European XFEL
Enlightening Science

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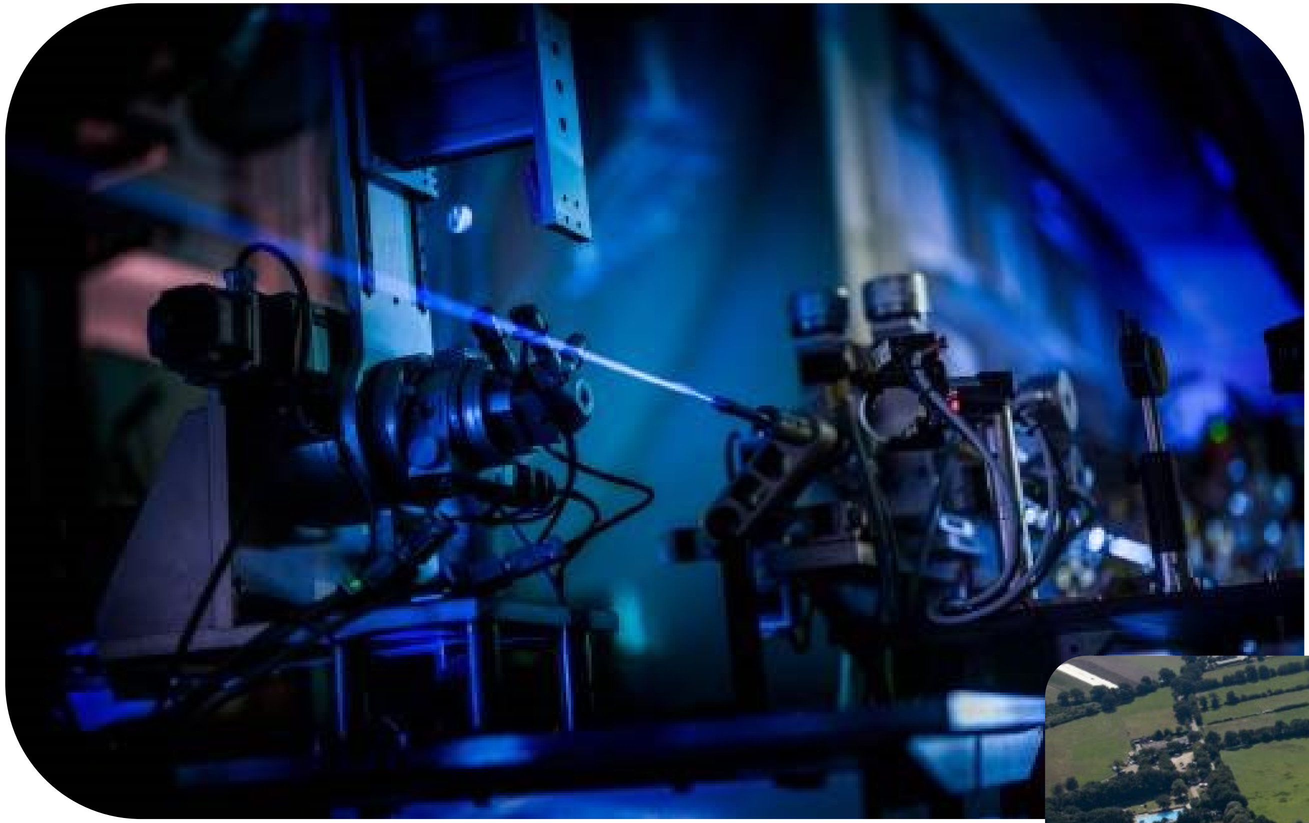
European XFEL—a leading new research facility

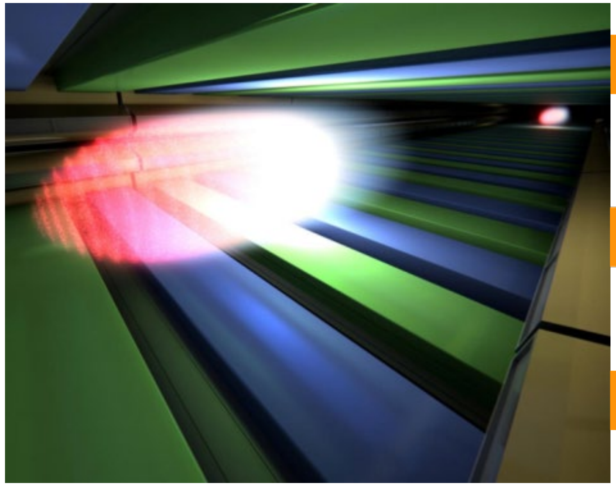


The European XFEL is a new research facility that uses high-intensity X-ray light to study the structure of matter.

- User facility with more than 400 employees (+250 from DESY)
- Location: Hamburg and Schenefeld, Germany
- September 2017 start of user operation

Schenefeld research campus on 14 August 2017

What can the European XFEL do?



<u>X-ray light</u>
See samples at atomic resolution

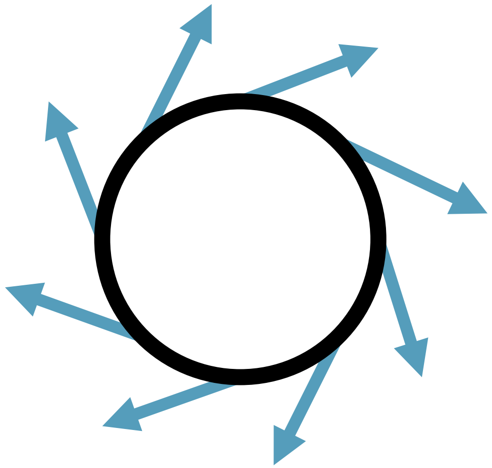
<u>Ultrashort flashes</u>
Film (bio-)chemical reactions

<u>Intense X-ray pulses</u>
Study single molecules or tiny crystals

Using X-rays to explore matter

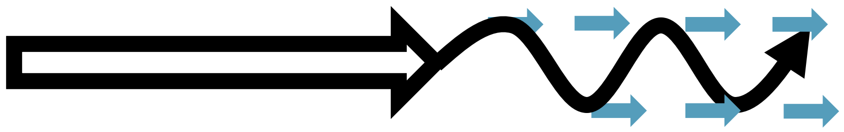
Synchrotrons

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



Free-Electron Lasers

- Electrons accelerated in a straight line and manipulated to generate light
- Light is coherent and intensely bright in very short pulses, showing objects in even more detail and revealing processes



About European XFEL

- Organized as a non-profit corporation in 2009 with the mission of design, construction, operation, and development of the free-electron laser

- Supported by 12 partner countries

- Total budget for construction (including commissioning)
  - 1.25 billion € at 2005 prices, about 140 M€ operating budget
  - 600 M€ contributed in cash, over 550 M€ as in-kind contributions (mainly manufacture of parts for the facility)

X-ray free-electron lasers worldwide

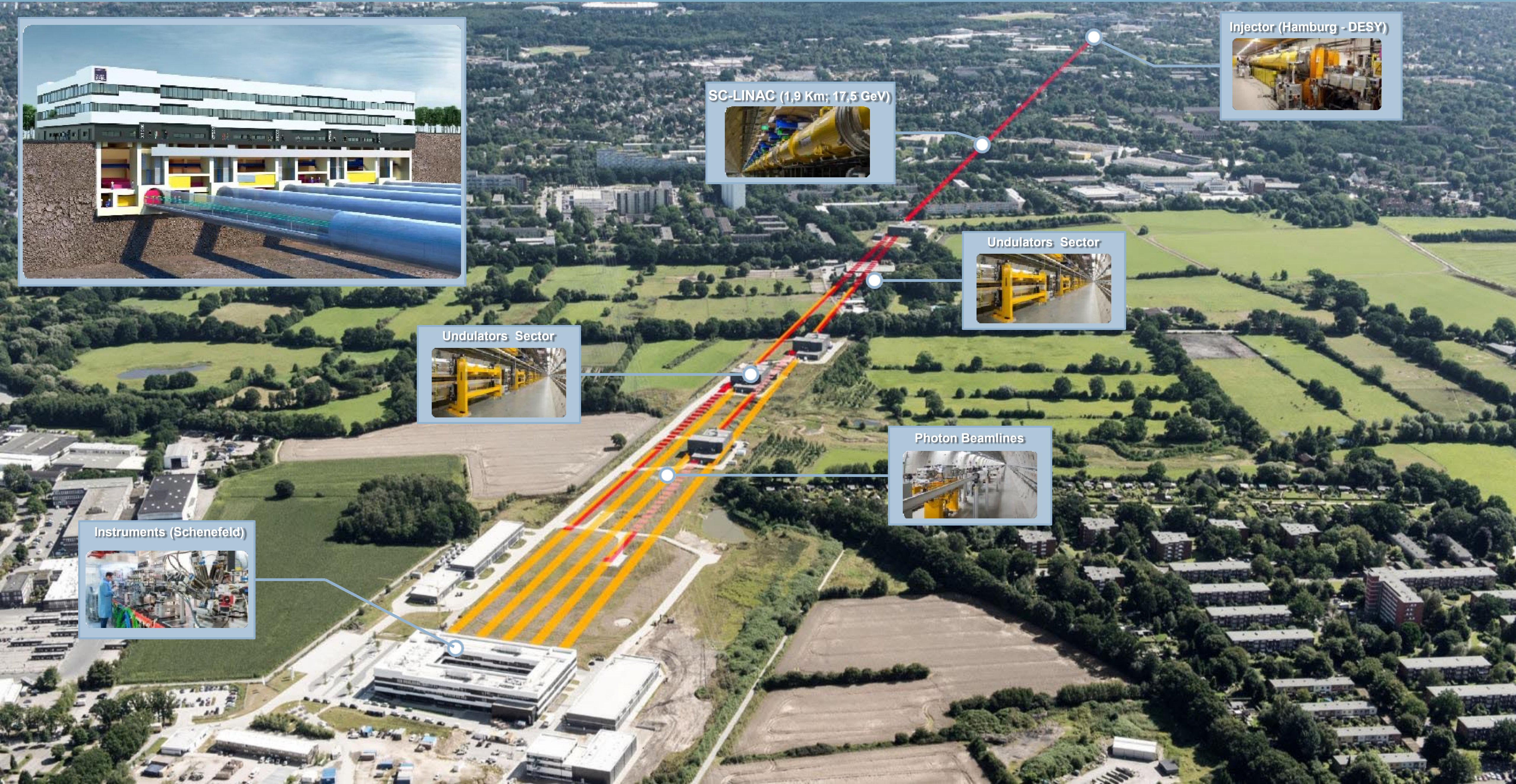
Project	LCLS (USA)	LCLS-II CuRF	LCLS-II SCRF	SACLA (Japan)	European XFEL	SwissFEL (CH)	PAL-XFEL (S. Korea)	SHINE (China)	FERMI (1)
Max. electron energy (GeV)	14.3	15	5.0	8.5	17.5	5.8	10	8	1.55
Wavelength range (nm)	0.1–4.6	0.05–5.0	0.25–5.0	0.06–0.3	0.05–4.7	0.1–7	0.06–10	0.05–3.1	4-100
Photons/pulse	~10^{12}	2 x 10^{13}	3 x10^{13} (soft X-rays)	2 x 10^{11}	~10^{12}	~5 x 10^{11}	10^{11}–10^{13}	10^{10}–10^{13}	10^{11}–10^{14}
Peak brilliance	2.7 x 10^{34} (with seeding)	2.7 x 10^{34} (with seeding)	1 x 10^{32}	1 x 10^{33}	5 x 10^{33}	1 x 10^{33}	1.3 x 10^{33}	1 x 10^{33}	10^{30}–10^{32}
Pulses/second	120	120	1 000 000	60	27 000	100	60	1 000 000	10-50
Date of first beam	2009	2019	2020	2011	2017	2016	2016	2025	2010

(1) Courtesy of Dr. Marco Peloi, Elettra

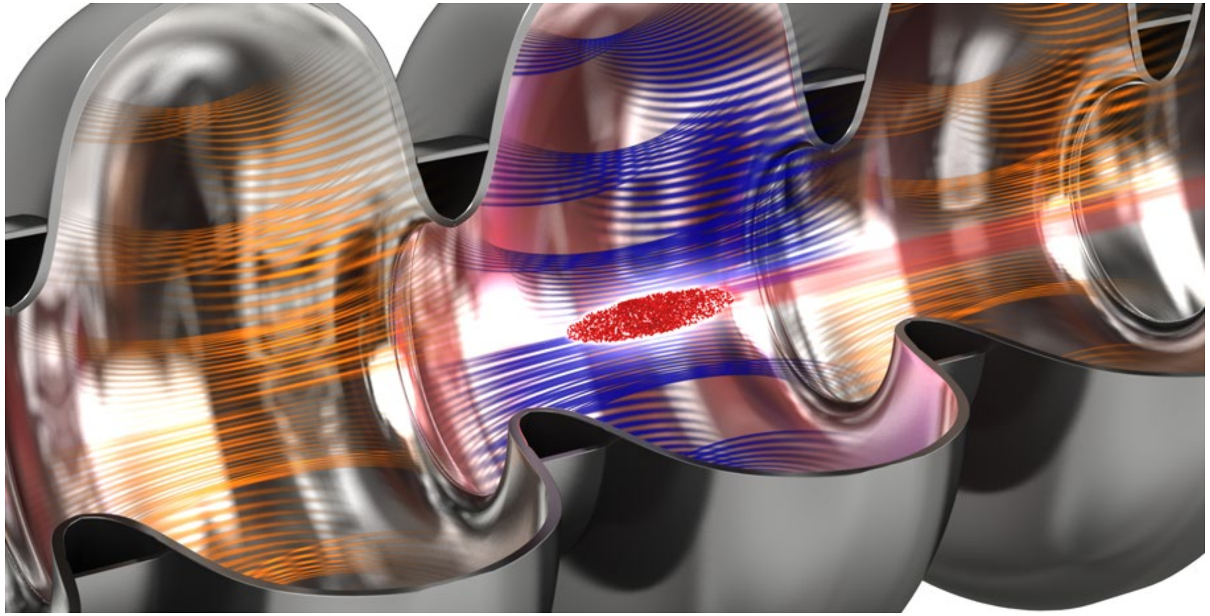
Outline

- General presentation of European XFEL
- Main description of the facility
- Highlights on typical technologies in the experimental hall
- Information about procurement procedures, hints on new internal procedures
- Technologies of interest

3.4 km from Injector to Experimental Hall.

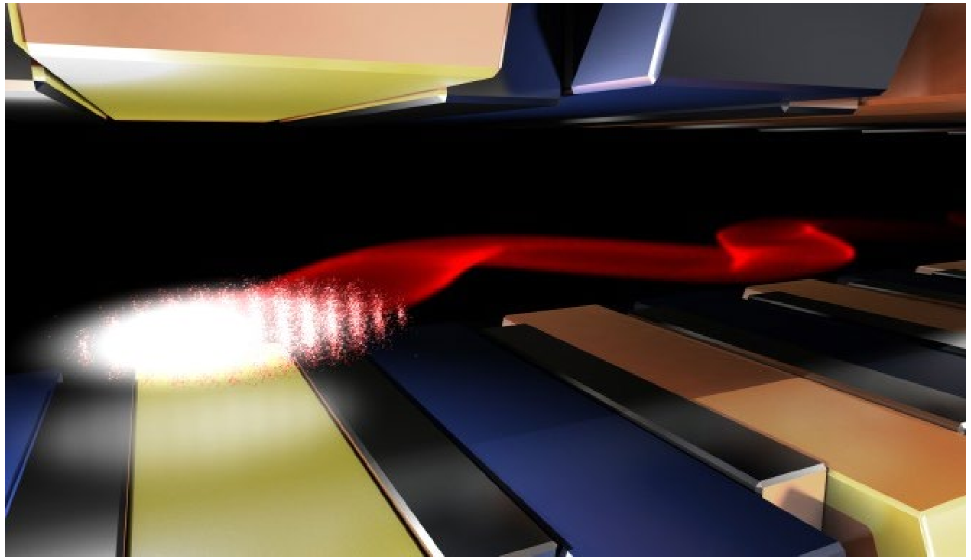


Accelerator: electrons at close to light speed

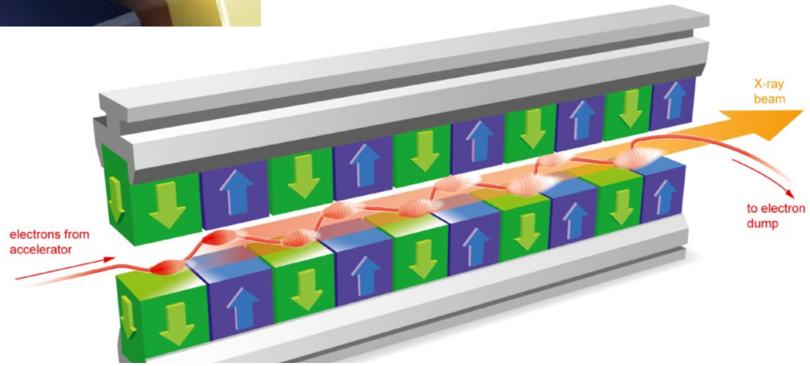


- Superconducting niobium cavities powered by intense radio frequency accelerate electrons
- Ninety-six accelerator modules over 1.7 km bring the electron bunch to near light speed and high energies

SASE (Self Amplified Spontaneous Emission) undulators: inducing electrons to emit X-ray light



- Alternating magnetic fields cause electrons to take “slalom” course
- Electrons release X-rays with each turn
- SASE process builds intense, laser-like flashes



The European X-Ray Free-Electron Laser **Technical design report**
https://xfelbau.desy.de/technical_information/tdr/tdr/

Outline

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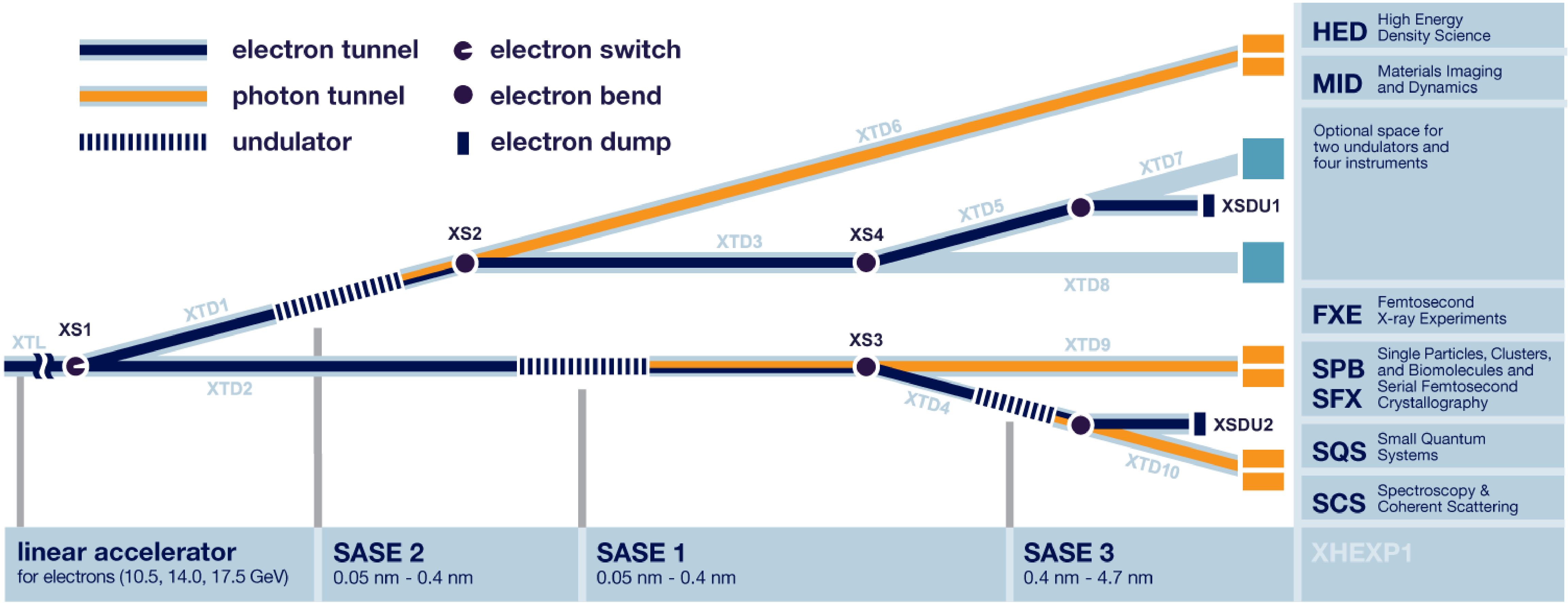
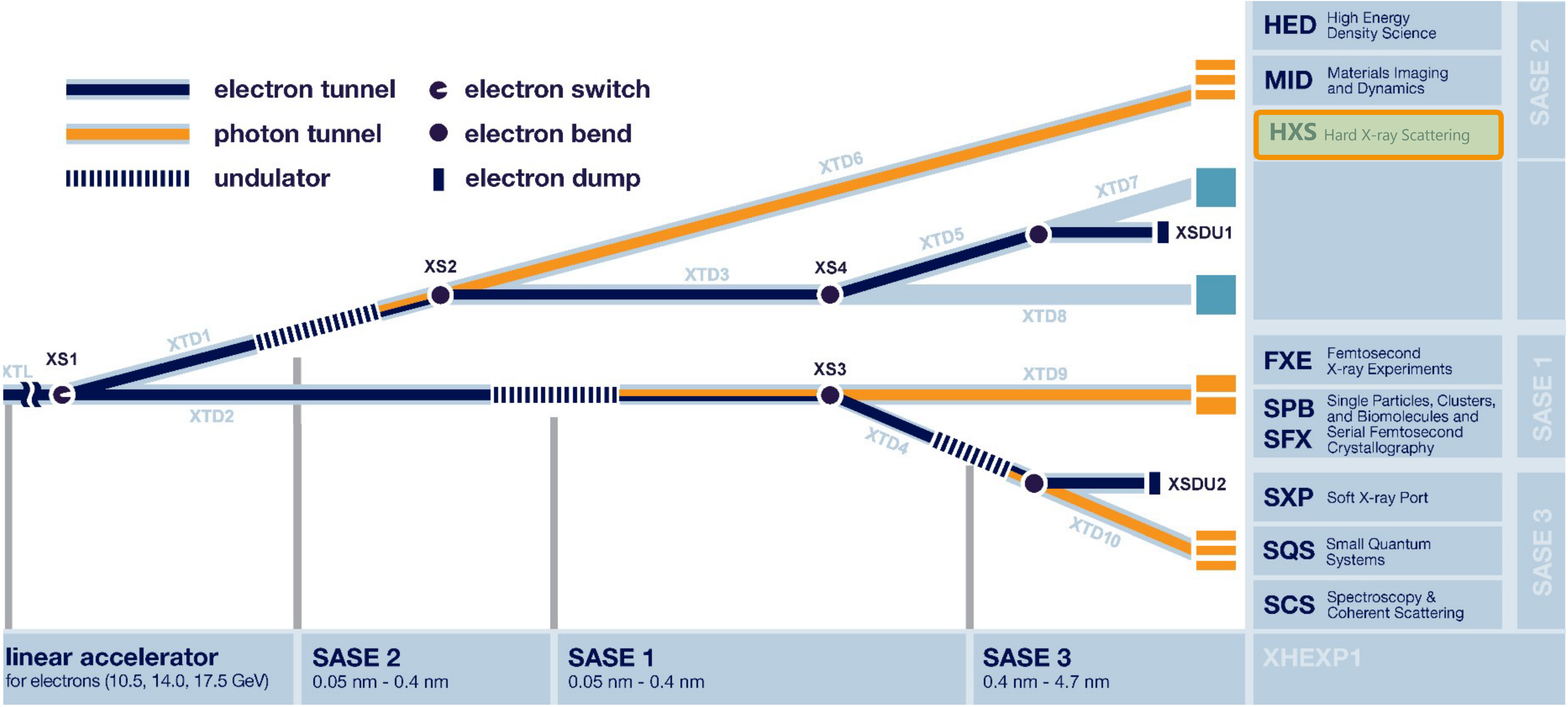
Beamline layout and experiment stations

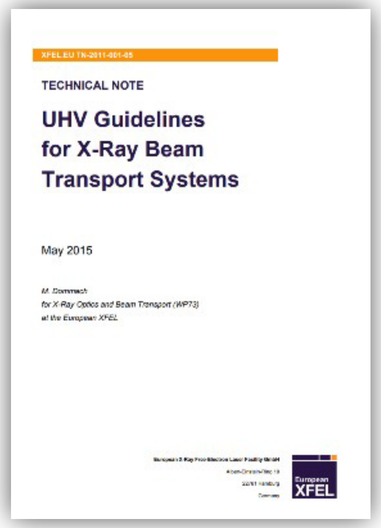


This decade: SASE2 Beamline 3rd port



Photon Beam Transport System

- According to XFEL UHV Guidelines.
- Outsourced manufacturing and cleaning.
- “Particle free“ specifications (ISO Class 5/6).
- Sectorization & Mobile clean tents.
- In-situ conditioning (specific cases): wet-cleaning, baking, plasma cleaning…
- Hundreds of meters beampipe (flanged and in-situ orbital-welded sectors)
- Standard vacuum components:
    - Pumping Stations
    - Beamline Pumping equipment (mechanical, SIP’s, NEG’s)
    - Controller for pumps, gauges…
    - Gauges, RGA‘s,…
- PLC Control system (racks, terminals, interfaces).
    - PLC terminals
    - Power supplies, connectors, cables
    - Controller for pumps, gauges…



XFEL.EU TN-2011-001-05

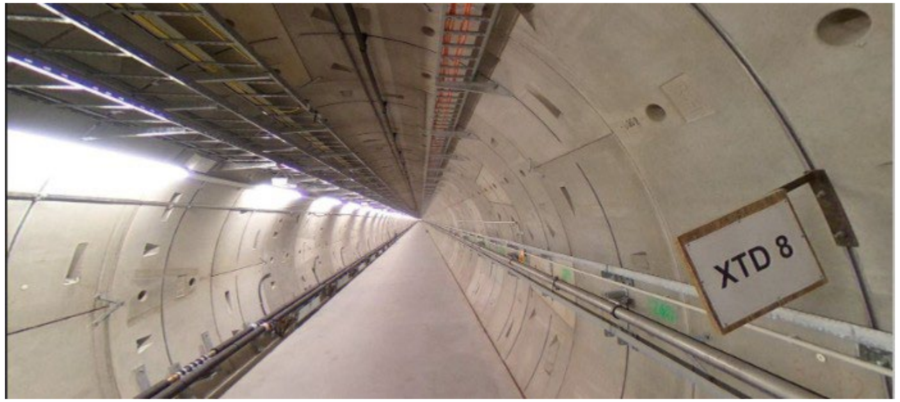
TECHNICAL NOTE

UHV Guidelines for X-Ray Beam Transport Systems

May 2015

M. Dommach
for X-Ray Optics and Beam Transport (WP73)
at the European XFEL

European XFEL



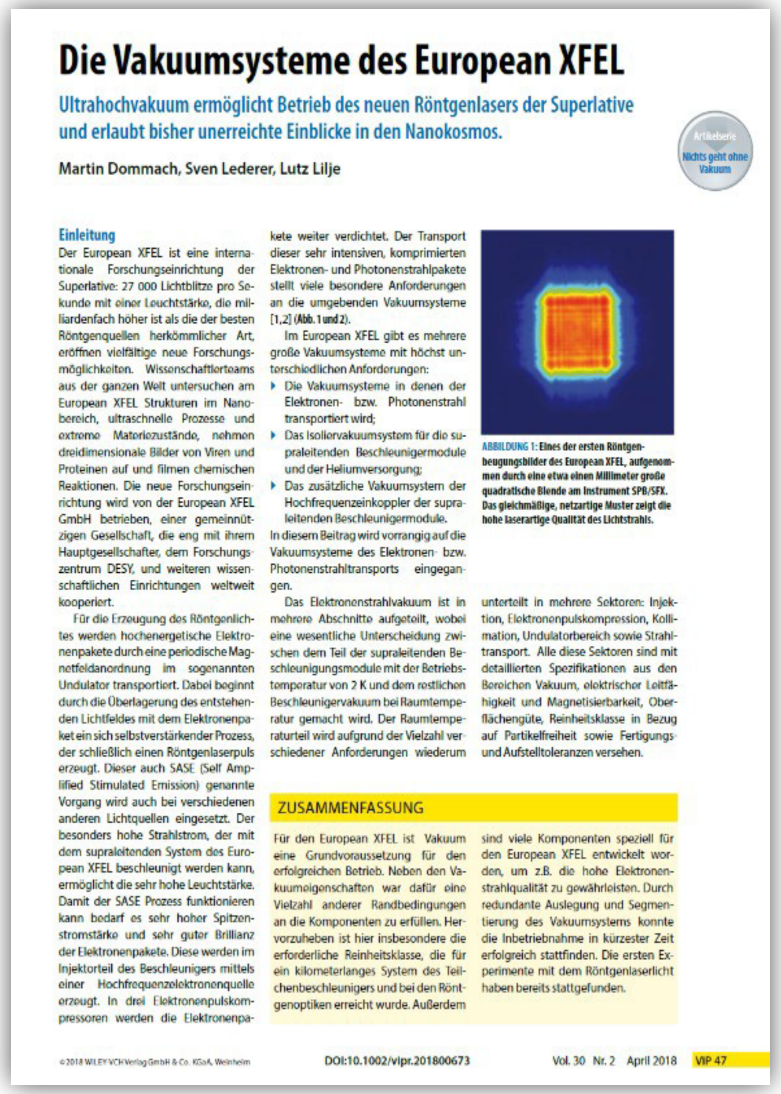
Some „sizing“ numbers for vacuum…

Construction phase (2011-2017)

- Accelerator warm vacuum system: 6 M€
- Accelerator cold vacuum system : 5 M€
- Photon beamlines (warm) vacuum system: 8 M€

Operation-related averaged procurement(*)

- Accelerator cold vacuum system: 250 k€/year
- Accelerator warm vacuum system: 500 k€/year
- Photon beamlines (warm) vacuum system: 600 k€/year



Die Vakuumsysteme des European XFEL

Ultrahochvakuum ermöglicht Betrieb des neuen Röntgenlasers der Superlative und erlaubt bisher unerreichte Einblicke in den Nanokosmos.

Artikelserie Nichts geht ohne Vakuum

Martin Dommach, Sven Lederer, Lutz Lilje

Einleitung

Der European XFEL ist eine internationale Forschungseinrichtung der Superlative: 27 000 Lichtblitze pro Sekunde mit einer Leuchtstärke, die milliardenfach höher ist als die der besten Röntgenquellen herkömmlicher Art, eröffnen vielfältige neue Forschungsmöglichkeiten. Wissenschaftlerteams aus der ganzen Welt untersuchen am European XFEL Strukturen im Nanobereich, ultraschnelle Prozesse und extreme Materiezustände, nehmen dreidimensionale Bilder von Viren und Proteinen auf und filmen chemischen Reaktionen. Die neue Forschungseinrichtung wird von der European XFEL GmbH betrieben, einer gemeinnützigen Gesellschaft, die eng mit ihrem Hauptgesellschafter, dem Forschungszentrum DESY, und weiteren wissenschaftlichen Einrichtungen weltweit kooperiert.

Für die Erzeugung des Röntgenlichtes werden hochenergetische Elektronenpakete durch eine periodische Magnetfeldanordnung im sogenannten Undulator transportiert. Dabei beginnt durch die Überlagerung des entstehenden Lichtfeldes mit dem Elektronenpaket ein sich selbstverstärkender Prozess, der schließlich einen Röntgenlaserpuls erzeugt. Dieser auch SASE (Self Amplified Stimulated Emission) genannte Vorgang wird auch bei verschiedenen anderen Lichtquellen eingesetzt. Der besonders hohe Strahlstrom, der mit dem supraleitenden System des European XFEL beschleunigt werden kann, ermöglicht die sehr hohe Leuchtstärke. Damit der SASE Prozess funktionieren kann bedarf es sehr hoher Spitzenstromstärke und sehr guter Brillianz der Elektronenpakete. Diese werden im Injektorteil des Beschleunigers mittels einer Hochfrequenzelektronenquelle erzeugt. In drei Elektronenpulskompressoren werden die Elektronenpakete weiter verdichtet. Der Transport dieser sehr intensiven, komprimierten Elektronen- und Photonenstrahlpakete stellt viele besondere Anforderungen an die umgebenden Vakuumsysteme [1,2] (Abb. 1 und 2).

Im European XFEL gibt es mehrere große Vakuumsysteme mit höchst unterschiedlichen Anforderungen:

- Die Vakuumsysteme in denen der Elektronen- bzw. Photonenstrahl transportiert wird;
- Das Isoliervakuumsystem für die supraleitenden Beschleunigermodule und der Heliumversorgung;
- Das zusätzliche Vakuumsystem der Hochfrequenzeinkoppler der supraleitenden Beschleunigermodule.

In diesem Beitrag wird vorrangig auf die Vakuumsysteme des Elektronen- bzw. Photonenstrahltransports eingegangen.

Das Elektronenstrahlvakuum ist in mehrere Abschnitte aufgeteilt, wobei eine wesentliche Unterscheidung zwischen dem Teil der supraleitenden Beschleunigungsmodule mit der Betriebstemperatur von 2 K und dem restlichen Beschleunigervakuum bei Raumtemperatur gemacht wird. Der Raumtemperaturteil wird aufgrund der Vielzahl verschiedener Anforderungen wiederum unterteilt in mehrere Sektoren: Injektion, Elektronenpulskompression, Kollimation, Undulatorbereich sowie Strahltransport. Alle diese Sektoren sind mit detaillierten Spezifikationen aus den Bereichen Vakuum, elektrischer Leitfähigkeit und Magnetisierbarkeit, Oberflächengüte, Reinheitsklasse in Bezug auf Partikelfreiheit sowie Fertigungs- und Aufstelltoleranzen versehen.

ABBILDUNG 1: **Eines der ersten Röntgenbeugungsbilder des European XFEL, aufgenommen durch eine etwa einen Millimeter große quadratische Blende am Instrument SPB/SFX. Das gleichmäßige, netzartige Muster zeigt die hohe laserartige Qualität des Lichtstrahls.**

ZUSAMMENFASSUNG

Für den European XFEL ist Vakuum eine Grundvoraussetzung für den erfolgreichen Betrieb. Neben den Vakuumeigenschaften war dafür eine Vielzahl anderer Randbedingungen an die Komponenten zu erfüllen. Hervorzuheben ist hier insbesondere die erforderliche Reinheitsklasse, die für ein kilometerlanges System des Teilchenbeschleunigers und bei den Röntgenoptiken erreicht wurde. Außerdem sind viele Komponenten speziell für den European XFEL entwickelt worden, um z.B. die hohe Elektronenstrahlqualität zu gewährleisten. Durch redundante Auslegung und Segmentierung des Vakuumsystems konnte die Inbetriebnahme in kürzester Zeit erfolgreich stattfinden. Die ersten Experimente mit dem Röntgenlaserlicht haben bereits stattgefunden.

DOI:10.1002/vipr.201800673 Vol. 30 Nr. 2 April 2018 ViP 47

https://onlinelibrary.wiley.com/doi/full/10.1002/vipr.201800673

(*)Estimations derived from the first years of operation

Hybrid permanent magnet undulators at European XFEL

Table 1
Specifications for the undulator segments of the EuXFEL.

The operational ranges for gap and K parameter match user requirements (Altarelli *et al.*, 2006). Only inside are all specifications strictly fulfilled. Magnetic tuning was always performed at the tuning gap to limit gap dependence of magnetic properties, see discussion of Fig. 4.

	SASE1 / SASE2	SASE3
Undulator type	U40	U68
Period length (mm)	40	68
Segment length (m)	5	5
Total number of poles	248	146
Magnetically active poles	246	144
Number of ending poles	3	3
Operational gap range (mm)	10–20	10–25
Operational K-parameter range	1.65–3.9	4–9
Maximum peak field @ 10 mm (T)	1.11	1.66
Tuning gap (mm)	14	16
Maximum gap (mm)	200	200
Maximum phase jitter (°)	≤ 8	≤ 8
Maximum 1st B_y field integral (T mm)	± 0.15	± 0.15
Maximum 1st B_x field integral (T mm)	± 0.15	± 0.15
RMS of 2nd B_y integral (T mm^2)	<100	<210
RMS of 2nd B_x integral (T mm^2)	<100	<100
Radiation wavelength range (nm)	0.05–0.4	0.4–5.2
Number of segments in system	35	21
System length (m)	205	121

S. Abeghyan et al., J. Synchrotron Rad. (2019). 26, 302–310

Components for SCU development at EuXFEL

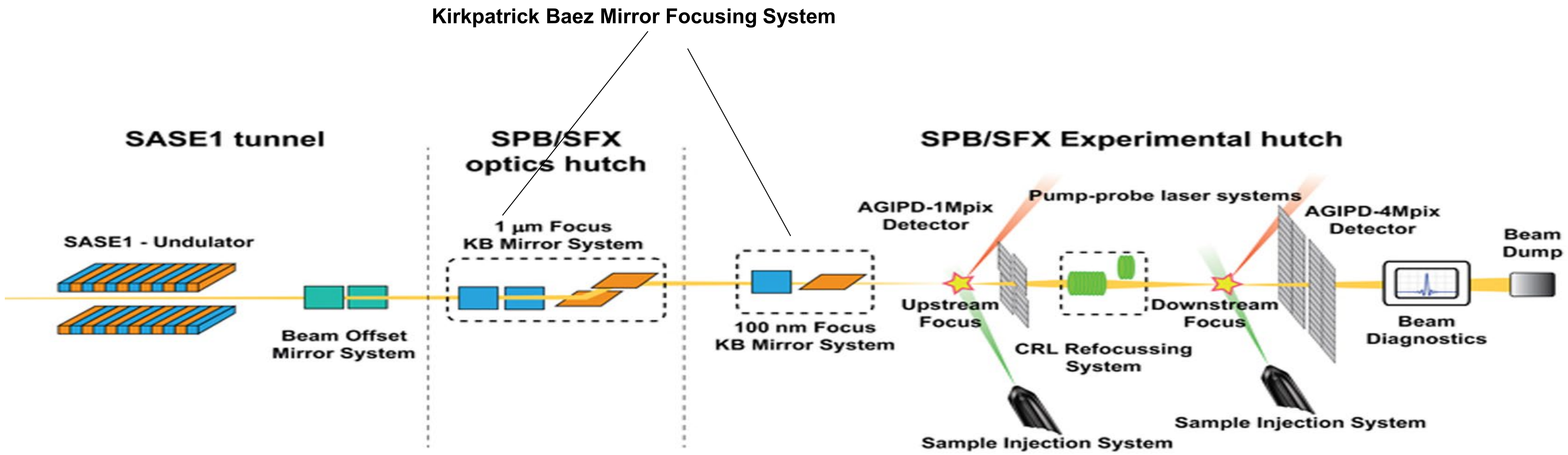
- Part of the SCU module:
  - Cryocoolers
  - Power supplies
    - ► Correctors and phase shifter: ±10 A, 10 V
    - ► Main coils: 400-1000 A, 10-20 V

    as small as possible to fit in the tunnel
  - Vacuum pumps
  - CAM movers
- Elements for intersections:
  - Quadrupoles, Quadrupole movers, Air coils
  - Granite stone, alignment mechanism
  - Absorbers, BPMs, BLMs
  - Phase shifters
  - RF bellows, RF valve
- SUNDAE1/2
  - CuBe wires
  - Vacuum pumps
  - Hall probes + readout and current source
  - Temperature sensors and monitors
  - In vacuum (UHV) motors and linear stages
  - …
- Advanced SCU coils
  - NbTi wires, HTS tapes
  - Precisely machined iron few tenths μm
  - Epoxy, kapton
  - …

SPB/SFX Instrument

https://www.xfel.eu/facility/instruments/spb_sfx/science_programme/index

- Diffractive imaging of micrometre-scale and smaller objects, at atomic or near-atomic resolution.
- Structural dynamics on the millisecond to femtosecond timescale.
- It consists of two experiment endstations (upstream and downstream),



SPB/SFX Instrument

https://www.xfel.eu/facility/instruments/spb_sfx/science_programme/index

MHE	Micron horizontal elliptical KB
Deflection	Horizontal (negative x)
Source—optic (centre) distance	894.779 m
Optic (centre) focus distance	24.005 m
Saggital radius (minimum)	10 km

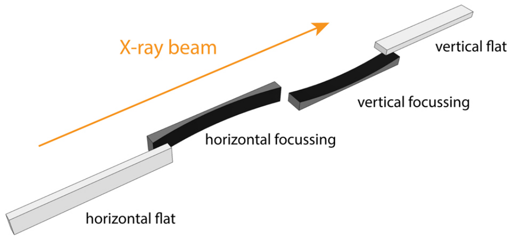
Controlled motion (relative to incident beam)	Minimum	Maximum	Resolution
X	−2 mm	+10 mm	<1 μm
Y (coating selection)	−15 mm	+15 mm	<1 μm
θ_y (pitch)	−0.5 mrad	+5.5 mrad	<20 nrad

Kirkpatrick Baez Mirror Focusing System

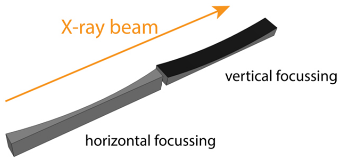
NHE	Nanometer horizontal elliptical KB
Deflection	Horizontal (positive x)
Source—optic (centre) distance	915.484 m
Optic (centre) focus distance	3.3 m
Saggital radius (minimum)	10 km

Controlled motion (relative to incident beam)	Minimum	Maximum	Resolution
X	−10 mm	+5 mm	<1 μm
Y (coating selection)	−15 mm	+15 mm	<1 μm
Z (astigmatism correction)	−5 mm	+5 mm	<1 μm
θ_y (pitch)	−0.5 mrad	+5.5 mrad	<20 nrad

Micron KB mirror system



Nano KB mirror system

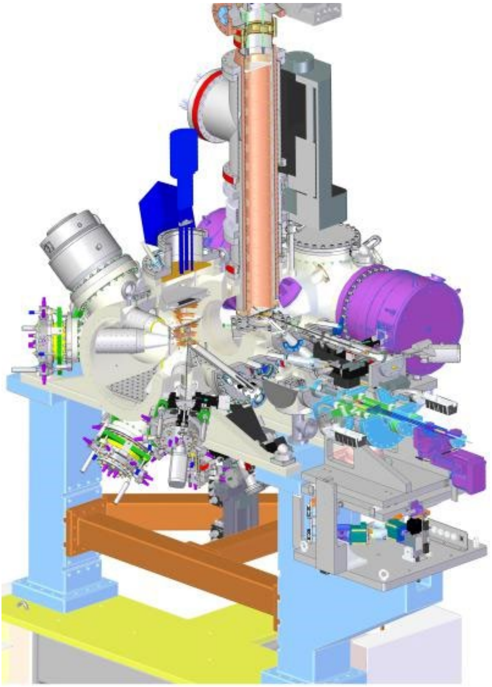


J. Opt. 18 (2016) 074011
https://iopscience.iop.org/article/10.1088/2040-8978/18/7/074011

SQS Instrument

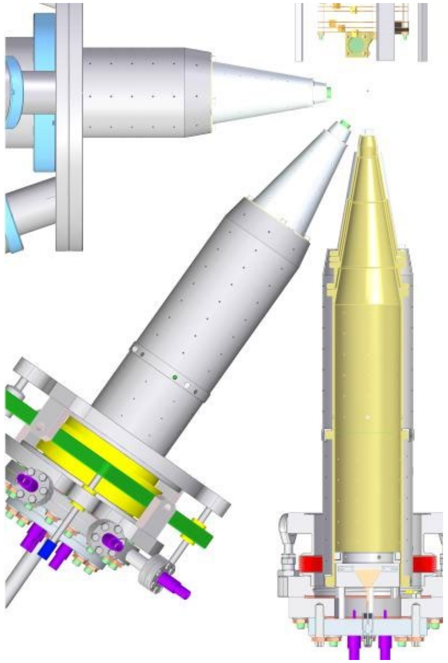
https://www.xfel.eu/facility/instruments/sqs/index_eng.html

Investigations of fundamental processes of light-matter interaction in the soft X-ray wavelength regime.

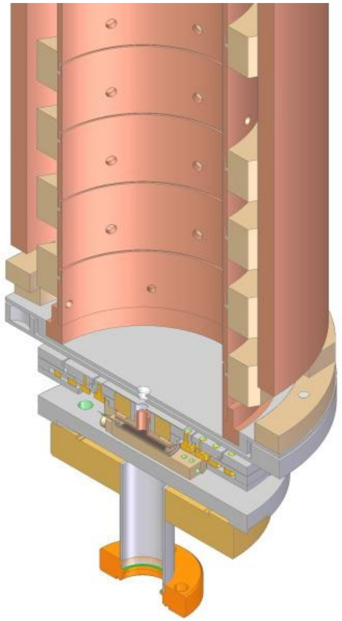


Atomic-like Quantum Systems (AQS) quantum systems, i.e. free atoms or small molecules.

The alignment of the AQS chamber with respect to the FEL beam is realized with a set-up enabling translation (50 mm) and rotational movements of the vacuum chamber with a precision of less than 0.5 μm.



Electron Time-Of-Flight (eTOF)
In combination of fast digitizer, (till 4.5 MHz)
Detector MCP, 450 ps timing resolution

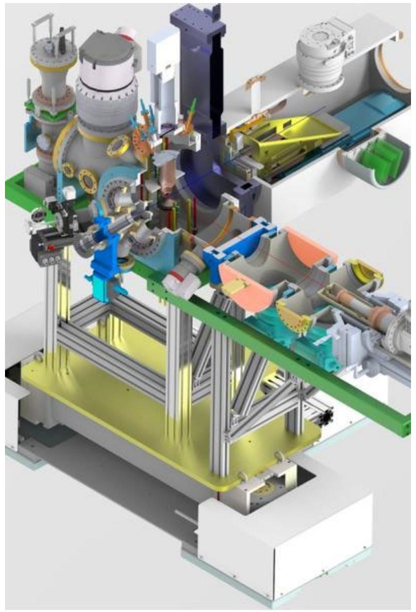


Magnetic Bottle Electron Spectrometer (MBES)
Time of flight spectroscopy

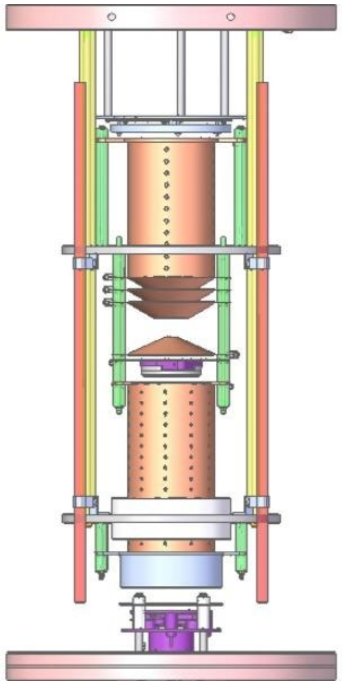
SQS Instrument

https://www.xfel.eu/facility/instruments/sqs/index_eng.html

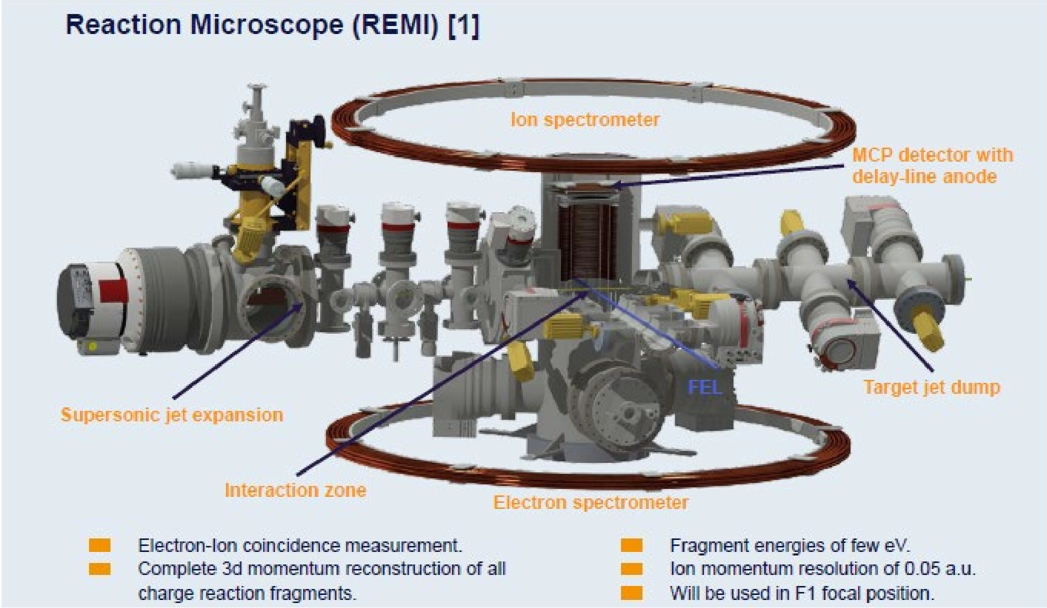
- Investigations of fundamental processes of light-matter interaction in the soft X-ray wavelength regime.



Nano-sized Quantum Systems (NQS) Nanoparticle The vacuum conditions in the NQS chamber are mainly limited by the imaging detector and are at best about 10^{-10} mbar



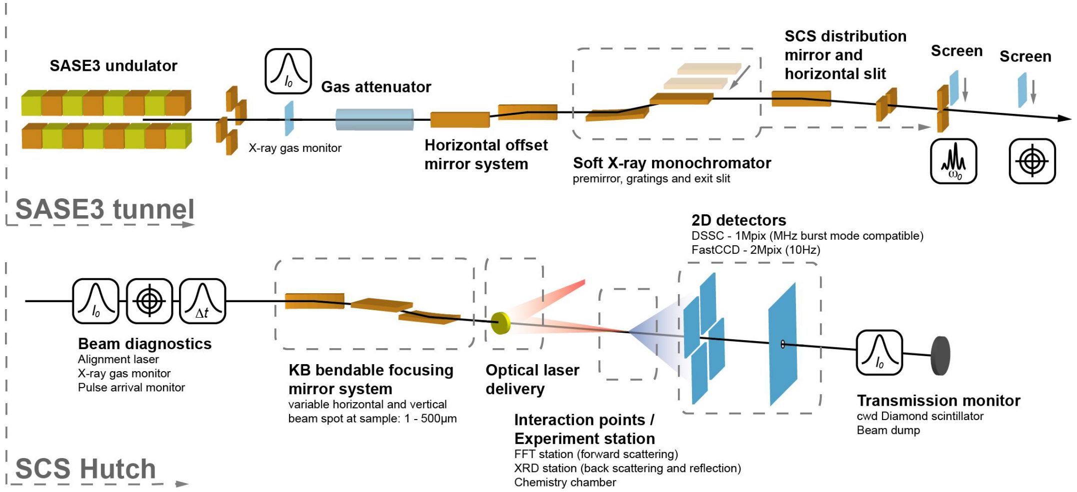
Ion Time-Of-Flight (iTOF- Wiley-McLaren design) Velocity Map Imaging (VMI) spectrometer



A Reaction Microscope (REMI) ion and electron momentum imaging experiments in the gas phase: a three-stage supersonic gas jet four piezo-controlled apertures, nozzle 5 µm to 300 µm, temperatures from 5 K to 450 K

SCS Instrument

https://www.xfel.eu/facility/instruments/scs/index_eng.html



- Enables time-resolved experiments to unravel the electronic and structural properties of complex materials, molecules, and nanostructures in their fundamental space-time dimensions.

- The SCS instrumentation is equipped with:
  - the FFT experiment station (forward-scattering and transmission geometries)
  - the XRD experiment station (back- scattering and reflection geometries).
  - 2D array detectors, the 1MPix DSSC detector (4.5 MHz rep rate) and the 2Mpix FastCCD detector (10Hz), for coherent x-ray diffraction experiments
  - A high-resolution Resonant Inelastic X-ray Scattering (RIXS) spectrometer
  - a chemistry chamber station for liquid jets will be available in addition to the XRD experiment station.

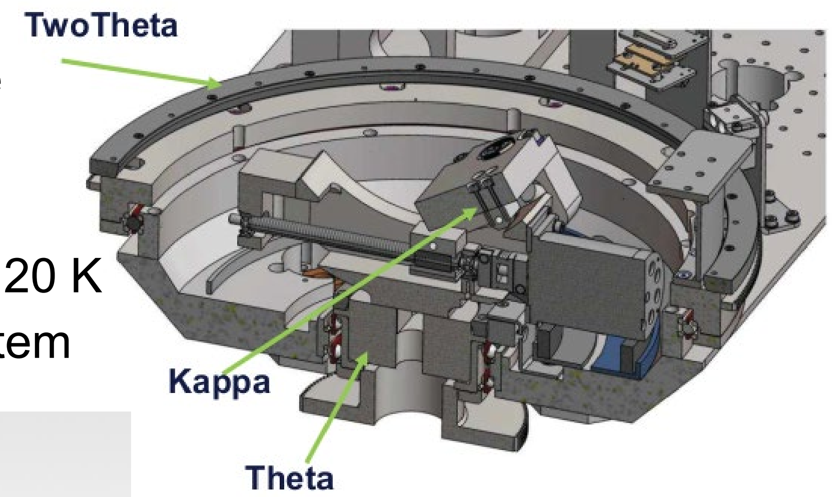
Parameter	Current Value
Photon energy	0.5 keV – 3.0 keV
X-ray pulse duration	10-25 fs fwhm
X-ray pulse stretching (Expected durations based on Monochromator)	80-150 fs (mono HR) 30-50 fs (mono LR)
X-ray polarization	Linear horizontal (π-polarization) Linear vertical and circular polarizations may become available during 2022
X-ray focal spot size at sample	5 μm (hor & ver) tunable up to 500 μm
Mono resolving power	10.000 (HR) 3.000 (LR)
Photon energy hRIXS	0.5 keV – 1.4 keV
Combined resolving power (Monochromator & hRIXS)	Up to 10.000

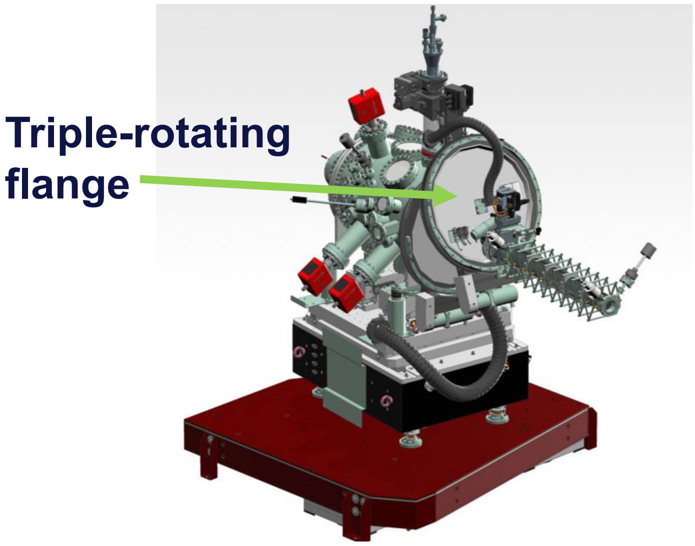
SCS Instrument

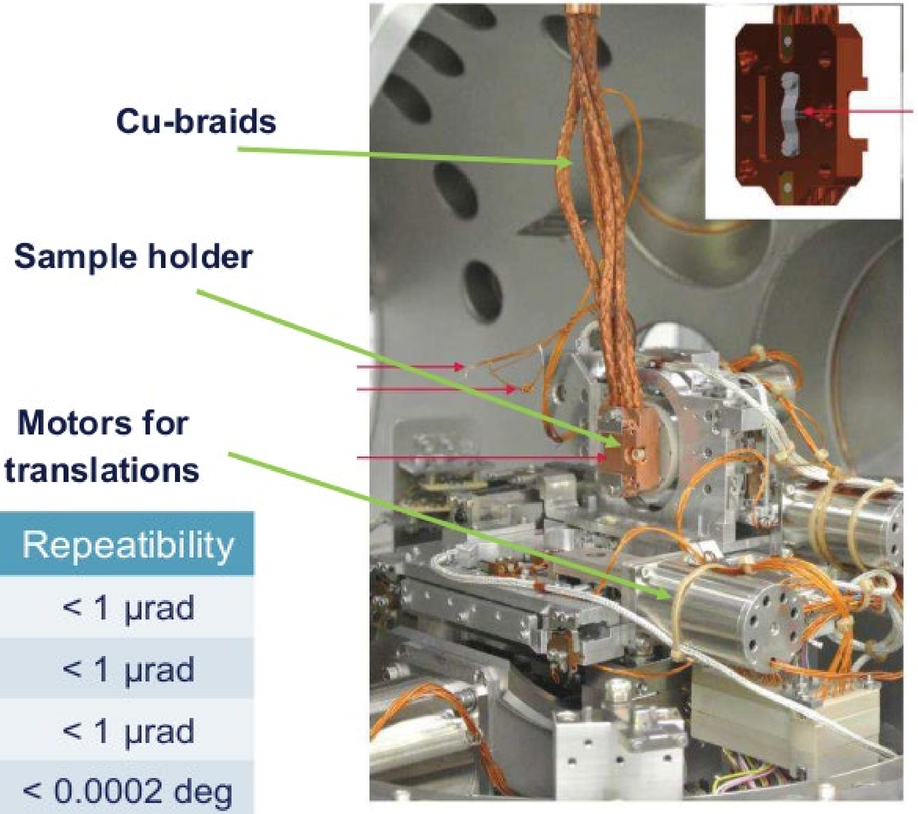
https://www.xfel.eu/facility/instruments/scs/index_eng.html

X-ray diffractormeter Inner Mechanics

- Triple-rotating flange to change scattering angle
  - Sample: 6 DOF
  - UHV (p< 10-9mbar)
  - Temperatures: RT – 20 K
  - Sample transfer system







Motion	Range	Repeatibility
TwoTheta	± 180 deg	< 1 µrad
Theta	± 180 deg	< 1 µrad
Kappa	± 30 deg	< 1 µrad
Azimuth	± 90 deg	< 0.0002 deg
X	± 5 mm	0.5 µm
Y	± 5 mm	0.5 µm
Z	± 5 mm	0.5 µm

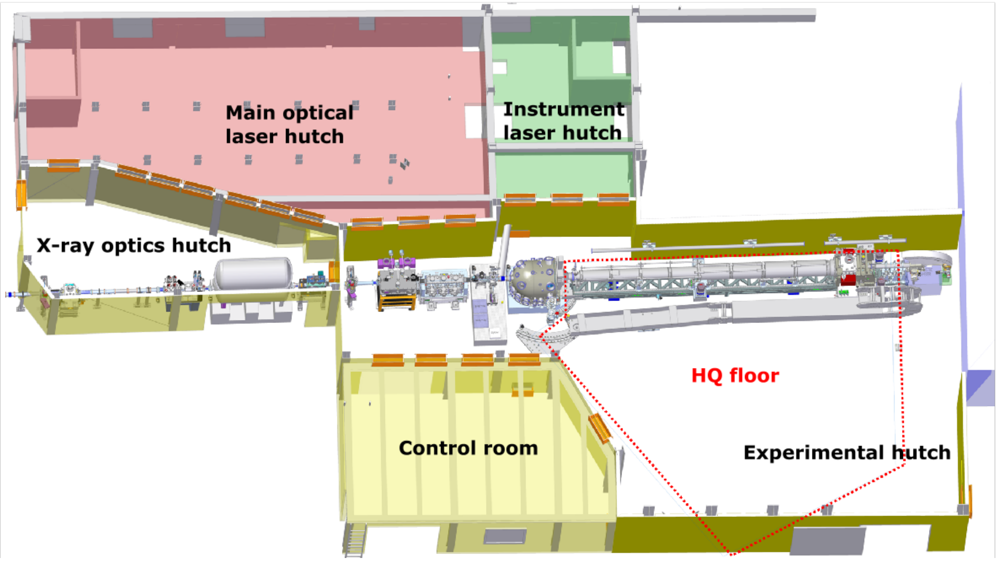
https://www.xfel.eu/sites/sites_custom/site_xfel/content/e35165/e46561/e46895/e146931/xfel_file146932/WebinarhRIXS_2021Oct21_final_eng.pdf

MID Instrument

https://www.xfel.eu/facility/instruments/mid/index_eng.html

- The scope of the MID instrument are material science experiments. The scientific applications reach from condensed matter physics, studying for example glass formation and magnetism, to soft and biological material, such as colloids, cells and viruses.

- Special Optics:
  - 2 monochromators (Si111 and Si220)
  - 2 compound refractive lens (CRL) transfocator units
  - Split and delay line
  - High-energy Laue monochromator (optional)
  - Mirror in experiment hutch (for grazing incidence liquid scattering)



- Equipment:
  - Multipurpose chamber
  - SAXS/WAXS geometries with long horizontal detector arm
  - Small vertical WAXS setup
  - Single-pulse X-ray diagnostics
  - Different detector systems (AGIPD, FastCCD)
  - Optical pump laser source

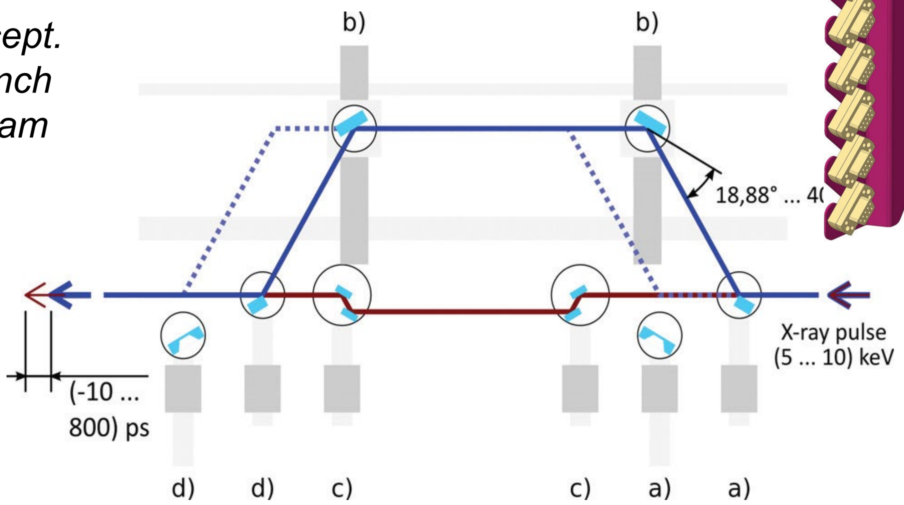
MID Instrument

https://www.xfel.eu/facility/instruments/mid/index_eng.html

Split and delay line (SDL)

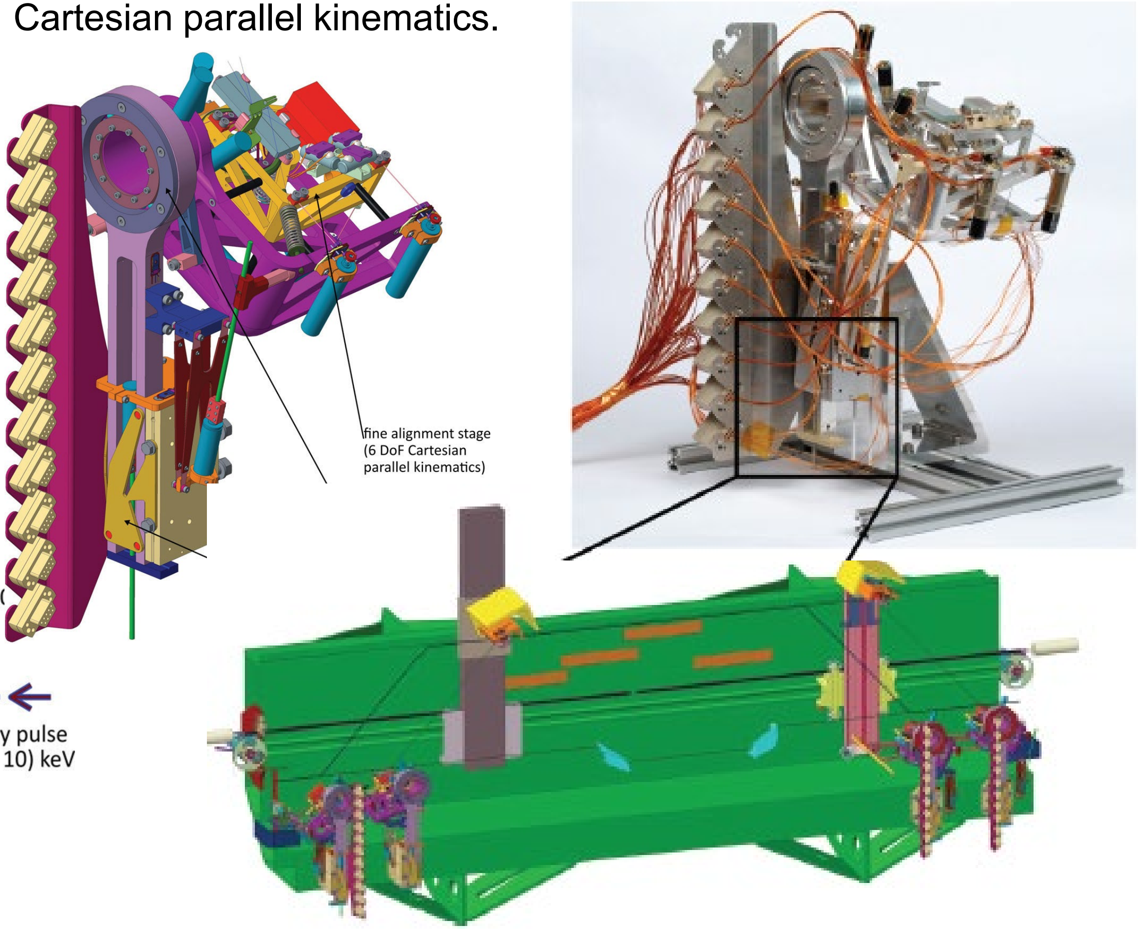
- Separate positioning stages mounted to the optical bench for all optical elements
- Demands:
  - Providing **a fast long-range travel** – in some cases of up to 1000 mm
  - Allowing a precise alignment with a **resolution in the range of single nanometre and tens of nanoradians**

Conceptual view of the SDL indicating the mechanical concept. a) beam splitters; b) upper branch crystals; c) channel cuts; d) beam merger.



Positioning stage for the beam splitter.

- Serial combination of coarse motion axes with a fine alignment stage
- The fine alignment stage is implemented as a 6 DoF Cartesian parallel kinematics.



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HED Instrument

https://www.xfel.eu/facility/instruments/hed/index_eng.html

- Combining hard X-ray FEL radiation and the capability to apply extreme conditions of pressure, temperature or electric field using the FEL, high energy optical lasers, or pulsed magnets.

https://www.xfel.eu/virtualtour/#node42

- Diamond Anvil Cells (available)
  dynamic DAC; pulsed laser heated DAC; double-stage DAC
- Powerful optical lasers (2020-2021)
  100 J 15 ns 10 Hz; 400 TW 30 fs 10 Hz
- XFEL split&delay line (2021) x-ray pump-probe, 0-20 ps delay
- 60 T pulsed magnetic field coil (2021)
  cryogenic sample environment, superconductivity

The goal will be to achieve pressures of 1 TPa and temperatures up to 10 000 K using 5 ns, frequency-doubled 50 J pulses from the DiPOLE100X laser focused to 100 µm

Additional laser

	Abbreviation	Repetition [Hz]	Wavelength [nm]	Pulse energy	Pulse duration	Max. power or B field	Remarks
Pump–probe laser	PP-OL	4.5 M	~ 800	0.2 mJ / 4.5 MHz 5 mJ / 200 kHz	15–00 fs	10–250 GW	NOPA
		200 k	~ 1030	100 mJ	0.8 ps or 0.5 ns	~ 100 GW	Yb amplifier
High-energy laser	HE-OL	1–10	1057 or 1064	~ 150 J/ω ~ 100 J/2ω	2–20 ns	~ 75 GW	Nd-glass or Nd-YAG
		< 1	528 or 532	> kJ	2–20 ns	> 500 GW	Beyond 2016
Ultrahigh-intensity laser	UHI-OL	10	~ 800	3–5 J	~ 30 fs	~ 100 TW	Ti-sapphire
		~ 1		10–30 J	~ 30 fs	~ PW	Beyond 2016
High-field pulsed magnet	HFM	0.1 – ~ 0.01	—	~ 30 kJ	> 100 µs	> 30 T	—
		< 0.01	—	> MJ	—	TBD	Beyond 2016

Campus constructions

Plans for the other major part of the European XFEL:

- An accommodation service, the facility's 59-room Guest House - were finalized and it is in operation.
- …and a 940 m^2 building for tuning and measuring the facility's X-ray generating undulators was just finalized.
- A visitor centre, including school laboratories and an auditorium, was approved by the European XFEL Council in November 2018. It will also receive significant funding from Schleswig-Holstein.
- A building housing infrastructure for the HED instrument as well as offices for staff members and users has been finalized.