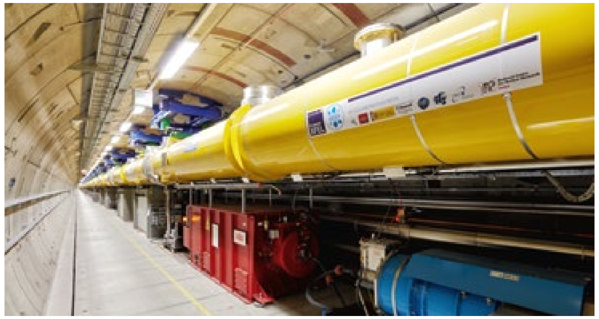
Free-Electron Lasers: Delivering brilliant science

Breakthroughs from the last 10 years

FELs OF EUROPE

Lighting up our world: free-electron lasers

Free-electron lasers (FELs) enable us to probe and explore the details of the world and universe around us with unprecedented precision. For the past 15 years X-ray free-electron lasers have shed light on the smallest structural details and most fleeting of reactions, generating insights that continually push at the frontier of our knowledge and light up entirely new fields of science. This builds on over 40 years of free-electron laser experience in the infrared and ultraviolet spectrum which, alongside the more recently developed X-ray sources, continue to deliver cutting edge science today and into the future.



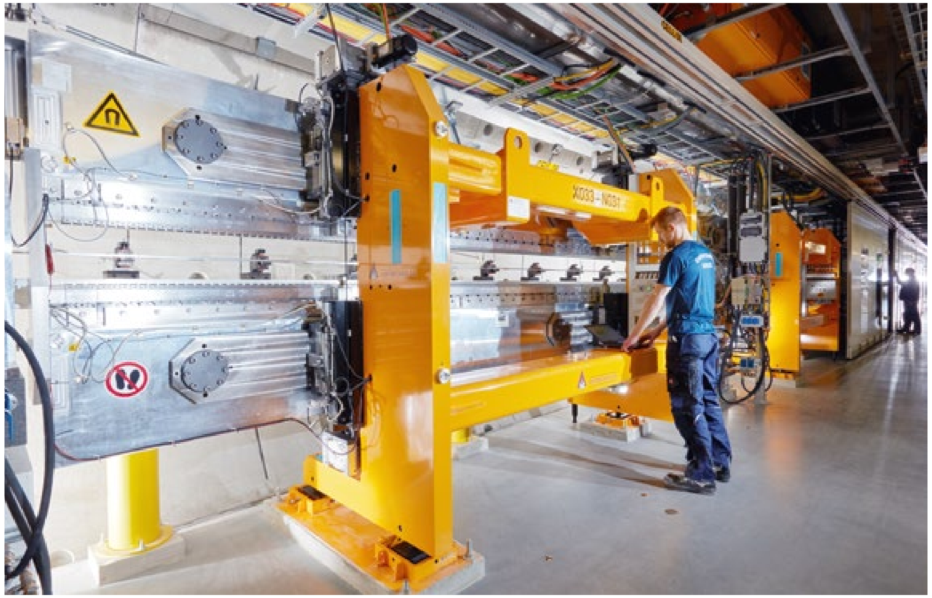
Free-electron lasers are powered by high performance electron accelerators and are usually built in dedicated tunnels. The European XFEL, for example, is located underground where a 1.7 km long accelerator brings electrons to the high energies necessary for X-ray generation.

How it works

Using cutting edge technology, extremely short and intense electron bunches are accelerated to high energies near the speed of light. The electrons are then directed through special magnets called undulators. In the process, the particles emit radiation that is increasingly amplified until an extremely short and intense flash of light is finally created. This results in ultrashort laser-like light flashes with a brilliance a billion times higher than the best sources previously available, and with colours ranging from the infrared to X-ray spectral regions.

What it can do

Free-electron lasers excel in peak power, tunability, coherence and ultra-short pulse duration. This allows researchers to investigate dynamical processes in materials and molecules with unprecedented precision. X-ray lasers enable atomic spatial resolution and the ability to penetrate samples. Longer wavelength extreme ultraviolet, infrared and terahertz free-electron also offer high spatial and temporal resolution and excel in domains such as molecular and surface science.



Extremely precise periodic arrangements of magnets called undulators steer electrons into a slalom course. This process causes electrons to emit light in the form of X-rays or infrared radiation. Short but intense pulses of electrons combined with long lengths of magnets result in exponential gain as the electrons continue down the magnetic structures, generating the brilliant flashes unique to FELs for use in experiments.

The brilliant light pulses allow scientists to …

… decipher the structure of many more biomolecules and cellular components than previously possible.

… study fast biochemical processes, an important basis for the development of new medications and therapies.

… better understand many chemical processes such as catalysis, which plays an important role in nature and in the manufacturing of most chemical substances produced in industry.

… study new processes and materials, with a wide range of applications from improved harnessing of solar energy to higher density data storage.

… analyse the properties of various materials in order to develop completely new materials with revolutionary characteristics.

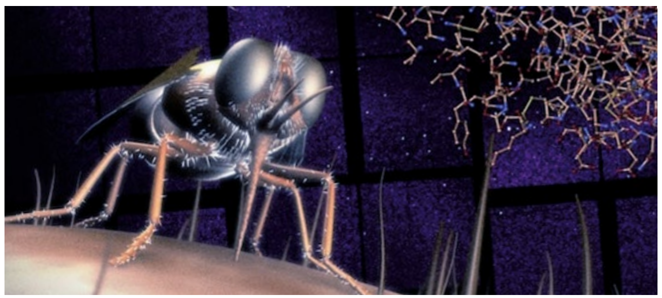
… to gain new insights into the nanocosmos – for instance, to develop components with specific electronic, magnetic, and optical properties.

Health

Free-electron lasers enable scientists to shine a light on how drugs and pathogens interact with each other and our bodies. By watching these processes unfold in real time, we can reveal unprecedented details leading to insights that contribute to a healthier society by, for example, enabling the development of more effective drugs and therapies.

Shining a light on critial drug targets

The intense and powerful femtosecond pulses generated by X-ray free-electron lasers make it possible to use microscopic protein crystals for structure determination. This has enabled the study of complex and large, but important molecules which tend to form extremely small and fragile crystals which can not be studied at other light sources. In this way, scientists have been able to determine the structure of many critical drug targets, in particular membrane proteins which regulate cell function.



One of the first studies of a biological molecule using an X-ray free electron laser revealed the structure of a protein found in the pathogen that causes sleeping sickness.

Molecular movies

The ultra-short pulses from a free electron laser help scientists study changes in molecules with temporal resolution faster than the motion of atoms.

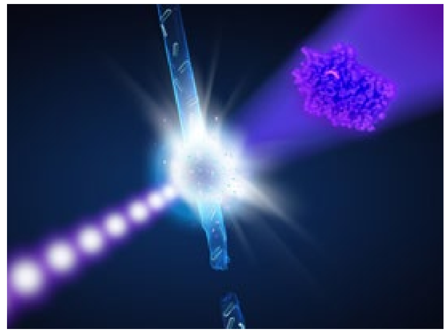
The complex way in which proteins interact and operate determines their function, and can now be studied on relevant timescales with XFELs. This is often achieved by overlapping two short pulse lasers in space and time, one in the visible spectrum and another from the FEL in the X-ray spectrum.

FELs enable unprecedented insights into protein function at atomic resolution such as the light activated dynamics of visual proteins, or the structural changes associated with drug binding. Moving from static structures to the molecular movie is key to unlocking the biological function of molecular machines.

In a typical pump-probe experiment, a sample is first excited by a laser working with visible light and then analysed with the X-ray flashes of an FEL. The result is a slow-motion molecular movie that enables a better understanding of the chemical and molecular processes.

From molecular structures to clinical biomarkers

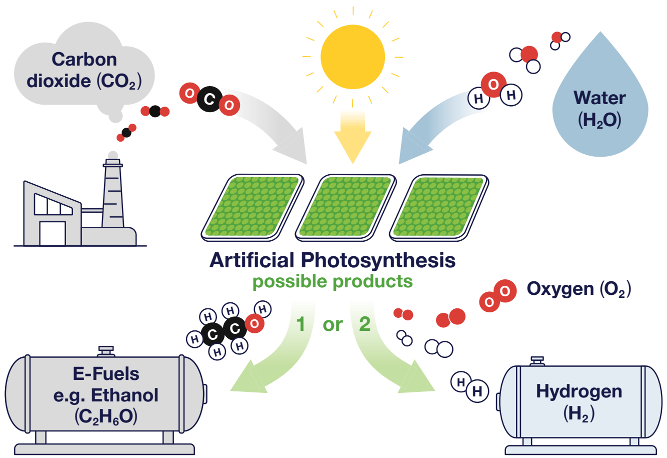
The widely tuneable light from infrared FELs allows researchers to precisely identify molecules that previously could not be identified. For example, recent developments enable the identification of metabolites that serve as novel biomarkers for metabolic diseases. Fewer than 2% of the more than 1500 of these disorders are currently included in newborn heel prick screening programs, often due to the absence of a suitable biomarker. FELs have recently enabled the discovery of biomarkers for the diagnosis of medical conditions including pyridoxine-dependent epilepsy and glucose transporter type-1 disorder syndrome.



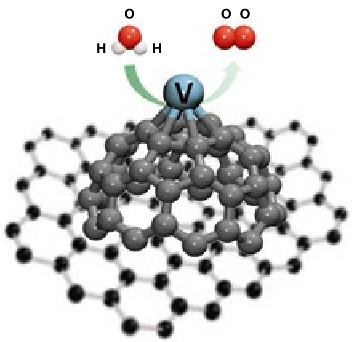
FEL pulses help to identify and classify important biomolecules

Energy and climate

To mitigate the effects of climate change, we urgently need solutions and new technologies for a safer, cleaner, and more sustainable future. Understanding natural processes such as photosynthesis which naturally use carbon dioxide and split water will enable the development of new sources of renewable energy, while effective catalysts can contribute to reduced energy consumption and pollution.



Artificial photo-synthesis could generate E-fuels or hydrogen from carbon dioxide, water and sunlight.



With infrared FELs researchers were able to show that water can easily be split with the help of a vanadium atom on a carbon 60 buckyball.

Single-atom catalysis

Water splitting is an important source of hydrogen and a promising method for producing clean and renewable energy. However, it consumes a lot of energy.

Using infrared FELs, researchers have shown how a single atom of the element vanadium supported by a carbon 60 'buckyball' molecule can assist in water splitting. This fundamental finding reveals the importance of C-60 in reducing the amount of energy required to drive such reactions.

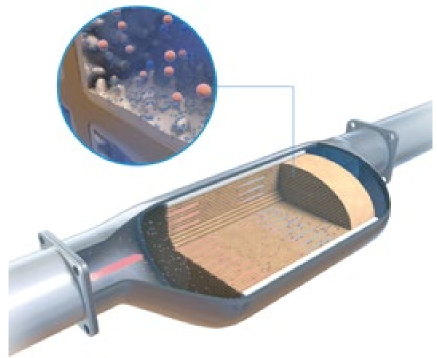
A detailed understanding of the water splitting reaction mechanisms, in particular how the energy needed for a reaction can be modified by interacting systems, is essential for the design of efficient catalysts.

Imaging pollutants in flight

Soot is a major pollutant. The structure of soot in the aerosol phase has been studied using X-ray imaging at FEL sources. This was made possible by the intense X-ray pulses from soft X-ray FELs which are able to image nanoscale aerosols in flight with a single X-ray pulse, yielding new insights into the morphology of pollutant nanoparticles. Previous studies were limited to particles captured on surfaces, which changed the soot structure compared to the aerosol phase.

Probing catalysts in action

Catalysts are substances that can enhance chemical reactions and are important in many industrial processes. Soft X-ray free-electron lasers can be used to study the chemical states of matter during reactions, giving scientists insights into chemical changes occurring during the extremely short timescales on which catalytic reactions take place. These studies are leading to a new understanding of chemical processes and enabling the design of new and more efficient catalysts – tools which increase energy efficiency thus reducing energy consumption and pollution.



XFELs can help to make the catalytic process more efficient, for example in catalytic converters.

Understanding Photosynthesis

Photosynthesis is central to life on Earth. It is the process by which plants split water to produce oxygen and convert sunlight into chemical energy . The oxygen is released into the atmosphere which other organisms need to live. Photosynthesis also results in carbon capture – the basis of all carbon-based energy sources such as coal and oil. XFELs are being used to study the complex process of photo-synthetic water-splitting in action. This is leading to insights into the fundamental question of how our world became habitable, but also how we might engineer more efficient solar energy capture methods.

The photosystem I protein trimer structure from measurements at European XFEL at 2.9 Å resolution. In photosynthesis, light is absorbed and converted into chemical energy by pigment-protein complexes photosystem I and photosystem II.

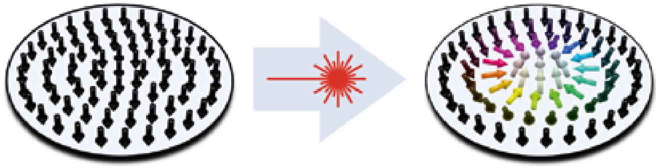
Information technology

Faster and more energy efficient digital technologies are needed to keep pace with society's growing data requirements. A world without information technology is now unthinkable, yet there is much research necessary to develop the technologies for the future. Free-electron lasers can now reveal details of the structural, electronic and magnetic dynamics of materials relevant for future digital technologies.

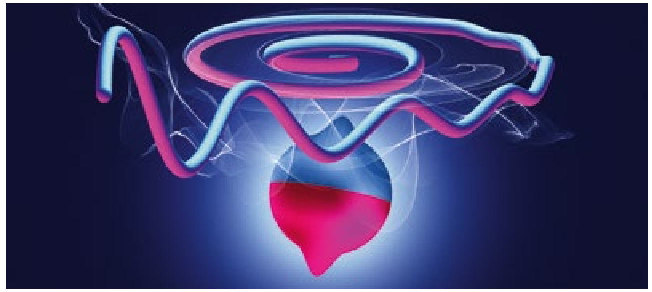
Understanding magnetism

The unique properties of magnetic and semiconductor materials lie at the heart of today's information revolution. Femtosecond X-ray pulses from XFELs have enabled the measurement of fluctuations in electron spins, revealing how local magnetism grows to form so-called transient spin nanostructures. Studies at such time resolution are not possible without the intense and ultra-short X-ray pulses from an FEL.

At longer wavelengths, short pulse terahertz radiation from FELs can directly drive the magnetization dynamics in magnetic films. This enables the development and manipulation of faster and higher performance materials for computing.



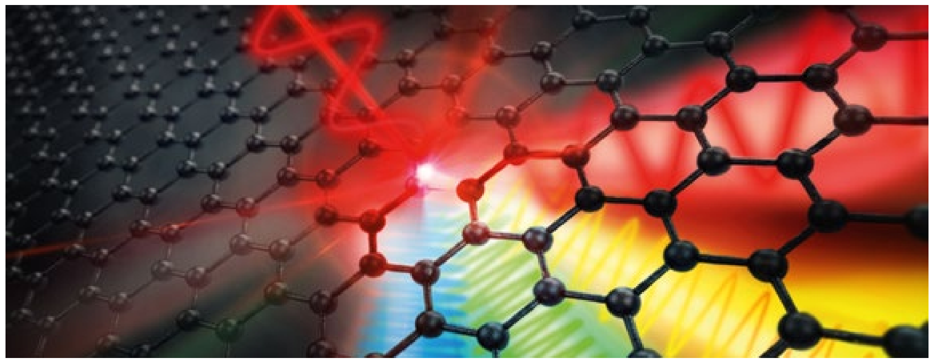
Twisted magnetic states can be manipulated by light and studied with an XFEL.



Inertial spin dynamics such as precession and nutation can be measured using ultra-short FEL pulses.

Engineering semiconductor materials

Studies using FEL-based terahertz sources have shown that graphene can be extremely efficient at converting electronic signals with frequencies in the gigahertz range into signals with several times higher frequency. Graphene is an ultra-thin material consisting of a single layer of interlinked carbon atoms, and is considered a promising candidate for the nanoelectronics of the future. Graphene based electronics in theory should allow clock rates up to a thousand times faster than today's silicon-based electronics, hence the importance of these studies. Such material studies at FELs are contributing to the development of next generation electronics based on new materials.

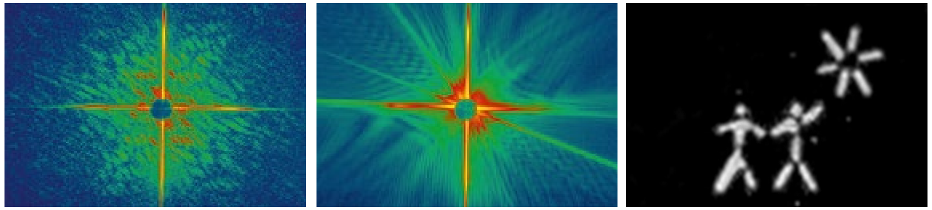


Graphene crystal lattice is hit by a THz pulse, leading to the emission of higher THz harmonics.

Creating fundamental knowledge

Opening new science frontiers

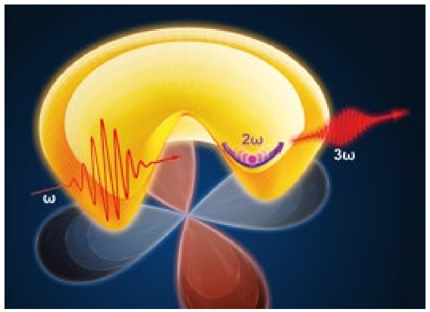
Fundamental experiments using XFELs have opened the door to entirely new measurement methods for structural studies. For example, the ability to capture information using a single XFEL pulse before the sample is destroyed by radiation damage – diffraction before destruction – enables us to overcome some previous resolution limitations caused by radiation damage during longer duration exposures. This basic research enabled the development of serial crystallography and single particle imaging, which have a wide range of applications ranging from health science to high energy density science.



Taking pictures at very fast timescales: Single pulse coherent diffraction imaging with the free-electron laser FLASH at DESY. Image obtained from of the first (left) and second pulse (middle) using femtosecond duration 32 nm wavelength UV pulses. The second pulse shows that the structure has been completely destroyed by the first pulse. Yet the original microstructure can be recovered from the diffraction pattern of the first pulse.

Revealing the basis of superconductivity

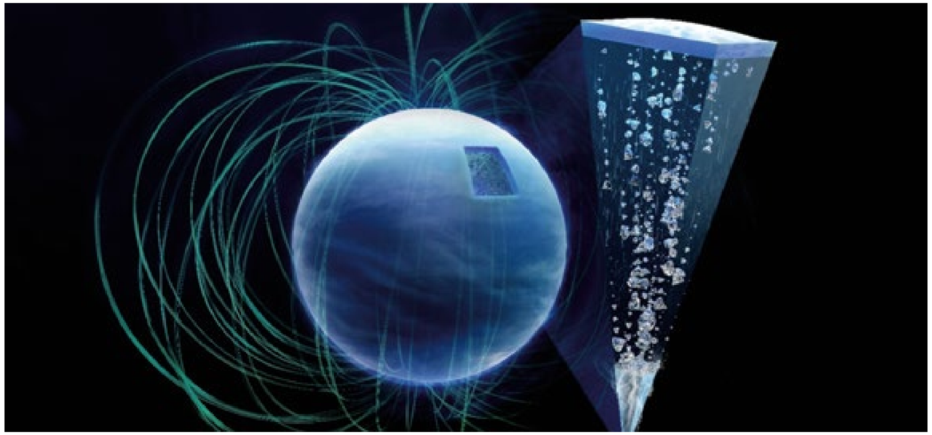
High-temperature superconductors have the potential to revolutionize technologies from sustainable energy to quantum computers. Intense terahertz FEL sources enable us to understand high temperature superconductors by revealing the dynamics of paired electrons in superconductors using “Higgs spectroscopy“. Remarkably, the dynamics also reveal typical precursors of superconductivity, even above the critical temperature, perhaps showing a route towards room-temperature superconductivity.



Nonlinear coupling of a THz pulse to the superconducting condensate leads to the emission of the third THz harmonic.

Probing extreme states of matter

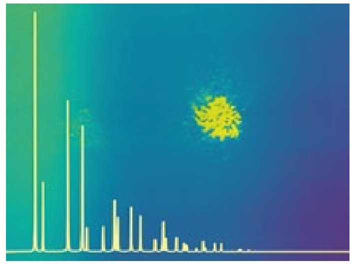
Materials exposed to high pressures and temperatures show profound new properties and a rich variety of material structures. We can now create, in the laboratory, pressures exceeding those that exist at the center of the Earth, and conditions approaching those found inside giant planets and in the interiors of stars. The intense, femtosecond duration X-ray pulses from FELs enable us to reveal the fast structural changes occurring under such extreme conditions.



Pressure and temperature continuously increase on the way deeper inside a planet. Here, diamond rain falls inside a planet, which consists of diamonds sinking through the surrounding ice. Even in extremely hot regions, the ice remains due to the extremely high pressure.

Astrochemistry and the origins of life

The combination of the widely tuneable and intense infrared radiation from FELs with a cryogenic ion trap has been used to gain a detailed understanding of fundamental growth processes of organic molecules under conditions mimicking those in space. This revealed the presence of unexpected but important molecular structures not considered so far in astrochemical processes. The recorded infrared spectra of these species provide crucial spectral fingerprints needed for their detection with powerful infrared observatories such as the recently launched James Webb Space Telescope.



Free-electron lasers can be used to reveal the structure of molecules that are similar to those in space. Telescopes use this knowledge as important reference for their observations.

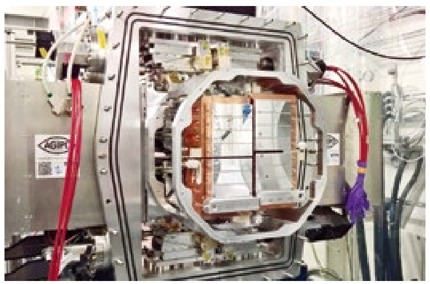
Nucleating innovative technology

Precision manufacturing

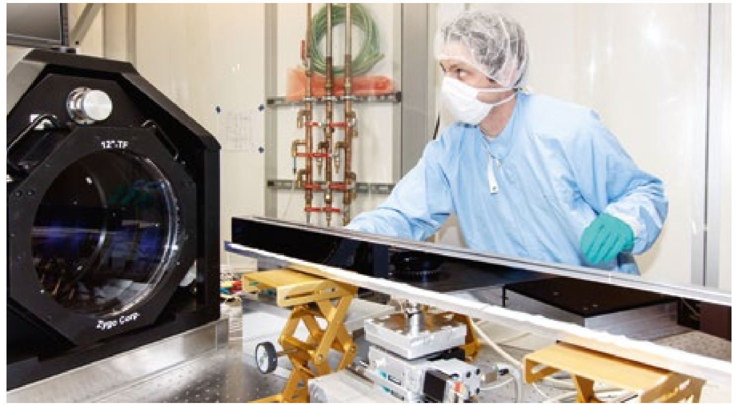
Particle accelerating structures are a key element of any FEL, and these complex accelerators require significant precision engineering and manufacturing capability. Both the so-called copper and superconducting accelerators push the envelope of state-of-the-art technologies to achieve the high-precision and high-performance needed for ultra-high brightness FEL photon source. Ready-to-use mass-produced cavities are now manufactured in close collaboration with industrial partners.

Semiconductor detection technology

New generations of high-performance detectors with high frame rates and high dynamic range, low noise and small pixel size over large detection areas have been mastered to enable experiments at XFEL facilities. Detectors are developed in close collaboration with industry and rely on custom semiconductor technology manufacturing, and precision mechanics to keep alignment well below pixel dimensions.



The intense pulses from XFELs require the development of new detector technologies, with spinoff to industry. The picture shows the AGIPD detector at the SPB/SFX instrument of European XFEL.



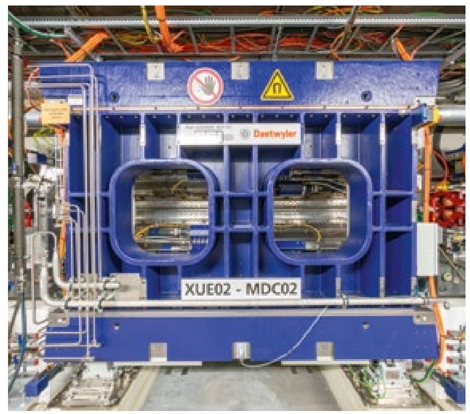
Inspecting a superflat X-ray mirror in the laboratory. The profile does not deviate from a perfect surface by more than a billionth of a metre.

Advanced optics

The optics used to transport the FEL beam to the experiment need to be radiation hard and be as close as possible to perfect in order to maintain the high FEL beam quality. This has pushed the state of the art beyond previous supplier capabilities. Super polished and extra-long mirrors with nano-precision and diffractive X-ray optics are now available and currently used for beam transport at XFELs. Leadership in X-ray optics drive the latest generation of chip making technology, where European manufacturing is the leading player.

Precision alignment

The long lines of precisely aligned magnets needed to generate XFEL radiation have pushed existing technologies to the next level of complexity. Magnetic structures up to 100m long have to be aligned to within micron precision. Strong collaboration with industrial partners allows large-scale production of cost effective undulators for XFELs. New schemes further extend FEL beam quality with properties ranging from short and intense X-ray pulses, high energy density, and polarization flexibility.



An APPLE-X undulator installed in the European XFEL photon tunnel

Ground-breaking science

The science referenced in this brochure comes from the following peer reviewed papers.

Page 4, 5 – Health

- ***Crystal structure of rhodopsin bound to arrestin by femtosecond X-ray laser***.
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Page 6 , 7 – Energy and climate

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Page 8, 9 – Information technology

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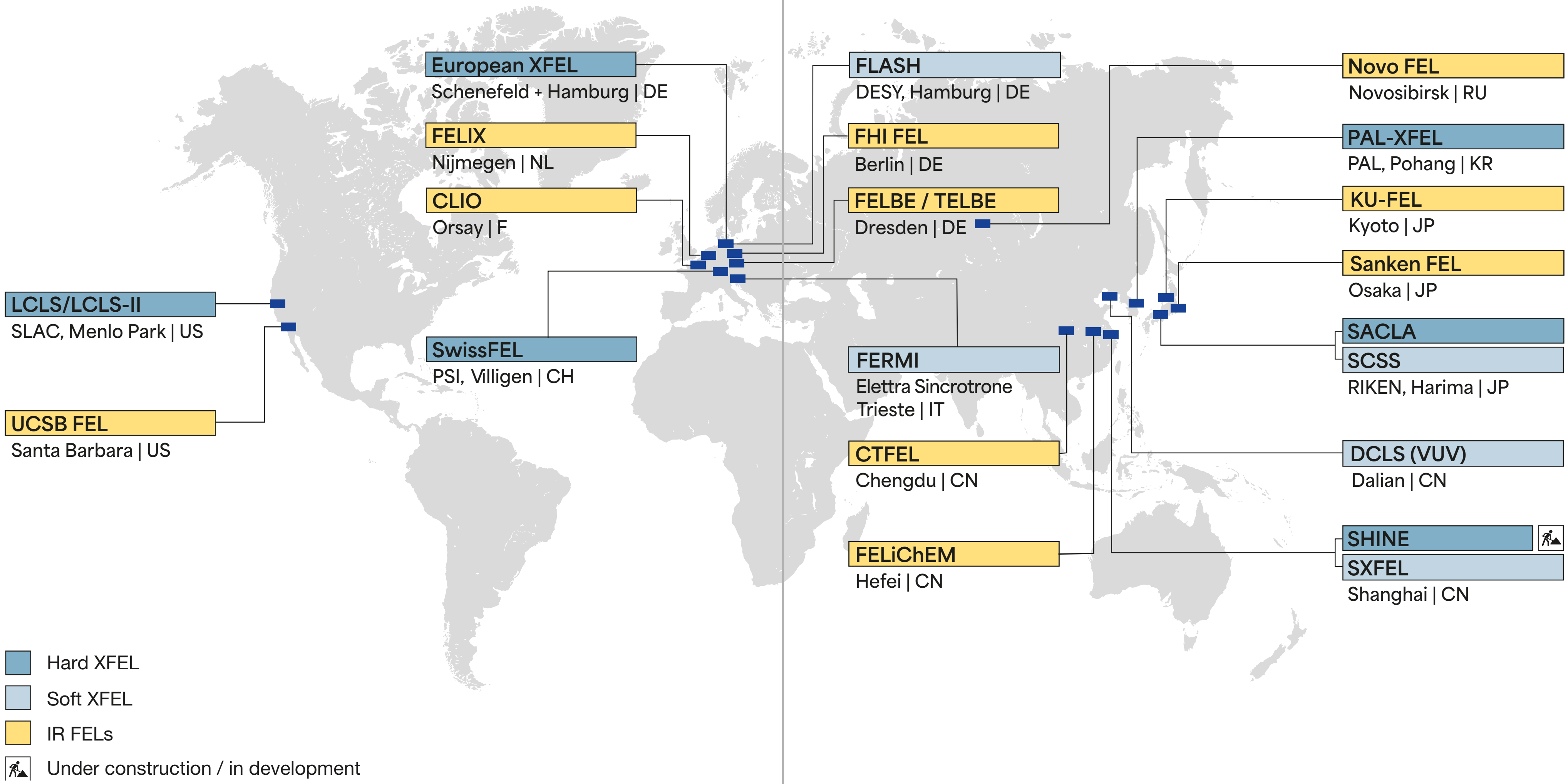
FEL sources of Europe / Worldwide



Most of the IR/THz FELs outside Europe offer user access only on a national and/or informal basis (without formalized proposal system). There exist even more FELs dedicated to FEL machine research without user access.

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