European XFEL

General Information

The European XFEL is an international user facility for the application of soft and hard X-ray free-electron laser radiation for applications from multiple science areas. A focus will be on applications in physics, material and nano-sciences, reaction chemistry, structural biology, and extreme states (as found in planets or dense plasmas). Funded in 2009 the first light is scheduled for end of 2016. European XFEL is designed as a user facility serving several user groups in parallel. For this the electron beam is distributed to 5 (initially 3) different undulators, each serving two or three end-stations.

European XFEL is financed by contributions from its 12 shareholder countries: Denmark, France, Germany, Greece, Hungary, Italy, Poland, Russia, Slowakia, Spain, Sweden, Switzerland

Electron energy: 8.5 – 17.5 GeV

Number of FEL sources: 5 (3 in first implementation)

Number of end-stations: 15 (max., 6 in first implementation)

Photon energy: 0.25~25 keV

Pulse duration: few fs - 100 fs

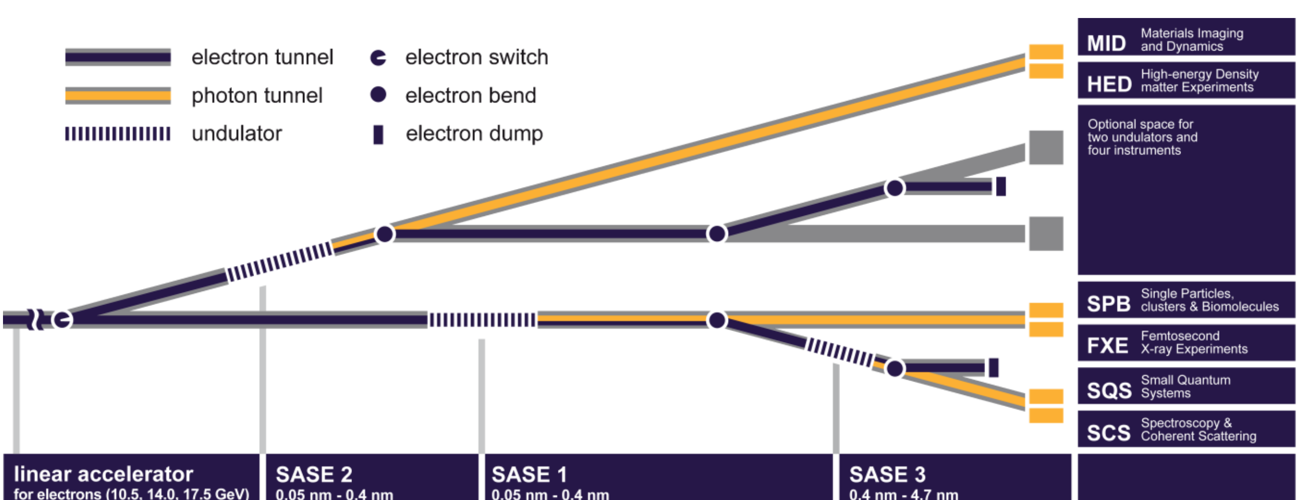
Annual operation for users: 4000 hrs

Construction budget: 1147 M€ (2005 value)

Operations Budget: ~100 M€

Accelerator modules during production

Beamline Map



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Current Activities

X-ray optics and beam transport

The beam transport system guides the X-ray laser beam from the undulators to the 1 km distant experiment hall in an underground tunnel system.

Deflections of the X-ray beam are achieved by 950 mm long X-ray mirrors working in extreme grazing incidence angle geometry. To conserve the high degree of coherence and the shape of the laser beam, these mirrors have to be ultra-flat (larger than 6000 km residual bending radius) and ultra-smooth (less than 2 nanometers peak-to-valley polishing error over the entire mirror length).

Figure 1 shows a prototype mirror with piezo benders. Here, piezo actuators can be used to compensate for mounting errors and long-range polishing errors. To keep the mirrors mechanically stable in an ultra-high-vacuum environment, special mirror vacuum chambers were developed (Figure 2). Angular vibrations of a mirror mounted is such a chamber are better than 20 nanoradians.

See poster P1-6 A hard x-ray split-and-delay unit for the HED instrument at the European XFEL, S. Roling

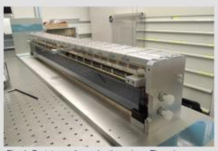

Fig. 1: Prototype of an adaptive mirror. The mirror deflects in horizontal geometry with the deflecting surface facing the camera. Bending can be controlled using piezo elements located at the four edges on the top and bottom of the mirror.

Fig. 2: Mirror chamber for offset and distribution mirrors

X-ray photon diagnostics

The photon diagnostics devices for monitoring the XFEL beam will be placed into the photon transport system in the tunnels between the undulators and the experimental hall. Most of these devices have passed from design through prototype to production phase. The challenges for the design are the extremely high brilliance and the high repetition rate of 4.5 Mhz.

Currently we are receiving from industrial production the imaging stations for beam alignment at the X-ray optics, we obtained the so-called MCP-based detectors, we produced the first undulator commissioning spectrometer, and we are assembling the first prototype of an online photoemission spectrometer for the soft X-ray branch. This device can measure shoto-to-shot wavelength and polarization of the beam. The first tunnel for photon machine installation is the SASE1 tunnel XTD2, in which recently the device support structures were installed, here consisting of concrete pedestals and steel pillars. Until end of 2014 the installation of mechanical and vacuum parts in XTD2 will be finished, and the work focus will shift to cabling and electronics, and to the next tunnels.

See presentation Session 8 Röntgenstrahl-diagnostik für den European XFEL, J. Grünert

Fig. 1: Photo of the popin monitor imaging station in the cleanroom at European XFEL

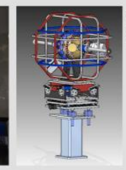

Fig. 2: CAD view of the photoeectron spectrometer which is under development in WP74

Optical lasers

A significant number of the experiments at the European XFEL (up to 75%) will require optical lasers for pump-probe experiments. Naturally, such a laser must be adapted to the European XFEL lasing-mode, i. e. it should deliver synchronized pulses of XFEL-comparable pulse width within bursts of 600µs length and an intra-burst repetition rate of up to 4.5MHz. Some degree of freedom in the choice of pulse width and wavelength (around 800nm) is also desirable. Energy requirements for single pulses usually range from µJ to mJ. Moreover, different experiments need different repetition-rates and pulse patterns inside the burst. Considering such difficult demands and lacking off-the-shelf commercial laser technology, the European XFEL embarked on a highly challenging development project.

The scheme of the European XFEL pump-probe laser is shown in Fig. 1. It consists of a picosecond-pumped multi-stage non-collinear optical parametric amplifier (NOPA), employing an Yb-fiber based synchronized front-end, Yb:YAG pump amplifiers and dispersion managed super-continuum seed.

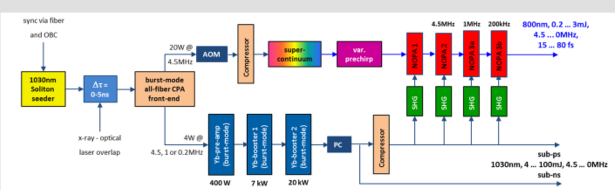

Fig. 1: Scheme of the European XFEL pump-probe laser under development and to be installed in each of the SASE 1, 2 and 3 pump-probe laser hutches starting 2016.

In Q4 of 2013, all essential features of the pump-probe laser were achieved in proof of principle experiments with the R&D prototype using only the first stage (400W) pump amplifier:

- essentially pedestal-free 15fs pulses at an intra-burst repetition rate of up to 4.5MHz and center wavelength of 810nm (see Fig. 2).
- pulse energy of 180µJ from two sequential NOPA stages with an intra-burst repetition rate of 188kHz.
- possibility of generating longer pulses (up to 75fs), enabling efficient non-linear conversion as well as wavelength tuning over a range of more than 100 nm.
- diffraction-limited beam quality.
- transient free bursts and arbitrary pulse selection from single pulses to 4.5MHz.

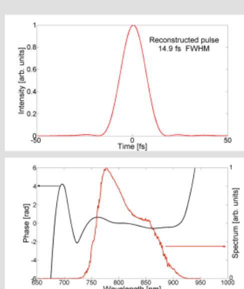

Fig. 2: Complete characterization of 15 fs NOPA output pulse using SPIDER. Left: Intensity. Right: Spectrum and spectral phase. The pulses have a peak to pedestal contrast of 20dB.

The upgrade to the next level of pump power (10-fold increase) has been carried out and NOPA experiments are under way. The start of installation of 3 pump-probe lasers in the experiment hall is planned for 2016.

Sample environment

The high repetition rate of the European XFEL (2.700 bunches ten times a second) opens chances for experiments that are too time consuming for lower repetition rate sources. However, to make use of this feature, sample environments for fast and precise sample exchange have to be designed. The Sample Environment Group develops state of the art sample delivery technologies in the fields liquids, solid samples, magnetism and biology.

Liquid jet systems will be the work horse of sample delivery for nano-crystallography; one of the most promising applications of XFELs. For solid samples or samples fixed to surfaces a 10Hz sample scanner is under development.

See poster P1-80 Sample refreshment schemes for high repetition rate FEL experiments, C. Deiter

Fig. 1: Liquid jet prototype

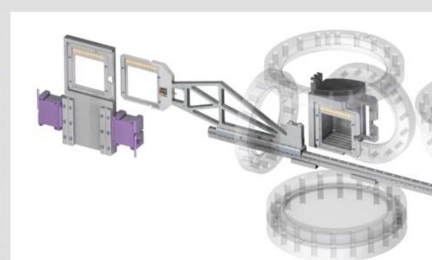

Fig. 2: Design study for a 10Hz solid sample scanner with fast sample exchanger.

Detectors

High-speed imaging X-ray detectors are essential for users to exploit the full potential of the ultrafast burst mode of the European XFEL and record valuable data. In collaboration with national and international partners, the Detector Development group develops ultrafast large- and small-area X-ray detectors required by the photon experiments for imaging, monitoring, veto, and spectroscopic applications. Low electronic noise, large dynamic range up to 10^5, the possibility to discriminate single photons from electronic noise with high significance up to 5σ, high angular resolution and the ability to endure the high demands on irradiation damage are essential detector performance parameters required to exploit the full potential of the European XFEL.

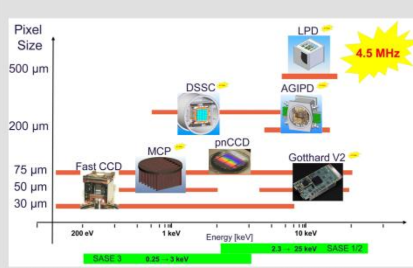

Fig. 1: overview of the detectors available for the European XFEL from the first day of operation

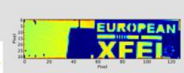

Fig. 2: X-ray image taken with the LPD two-tile prototype detector system operated at a sampling rate of 4.5 MHz.

Fig. 3: Installation of the Large Pixel Detector (LPD) 1/4 Mpixel prototype

European XFEL

Scientific Instruments

FXE (Femtosecond X-ray Experiments)

The FXE instrument will offer world-wide unique and versatile end-station for time-resolved studies of ultrafast dynamics in various condensed matter systems, mainly liquids. For this purpose it will exploit the high repetition rate, X-ray photon flux and ultrashort pulse duration of the European XFEL.

FXE will offer a flexible sample environment optimized for liquid-phase photochemistry using a suite of complementary X-ray spectroscopic and scattering techniques in a pump-probe arrangement. Simultaneous measurements of several observables will deliver a more complete picture of the dynamics both of the solute and solvent molecules.

Parameter	Monochromatic	Pink beam
Energy range	5-20(25) keV	5-20(25) keV
Beam position	Sample (fixed)	Sample (fixed)
Energy bandwidth	$1.4x10^{-4}$ Si(111) $3x10^{-5}$ Si(311)	0.3-1 %
Bunch charge	≤ 250 pC	≤ 250 pC
X-ray pulse duration	< 25 fs	< 25 fs
Optical pulse duration	15 fs	15 fs
Sample delivery: Liquid flat-sheet jets	Up to 15 m/s (sapphire nozzles) Up to 100 m/s (colliding μjets)	Up to 15 m/s (sapphire nozzles) Up to 100 m/s (colliding μjets)
X-ray beam spot	1-10 μm in focus Up to 0.1 mm out of focus	1-10 μm in focus Up to 0.1 mm out of focus
Energy resolution	ca. 1 eV (cylindrical) 0.3 - <1eV (spherical)	ca. 1 eV (cylindrical) 0.3 - <1eV(spherical)
Q range (XDS)	0.7 – 13 $Å^{-1}$	0.7 – 13 $Å^{-1}$

See poster P1-185 Visualizing ligand exchange reactions with time-resolved X-ray absorption spectroscopy, Tadesse Abebaw Assefa

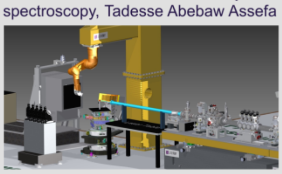

Fig. 1: Side view of the FXE instrument

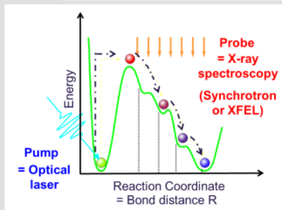

Fig. 2: Artists view of an excited state landscape looking at a single reaction coordinate

HED (High-Energy Density matter experiments)

The HED instrument focuses on matter at extreme conditions of temperature, pressure electric and/or magnetic field strength. Major applications are high-pressure planetary physics, warm- and hot- dense matter, laser-induced relativistic plasmas and complex solids in pulsed magnetic fields.

The extreme states can be reached by different types of optical lasers (either 200 kHz/3 mJ/15 fs, 10 Hz/100 TW/30 fs or 10 Hz/100J/ns), the pump-probe FEL beam (delays of up to 2 -23 ps for 5 -20 keV using a split-and-delay unit) and pulsed magnetic fields (up to 50 T). Pump probe experiments can be performed at adapted repetition rates (4.5 MHz, 1 – 10 Hz, shot on demand). Available X-ray techniques comprise diffraction, imaging and spectroscopic methods.

See posters P1-6 A hard x-ray split-and-delay unit for the HED instrument at the European XFEL, S. Roling; **P1-203**: New perspectives for extreme states of matter research: The high-energy density instrument at European XFEL, K. Appel

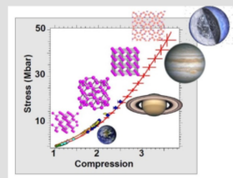

Fig. 1: Dynamic compression of carbon with HE lasers: this technique enables studying and discovering structures and phases at conditions relevant inside large planets and exoplanets.

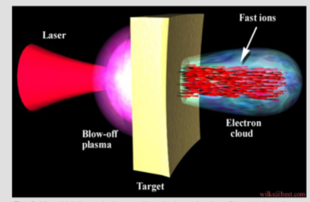

Fig. 2: Ultra-high intensity lasers allow the investigation of laser induced relativistic plasmas as well as warm and hot dense matter.

MID (Materials Imaging and Dynamics)

The MID station will offer extended capabilities for scattering and imaging experiments, e.g. coherent X-ray diffractive imaging (CXDI) and X-ray photon correlation spectroscopy (XPCS), compared to present state-of-the-art facilities. Based on the high degree of coherence, the exceptional flux, and the ultra-short pulses of the X-ray laser it will be possible to investigate materials with unprecedented resolution in space and time.

In order to optimize the FEL beam to the different user demands, the MID beamline offers optics to collimate or focus the beam. The spectral bandwidth of the pulses is tunable through single-crystal monochromators (Si 111 & Si 220) operating in Bragg diffraction geometry.

The MID sample chamber will allow in-vacuum scattering and diffraction experiments on solid (crystalline and non-crystalline) and liquid samples. An X-ray split-delay line (up to 800 ps delay) will be available for ultrafast dynamics studies as well as for X-ray pump / X-ray probe experiments as well as an optical laser system for optical pump / X-ray probe measurements.

See poster P1-169 Development of a hard X-ray Split and Delay Line for the MID station at the European XFEL, T. Roth

Fig. 1: 3D model of the MID experiment hutch with the MID sample chamber and the detector in wide angle X-ray scattering geometry.

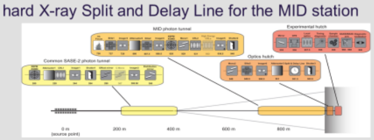

Fig. 2: Schematic top view on the SASE2 photon tunnels and the MID hutches. Devices relevant for the MID instrument are shown as pictograms. Four different areas are of particular interest: the common SASE2 tunnel, the MID tunnel, and the optics and experiment hutches of the MID instrument. (XGMD = X-ray gas monitor detector, XBPM = beam position monitor, Mono = monochromator, CRL = compound refractive lenses, DPS = differential pumping section, SAXS = small-angle X-ray scattering, WAXS = wide-angle X-ray scattering)

SCS (Spectroscopy & Coherent Scattering)

The SCS instrument will be dedicated to the study of electronic, spin, and atomic structures on the nanoscale using soft X-rays. Its purpose is to enable users to explore excited-state dynamics on ultrafast time scales and to unravel the function of complex materials. Areas of application are materials science, nanoscience, and condensed-matter dynamics as well as bioscience.

The SCS instrument design includes monochromatic-beam operation at high and medium resolving powers as well as pink (non-monochromatized) beam operation. The tunable monochromator grating illumination concept is intended to provide a minimum spectral bandwidth–time duration product for a broad range of user experiments, which will enable, at the same instrument, high energy-resolution spectroscopy experiments with lower time resolution and ultrafast dynamic studies at reduced energy resolutions.

The Kirkpatrick-Baez KB mirror will provide an adjustable X-ray spot of up to 1 mm in size on the sample position with a 1.5 μm nominal focus. The baseline SCS instrument would allow for X-ray resonant diffraction (XRD) studies in Bragg scattering and forward small-angle scattering geometries as well as absorption spectroscopy.

See posters P1-93 Technical Design of the SCS instrument at European XFEL, J.T. Delitz; **P2-263** Coherent Soft X-Ray Scattering at the European XFEL, R. Carley

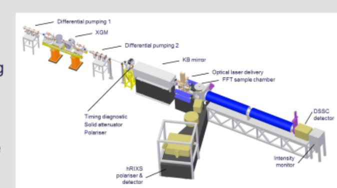

Fig. 1: 3D model of the SCS instrument

SPB (Single Particles, clusters, and Biomolecules)

The Single Particles, Clusters and Biomolecules/Serial Femtosecond Crystallography (SPB/SFX) instrument of the European XFEL aims to discern the structure–predominantly of biomolecules–that are prepared either as crystals or in non-crystalline form. The structure of biomolecules helps one understand how they work, and may be ultimately useful in combating diseases. The ultrabright pulses of X-rays produced by the European XFEL allow us to "see" these tiny samples in almost atomic detail by illuminating these small objects with an unprecedented flux of X-rays–some of which scatter into x-ray cameras that record the information we need to understand their structure.

The SPB/SFX instrument operates in the forward scattering modality, from 3 –16 keV photon energy. Two focal spots sizes– one of about 1 um and another of about 100 nm–are planned to illuminate samples smaller than about a micron and about 100 nm respectively. Fast 2D detectors will be installed at SPB/SFX to measure the crystalline and non-crystalline diffraction produced from different samples. Ancillary diagnostics and detectors further complement the instrumentation suite.

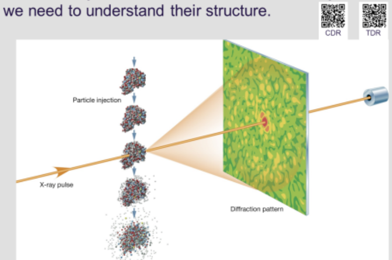

Fig. 1: Generation of single-particle diffraction patterns. A pulse of X-rays from a free-electron laser illuminates an injected biomolecule. Before the molecule is destroyed by the pulse, it scatters a portion of these X-rays, thereby creating a diffraction pattern. A camera downstream of the interaction region records the diffraction pattern, which contains information about the structure of the molecule. Measuring many such diffraction patterns from differently aligned copies of the same biomolecule will enable scientists to understand its three-dimensional structure.

SQS (Small Quantum Systems)

The SQS scientific instrument is dedicated to investigations of non-linear phenomena and time-resolved experiments on atoms, molecules, clusters and nanoparticles stimulated by intense and ultra-short FEL radiation pulses in the Soft X-Ray wavelength range.

Main components for electron, ion and fluorescence spectroscopy and imaging:

1) The "KB" (Kirkpatrick-Baez) focusing optics enables a tight focus (≤ 1 micron) of the XUV radiation and to access different focus position by a set of bendable mirrors.
2) The "AQS" (Atomic-like Quantum Systems) chamber for investigations on small targets comprises 5 TOF (Time-Of-Flight) spectrometers, 1 VMI (Velocity-Map-Imaging), 1 MBES (Magnetic-Bottle-Electron-Spectrometer), 1 XUV high-resolution 1D-imaging spectrometer and 1 VUV-XUV spectrometer for single-pulse analysis
3) The "NQS" (Nano-size Quantum Systems) chamber for investigations of clusters, nano-particles and bio-molecules comprises 1 DSSC 2D-Imaging detector for coherent diffraction experiments, 1 ion-TOF and 1 VMI spectrometer.
4) "SQS-REMI" (Reaction Microscope) chamber for studies on single-molecule dissociation dynamics by energy- and angle-resolved spectroscopy of electrons and ions in coincidence.

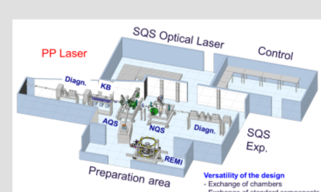

Fig. 1: 3D model of the SQS instrument