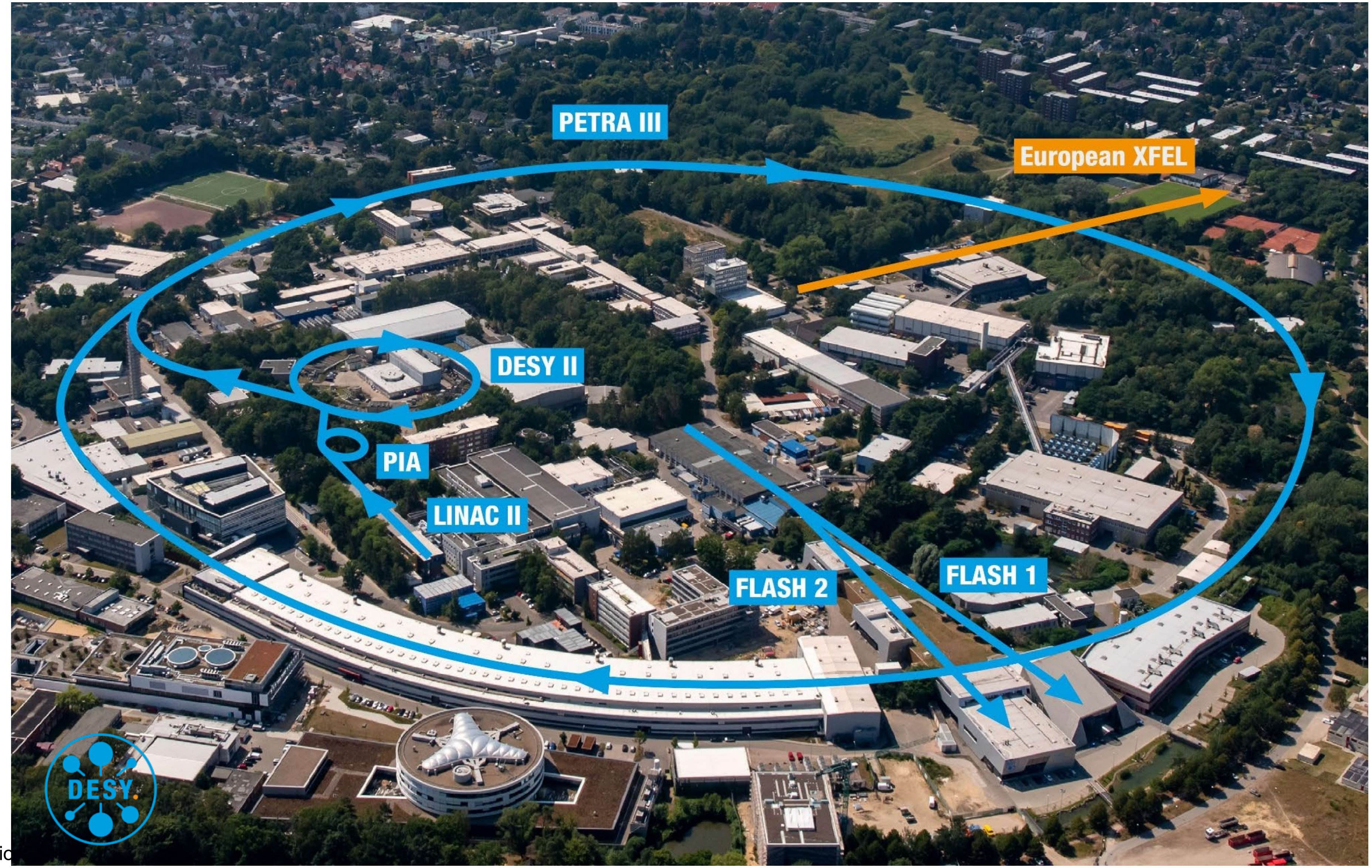
Introduction to Photon Science

Part II: Basics of Free-Electron Lasers

FELs at DESY

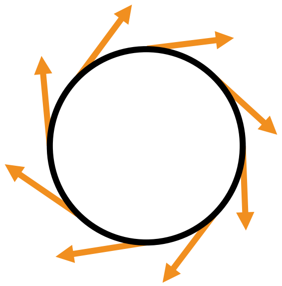
FLASH and European XFEL



Synchrotrons vs. free-electron lasers

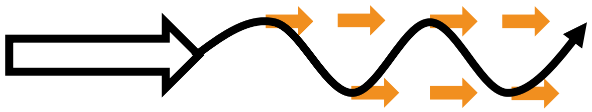
Synchrotrons

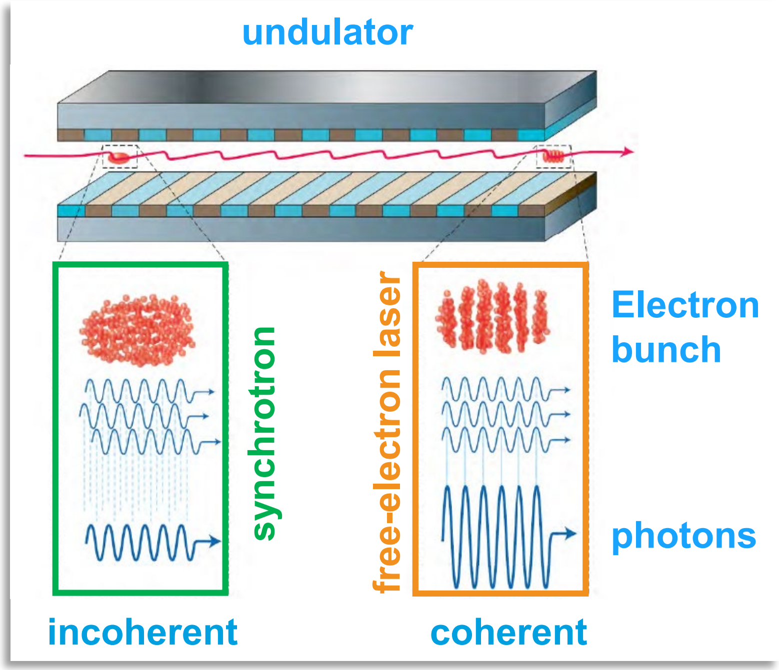
- Electrons traveling in a wide circular path, emitting light as they change directions
- Light is UV or X-ray, but not (fully) coherent
- Multiple users



Free-electron lasers

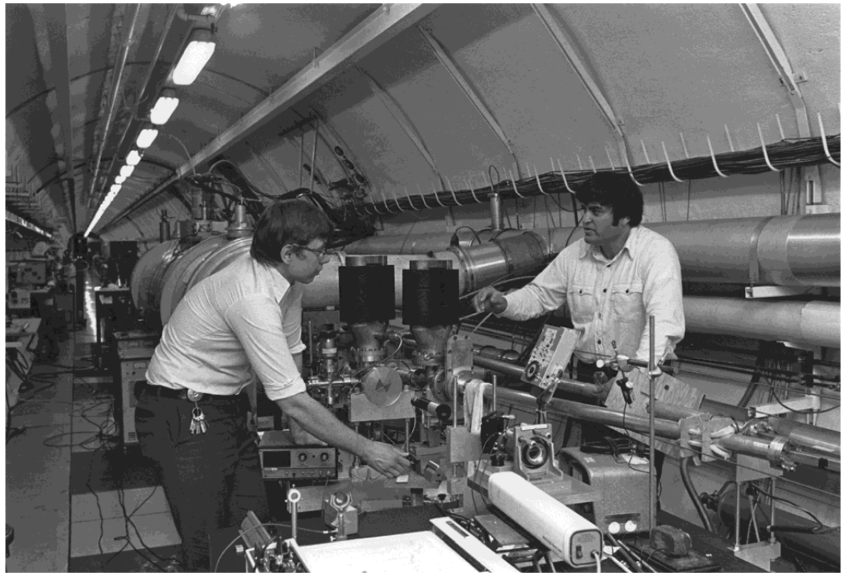
- Electrons accelerated in a straight line and manipulated to generate light
- **Light is coherent and intensely bright in very short pulses**
- Single user



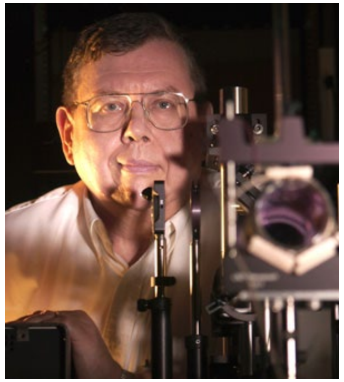


Courtesy European XFEL

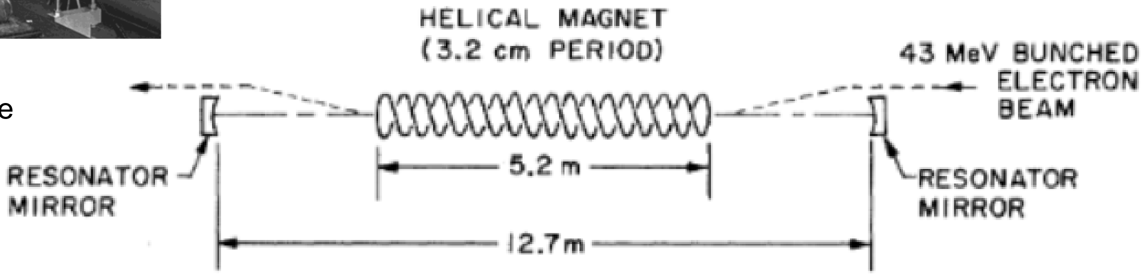
Invention of free-electron laser



John Madey and Luis Elias working inside the Superconducting Acceleration (SCA) tunnel with the FEL equipment, Stanford University, 1995



John Madey, The University of Hawai‘i



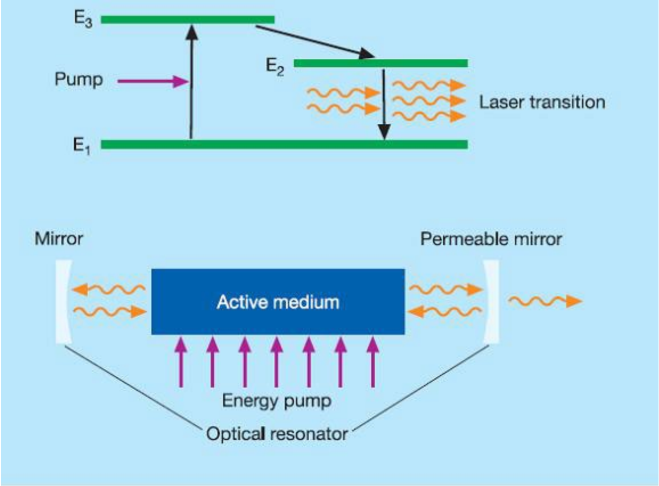
FEL was theorized by John Madey in his Ph.D. thesis, Stanford 1970:
J.M.J. Madey, J. Appl. Phys. 42, 1906 (1971)

First realization: Stanford, Electron energy: 43.5 MeV, FEL radiation: 3.4 µm
D.A.G. Deacon, L.R. Elias, J.M.J. Madey, G.J. Ramian, H.A. Schwettman, T.I. Smith; Phys. Rev. Lett. 38, 892 (1977)

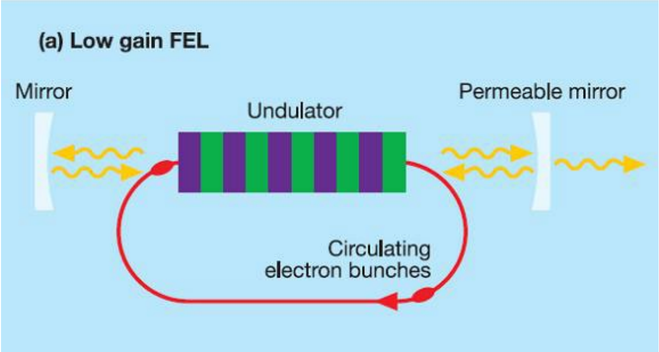
Free-electron laser (FEL) vs. conventional laser

- **Laser:**
  amplification due to stimulated emission of electrons bound to atoms (crystal, liquid dye, gas)
- **FEL:**
  amplification / gain medium = „free“ (unbound) electrons, stripped from atoms in an electron gun, accelerated to relativistic velocities and travelling through an undulator (= periodic magnetic multipole structure) to produce intense radiation

Free-electron laser (FEL) vs. conventional laser



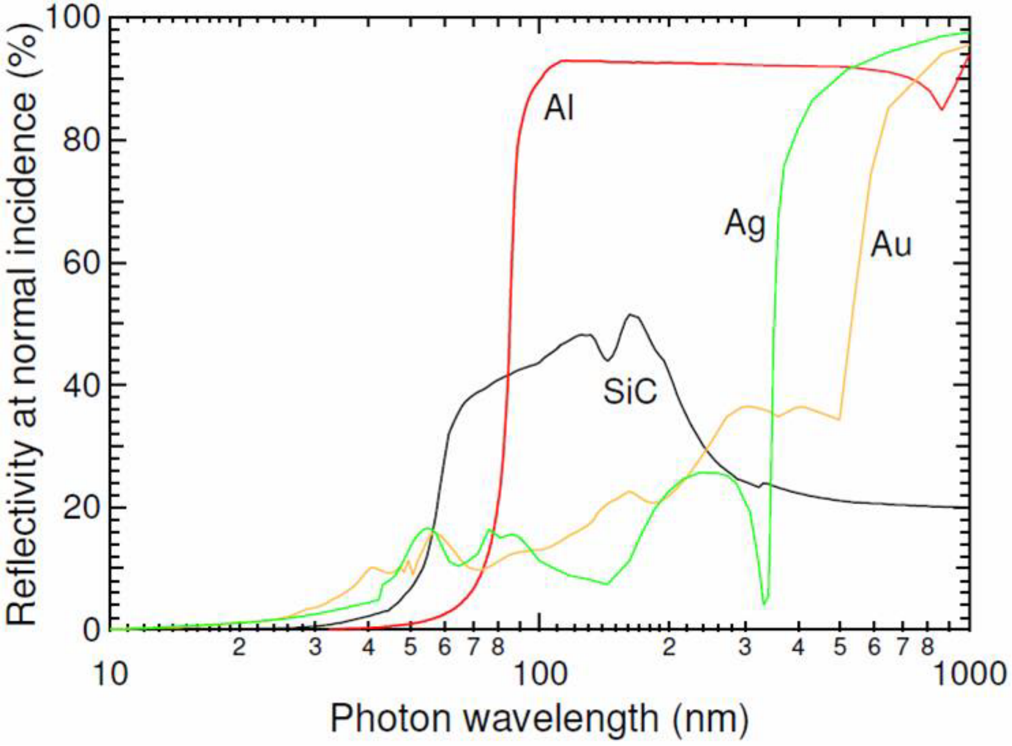
- Quantized energy levels
- Pump energy initiates population inversion
- Stimulated emission
- Optical resonator (cavity)



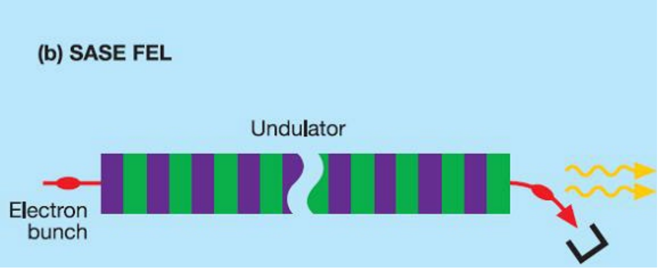
- Electron energy is not quantized
- ”Pump energy” is the kinetic energy of the electrons
- Stimulated emission
- Optical cavity or single pass SASE

Free-electron laser at short wavelength

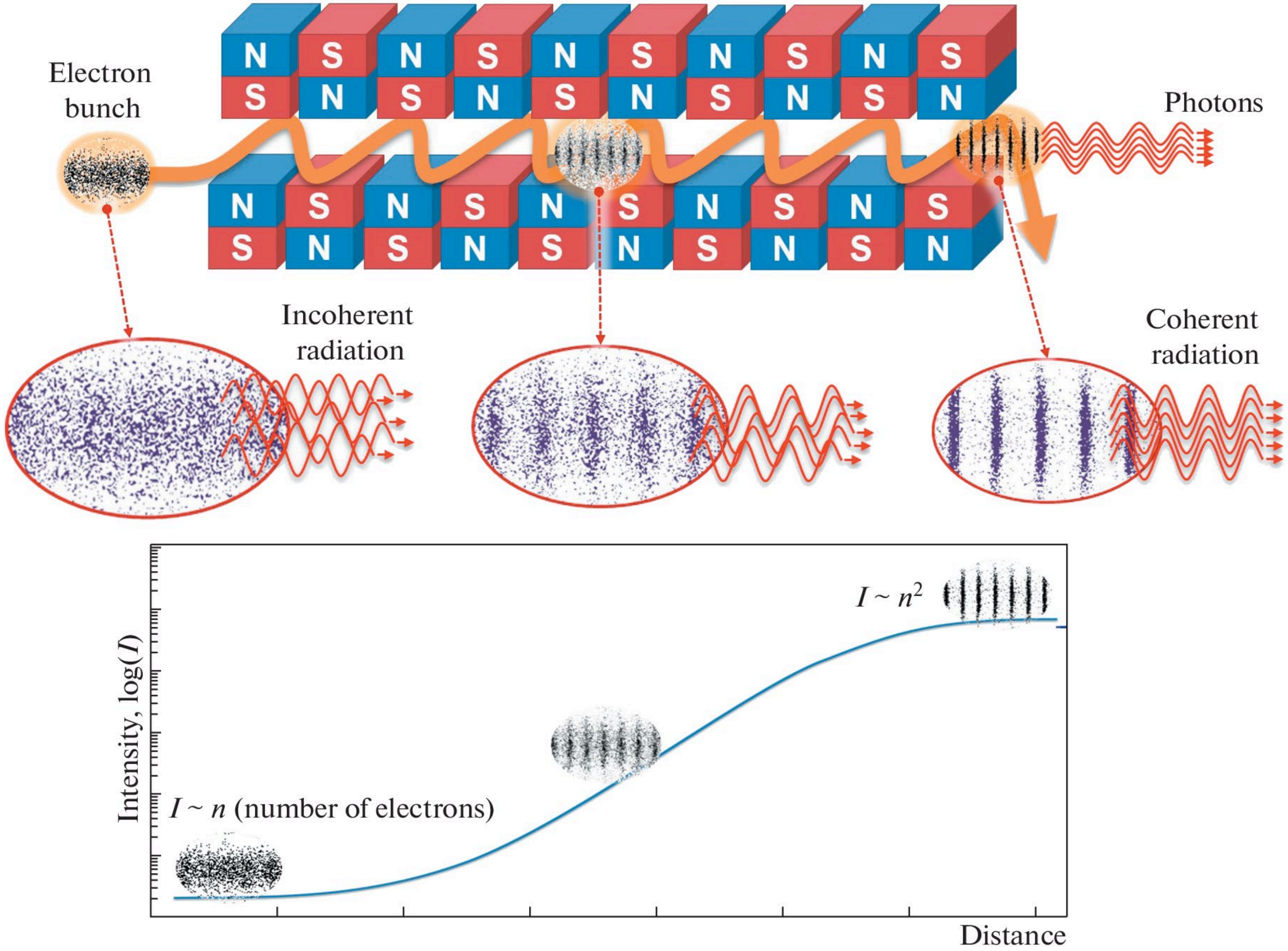
- Optical cavity does not work for wavelength $\lambda < 100$nm (low reflectivity, radiation damage)



- → single pass SASE FEL



Self-amplified spontaneous emission – SASE FEL

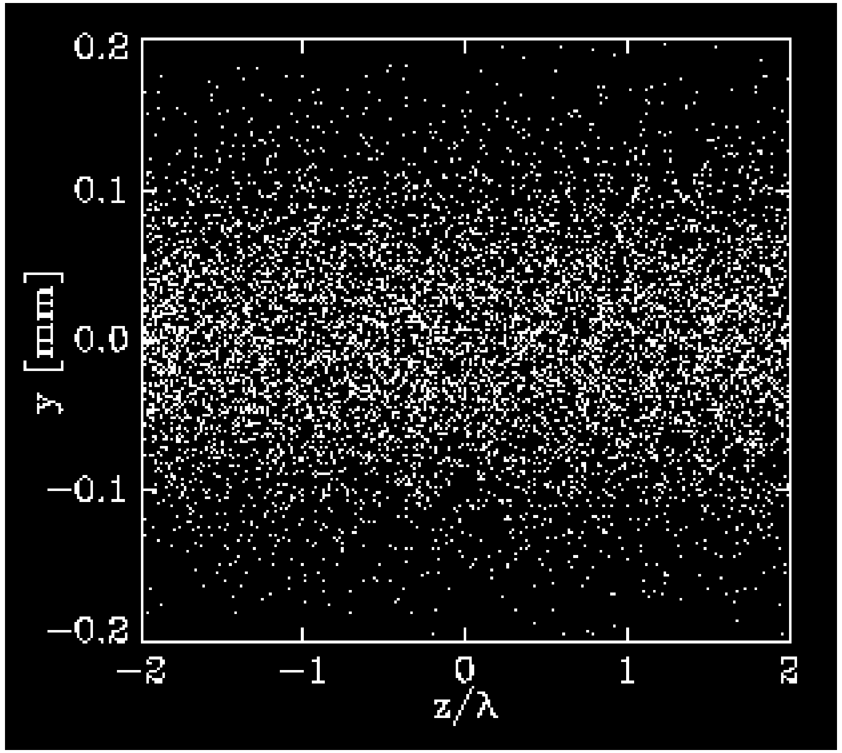


Crystallogr. Rep. 67,5 (2022)

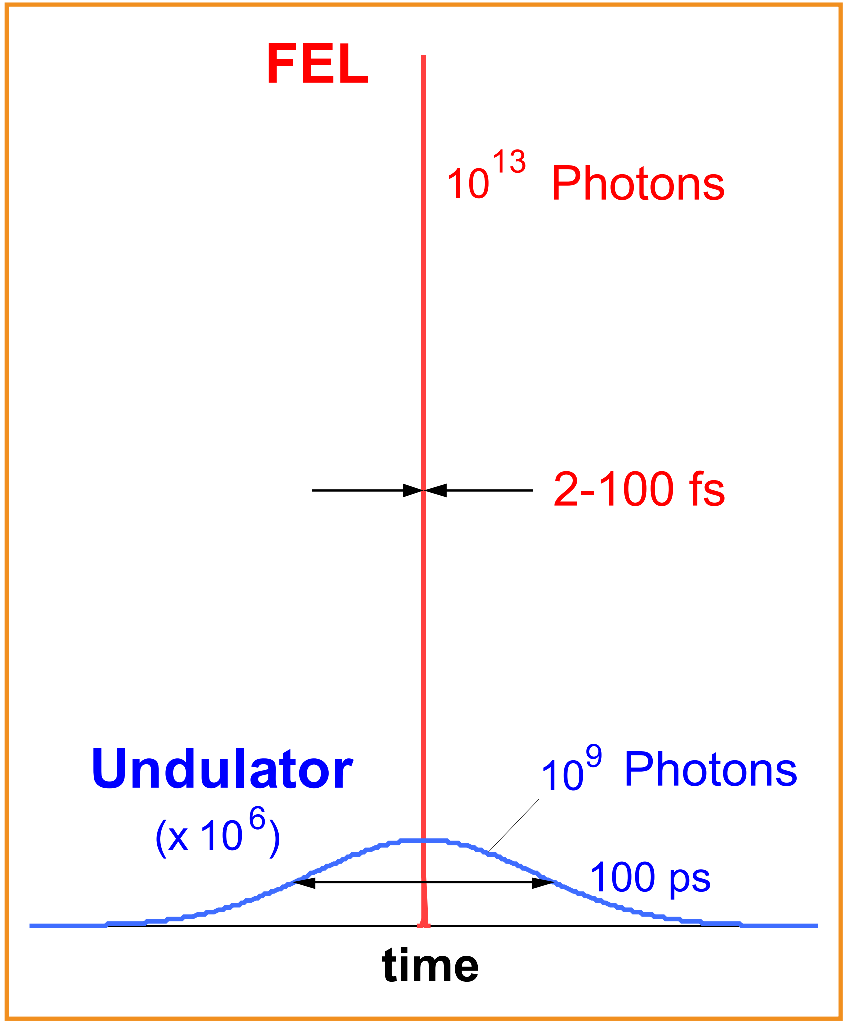
- Slippage between electrons and photons is λ_{phot} per undulator period
- Electrons in phase with e.m.-wave are retarded (“emit photons”), electrons with opposite phase gain energy (“absorb photons”)
- -> Longitudinal charge density modulation (“micro-bunching”) with periodicity equal to λ_{phot}
- -> Self-amplification of spontaneous emission due to increasingly coherent emission from micro-bunches (like point charge)
- $I \sim N_e^2 N_p^2$

Comparison undulator radiation – X-ray FEL radiation

Microbunching in the SASE process



(simulation by Sven Reiche)



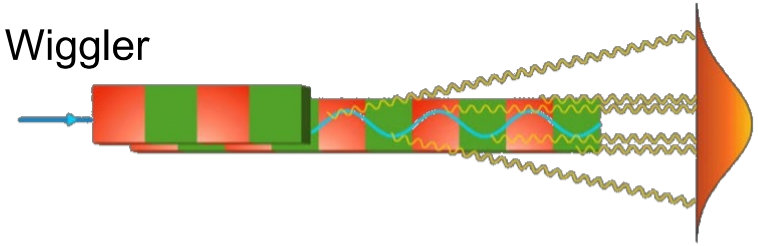
Insertion devices: Wigglers and Undulators

Intensity of the emitted radiation

N_p = Number of magnet poles

N_e = Number of electrons/bunch

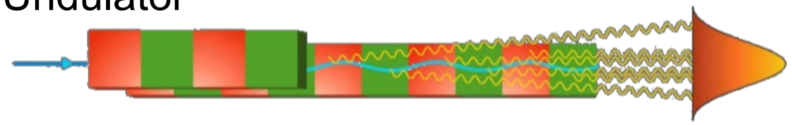
Wiggler



Incoherent superposition

$$\boxed{I \sim N_e N_p}$$

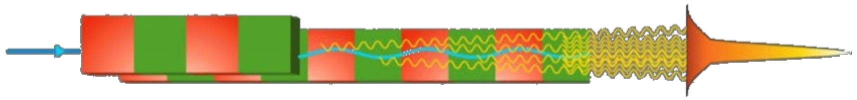
Undulator



Partially coherent superposition

$$\boxed{I \sim N_e N_p^2}$$

Free-Electron Laser



Fully coherent superposition

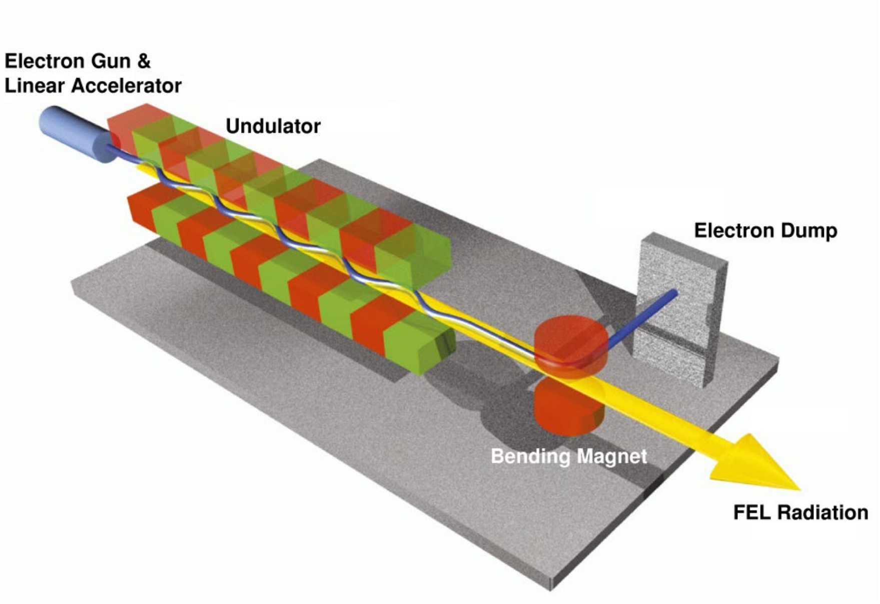
$$\boxed{I \sim N_e^2 N_p^2}$$

Self-Amplified Spontaneous Emission (SASE)

Self-amplified spontaneous emission – SASE

Requirement for SASE

- Good electron beam quality and sufficient overlap between electron-beam and radiation pulse along the undulator:
  - **low emittance, low energy spread of electron beam**
  - **extremely high charge density (kA peak currents)**
  - **precise magnetic field of undulator**
  - **accurate beam steering through undulator (few µm precision)**



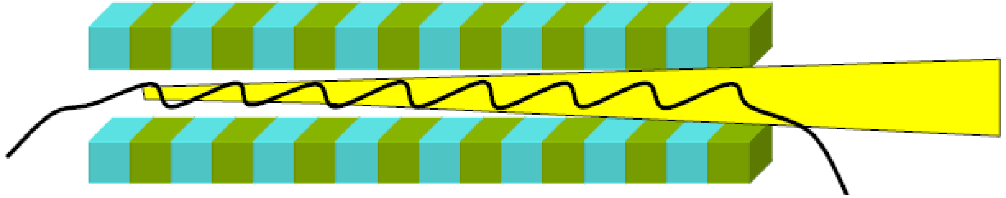
Self-amplified spontaneous emission – SASE

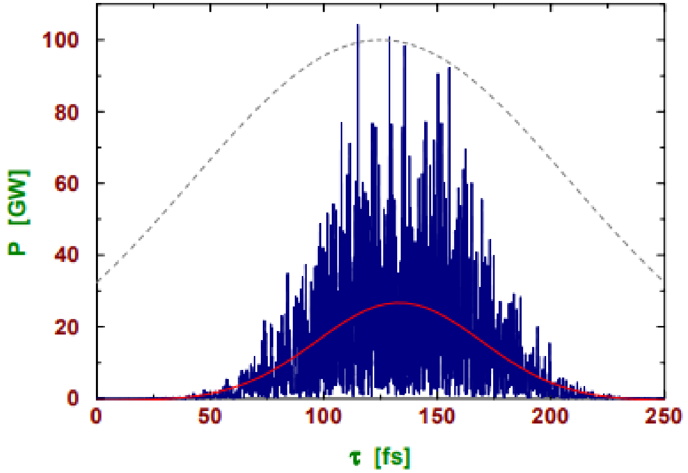
Emitted light, temporal distribution

- For a given wavelength there is only one resonant electron energy (continuous energy transfer)

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

- Wavelength change by changing the electron energy or magnetic field strength
- FEL process starts from noise: randomly distributed electron bunch and spontaneous undulator radiation
- Radiation pulse is “spiky” in time (and frequency) domain





SASE FEL properties

- high intensity (GW peak power)
- coherence (laser-like radiation)
- femtosecond pulses!
- narrow bandwidth!
- full wavelength tunability!
- down to X-rays!

- but: shot-to-shot fluctuations (w/o seeding)

  -> very good photon diagnostics are mandatory!

X-ray free-electron lasers worldwide

LCLS | **LCLS-II**
SLAC, Menlo Park | US

European XFEL
Schenefeld + Hamburg | DE

FLASH | **FLASH II**
DESY, Hamburg | DE

SwissFEL
PSI, Villigen | CH

FERMI
Elettra Sincrotrone Trieste, Trieste | IT

PAL-XFEL
PAL, Pohang | KR

SACLA
SCSS
RIKEN, Harima | JP

SXFEL
SINAP, Shanghai | CN

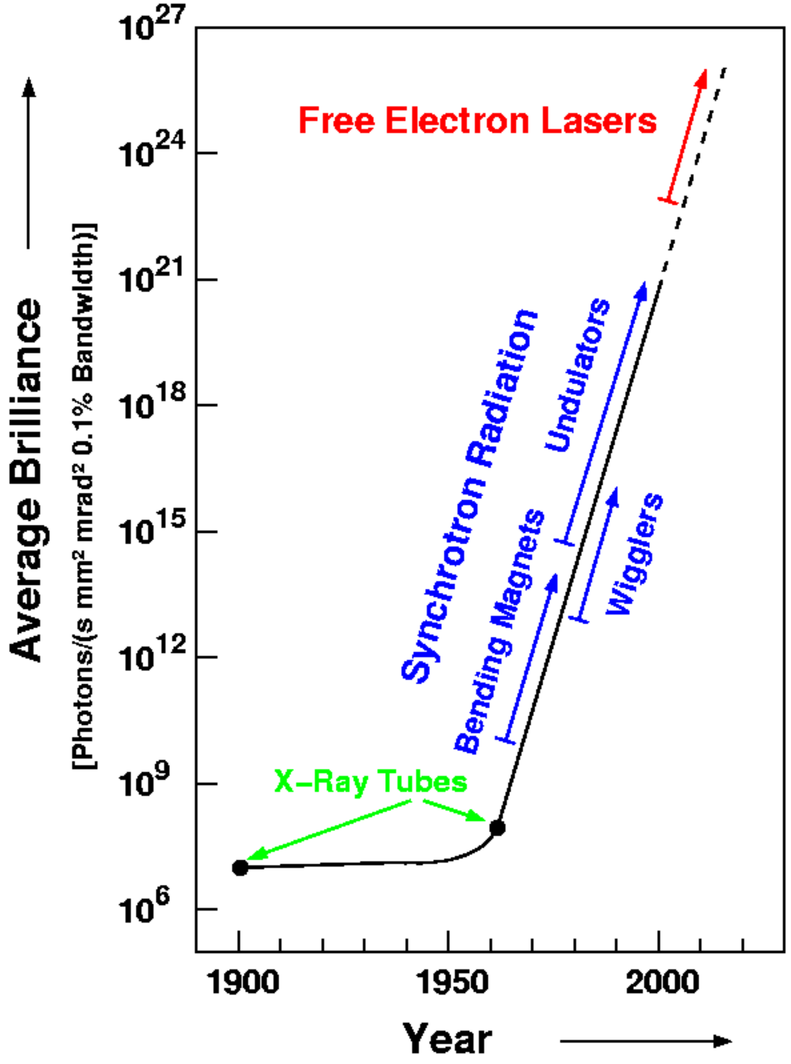
🟪 Hard XFEL

🟧 Soft XFEL

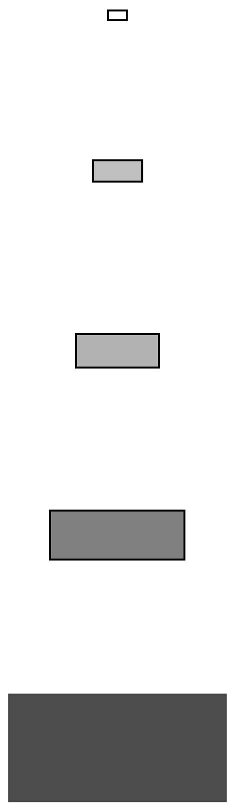
Courtesy European XFEL

Free-electron lasers

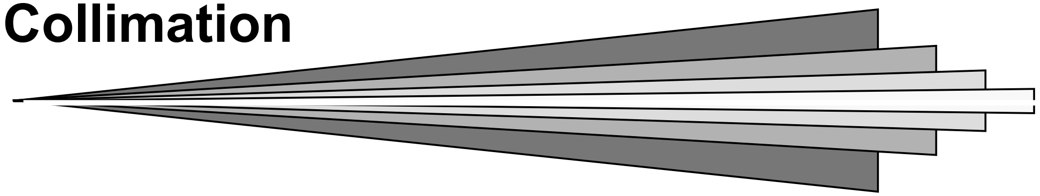
FLASH



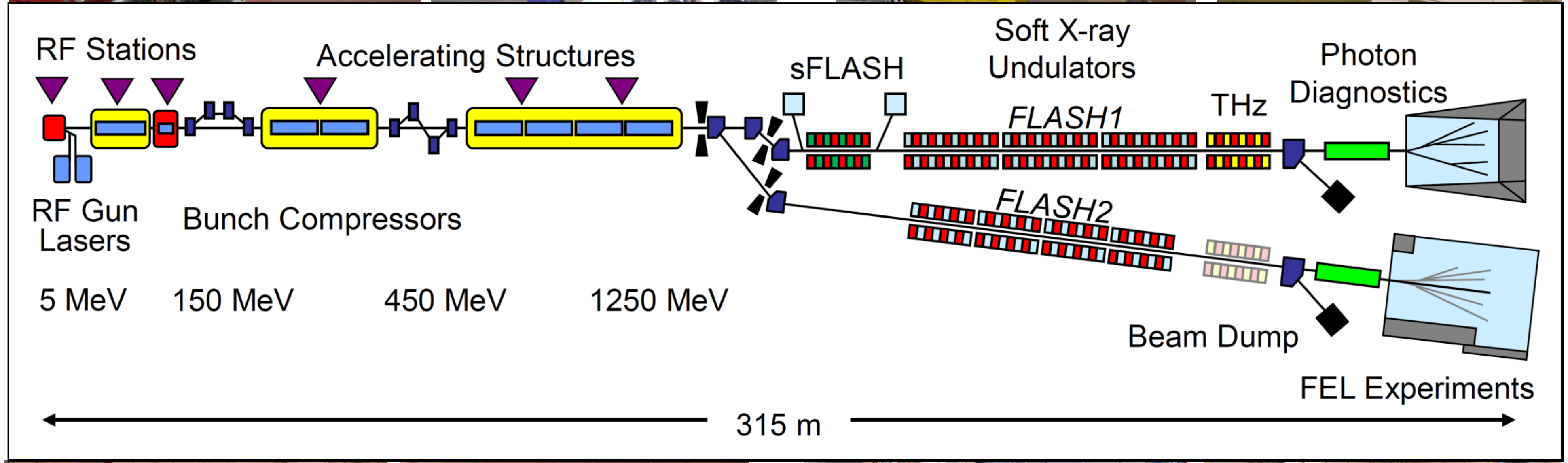
Source size

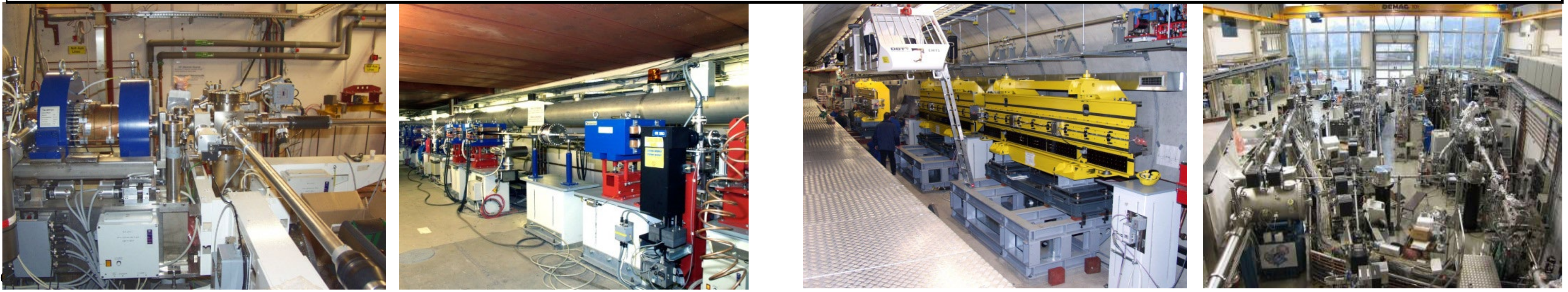


Collimation

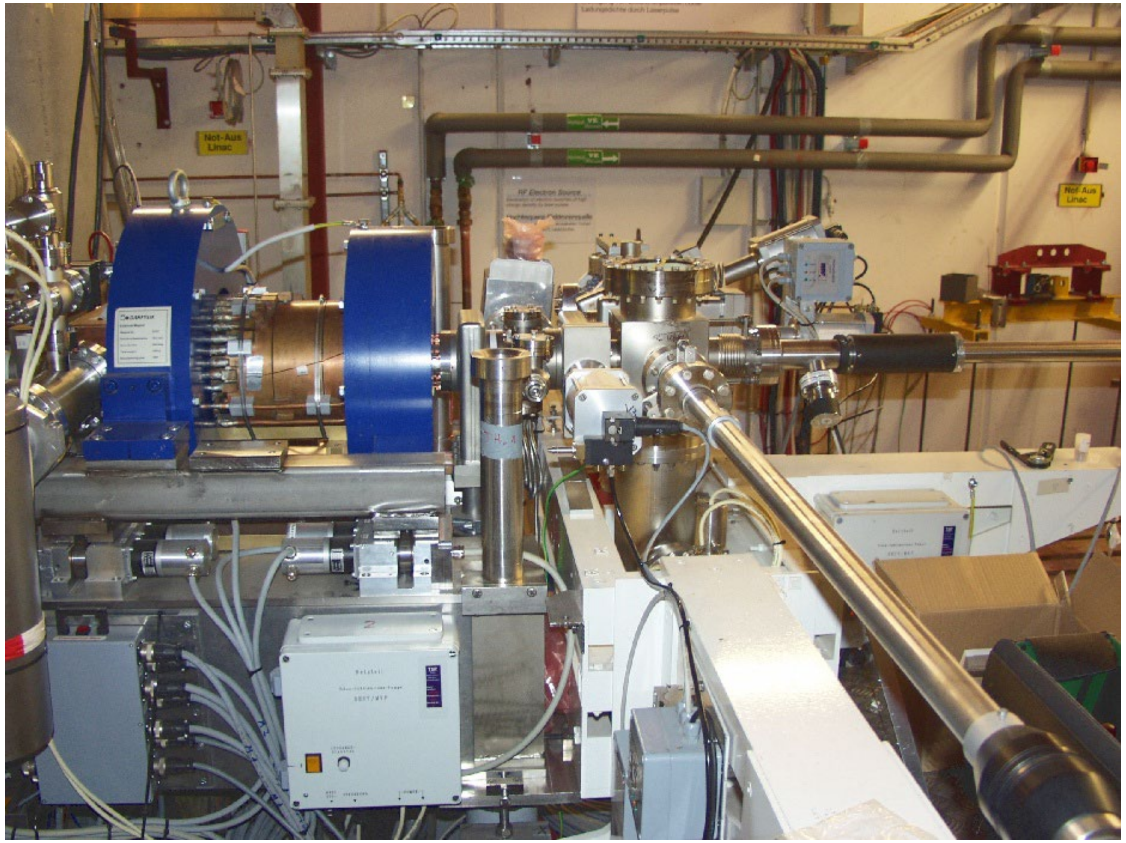


The FLASH facility



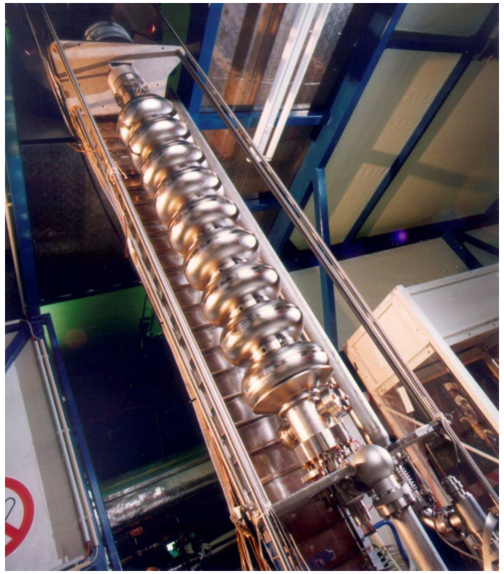


Injector: creating bunches of electrons



- Optical laser strikes Cs_2Te photocathode, releasing a cloud of electrons (1-3% quantum efficiency)
- Electrons move into a magnetic field, 11/2-cell resonator, shaping into a bunch
- Small accelerator module "fires" bunch into the main electron accelerator

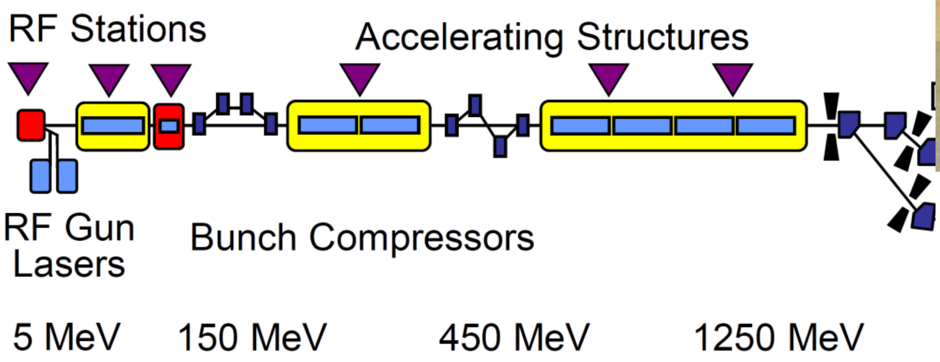
Superconducting accelerator module



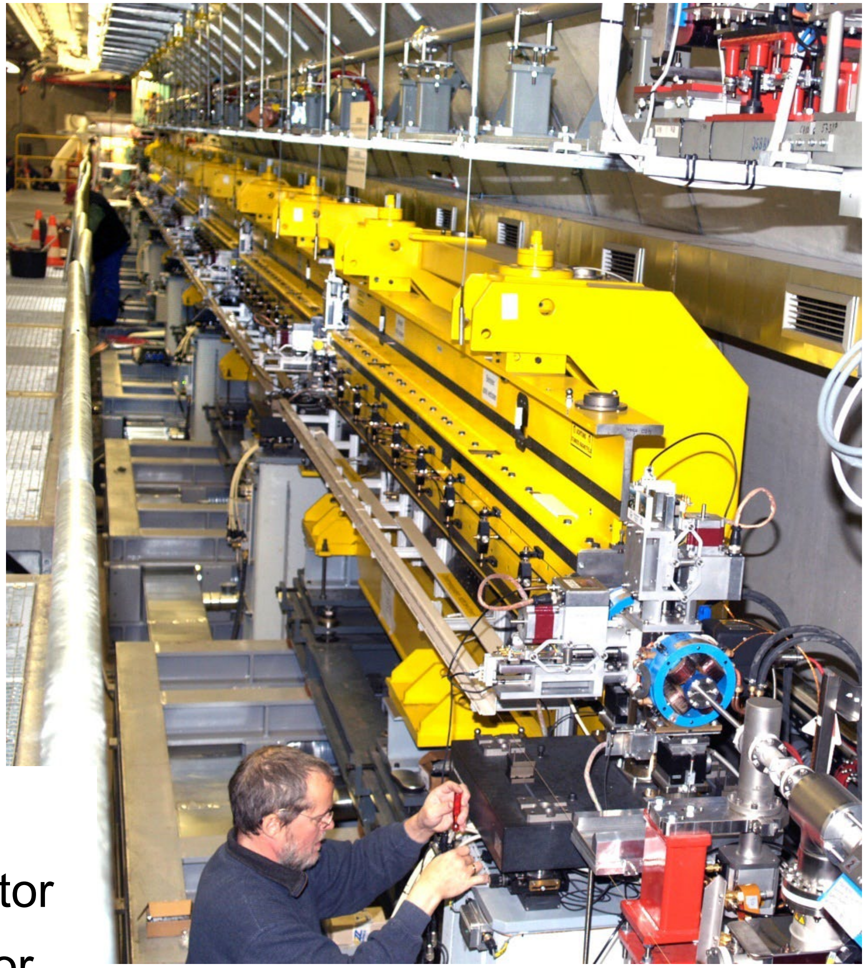
- Accelerator module with superconducting niobium cavities
- 25 MV/m routinely
- Length: 12 m
- Weight: about 10 tons!

Bunch compressors

- electromagnetic chicane
  (4 dipole magnets)
- longitudinal compression
  of electron bunches
- ~1 mm → 0.1 mm

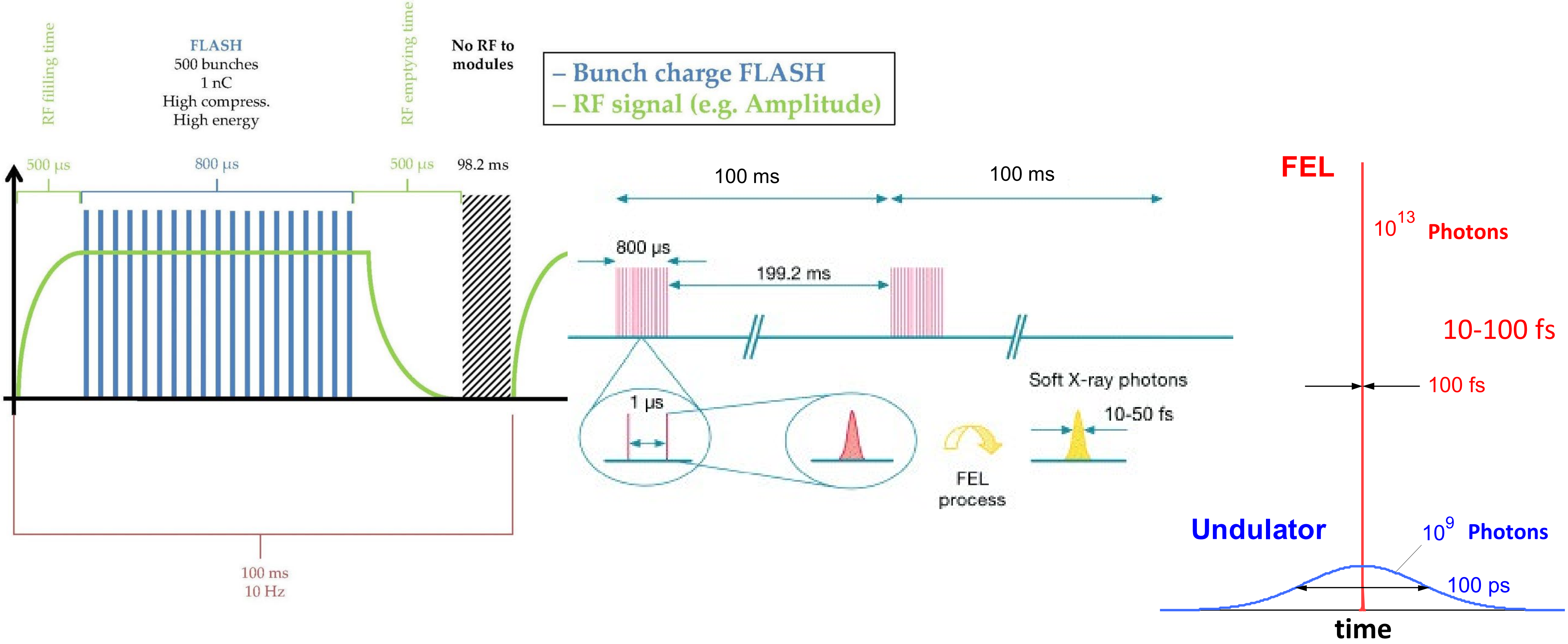


Undulators

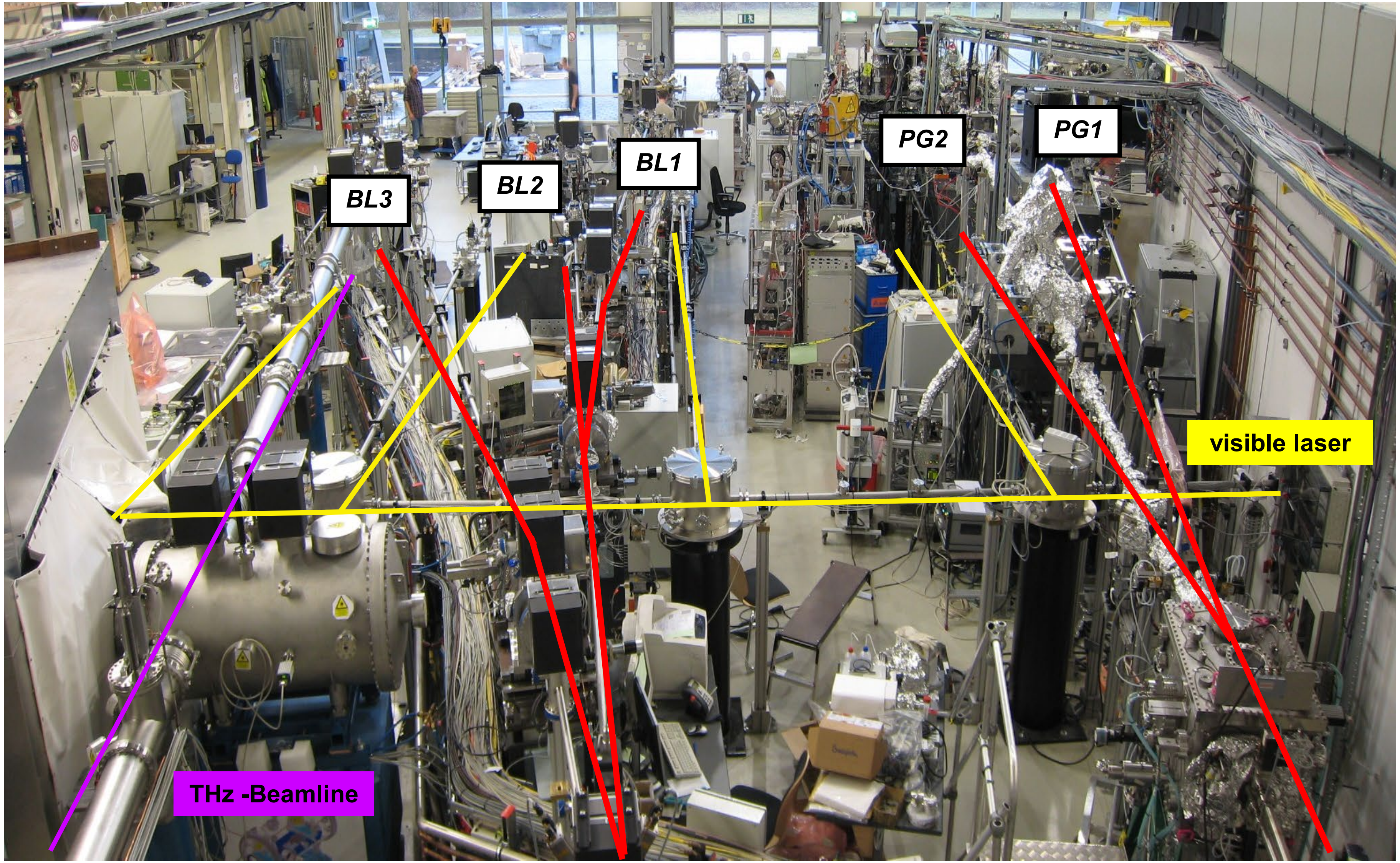


- 27 m undulator
- 12 mm fixed gap → tuning with accelerator
- Intersections with quadrupole doublets for focusing electron beam, electron beam diagnostics and steerer coils

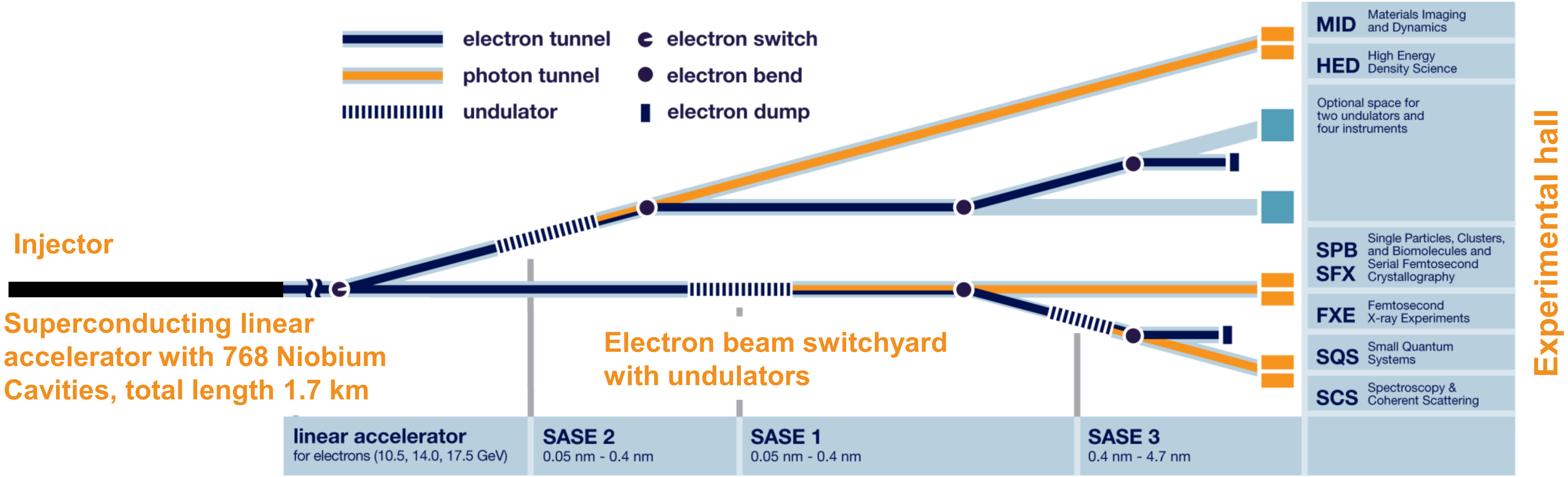
Superconducting modules: bunch structure



FLASH1 experimental hall – Albert-Einstein hall



European XFEL: schematic layout



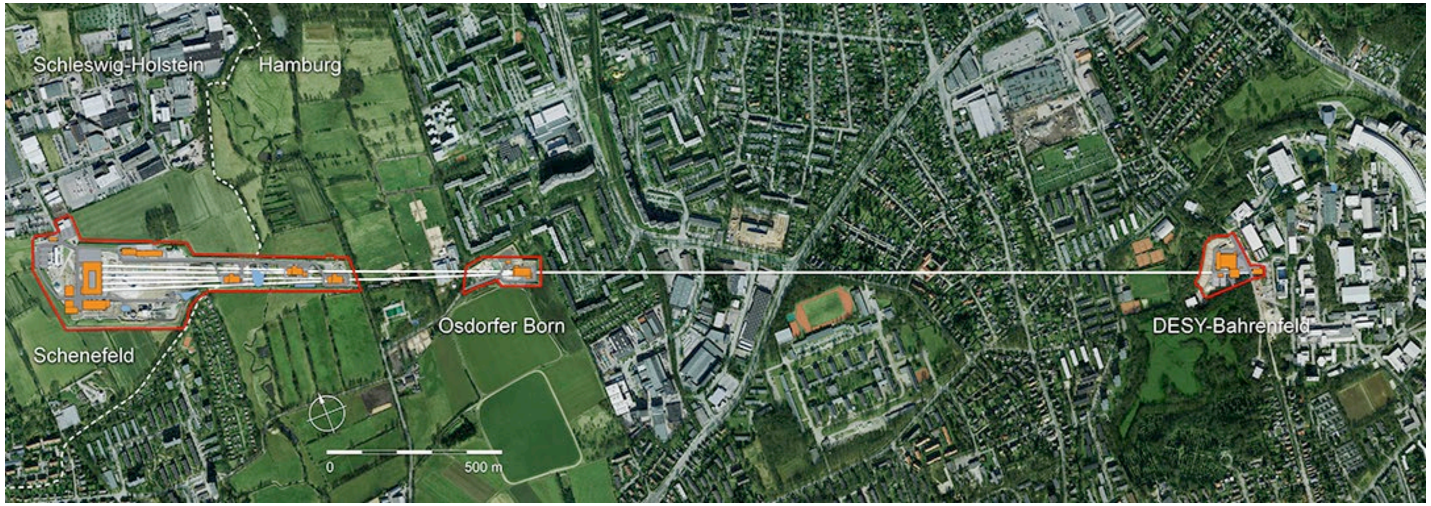
Supercond. Linac: up to 17.5 GeV

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·mm^2·mrad^2·0.1%BW)

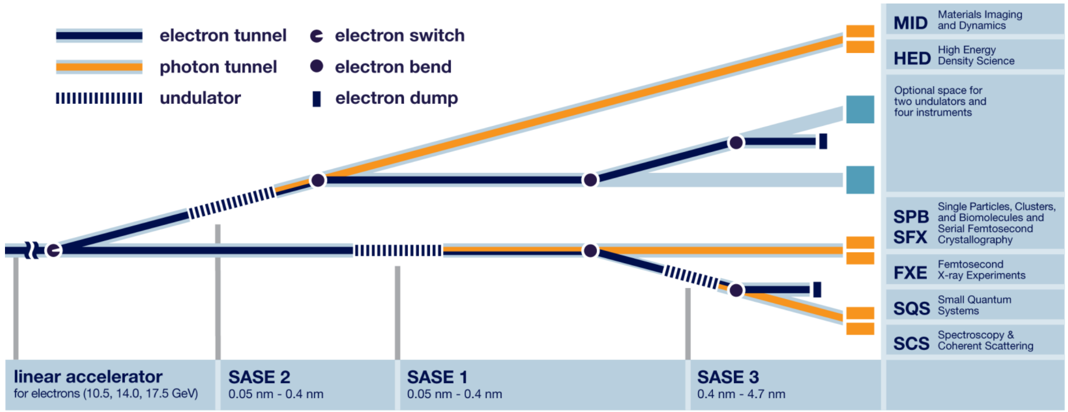
Peak brilliance: ~10^{33}

Pulse length: <100 fs (< 1 fs)



European XFEL

Science at the beamlines



Endstation	Science
MID	**Materials imaging & dynamics:** structure determination of nanodevices and dynamics at the nanoscale
HED	**High energy density science:** investigation of matter under extreme conditions using hard X-ray FEL radiation, e.g. probing dense plasmas
SPB/SFX	**Ultrafast coherent diffraction imaging of single particles, clusters and biomolecules**: structure determination of single particles (atomic clusters, biomolecules, virus particles, cells), serial femtosecond crystallography
FXE	**Femtosecond X-ray experiments**: time-resolved investigations of the dynamics of solids, liquids, gases
SQS	**Small quantum systems:** investigation of atoms, ions, molecules and clusters in intense fields and non-linear phenomena
SCS	**Spectroscopy & coherent scattering**: Electronic and atomic structure and dynamics of nanosystems and of non-reproducible biological objects using soft X-rays

3100-24800 eV

260-3100 eV