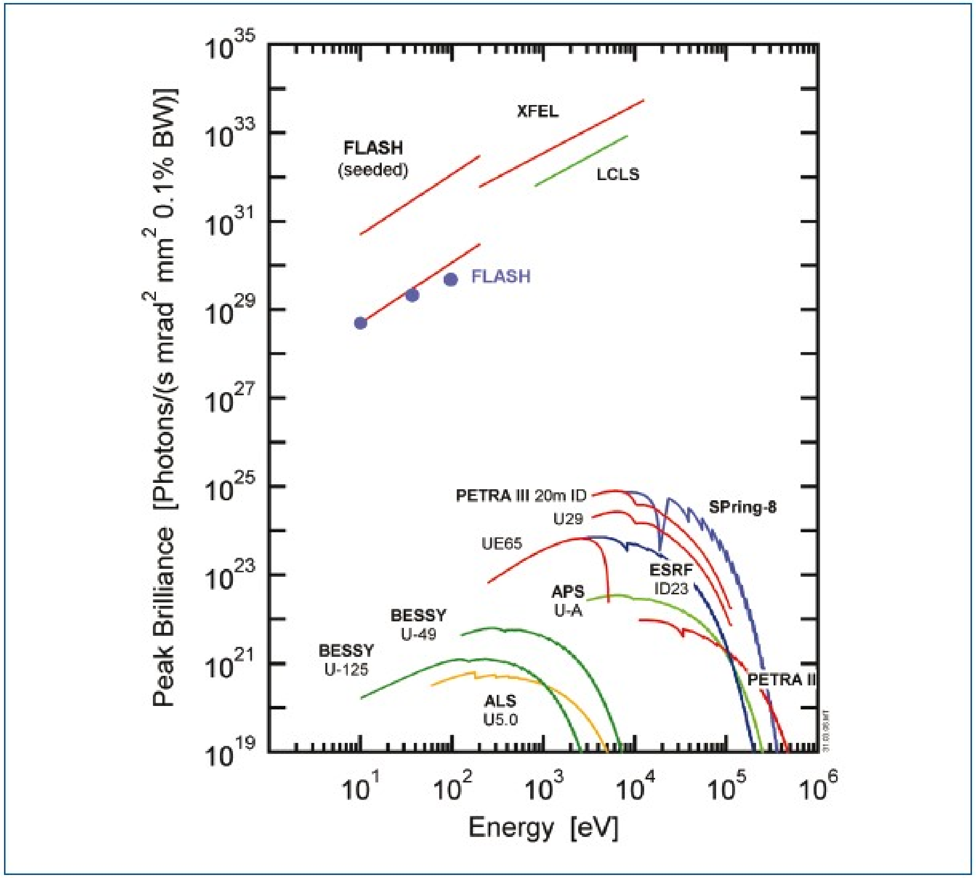




The development of X-ray radiation sources

Source: DESY, Hamburg

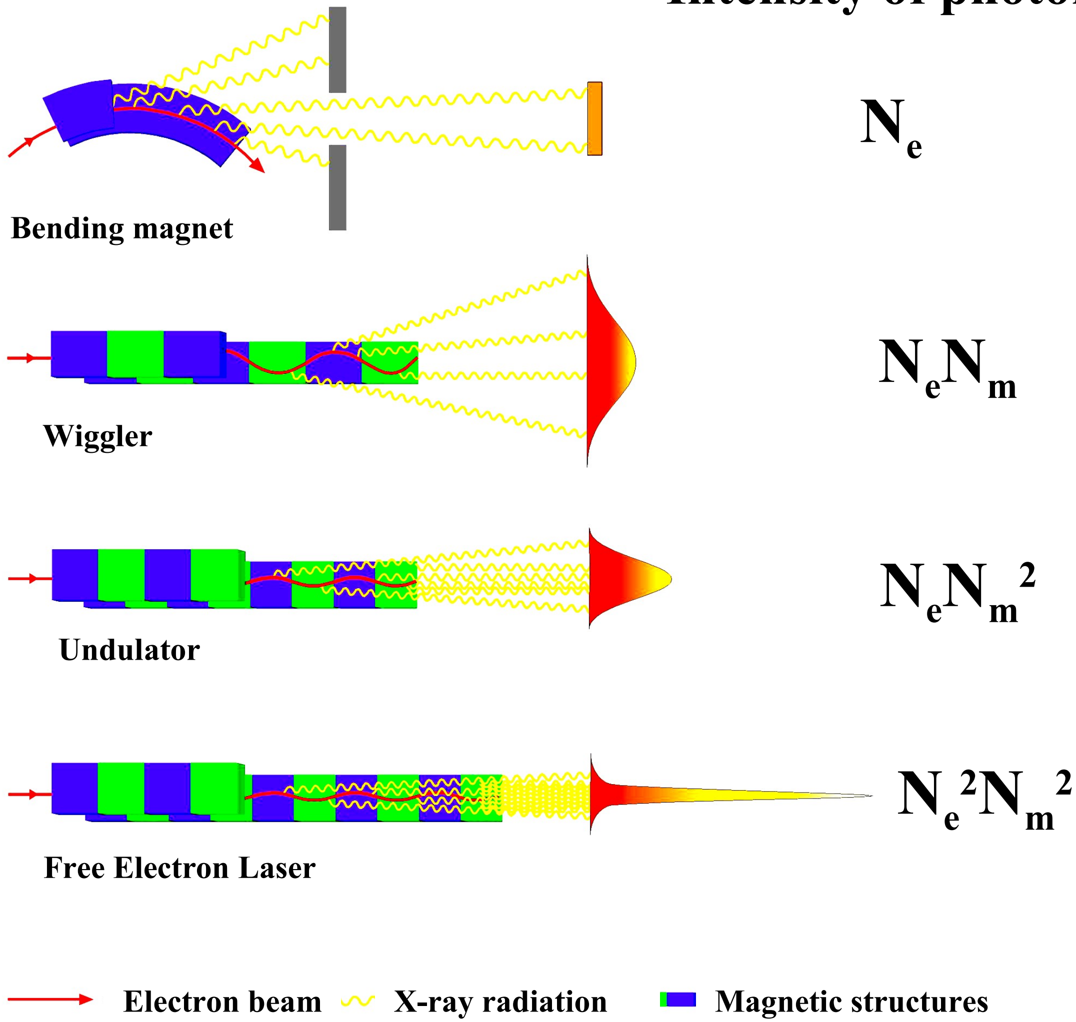




Average and Peak Brilliance in Comparison

Source: DESY, Hamburg

Intensity of photon flux



Source: DESY, Hamburg

The advantages of XFEL

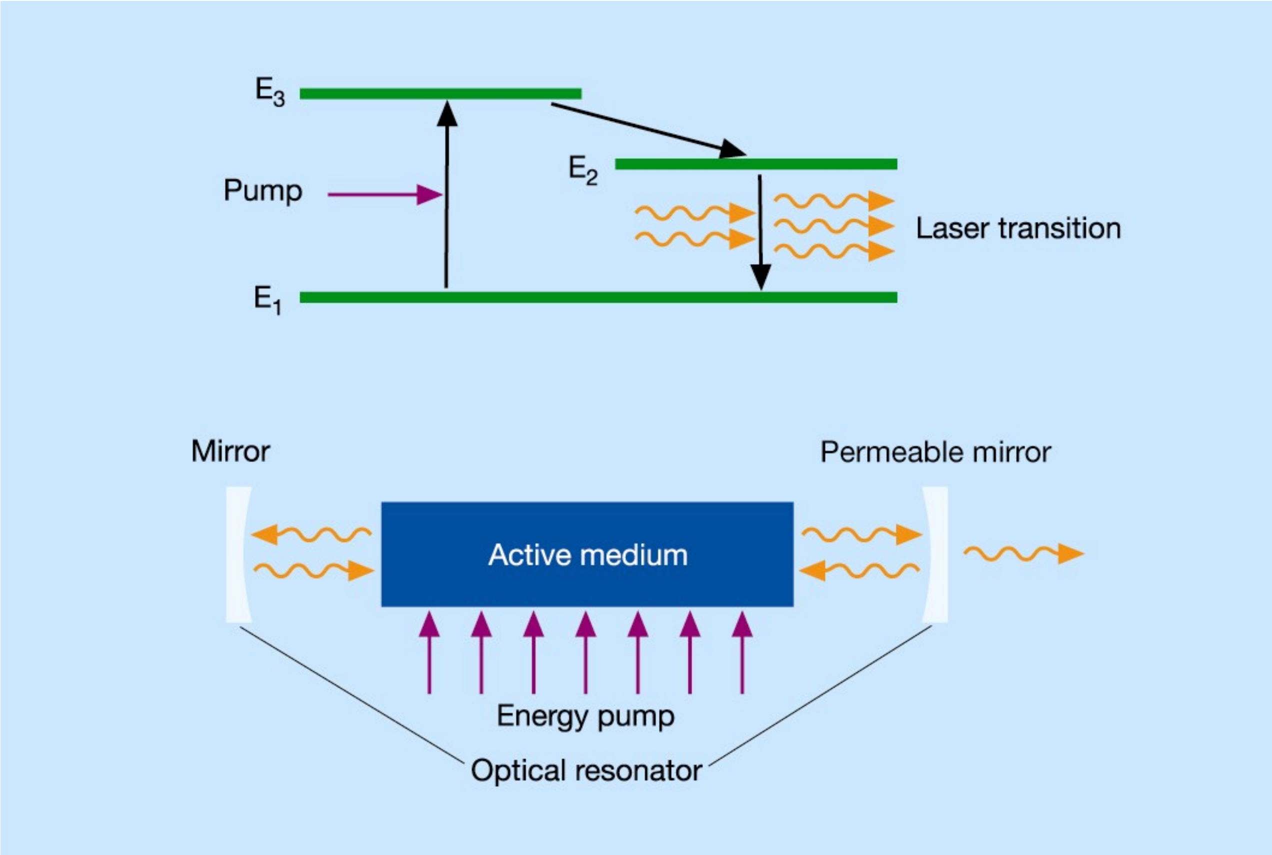
- ultra-high brilliance and photon flux intensity
- high collimation
- wide energy/wavelength tunability (up to hard X-rays)
- specific polarization
- spatial coherence (transverse and longitudinal)
- pulsed time structure

Source: DESY, Hamburg

Free-electron laser and conventional laser

LASER- Light Amplification by Stimulated Emission of Radiation

XFEL- X-Ray Free Electron Laser based on
SASE- Self-Amplified Spontaneous Emission



Principle of a conventional quantum laser where the electrons are bound to atomic, molecular or solid-state energy levels (”bound-electron laser”).

Source: DESY, Hamburg

Plasma X-ray laser

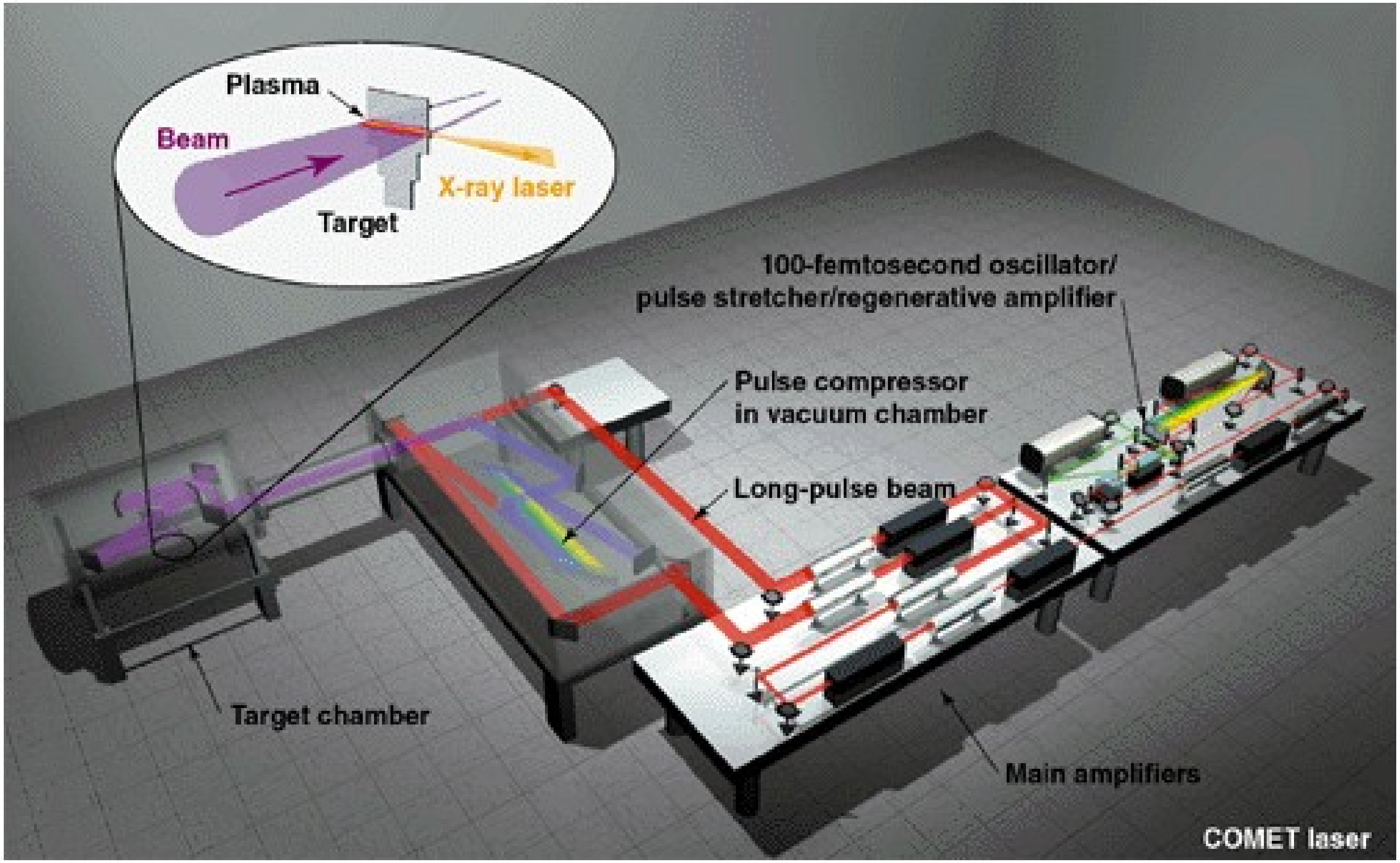
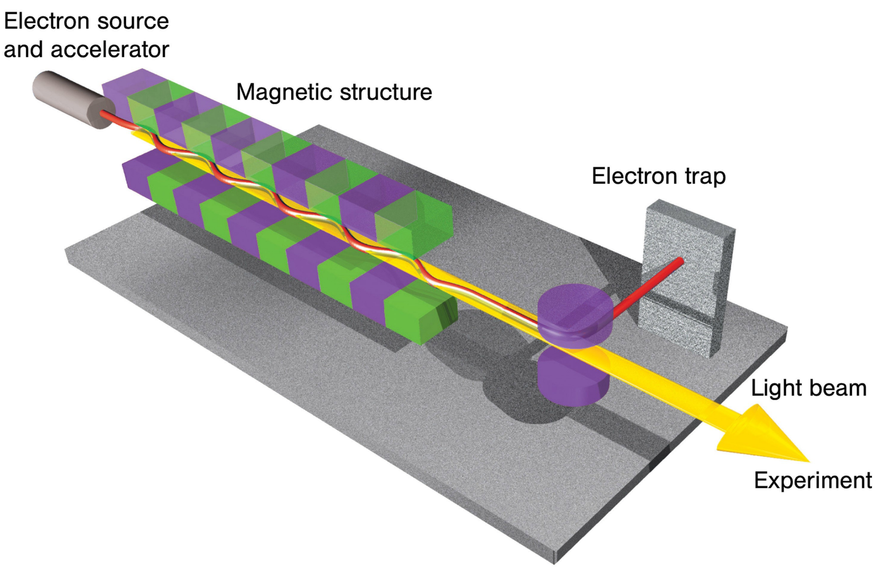
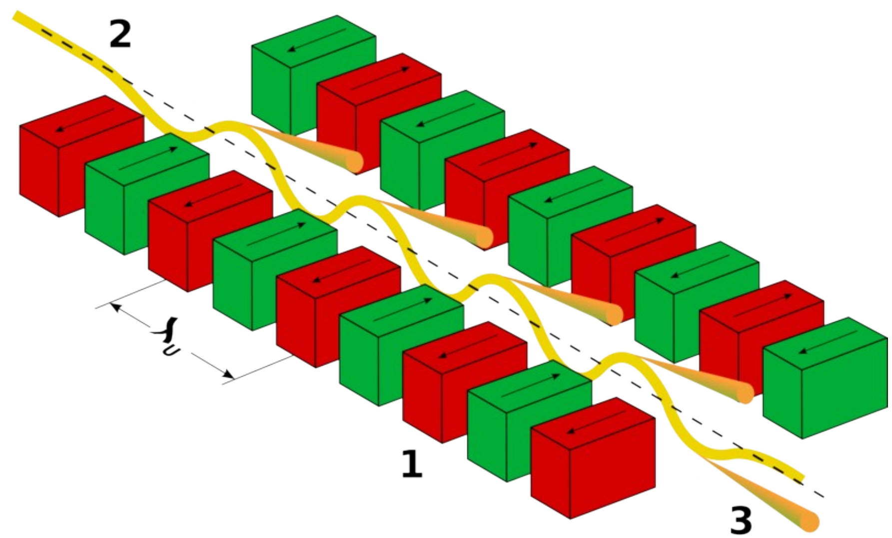


Figure 2. Rendering of Livermore's COMET (compact multipulse terawatt) tabletop x-ray laser showing the laser system and target chamber. The inset shows laser beams hitting the stepped target and producing a plasma, which in turn generates an x-ray laser beam.

The FEL is not, strictly speaking, a laser, i.e. a device based on quantum-mechanical stimulated emission, and its operation is completely described within the framework of classical physics. The FEL is a system consisting of a relativistic electron beam and a radiation field interacting with each other while propagating through an undulator.



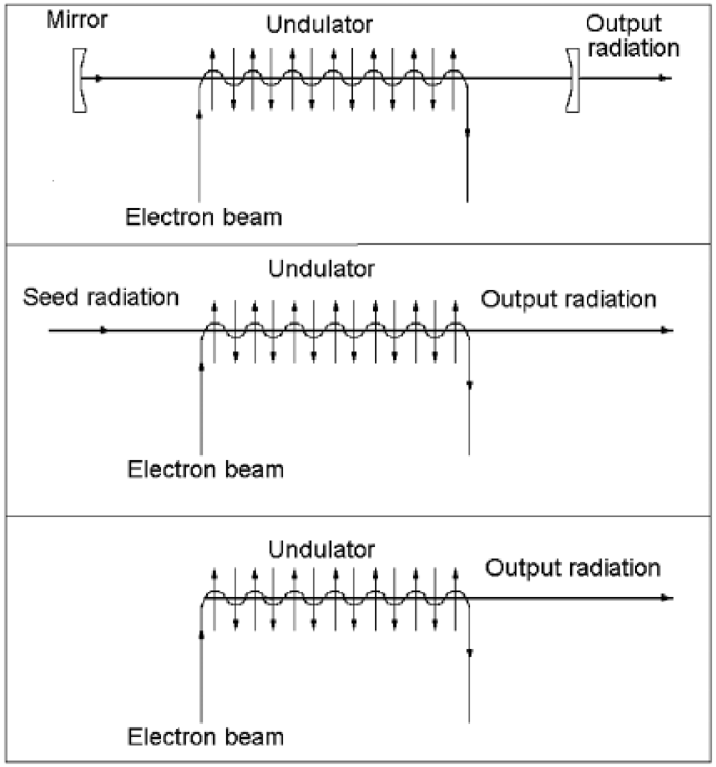


Schematic representation of undulator radiation.

XFEL_Linac_Accelerator.mov

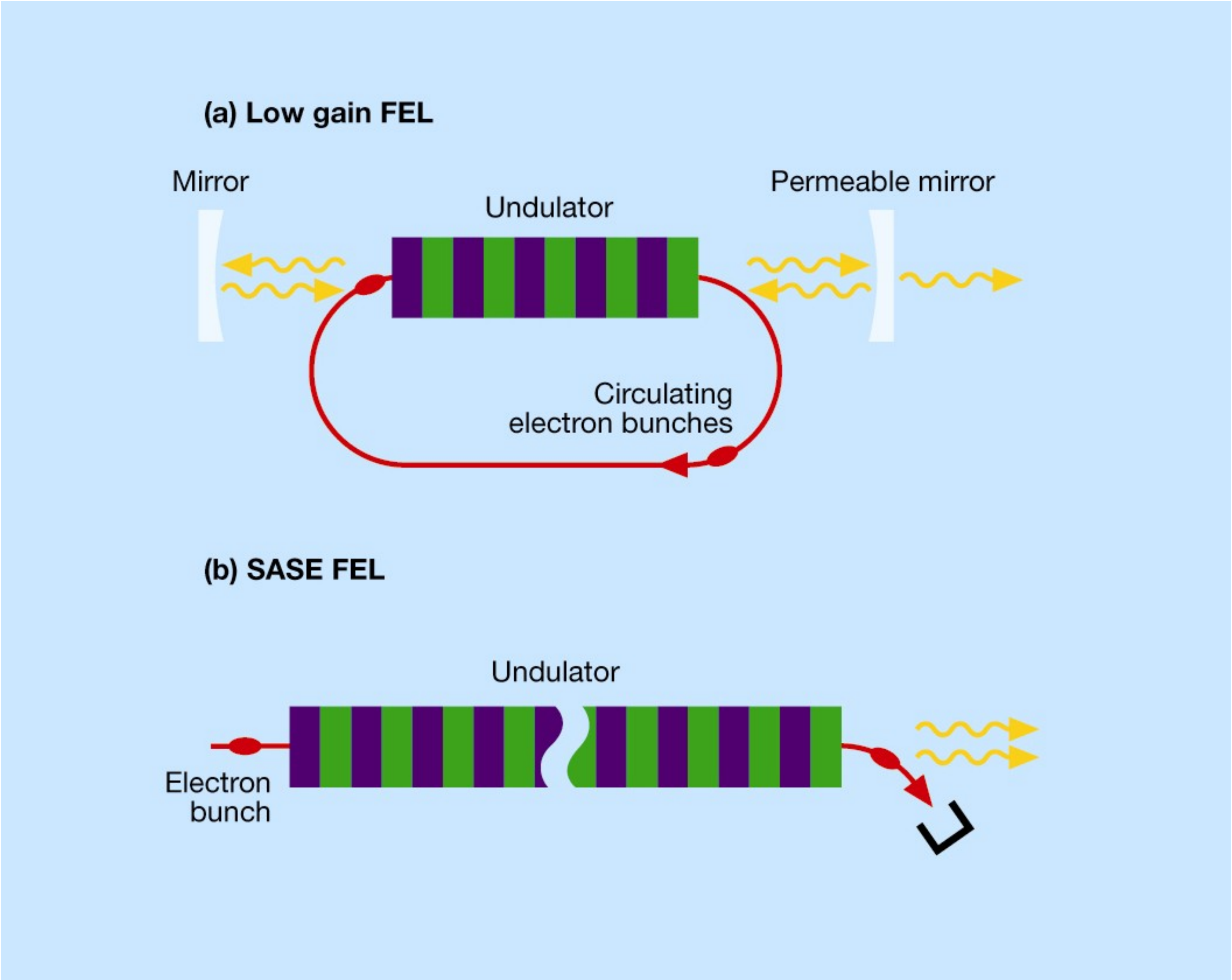
XFEL_SASEFEL.mov

Source: DESY, Hamburg



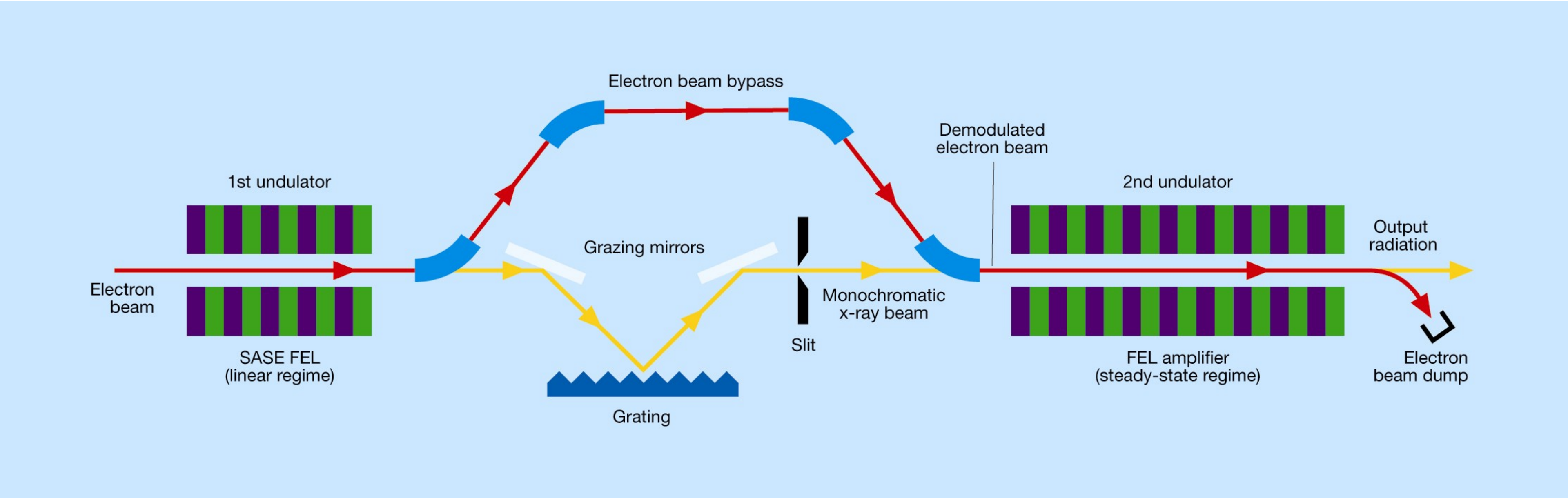
Free-electron laser configurations: oscillator (top), seeded amplifier (middle), and SASE FEL (bottom).

Source: DESY, Hamburg



Principle of a free-electron laser: (a) For visible or infrared light
(b) In the ultraviolet and X-ray region one can apply the mechanism of self-amplified spontaneous emission

Source: DESY, Hamburg



The self-seeding mechanism:

Source: DESY, Hamburg

Wavelength of undulator radiation

$$v_z = c\left(1 - \frac{2 + K^2}{4\gamma^2}\right)$$

v<c - electron velocity

v_z - electron velocity component along the z axis

γ - Lorentz factor

Relativistic Doppler shift

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

λ_t- wavelength of undulator radiation in the forward direction

K- undulator parameter

λ_u-undulator period

$$K = \frac{eB_0\lambda_u}{2\pi\ m_0 c} \approx 1$$

B_0- peak magnetic field in the undulator

Source: DESY, Hamburg

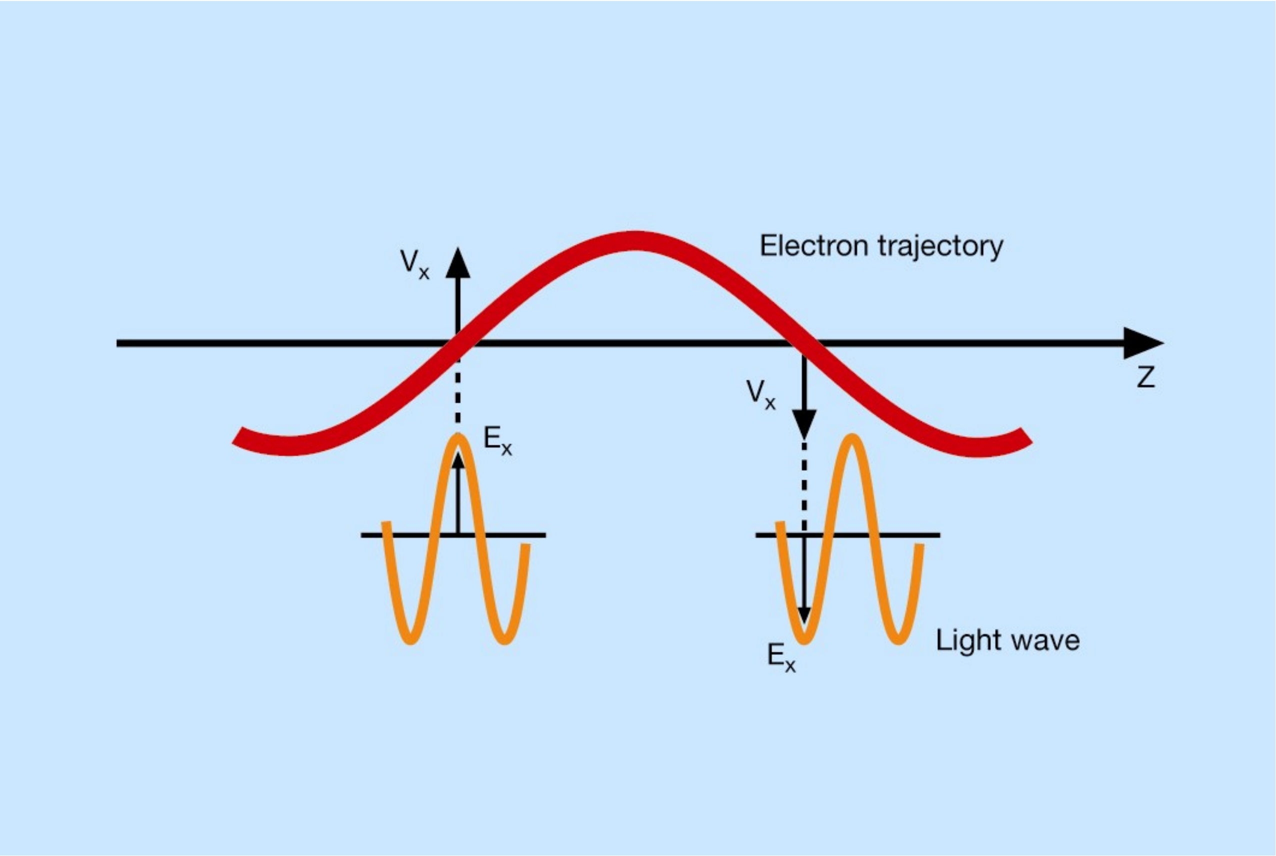
$$\gamma = \frac{m}{m_0} = \frac{W}{W_0}$$

for λ_u= 30 mm i γ = 1000

$$\lambda^* = \frac{\lambda_u}{\gamma} = 30\mu m$$

$$\lambda_t \approx \frac{\lambda^*}{2\gamma} = \frac{\lambda_u}{2\gamma^2} = 15nm$$

Source: DESY, Hamburg



Condition for sustained energy transfer from electron to light wave in an undulator: The light wave has to slip forward by per half-period of the electron trajectory.

Source: DESY, Hamburg

Plane electromagnetic wave

$$E_x(z,t) = E_0 \cos(k_t z - \omega_t t)$$

$$with \quad k_t = \omega_t / c = 2\pi / \lambda_t$$

The time derivative of the electron energy

$$W = \gamma \, m_0 c^2$$ **is**

$$\frac{dW}{dt} = \vec{v} \bullet \vec{F} = -e v_x(t) E_x(t)$$

Source: DESY, Hamburg

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

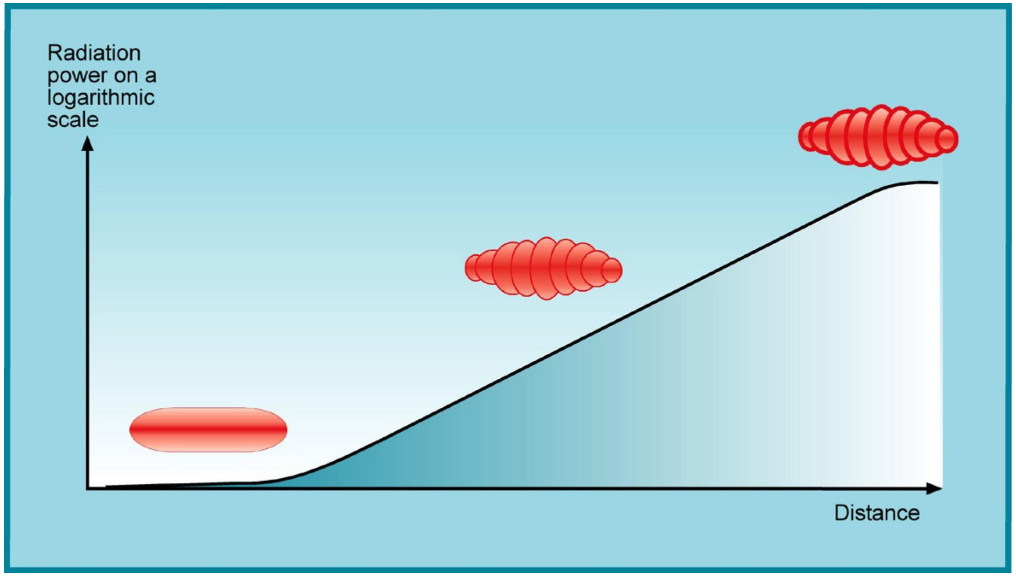
To achieve light amplification the electron energy must exceed the resonance energy

$$W > W_t \equiv \gamma_r m_0 c^2$$

The resonant Lorentz factor is

$$\gamma_r = \sqrt{\frac{\lambda_u}{2\lambda_t}\left(1 + \frac{K^2}{2}\right)}$$

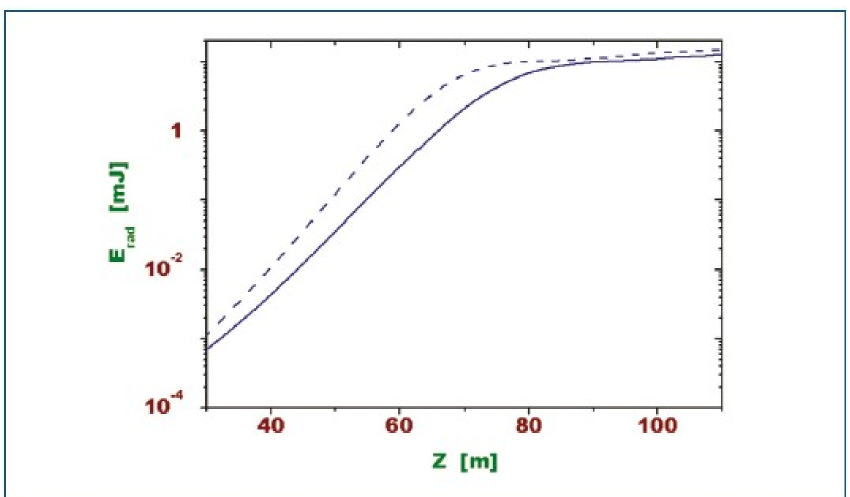
Source: DESY, Hamburg



The principle of the free-electron laser (XFELinfo).url

microbunching.mov

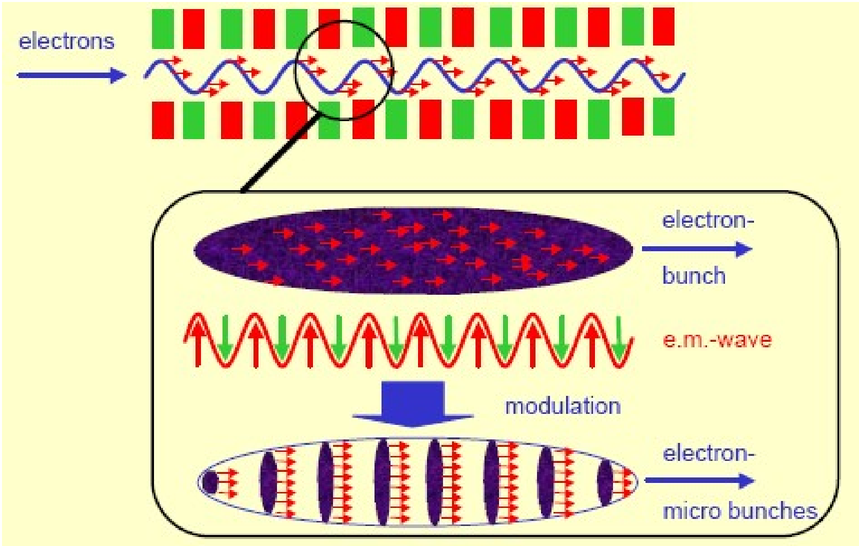
The exponential growth of the FEL pulse energy E as a function of the length z traveled in the undulator.

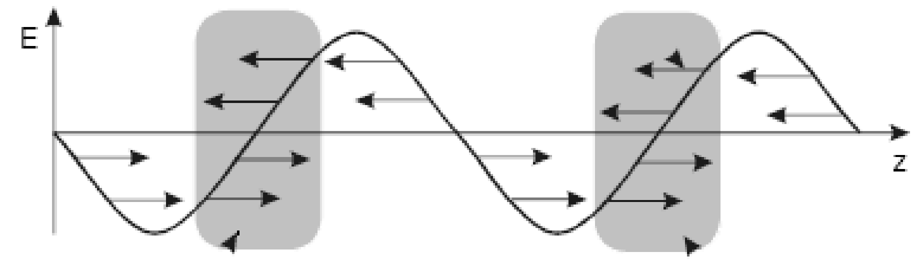


Average energy in the radiation pulse against magnetic undulator length for SASE 3 operating at 0.4 nm

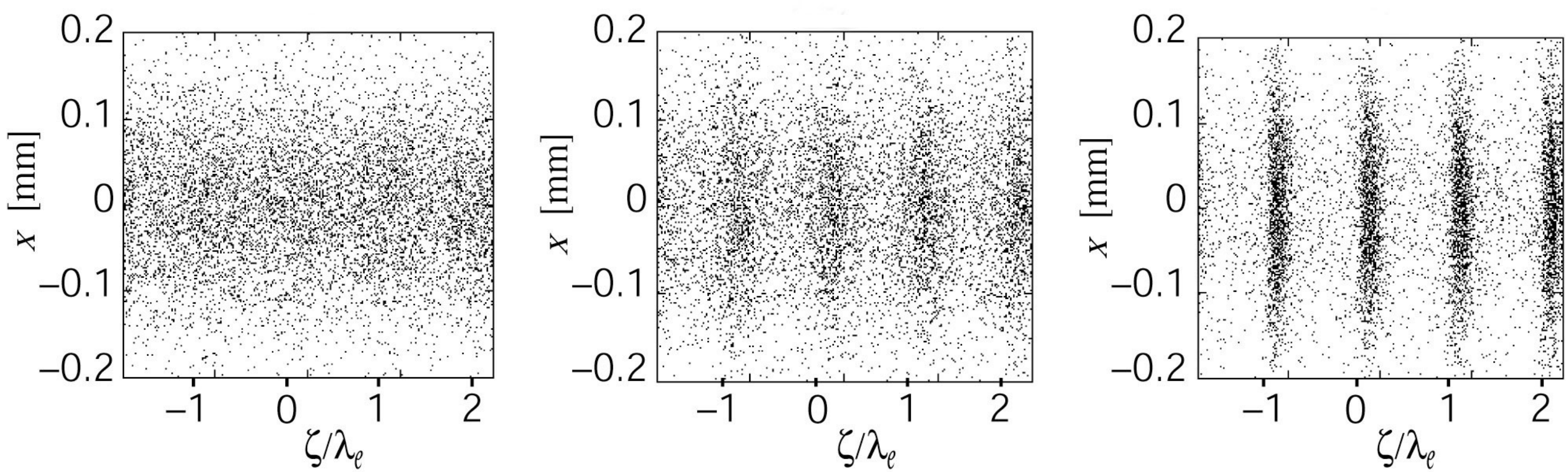
Source: DESY, Hamburg

microbunching.mov





microbunching



Numerical simulation of microbunching

Source: DESY, Hamburg

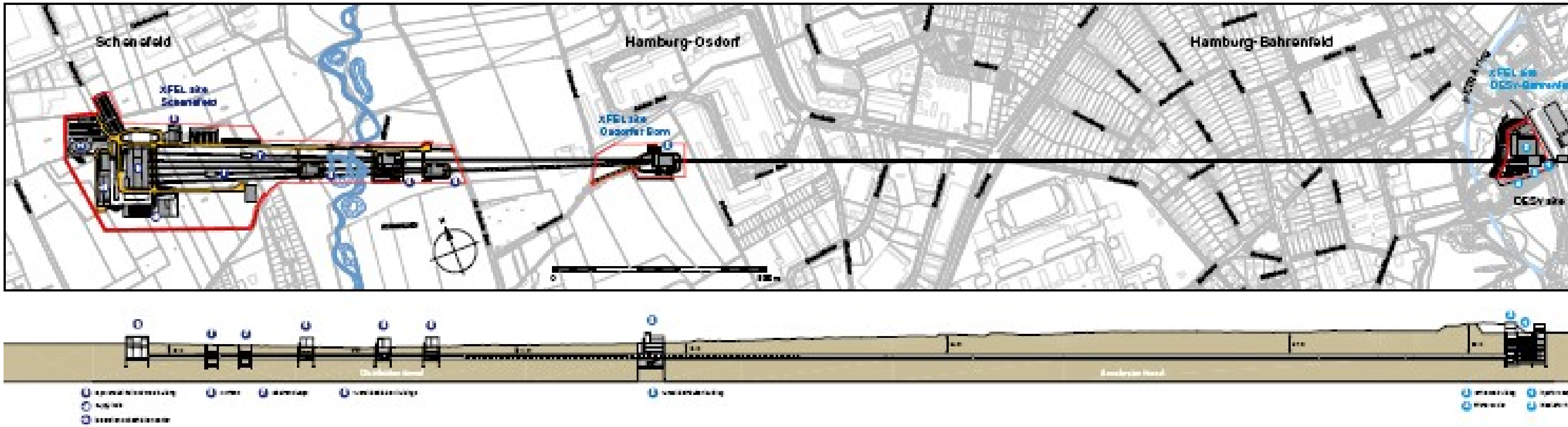
The power gain

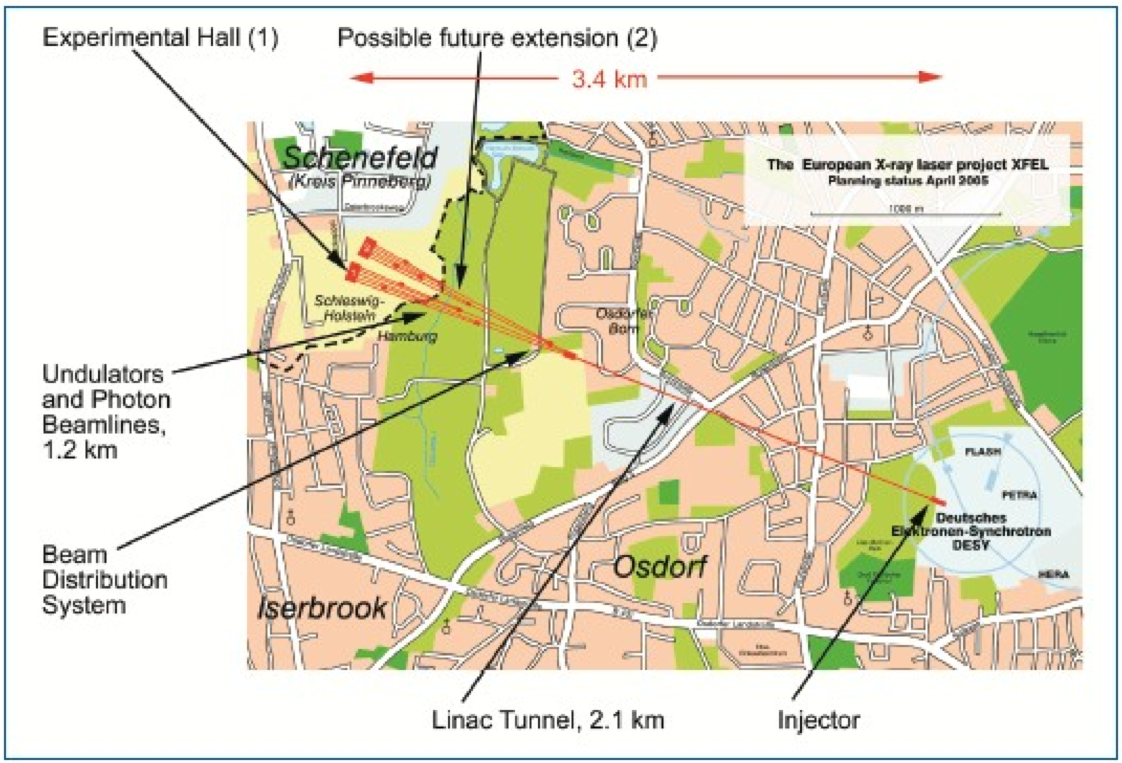
$$P(z) = \frac{P_{in}}{9}\exp(2z / L_g) \;\; for \; z \geq 2L_g$$

L_g- field gain lenght
P_{in}- effective input power

$$L_{sat} = 10 \bullet L_g \qquad L_g = \frac{\lambda_u}{4\pi\rho}$$

ρ-saturation efficiency
L_{sat}- saturation lenght

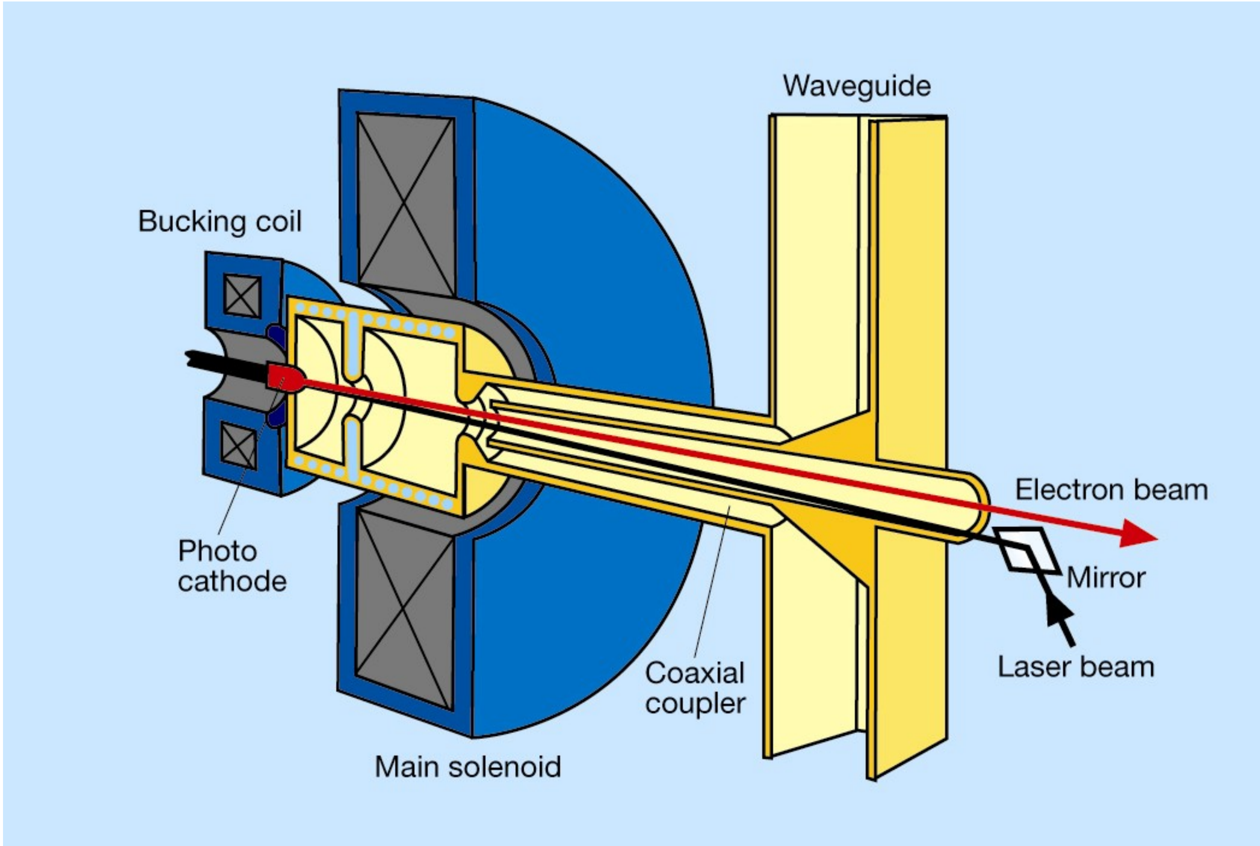




Electron energy – 17.5 GeV
Bunch peak current- 5 kA
Peak power- 100 TW
Conversion efficiency-0.1%
Peak power of X-rays- multiGW
X-ray intensities- 10^{18} W/cm^2

Location of the European XFEL

Source: DESY, Hamburg

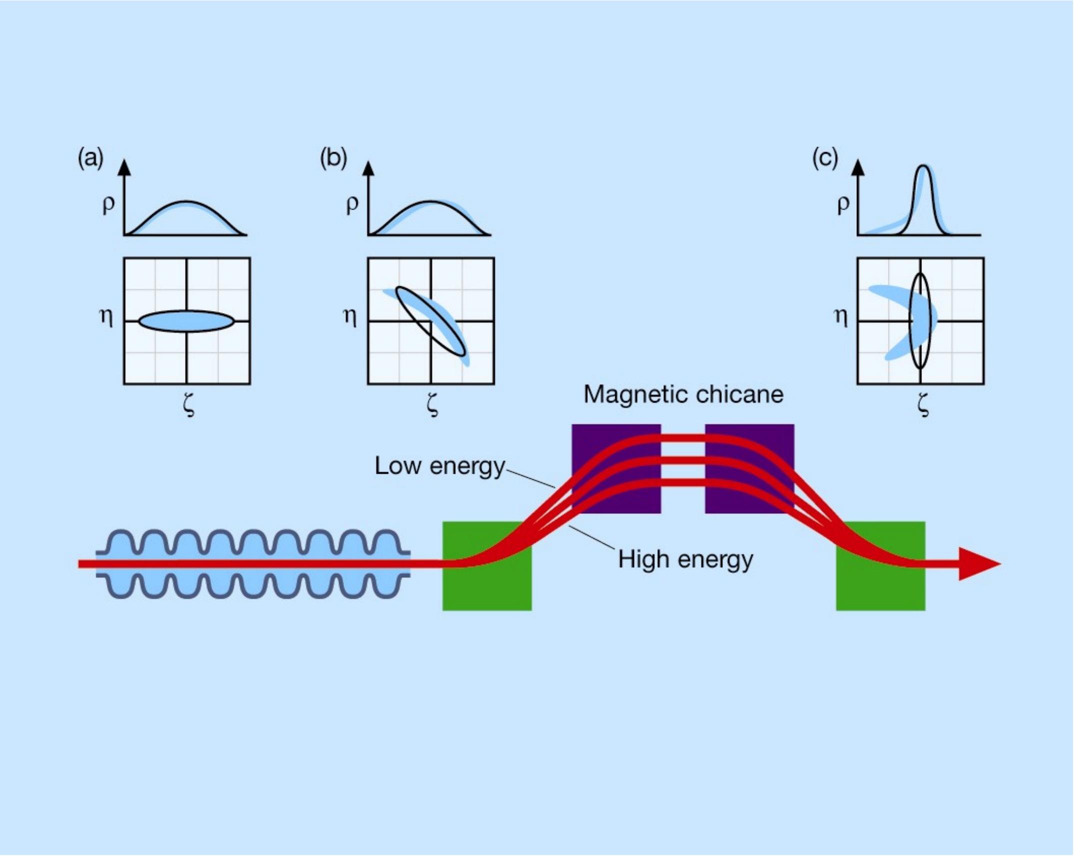


Cut through the electron source of FLASH.

Source: DESY, Hamburg

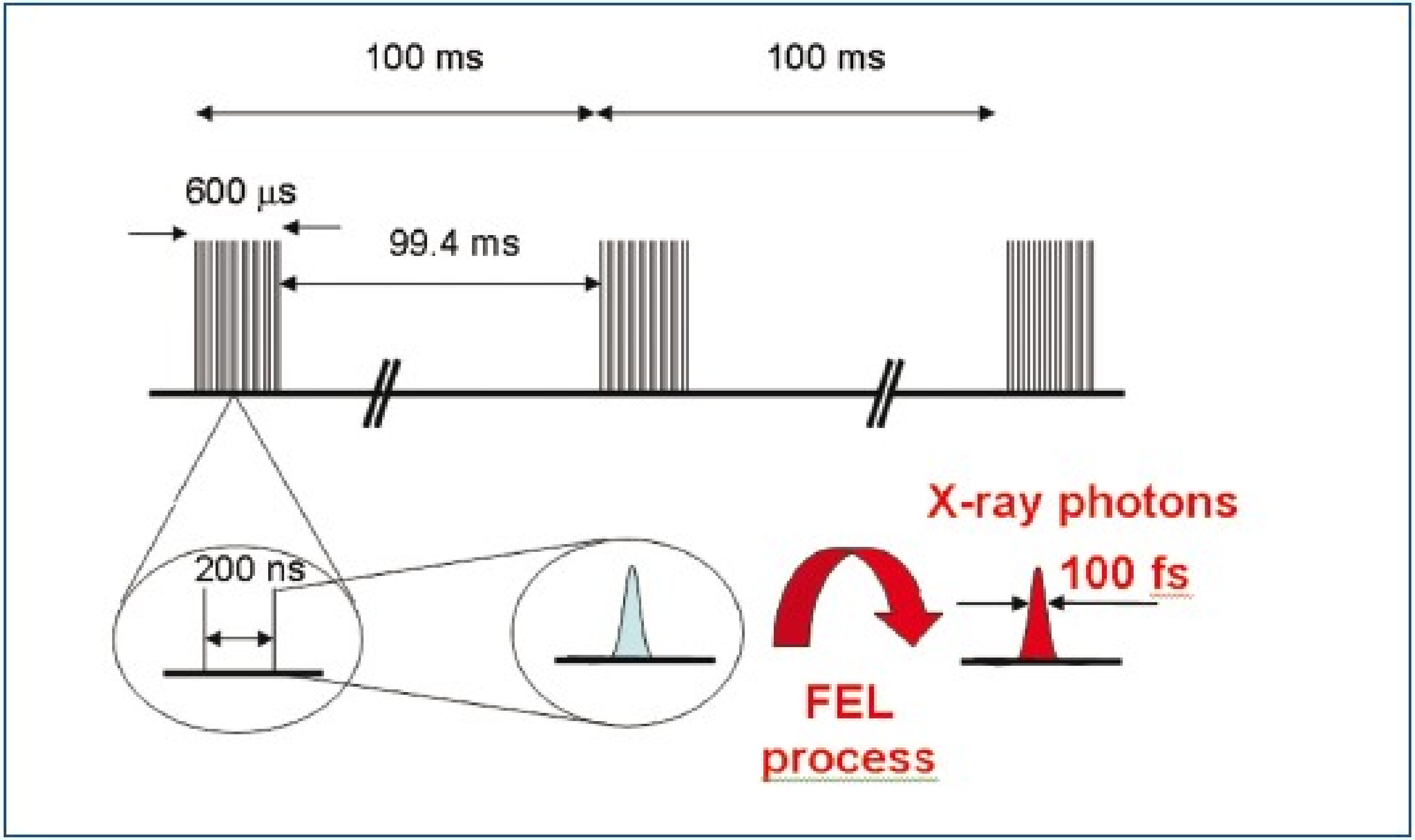
Requirements on the drive beam of an X-ray FEL

- High peak current
- Very low emittance
- Small energy spread



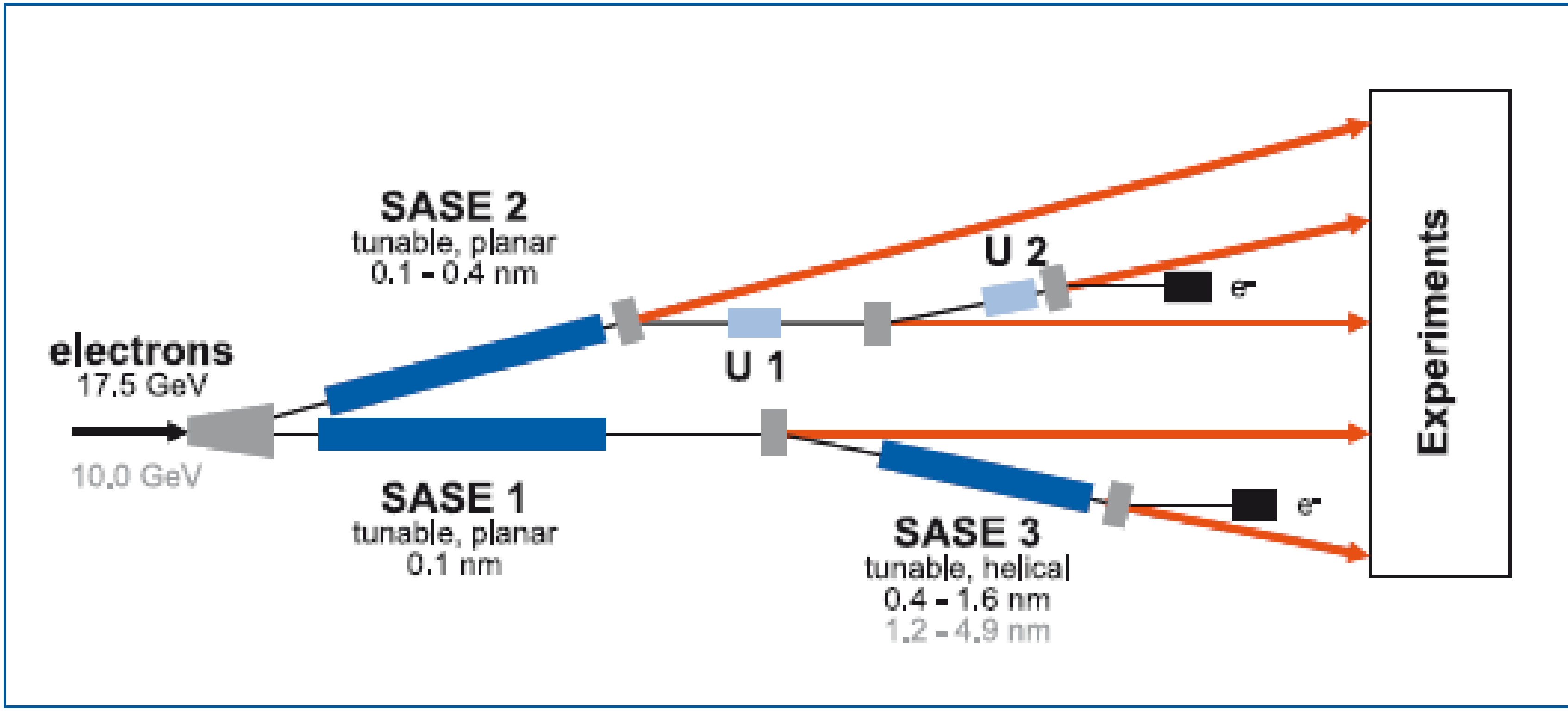
Principle of longitudinal electron bunch compression.

Source: DESY, Hamburg



Electron bunch time pattern with 10 Hz repetition rate and up to 3,000 bunches in a 0.6 ms long bunch train. The separation of electron bunches within a train is 200 ns for full loading. The duration of electron bunches is ~200 fs and the non-linear FEL process reduces the duration of the photon pulses to ~100 fs.

Source: DESY, Hamburg



Schematic layout of the planned X-ray laser laboratory in a top view. Black and red lines indicate electron and photon beam lines, respectively. The undulators are marked in blue and violet.

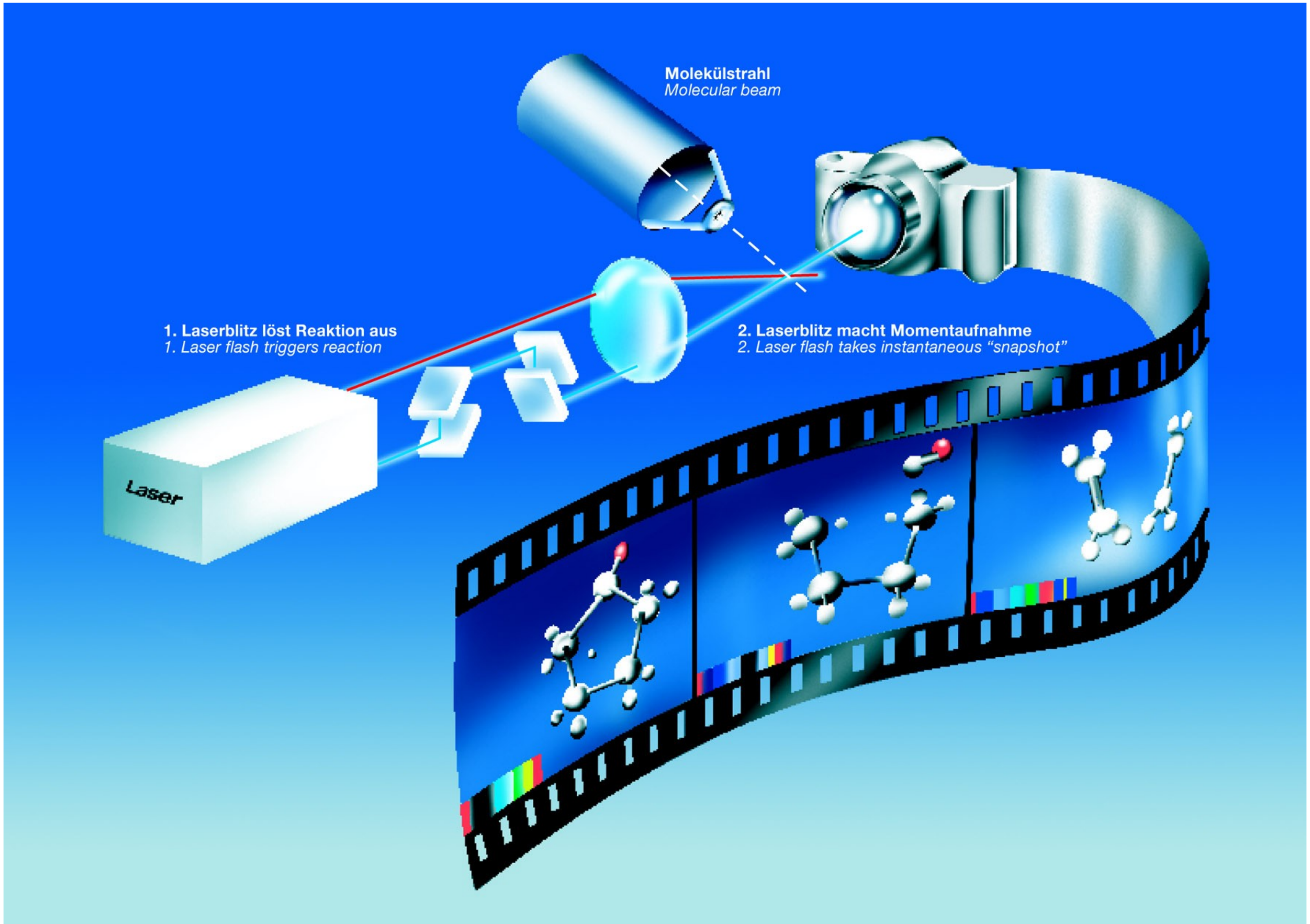
	Photon energy [keV]	Polarisation	Tunability	Gap varia-tion
SASE 1	12.4	Linear	No	Yes
SASE 2	3.1 – 12.4	Linear	Yes	Yes
SASE 3	0.8 – 3.1 (0.25 – 1.0)*	Circular/Linear	Yes	Yes
U1, U2	20 – 100	Linear	Yes	Yes

Source: DESY, Hamburg

Scientific applications of XFEL radiation

- Femtosecond chemistry
- Investigation of single molecules
- X-ray microscopy
- Plasma physics
- Coherent scattering experiments

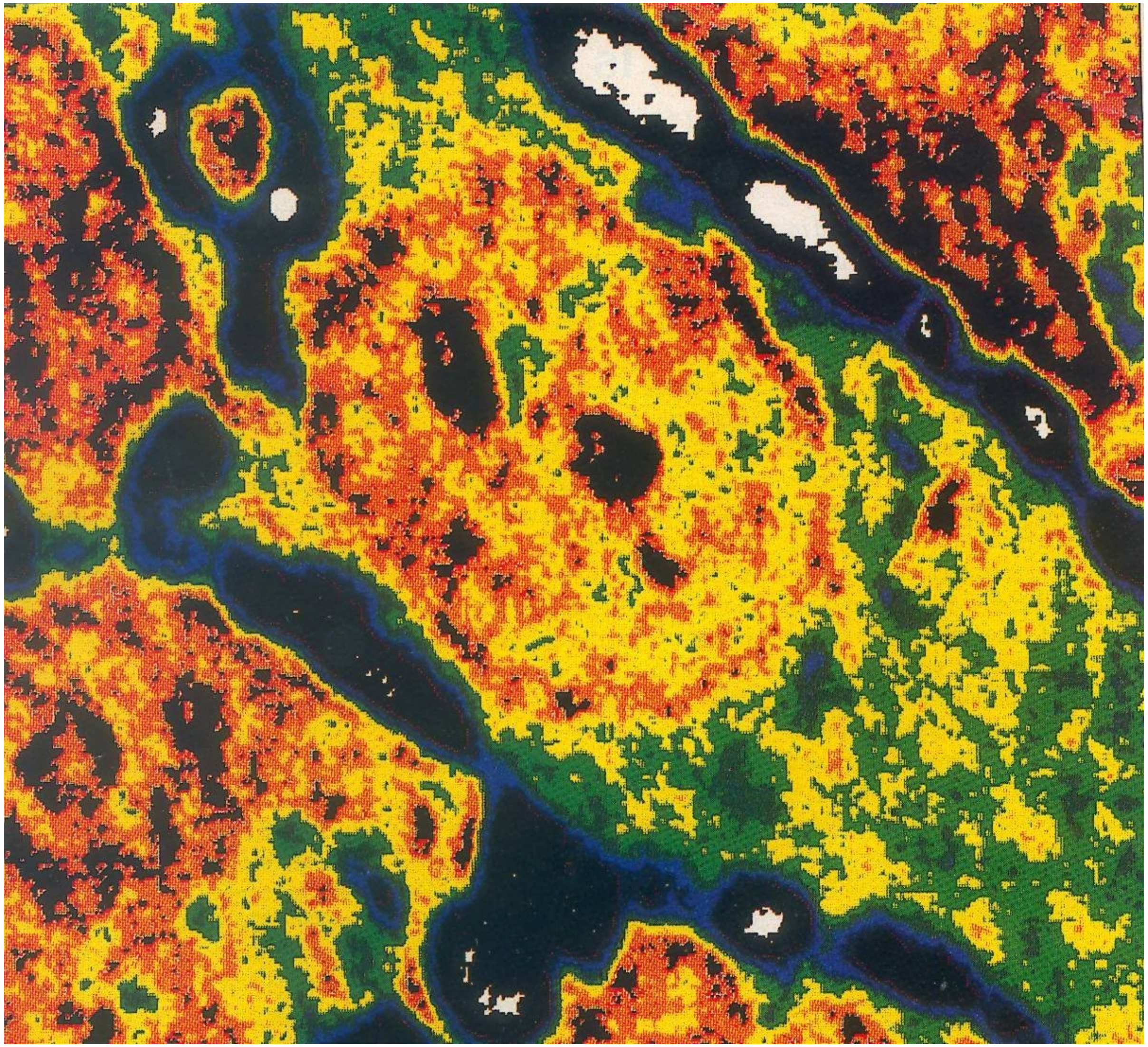
Femtochemistry



"Filming" chemical reactions using ultra-fast lasers.
The brilliance of one single laser flash is so high that it can generate images of reacting molecules with atomic resolution

Source: DESY, Hamburg

X-ray microscopy



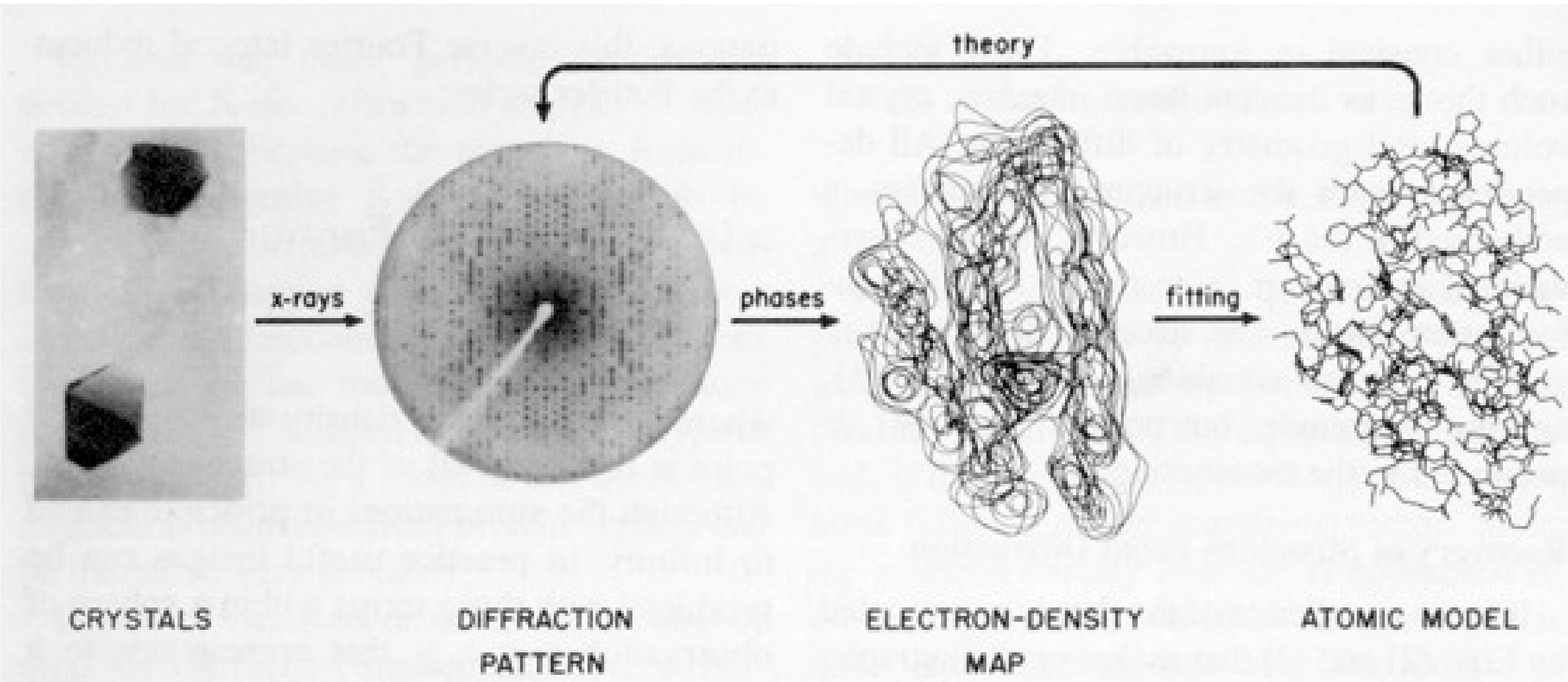
Structural biology

The X-ray laser opens up completely new opportunities to decipher biological molecules with atomic resolution without the need for the extra step of growing crystals. The X-ray laser flashes are so intense that they can be used to create a high-resolution image of a single molecular complex. The flash duration is shorter than 100 femtoseconds and is thus short enough to produce an image before the sample is destroyed by the intense X-rays.

Ribosomes

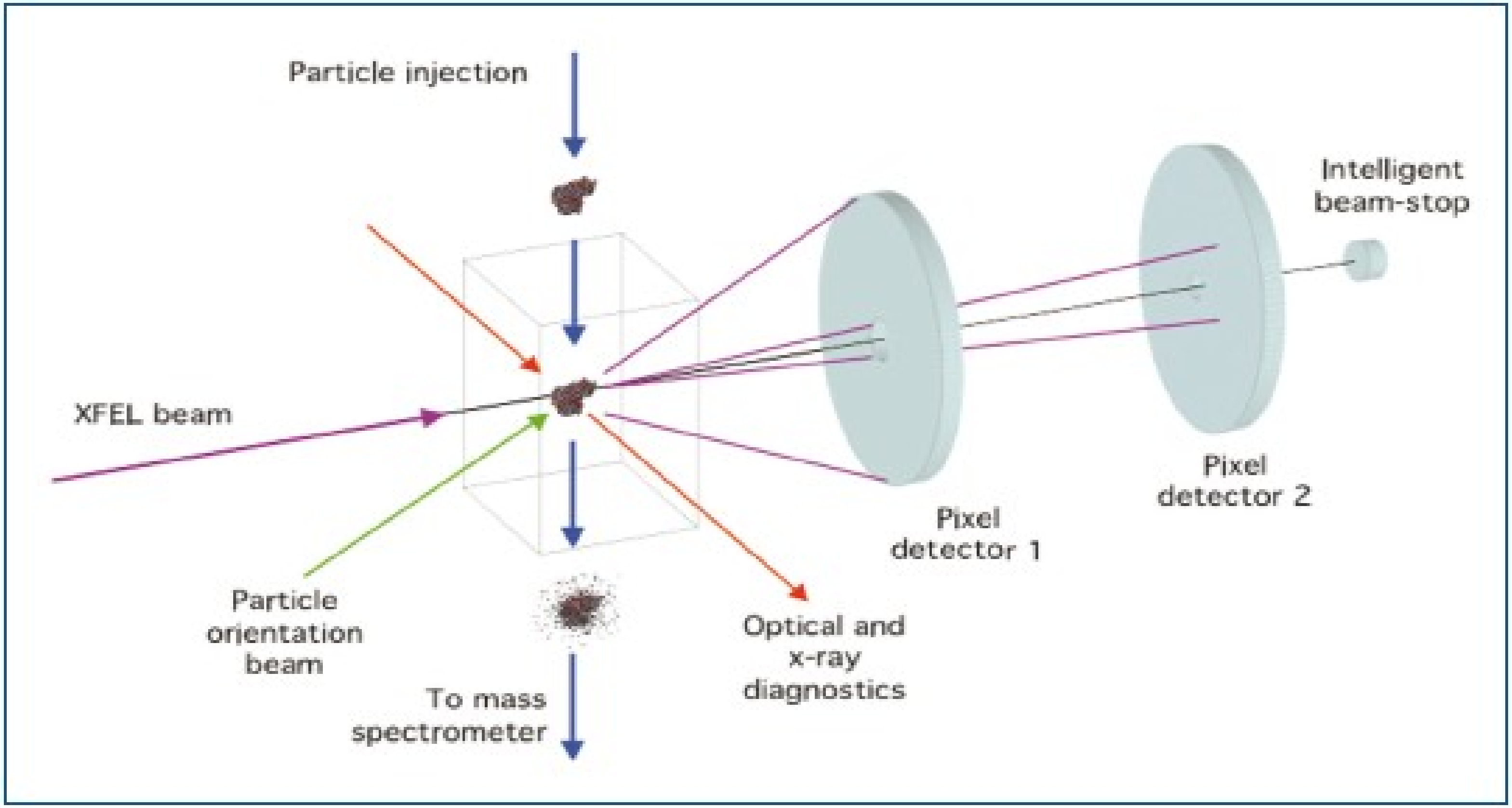
Source: DESY, Hamburg

Ribosomes are large molecular complexes that act as "protein factories" and occur in every cell. The X-ray laser opens up completely new opportunities to decipher such biological structures with atomic resolution without the need for the extra step of tediously growing them into crystals first.


theory
x-rays
phases
fitting
CRYSTALS
DIFFRACTION PATTERN
ELECTRON-DENSITY MAP
ATOMIC MODEL

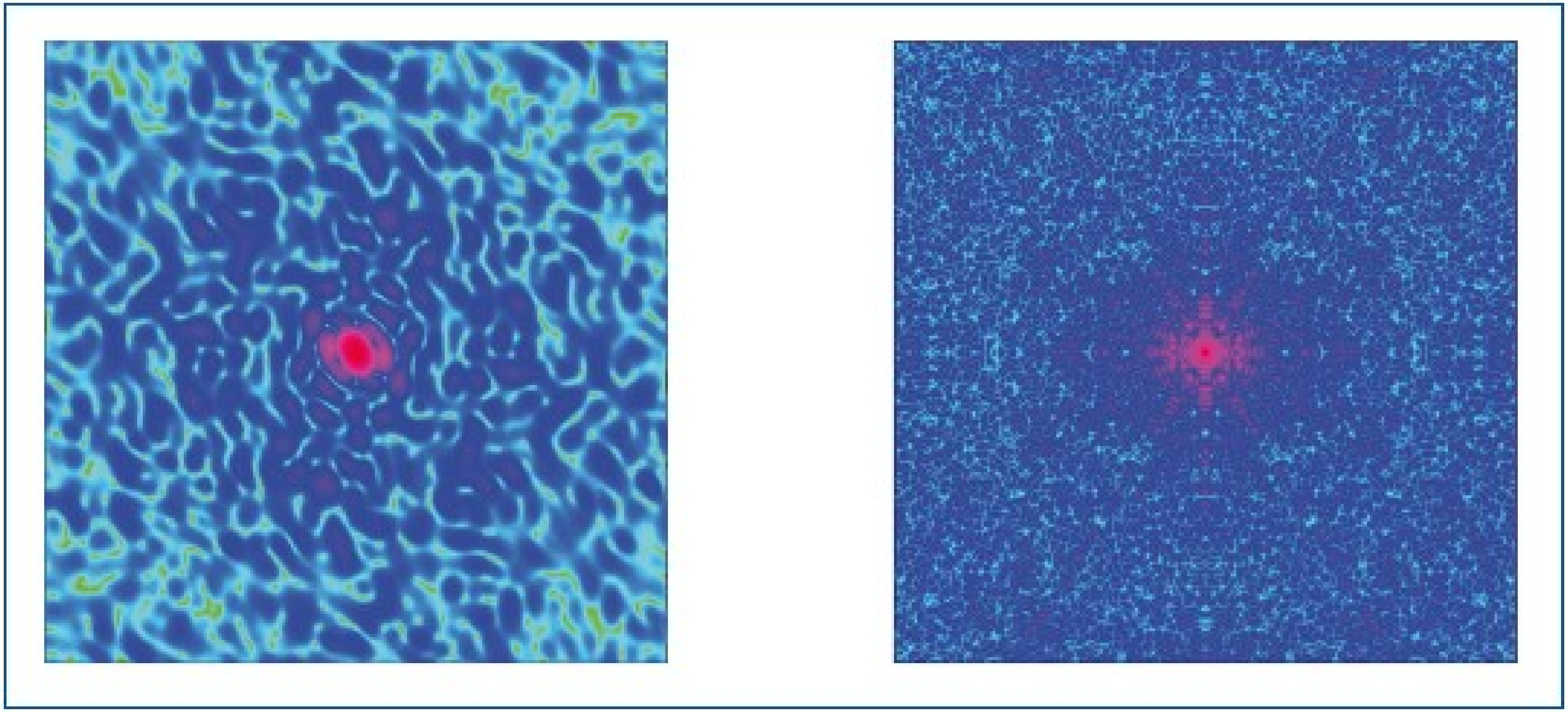
Source: DESY, Hamburg

Diffraction imaging



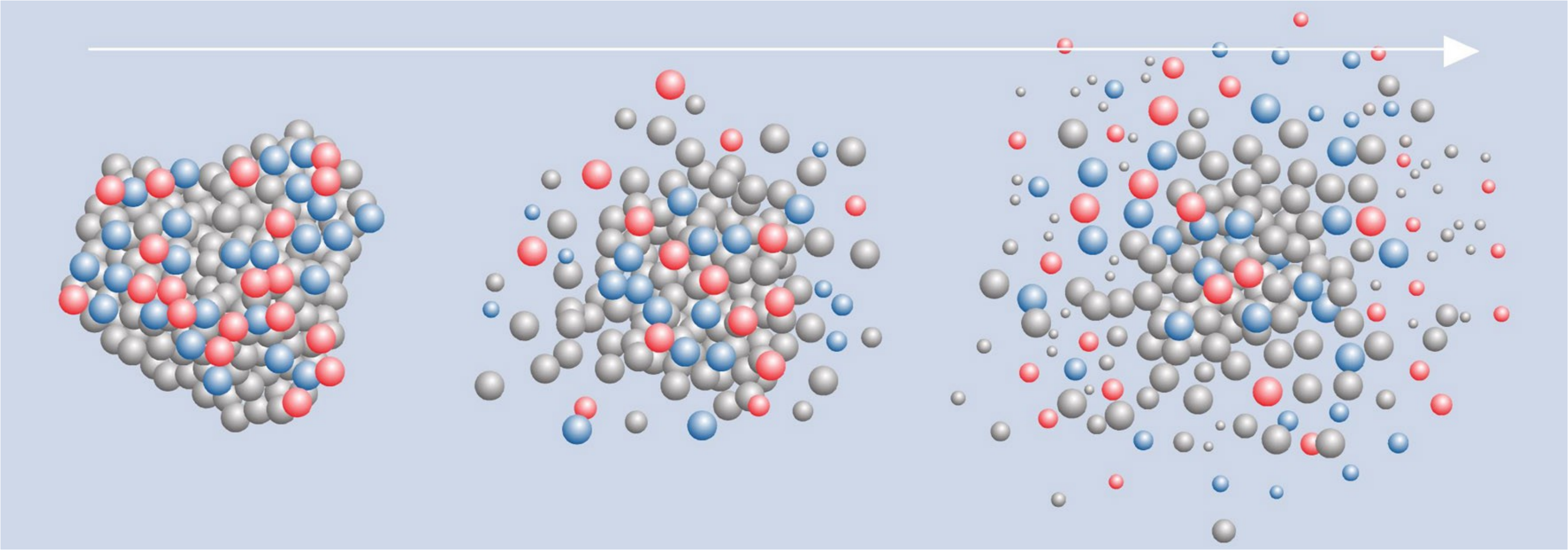
Schematic diagram of the single-particle diffraction imaging experiment.

Diffraction of proteins



Planar section through the centre of the molecular transform of a small protein molecule (lysozyme, left) and of a larger virus capsid (tomato bushy stunt virus, right)

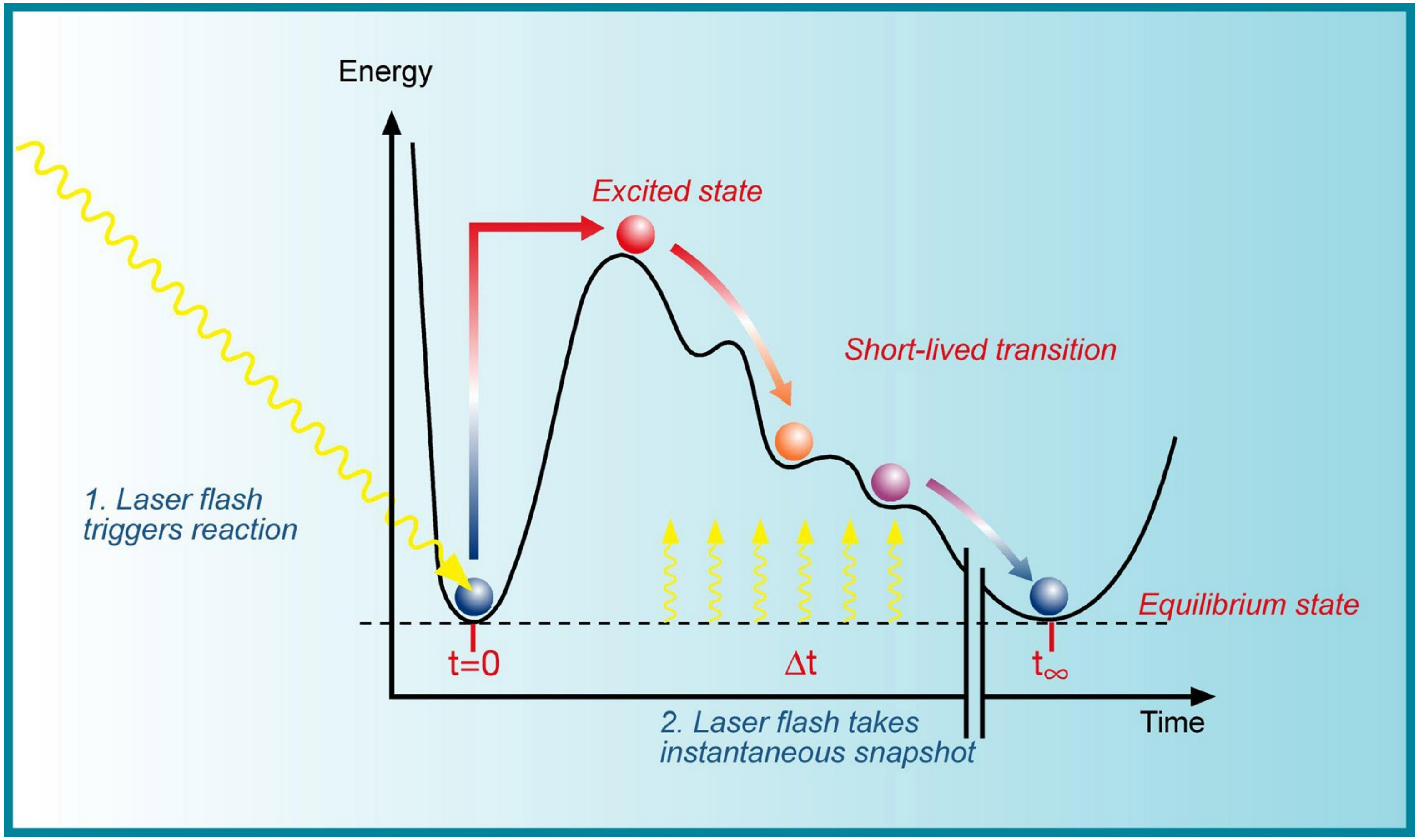
Source: DESY, Hamburg



Biomolecules are destroyed by intense X-ray radiation: they "explode". The illustration shows a simulation of this process. In order to obtain a usable image of the biomolecule, the image must be recorded very quickly before the sample is destroyed.

Source: DESY, Hamburg

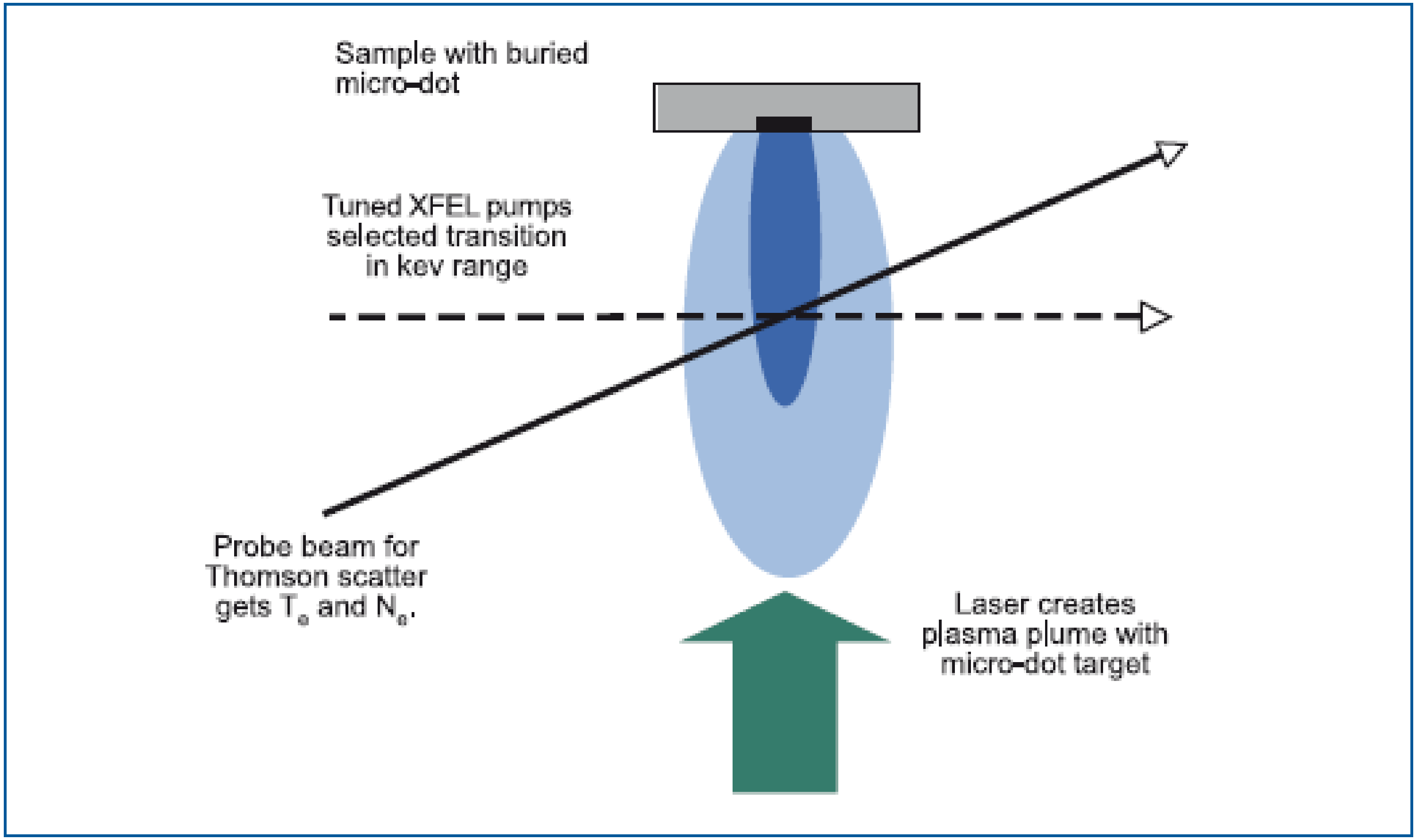
Femtochemistry



A chemical reaction is triggered by a laser flash: The molecules are excited to a more energetic state, after which they "drop" back to their less energetic equilibrium state. A second laser pulse is then sent at varying intervals (t) after the first one to take instantaneous snapshots of the changes that have occurred in the molecule.

Source: DESY, Hamburg

Plasma physics



Experimental arrangement for spectroscopy experiments. The burial of a microdot in a matrix helps to better define the plasma conditions at the time and plac of excitation by the XFEL pump. Time- and space-resolved spectroscopy will be used todiagnose the emission.

Source: DESY, Hamburg

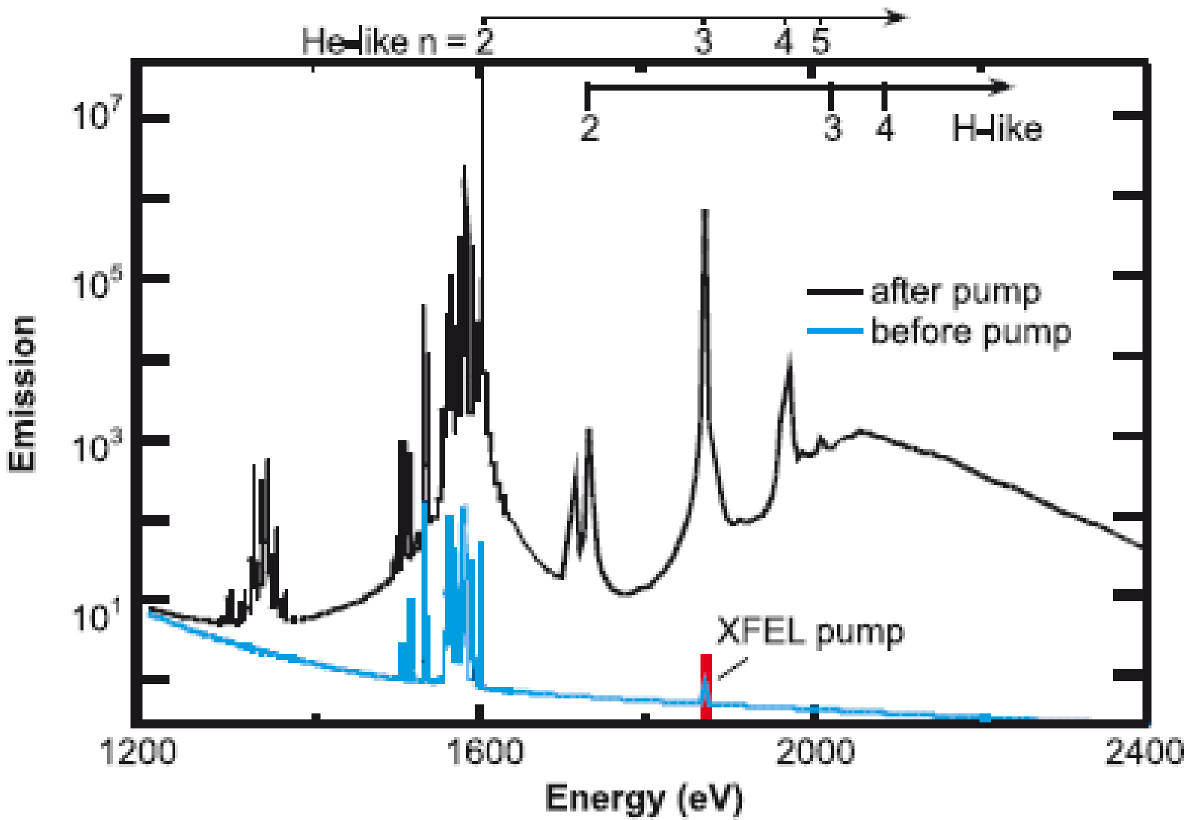
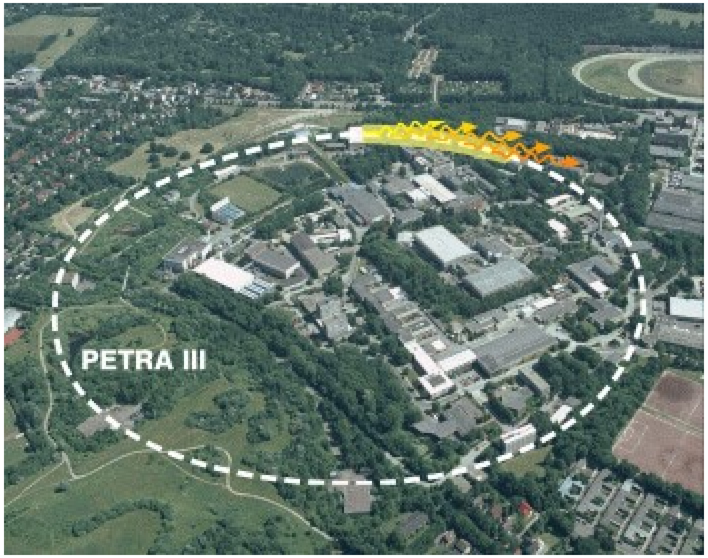
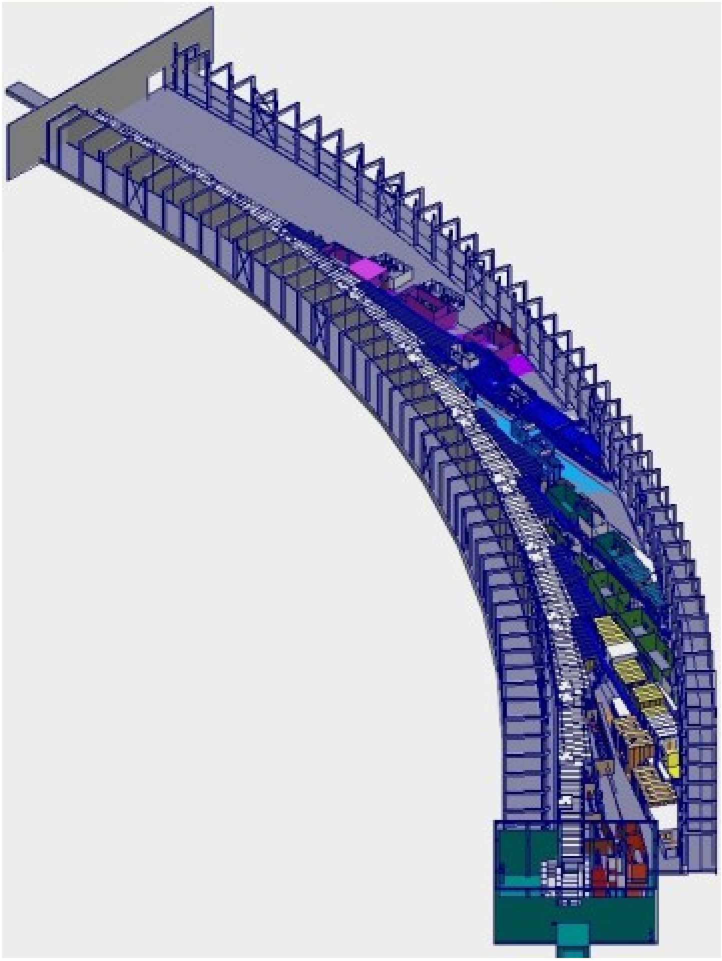


Figure 6.4.12 *Simulation of change to emission spectrum for an Aluminium plasma pumped with an XFEL tuned to 1,869 eV in order to pump the Helium-like 1s²-1s3p transition.*

Source: DESY, Hamburg



PETRA III



Source: DESY, Hamburg

PETRA III

Number	Name		Energy range	Comment	Contact
P01	Dynamics beamline	Dynamik Strahlführung	5 - 40 keV		H. Franz, DESY
P02	Hard X-ray scattering	Harte Röntgenstrahlen/Beugung	20 - 100 keV	straight	DESY
P03	Micro SAXS/WAXS	Mikro SAXS/WAXS	8 - 25 keV	down	S. Roth, DESY
P04	Variable Polarization XUV	XUV Strahlführung	0.2 - 3.0 keV		J. Viefhaus, DESY
P05	Micro- and nano-tomography	Mikro/Nano-Tomographie	8 - 25 keV	side	A. Haibel, DESY/GKSS
P06	Hard X-ray micro probe, imaging	Nano-Analyse/Abbildung	2.4 - 50 keV	straight	G. Falkenberg, DESY
P07	High energy materials science	Materialforschung	40 - 300 keV		N. Schell, GKSS/DESY
P08	High resolution diffraction	Hochauflösende Diffraktion	5.4 - 30 keV	top	O. Seeck, DESY
P09	Resonant scattering/diffraction	Resonante Streuung/Diffraktion	2.4 - 50 keV	straight	J. Strempfer, DESY
P10	Coherence applications	Kohärenzanwendung	4 - 25 keV		O. Leupold, DESY
P11	Bio imaging/diffraction	Proteinkristallographie/Abbildung	8 - 25 keV	side	MPI, HGF, DESY
P12	BioSAXS	Bio SAXS	4 - 20 keV	straight	M. Rößle, EMBL
P13	Macro molecular crystallography I	Biokristallographie I	5 - 35 keV	side	M. Cianci, EMBL
P14	Macro molecular crystallography II	Biokristallographie II	5 - 35 keV	straight	G. Bourenkov, EMBL

high beta section	142x5 µm
low beta section	35x6 µm

Positron energy 6 GeV
14 beamlines with 30 experimental stations
X-ray spectral range from 0.2 to 300 keV, t=1ps

Source: DESY, Hamburg