femto

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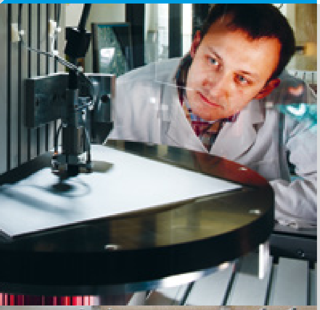
ZOOM

The super X-ray laser

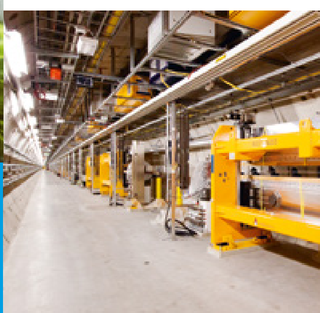


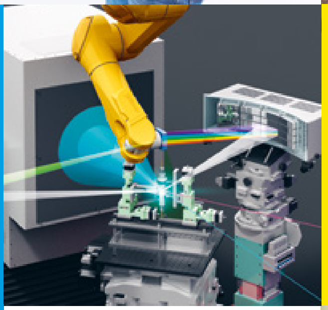
ZOOM

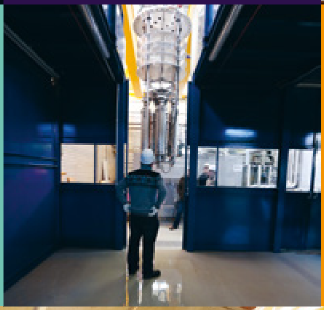
A superlative X-ray laser

The European XFEL is a high-speed camera, a supermicroscope and a planet simulator rolled into one. Starting in 2017, its intense ultrashort X-ray laser flashes will give researchers from scientific institutes and industry completely new insights into the nanoworld. They'll be able to study the details of viruses at the atomic level, the molecular composition of innovative materials, films of chemical reactions and the characteristics of matter under extreme conditions.

Eleven countries are participating in this joint European project. DESY is the main shareholder and is responsible for the construction and operation of the particle accelerator with its innovative superconducting technology. The European XFEL is mostly located in underground tunnels. The 3.4-kilometre-long facility extends from DESY in Hamburg to the neighbouring town of Schenefeld in the German federal state of Schleswig-Holstein.





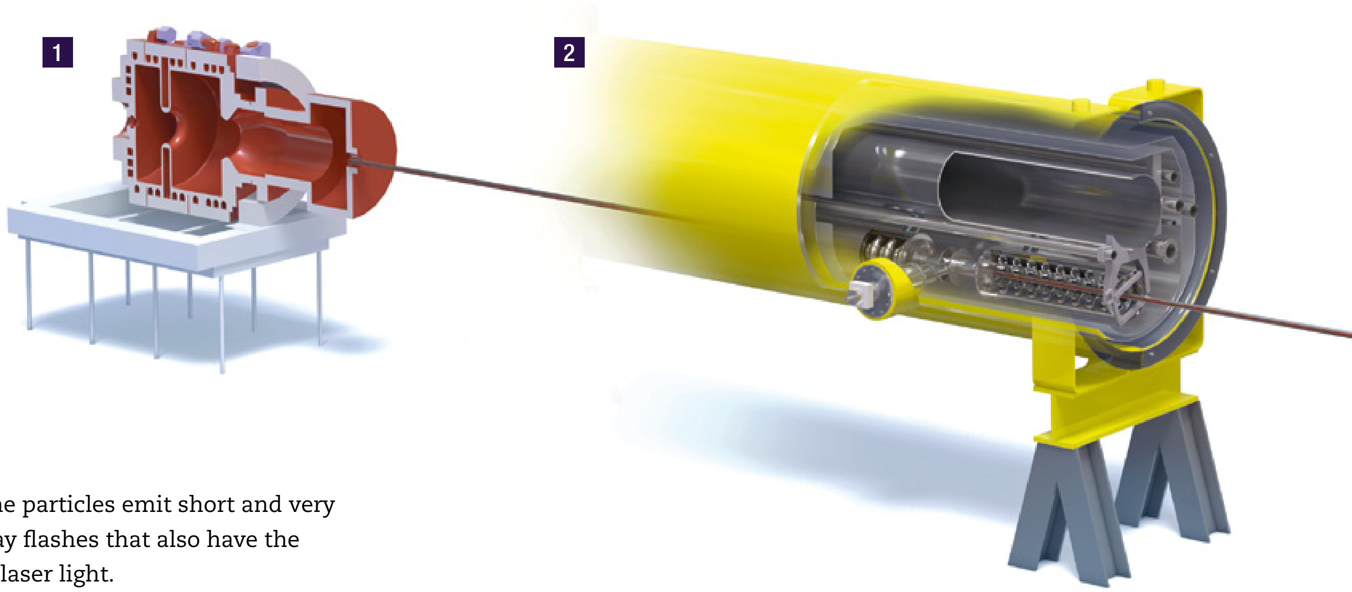


Pictures: European XFEL / DESY

Light for the future

The European XFEL in Hamburg will produce the most intense X-ray laser flashes in the world

The European XFEL stretches for 3.4 kilometres from Hamburg-Bahrenfeld to the town of Schenefeld in Schleswig-Holstein. It's the world's most powerful X-ray laser and one of Europe's biggest scientific facilities. At its heart is a particle accelerator that is close to two kilometres long. It accelerates electrons to almost the speed of light. Special magnet structures called undulators force the speeding electrons to fly along a slalom path.



As a result, the particles emit short and very powerful X-ray flashes that also have the properties of laser light.

The X-ray flashes make it possible for researchers to image ultrafast processes, because each individual flash is less than 100 quadrillionths of a second long and bright enough to create snapshots. This makes it possible to "film" molecular reactions and thus understand processes that are fundamental to chemical production methods in industry or to the mechanisms of medical effects. In addition, the short-wavelength laser flashes can make the composition of nanomaterials and complex biomolecules visible at the atomic level. On the basis of this knowledge, researchers can go on to develop innovative customised materials and drugs. The X-ray laser also makes it possible to

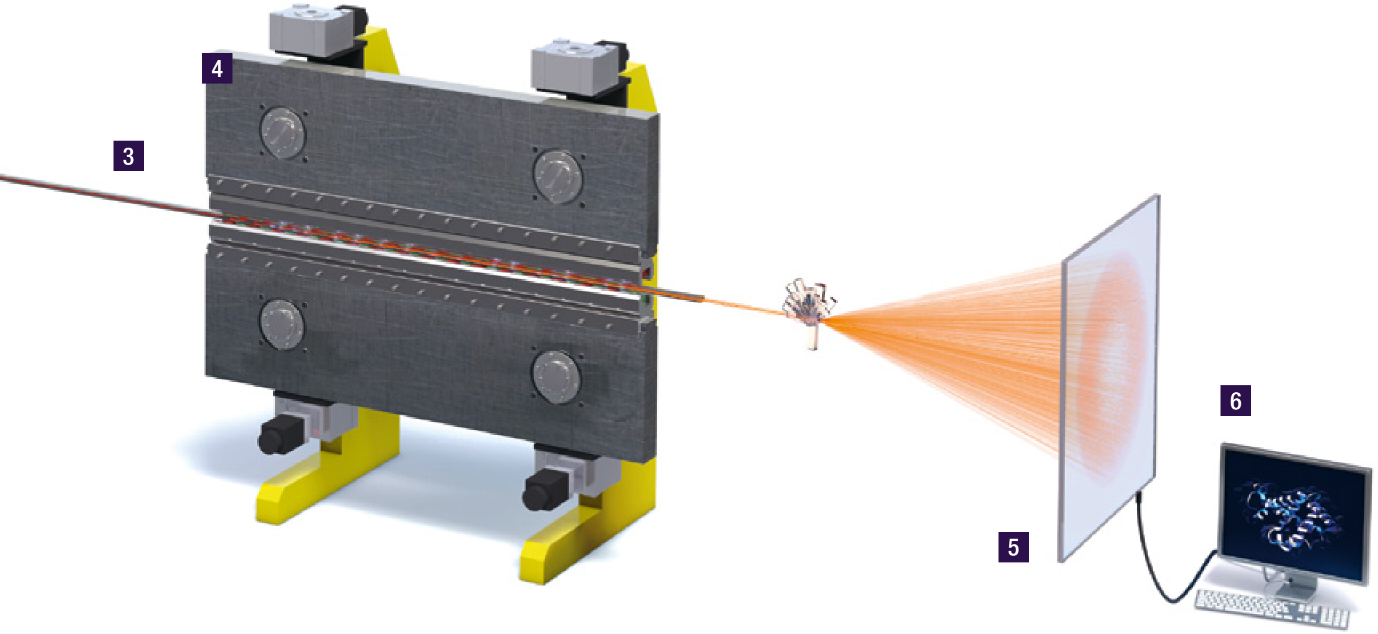
At the **electron source [1],** a powerful laser knocks several billion electrons at a time out of a caesium telluride electrode. These electrons are bundled into tiny bunches, which are given a boost in the **accelerator modules [2]**. Powerful radio waves are fed into these modules, and the electrons "ride" the waves like surfers on the ocean. To ensure that the speeding electrons are generate and analyse extreme states of matter – for example, the high pressures and temperatures that exist in the interior of planets. Under such extreme conditions, matter behaves very differently than under “normal” conditions.

“The European XFEL will open up entirely new opportunities for scientists from research institutes and industry,” says Massimo Altarelli, Chairman of the European XFEL Management Board. “Much of this work will be fundamental research. This kind of research develops its biggest effects usually not in the short term and sometimes not in the area that was originally targeted. But without fundamental research, the life we live today would not be conceivable.”

A race track for electrons

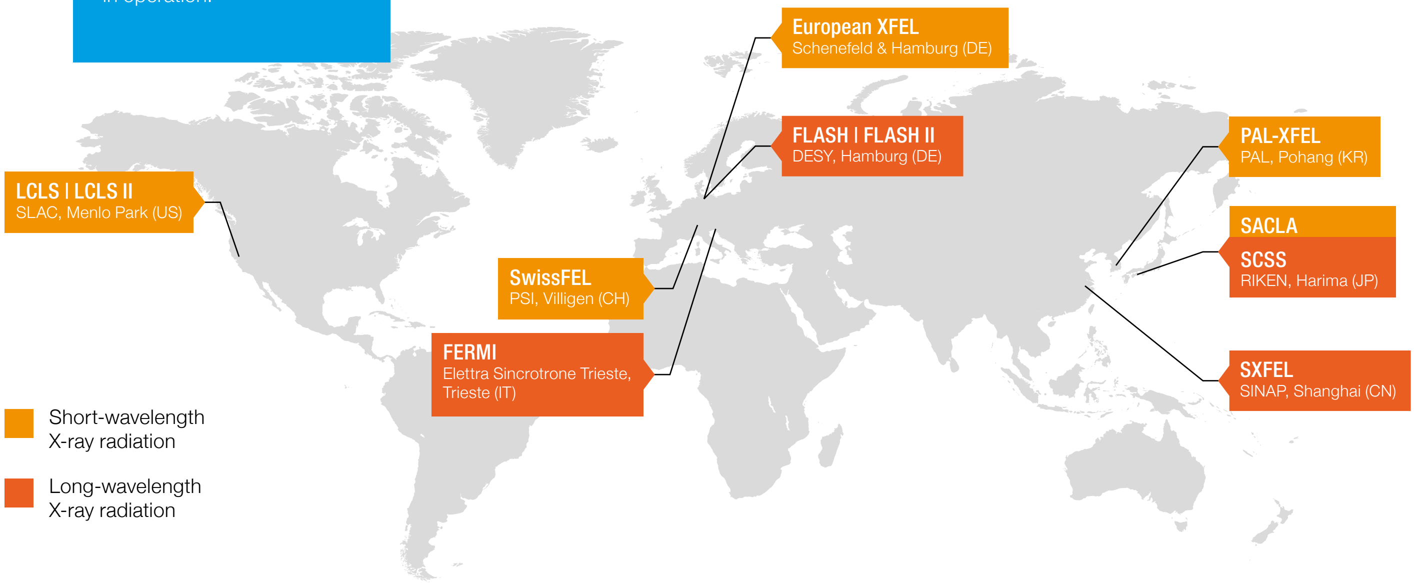
Eleven countries are participating in this joint European project. DESY is the main shareholder and is responsible for the construction and operation of the particle accelerator with its innovative superconducting technology, which has already been tested at DESY’s pioneering X-ray laser facility FLASH. The accelerator modules are massive yellow pipes that are 12 metres long and almost one metre thick. A look at the interior of such a module reveals a complex structure. The electrons fly through a thin pipe from which all the air has been evacuated. Most of the module’s components are used for thermal insulation and cooling – various pipes through which liquid helium is pumped in order to reduce the temperature inside the pipe to minus 271 degrees Celsius.

These extreme measures are necessary to ensure that the core components – the cavity resonators – can function properly. These shining silvery components are responsible for the actual acceleration of the electrons. With the help of powerful radio waves, they accelerate the tiny electron bunches to almost the speed of light. Every module is equipped with eight cavities made of the superconducting metal niobium. “Superconducting” means that the metal completely loses its electrical resistance and thus conducts electricity without any loss of energy – when cooled to ultracold temperatures, that is. The advantage of this technology is that it enables considerably more electron bunches to be accelerated and thus more X-ray flashes to be generated per second than conventional, normal-conducting accelerator technology. ››



not slowed down by air, they fly through **vacuum pipes [3]**. Once the electrons have reached their maximum energy, they pass through special magnet structures called **undulators [4]**. The undulators force the electrons to run a slalom course, causing them to emit X-ray flashes. At the end of the undulator section, this radiation has amplified into extremely intense ultrashort X-ray flashes, which are used by researchers at the **measuring stations [5]** to illuminate a variety of samples. The basic principle here is that the atoms of the sample material deflect the X-ray light, and detectors then intercept the deflected radiation. Subsequently, **computers [6]** are used to precisely calculate the spatial structure of the sample, for example, at the atomic level.

X-ray free-electron lasers are being built all over the world. About half of these facilities are already in operation.



A total of 101 superconducting modules will put the electrons through their paces in the two-kilometre-long accelerator tunnel. At certain points, the particles pass through “warm” – that is, uncooled – sections of beam pipe on which various devices are mounted, including magnets that bundle the electron bunches. At the end of the accelerator, the tunnel branches into two tubes. Each of them contains another key component of the facility: the undulators. These are permanent magnets mounted above and below the electron beam pipe, with their north and south poles alternating at four-centimetre intervals. These force the electrons to follow a slalom course.

On a slalom course

The electrons, which are flying at almost the speed of light, emit intense X-ray radiation in each curve. The special feature of the free-electron laser is that it has not just one undulator but 35 of them, arranged one after the other over almost 200 metres. “When the X-ray light emitted by one undulator oscillates in sync with the light of the next one, the light is amplified,” explains Tobias Haas, technical coordinator at the European XFEL. “That’s the only way I can get the amplification effect I need for a laser.” In order to be able to optimally adjust the laser effect, the five-metre-long undulators are separated by intermediate sections called phase shifters.

Past the undulator section, the evacuated beam pipe branches into two. One branch is for the electron bunches, the other for the X-ray laser flashes generated in the undulators. To separate the two beams, bending magnets gently direct the electron beam to the right, into another tunnel. Meanwhile, the X-ray flashes race straight ahead until they hit a special mirror mounted at an obtuse angle. This mirror has been ground to nanometre precision and functions as a distribution station. It either allows the X-ray flashes to go straight on past it into one pipe or deflects them by a tenth of a degree into another pipe. The two pipes run alongside one another for 600 metres, with the distance between them gradually increasing. At the end of the tunnel, after 3.4 kilometres, they are 1.40 metres apart when they penetrate a thick wall of concrete. Directly behind this wall is the big experiment hall with its measuring huts, whose walls contain lead as shielding against the X-ray radiation. The first experiments will be conducted in these huts in 2017. The X-ray flashes will illuminate samples of various kinds, enabling the scientists to study their interior structures and processes.

“We’ve worked for many years to build this facility,” says Haas. “Now we feel as though we can finally see the marathon’s finish line.” The European XFEL will initially have six measuring stations, but two additional tunnels have already been dug and can be equipped with additional undulators if necessary. In the final configuration, the researchers in the experiment hall will be able to use up to 15 measuring stations.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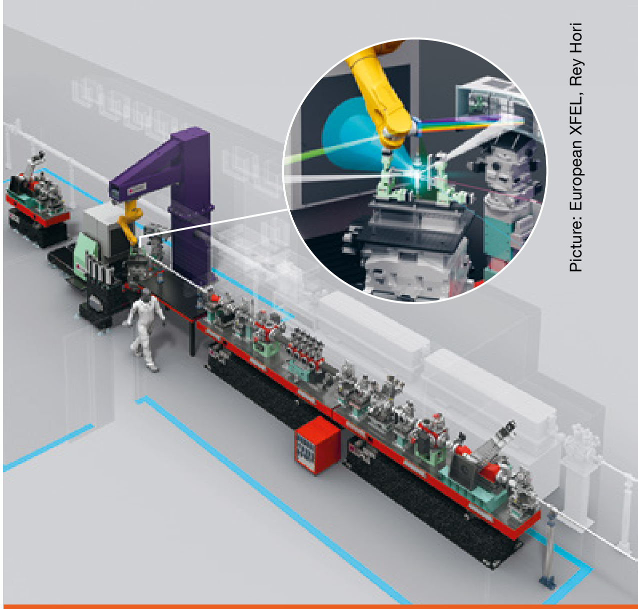
Experiments at the European XFEL

With its extraordinarily bright, highly energetic and extremely intense X-ray flashes, the European XFEL will yield new insights in a wide range of research fields. It will, for instance, enable scientists to produce images of viruses and biomolecules at atomic resolution, to film chemical reactions in superslow motion and to investigate materials under the extreme conditions that reign deep within giant gas planets. There are many fields of application, ranging from biology, medicine, chemistry and physics to materials science, electronics, nanotechnology and many others. With a total of six measuring stations, the facility offers a wide range of opportunities for scientific investigation. Through their membership in user consortia, among others, numerous institutions participate in various aspects of the experimental activities at the European XFEL. DESY too is involved in such consortia, sometimes in a leading capacity.



Picture: European XFEL, Rey Hori

Planned setup
of the FXE measuring station

Investigating the dynamics of the nanoworld

Nanosystems are an increasingly common feature of the everyday world. Examples include metallic nanoparticles in the catalytic converters of cars. An investigation of the properties and the dynamics of such systems not only provides a better understanding of their fundamental nature but also enables an enhancement of everyday products containing nanoparticles. The **MID** (Materials Imaging and Dynamics) measuring station is used for such research. It enables researchers to investigate the nanostructure and dynamics not only of solid materials such as metals but also of soft materials such as polymers and gels and even biological samples. For the investigation of a broad range of samples, various analytic methods are available, which make use of the laser properties of the X-ray free-electron laser radiation, its short pulses and its high intensity.

A 4D supermicroscope in space and time

The principal objects of investigation at the **SPB/SFX** (Single Particles, Clusters, and Biomolecules and Serial Femtosecond Crystallography) measuring station are biomolecules, nanocrystals, virus particles, cell organelles and atom clusters. As a rule, the aim is to determine the two and three-dimensional structure of the object under investigation to an atomic resolution of less than one nanometre (a millionth of a millimetre). However, the 3D microscope is, in fact, a 4D supermicroscope if the high time resolution is taken into account. The samples are shot laterally through the X-ray beam. Whenever a pulse of the intense radiation hits a crystal of biomolecules, for example, a distinctive X-ray diffraction pattern is generated, which enables the biomolecule’s structure to be computed. The spatial structure of a biomolecule provides information about its mode of action and can yield clues for the development of new drugs. Apart from structural biology and cell biology, a host of other fields will benefit from the methods of investigation available at this measuring station, including materials science and nanotechnology.

The exoplanet simulator

The “normal” conditions on the surface of the Earth are the absolute exception for the universe as a whole. Most matter in the universe exists at much higher pressures and temperatures and under more powerful electromagnetic fields. The **HED** (High Energy Density Science) measuring station can simulate the extreme conditions that exist for example in giant gas planets in other solar systems, also known as exoplanets. Various methods are used to generate these extreme conditions, including high-power optical lasers, diamond anvil cells and strong pulsed magnets. The investigation of matter under extreme conditions provides a more complete picture of its material properties beyond the narrow scope of what we call “normal”.

An ultrafast quantum film camera

Dynamic processes in the nanocosmos generally occur over an unimaginably short timescale of just a few quadrillionths of a second (femtoseconds). The **FXE** (Femtosecond X-Ray Experiments) measuring station uses the extremely short X-ray flashes from the European XFEL to produce sharp images of extremely rapid processes in solids, liquids and gases. Examples include shock waves propagating, nanoparticles exploding and just about any chemical reaction.

Thanks to the ultrashort exposure times, it is possible to observe processes such as the complex interplay of molecules during a chemical reaction, with the X-ray laser providing previously inaccessible information about the detailed steps. The process under investigation is first triggered by a laser pulse and then, after a precisely defined amount of time, imaged by means of an X-ray flash. The experiment is repeated many times, each time with the moment of exposure at a slightly later point in time. The result is a sequence of stills that can be assembled into a film of the process under investigation.

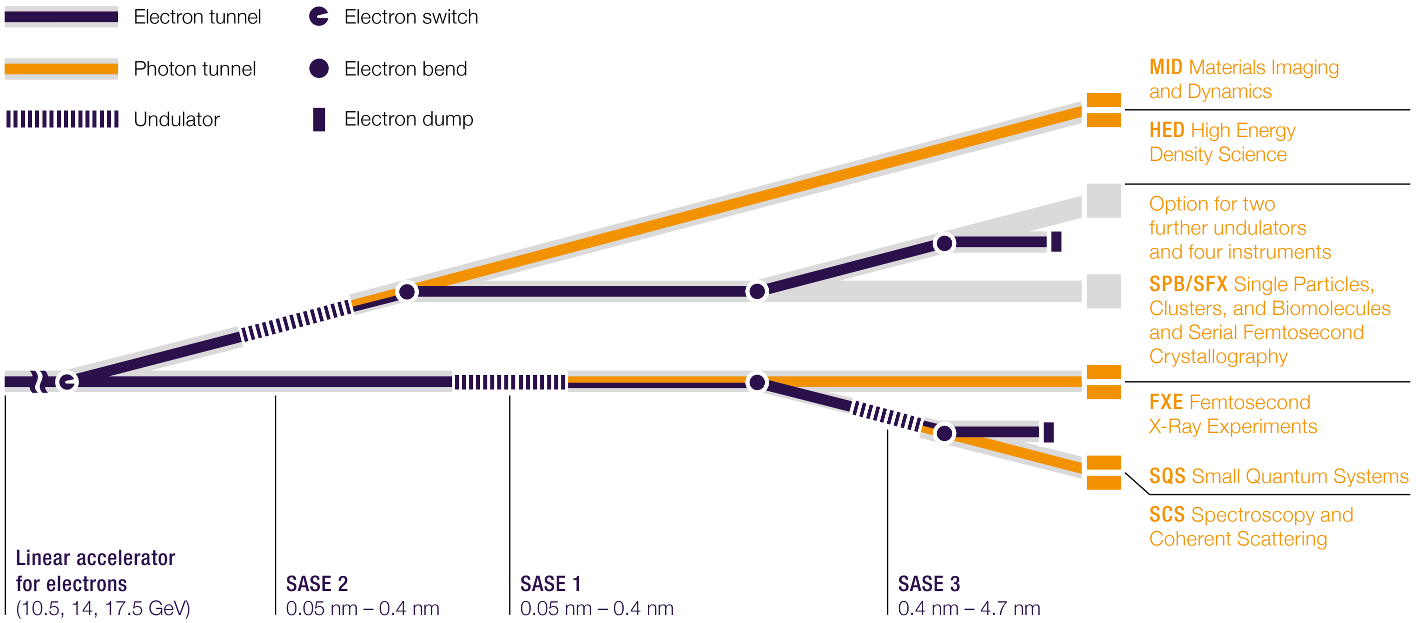
Zooming in on the quantum world

There are many unsolved questions in the realm of atoms and molecules. The **SQS** (Small Quantum Systems) measuring station is used to investigate the behaviour of small quantum systems comprising between one and tens of thousands of atoms. In particular, this multiphoton camera focuses on the interaction between these smallest structural units and the extremely intense X-ray laser flashes. Multiphoton processes often produce lots of electrons and highly charged ions, with molecules breaking up into many separate charged parts. SQS offers researchers a variety of methods with which to investigate these fragments in detail.

The determination of precise atomic data is vital for the development not only of new theoretical models but also of many other experimental methods. Scientists require reliable data in order to support and quantify their results – data that is often lacking even for comparatively simple systems. It is therefore vital to be familiar with the participants of this process – the atoms – in order to understand it as a whole.

The structure and dynamics of complex materials

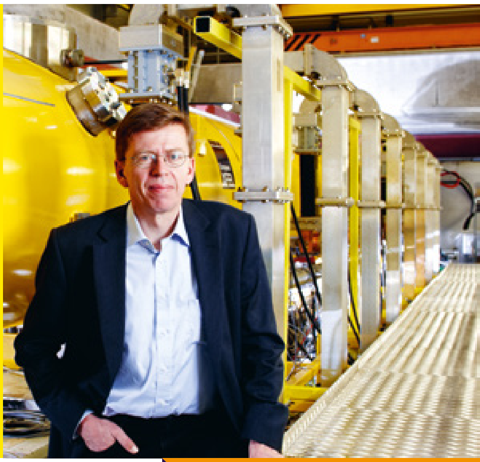
Researchers who are working with the **SCS** (Spectroscopy and Coherent Scattering) measuring station use what are called “soft” X-rays to investigate the electronic and atomic structure as well as the dynamics of complex and functional materials. Soft X-rays have less energy and a longer wavelength than hard X-rays. They are ideal for investigating, among other things, nanostructured materials and ultrafast magnetisation processes. The potential fields of application for this type of investigation include materials science, surface chemistry and catalysis, nanotechnology and the dynamics of condensed matter.



Graphic: European XFEL

Precision from the production line

The production of the superconducting accelerator modules was one of the major challenges in the project to build the European XFEL



Reinhard Brinkmann is Director of the Accelerator Division at DESY.

There are several accelerator-driven X-ray lasers in operation all over the world. The pioneer was FLASH, which commenced service in 2000 at DESY. For a number of years, LCLS in California and SACLA in Japan have been providing high-intensity X-ray pulses. As documented in numerous publications in the renowned journals *Nature* and *Science*, both facilities have delivered impressive proof of the value of such light sources to the research community. They will be joined at the end of 2016 by the SwissFEL at the Paul Scherrer Institute in Switzerland. The European XFEL has one key advantage over these other facilities: Because it uses superconducting technology, it is able to deliver significantly more X-ray flashes per second than normal-conducting facilities can. This capability is of major benefit for many experiments.

In conventional accelerators, water-cooled cavity resonators made of copper are used to accelerate the electrons to high energies. “But the copper heats up due to its electrical resistance,” explains Reinhard Brinkmann, Director of the Accelerator Division at DESY. “That’s why you can only feed radio waves into the cavities for a tiny fraction of a second; otherwise the material would melt.” This also means that you have to wait a moment for the copper to cool down before applying the next pulse of radio waves. This limits the rate at which the laser can deliver X-ray pulses. Current free-electron lasers can produce a maximum of 120 flashes per second.

More flashes thanks to superconductivity

To circumvent this limitation, DESY opted for another approach, namely superconductivity. A superconductor possesses zero electrical resistance. As Brinkmann explains, this means that the radio waves don’t heat up the cavity to any appreciable extent. “As a result, you can switch it on for much longer than a copper cavity.” Thanks to this technology, the European XFEL will be able to produce 27 000 X-ray flashes per second – more than 200 times as many as the number produced by the other facilities.

This means that experiments that take a number of hours to complete at other X-ray laser facilities will require only a few minutes at the European XFEL. It will therefore be possible to conduct more experiments in the same amount of time. Moreover, the higher rate of X-ray flashes from the European XFEL will provide greater temporal resolution, thus enabling even more-detailed investigations of chemical reactions.

However, superconducting accelerators do have one disadvantage: The technology is more expensive and much more complicated than that of conventional accelerators. For example, key components have to be cooled with liquid helium to around minus 271 degrees Celsius. “To a large extent, we were able to use the liquid-helium plant from the former large-scale accelerator HERA,” says DESY scientist Hans Weise, coordinator of the European XFEL Accelerator Consortium. “That meant we didn’t have to build everything from scratch.”

The biggest challenge was to develop and manufacture the superconducting cavities, which are made of niobium rather than copper. DESY produced the initial prototypes in collaboration with a large number of partners based both within Germany and abroad. This was a major breakthrough, but one problem remained: Over 800 superconducting cavities were needed for the three-kilometre-long European XFEL. Some form of series production was therefore required.

High purity for high performance

The researchers therefore devised a complex quasi-industrial process that involves numerous partners both in Germany and abroad. Even producing the raw material is an elaborate process. The niobium must be extremely pure, which means it has to be re-melted up to eight times in special furnaces. Each melting process successively reduces the level of impurities, and the final result is ingots of extremely pure niobium, which are then rolled into sheets. In order to check for any remaining impurities, DESY scientists inspected each individual sheet using a special eddy-current testing method. “We scanned all 16 000 niobium sheets,” Brinkmann explains. “Only a few percent had to be rejected.”

> *“We scanned all 16 000 niobium sheets; only a few percent had to be rejected.”*
>
> *Reinhard Brinkmann, DESY*

Each sheet that passed scrutiny was then cut and pressed into shape, before being welded into the shape of a cavity – a shiny silver tube, one metre in length and segmented like a caterpillar. “The manufacturing process has to be kept extremely clean,” says Brinkmann. “Even a speck of dust can be enough to stop a cavity working as it should.” For this reason, some of the process stages were conducted in cleanrooms, where the air is scrupulously filtered and particle counters monitor air quality. To prevent components being contaminated, workers wore what looked like surgical gowns, including face masks, hair nets and gloves.

An electron beam was used to weld the niobium sheets. After the welding, the cavities underwent an elaborate cleaning process. They were first dipped into an electrochemical acid bath, then given a high-pressure rinse with specially purified water and finally baked for

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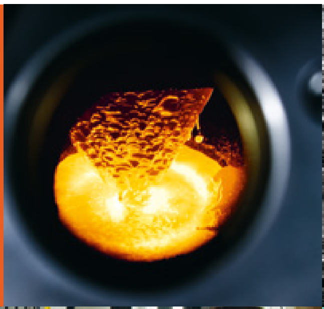
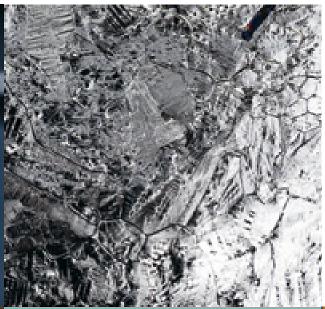




The niobium (above) is re-melted a number of times (above left) and the rolled sheets (left) are precisely scanned.

Superconducting cavities in the cleanroom several hours at 120 degrees Celsius. “There are processes here which we don’t yet fully understand in all their detail,” Brinkmann explains. “You could almost say that there’s a bit of alchemy to it all.”

Many of the methods that were used were first tested at DESY, then exported to industry and ultimately enhanced in partnership. “It took a while before we could achieve reliable series production; a lot of it was a laborious process of learning and practicing,” says Brinkmann. “But by the end, the whole industrial production process – from the niobium sheets to the finished cavities – ran very smoothly.” The cavities were supplied by an Italian and a German company, with the last one leaving the production line at the beginning of 2016. There were very few rejects. In fact, barely more than a dozen of the more than 800 niobium tubes required subsequent chemical treatment, and the average accelerating gradient proved to be well above the original specification.

Assembly of an accelerator module (right); connecting radio frequency couplers to cavities in the cleanroom (below).

> *“The industrial manufacturing process – from the niobium sheets to the finished cavities – ran very smoothly”*
>
> *Reinhard Brinkmann, DESY*

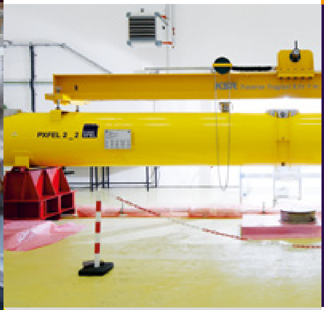
Following production, the cavities were shipped to Saclay near Paris, where they were assembled, in batches of eight, into yellow modules, each with an integrated helium cooling system, just like a large thermos flask. These 101 modules were successively sent back to Hamburg, where they underwent a final series of rigorous tests. Only then could they be installed in the tunnel for the European XFEL.

The construction of the accelerator posed not only technical but also organisational challenges. After all, eight countries were involved in the process. “Some partners are essentially providing financing, while others are contributing components,” explains Riko Wichmann, head of the XFEL Project Office at DESY. “In particular, coordinating the in-kind contributions was not easy and created much more work than we had originally imagined.” A great many institutes and companies were involved in building the accelerator modules. The DESY XFEL project team had to make sure that all the partners delivered their components as punctually as possible. “The late arrival of even a single component would have had a knock-on effect on the whole process, with the danger of a logjam.” A key factor in the success of this enterprise was the close cooperation between DESY, as the leader of the Accelerator Consortium, and European XFEL GmbH, the company responsible for managing the project as a whole.

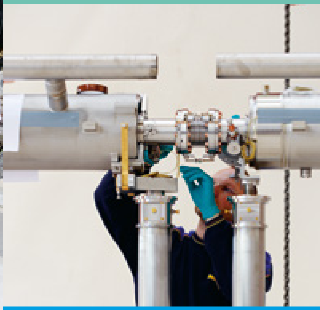
Bunches of billions of electrons

One key component of the facility is the injector. This 50-metre-long part of the facility is responsible for generating the electron bunches, which are then accelerated over a distance of 1.8 kilometres. The injector functions in the following way: At a rate of 27 000 times per second, a laser fires powerful pulses at a pill-shaped piece of metal. Each pulse blasts off a throng of around ten billion electrons. Two superconducting modules pre-accelerate this throng of electrons and shape it into customised bunches. Initially, these bunches are about three millimetres long and one millimetre across. During the acceleration, sophisticated technology ensures that these bunches are further compressed, until finally they are around one thousandth of their original volume. “In order to generate extremely intense X-ray flashes, the electrons have to be concentrated into a minuscule area,” explains Weise.

Another extremely sophisticated technique in use at the European XFEL is the one that ensures



Hans Weise is a leading scientist at DESY and coordinator of the European XFEL Accelerator Consortium.



Testing an accelerator module

precise synchronisation between the ultrashort electron bunches and the X-ray flashes. This synchronisation is required to be able to film chemical reactions, for example. Here, a pulse of light from a conventional laser triggers the reaction. Then, only a brief moment later, an image of the reaction is captured by means of an X-ray flash from the European XFEL. For this process to function, the optical laser and the European XFEL must be precisely coordinated with one another. This is accomplished by a special synchronisation system based on a "laser clock" that ticks in an optical fibre running along the accelerator tunnel. This system measures the exact intervals between the electron bunches and the X-ray flashes – key information for the scientists conducting the experiments.

"In order to generate extremely intense X-ray flashes, the electrons have to be concentrated into a minuscule area"

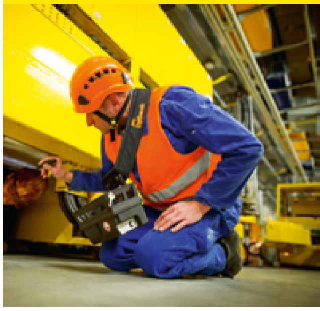
Hans Weise, DESY

This method was already tested at FLASH, also at DESY. Some 300 metres in length, this X-ray free-electron laser is based on the same superconducting modules used at the European XFEL, but it produces flashes in the soft X-ray and UV ranges. "If you like, FLASH is a 1:10 scale model of the European XFEL," says Reinhard Brinkmann. "Over the years, FLASH has given us countless valuable insights into how to design and build the larger facility." FLASH has been used by scientists from over the world for a decade now. In fact, such is the interest from the research community that DESY is currently doubling the facility's experimentation capacity.

Other research establishments are now also planning to use superconducting accelerator technology in the future. These include SLAC in California, which has been successfully ›› operating the Linac Coherent Light Source (LCLS), an X-ray laser based on a normal-conducting accelerator, since 2009. SLAC is now planning to set up a second light source in the same tunnel. LCLS-II will be 700 metres in length and equipped with 280 superconducting cavities of essentially the same design as those of the European XFEL.

The ambitious goal is to build a laser at SLAC that, from 2019 onwards, will be capable of producing one million flashes per second, albeit at longer wavelengths and therefore not with the same high resolution as the archetype in Hamburg. “DESY has given us a lot of support for our planning,” says project leader John Galayda. “Having access to DESY’s knowledge and experience is the reason why we’ve made such rapid progress.” This was particularly true when it came to designing the highly complex accelerator modules and the superconducting niobium cavities. “We’re buying them from the same two companies that supplied the European XFEL,” Galayda explains. “For us, it’s a great advantage that there are already manufacturers with such extensive experience in building these cavities.”

> *“Having access to DESY’s knowledge and experience is the reason why we’ve made such rapid progress”*
>
> *John Galayda, SLAC*



The accelerator modules were transported and installed within the tunnel using the special electric vehicle “Mullewupp” (bottom left).

“A triumph for DESY”

DESY is the main shareholder of the European XFEL. Helmut Dosch, the Chairman of the DESY Board of Directors, talks about the research centre’s expectations concerning the European X-ray laser.

femto: What does the European XFEL mean for DESY?

Dosch: The European XFEL is one of the world’s most revolutionary large-scale research projects. It brings together a completely novel particle accelerator technology, which was developed by DESY, with the tremendous potential for discovery that the unique experimentation opportunities will offer to scientists coming from all over the world. DESY designed this major facility and established the theoretical and technical foundations for its realisation. Last but not least, DESY built FLASH, the pioneering facility for X-ray lasers of this kind. I am therefore convinced that the European XFEL will become a great triumph for DESY.

femto: What perspectives does this open up for Hamburg as a centre of science?

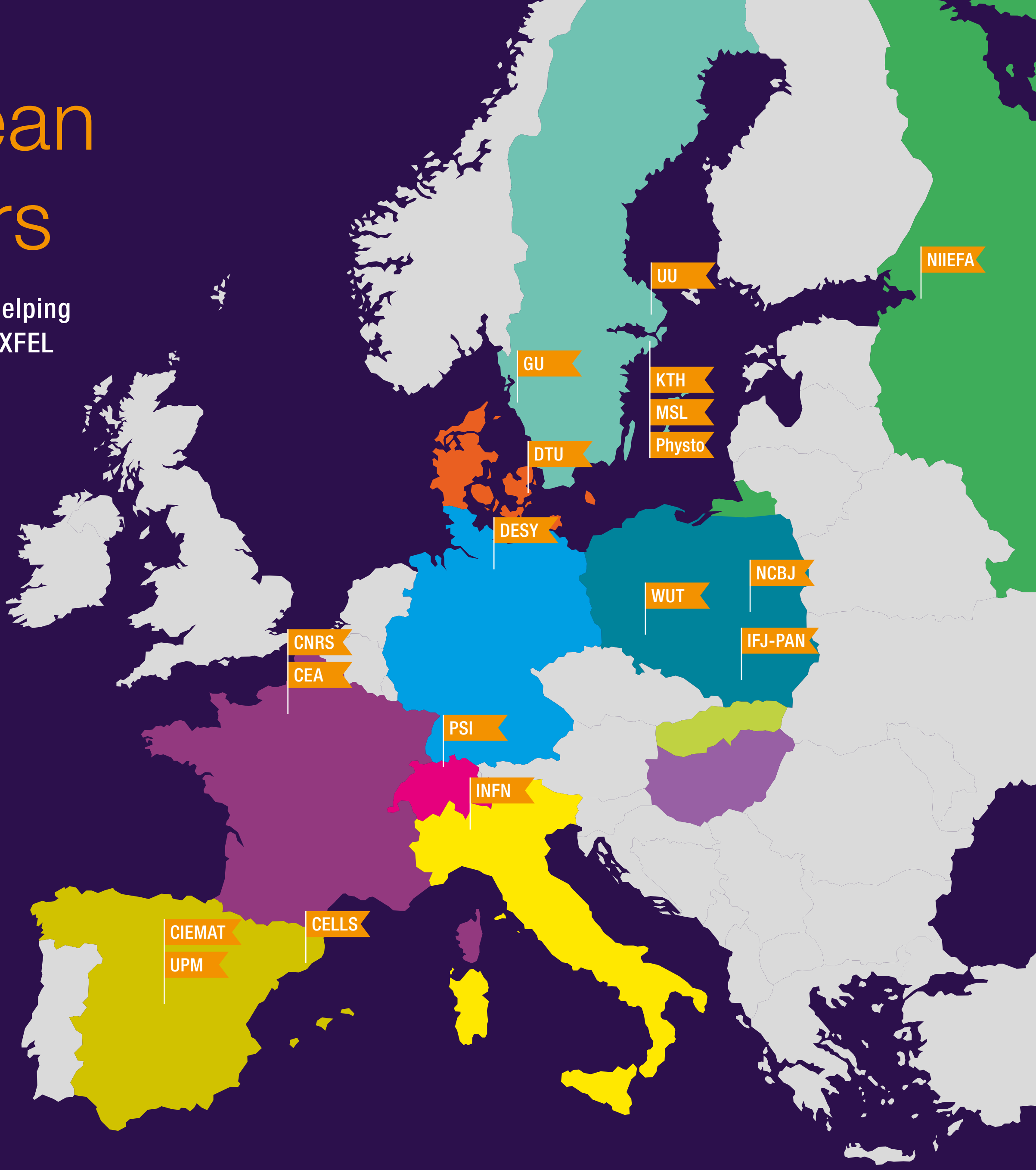
Dosch: With the European X-ray laser facility – in synergy with the outstanding X-ray light sources PETRA III and FLASH that already exist at DESY – a worldwide unique research infrastructure is being created in the Hamburg metropolitan region. Pioneering interdisciplinary research partnerships have already developed around these facilities in recent years – for example the Center for Free-Electron Laser Science (CFEL) and the Centre for Structural Systems Biology (CSSB), which is currently under construction. This development is attracting the best scientists to Hamburg, and it’s also offering high-tech companies a highly attractive environment where they can develop new ideas and technologies whose impact goes far beyond the research environment. In these ways, DESY and its cooperation partners are making a sustained contribution to a new culture of innovation in the Hamburg metropolitan region.

femto: What are the outstanding features of the European XFEL in addition to the scientific aspects?

Dosch: The European X-ray laser is already a beacon of highly professional project management. According to our present state of knowledge, the European XFEL will fulfil all of its projected design parameters, including the project costs. This once again demonstrates DESY’s expertise regarding the design and construction of highly complex particle accelerator facilities. The technologies that will be used at the European XFEL have already pushed back the boundaries of technical feasibility. That applies especially to the two-kilometre-long superconducting accelerator – a DESY technology. To make the European XFEL a beacon of science as well, we will have to make some pioneering scientific discoveries in the years ahead. But I have no doubt whatsoever in this respect – our top scientists are already raring to go.

European partners

Eleven countries are helping to build the European XFEL



Institutions and selected in-kind contributions

The complete detailed list is available at: http://www.xfel.eu/project/in_kind_contributions/

DTU Technical University of Denmark, Copenhagen (Denmark)

- High-tech components for scientific instruments

CNRS Centre National de la Recherche Scientifique, Orsay (France)

- Production of radio frequency couplers for the superconducting linear accelerator

CEA Commissariat à l'Energie Atomique et aux Energies Alternatives, Saclay (France)

- Assembly of modules consisting of eight superconducting cavities each
- Construction of the 103 accelerator modules (including two prototypes)

DESY Deutsches Elektronen-Synchrotron, Hamburg (Germany)

- Design, manufacturing support and testing of the superconducting cavities
- Design, manufacturing support and testing of the accelerator modules
- Cryogenics for the accelerator complex
- Radio frequency provision
- Construction and operation of the injector
- Construction and operation of the main accelerator
- Construction and operation of the beamlines
- Safety monitoring
- Contributions to the facility and IT infrastructure
- Coordination of the entire facility
- Awarding and monitoring of contracts
- Commissioning of the European XFEL

INFN Istituto Nazionale di Fisica Nucleare, Milan (Italy)

- Production, testing and delivery of superconducting cavities
- Cryostats
- 3.9 GHz accelerator module for the injector

NCBJ National Centre for Nuclear Research, Świerk (Poland)

- Production, testing and delivery of HOM couplers and absorbers for the accelerator
- Programmable logic controllers for scientific instruments

WUT Wrocław University of Technology, Wrocław (Poland)

- Production, testing and installation of vertical test stands for the cavity test

- Production, testing and installation of the XATL1 transfer line
- Vertical cryostats

IFJ-PAN Henryk Niewodniczański Institute of Nuclear Physics of the Polish Academy of Sciences, Kraków (Poland)

- Testing of all superconducting cavities, magnets and accelerator modules

JINR Joint Institute for Nuclear Research, Dubna (Russia)

- Design, production, testing and delivery of three MCP-based detectors

IHEP Institute for High Energy Physics, Protvino (Russia)

- Design, production and installation of cryogenic systems for the accelerator
- Design, production and installation of the beam stops

NIIEFA D.V. Efremov Institute of Electrophysical Apparatus, St. Petersburg (Russia)

- Design, production and delivery of normal-conducting magnets

BINP Budker Institute of Nuclear Physics, Novosibirsk (Russia)

- Design, production and testing of magnets, vacuum components and power supply
- Design, production and construction of test stands for superconducting accelerator modules
- Cryogenic equipment
- Power supply

INR Institute for Nuclear Research at the Russian Academy of Sciences, Moscow (Russia)

- Design, production and delivery of transverse deflecting structures and electron beam diagnostics

CELLS Consortium for the Exploitation of the Synchrotron Light Laboratory, Barcelona (Spain)

- Seven mechanical support systems for undulators

CIEMAT Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid (Spain)

- Design, production, testing and delivery of undulator intersections
- Design and production of superconducting beamline magnets

UPM Universidad Politécnica de Madrid, Madrid (Spain)

- Design, production, testing and delivery of the power supply for superconducting magnets

KTH Royal Institute of Technology, Stockholm (Sweden)

- Investigation of X-ray lenses and cooling systems

GU University of Gothenburg, Gothenburg (Sweden)

- Magnetic bottle electron spectrometer

MSL Manne Siegbahn Laboratory of Stockholm University, Stockholm (Sweden)

- Measurement of magnets
- Design, construction and delivery of temperature sensors for the undulators

Physto Department of Physics of Stockholm University, Stockholm (Sweden)

- Configuration, validation and delivery of the timing and synchronisation system

UU Uppsala University, Uppsala (Sweden)

- Design, production and delivery of a laser-controlled sample injector, including laser heating
- Secondment of physicists for equipping the structural biology measuring station

PSI Paul Scherrer Institute, Villigen (Switzerland)

- Design, production and installation of the beam position monitors and intra-bunchtrain feedback systems

The in-kind contributions are the result of cooperations between institutes, and there is some overlap in activities between the partners.

A bike ride through the X-ray laser

Two schoolboys explore the European XFEL

Friday, 19 February, is a grey day. But at least it's not raining as we set out on our bike ride down the road from Hamburg-Sülldorf to Bahrenfeld. Our destination is a long tunnel for a research facility that is expected to generate 27 000 X-ray flashes per second. At this point, we can't really imagine it. We're looking forward to the experience, a bit excited, though also exhausted from the past week at school.

We arrive at Albert-Einstein-Ring and the office buildings of European XFEL GmbH, where we have an appointment with Frank Poppe from the PR group. He's going to ride through the tunnel with us and explain the X-ray laser that is being constructed inside it. But there's no tunnel in sight. First of all, we're given our equipment and a lecture on safety. Each of us gets an access card and a pair of rubber boots with steel caps, because there's still a construction site at the end of the tunnel and safety shoes are mandatory. We also have to wear helmets, in case we bump our heads against the technical equipment in the tunnel or something falls on our heads. When we arrive at the entrance building of the X-ray laser on the DESY campus, each of us also gets a "self-rescuer". It's a self-contained breathing apparatus that looks like a snorkel with a bag, and it enables you to go on breathing for half an hour if a fire should break out in the tunnel. We also get goggles to protect our eyes from smoke. Frank demonstrates the equipment, a bit like a flight attendant showing you how to use the oxygen masks in a plane.

Finally, our tour begins. In the entrance hall is a shaft that's almost 40 metres deep and is securely protected by a railing. A huge indoor crane hanging from the ceiling is used to transport heavy loads down the shaft. This crane is very important, because all the components for the particle accelerator that is being built down there have to go down this shaft and be loaded directly on a special transport vehicle. This includes the yellow pipes weighing several tonnes that contain the components of the accelerator itself. Later on, we see this special vehicle in the tunnel. It's called the Mullewupp (which means "mole" in the local dialect) and it looks like a yellow mining locomotive. On its 360 degree tyres it can move in any direction from a standing position. That's an important skill when it has to manoeuvre inside the narrow tunnel. In addition, it can not only transport loads weighing several tonnes but also jack them up, because the accelerator hangs from the ceiling of the tunnel. To do all that, the Mullewupp needs lots of power, so it has gigantic batteries – using a petrol engine would be too hazardous inside the tunnel.

So, down we go – into the tunnel. Using our access cards, we pass through the safety barrier and push our bikes into the lift, which takes us down seven stories. The accelerator tunnel is built like an underground train tunnel. It's a round concrete pipe with a floor, completely straight, and it's so

long that you can't see the end of it. Yellow accelerator modules are hanging from the ceiling of the right half of the tunnel. The electrons could already start flying here – but they wouldn't get very far, because construction is still in full swing. The temperature in the modules is minus 271 degrees Celsius so the electricity can flow without any resistance. In addition, the electrons fly through a vacuum so that they don't bounce against anything and can be accelerated to almost the speed of light – 300 000 kilometres per second. That's very hard to imagine.

In the left half of the tunnel, there's a path for the Mullewupp and for our bikes. We've got to be careful to travel in a really straight line and not bump into anything. Riding through the tunnel is a weird and exciting experience! To our right are the yellow modules and lots of extremely large magnets. Frank explains that these magnets will help to bundle the electron beam. Two bright blue "dipole" magnets are larger than the others. They come from St. Petersburg and cost 57 000 euros each. They are part of the Russian contribution to the European XFEL. The programme's partner countries don't just contribute money to build the X-ray laser; they also provide important components such as these magnets.

After travelling the first two kilometres through the accelerator tunnel, we reach a plywood door. At that point, we are in a bleak-looking operations building located directly under the Osdorfer Born housing estate. This is where the tunnel divides into two branches, and from here on the electrons will be used to generate the X-ray laser flashes that the researchers are interested in.

We ride our bikes into the tunnel on the right. A few of the yellow structures in which the light flashes will be generated are already standing here. It's hard to remember what they're called. Demulators? Odolators? Emulators? No, these are undulators. Inside them, alternating magnets force the electrons to travel along a slalom course and radiate X-ray flashes. Undulators are strong magnets that can't be turned off, so your watch may get stuck on one of them if you bring it too close.

The yellow-orange undulators are produced in Germany and Spain. There's also another undulator that really stands out because of its neon yellow-green colour. It comes from China, and it works really well, but the Chinese somehow got the colour wrong. It really looks weird!

Then we come to yet another place where the tunnel divides into several branches. The two original tunnels branch into five tunnels in all, and each of these tunnels leads to various measuring stations. Our tunnel eventually becomes very narrow and warm, and we have to ride our bikes very carefully. There are no more undulators here. To our right is only the beam pipe, through which the X-ray laser radiation flies, and lots of testing devices that are used to monitor the light to see if it fulfils all the quality requirements. At last, we come to the end of the tunnel and to another door. We push our bikes through it, out of the tunnel and into the underground experiment hall. This hall is as big as a football field, and several measuring huts are now being built inside it. This is where the researchers will be looking at atoms and filming chemical reactions. In one of these huts, which has thick concrete walls, they will conduct experiments under extremely high pressure and at high temperatures – that is, under the same conditions that exist in the interiors of planets.

We push our bikes into the lift and it takes us back to the surface, where they are building labs and offices at the moment. We ride our bikes to the exit, give back our helmets, rubber boots and self-rescuers, and find ourselves standing in the town of Schenefeld, right next to a big tennis complex. By now it's dark outside. We say goodbye to Frank and ride our bikes home. It's been an exciting trip, but it's also been very tiring. We've seen a lot and learned a lot. And someday we'd like to go back down into the tunnel – this time with our skateboards.

Vincent van Beusekom and Louis Wild are sixth-formers at their secondary school, the Marion Dönhoff Gymnasium in Hamburg-Blankenese. When they're not outdoors on their bikes or longboards, they like to play Minecraft. They're planning to make a film about the X-ray laser facility using the images they recorded with their GoPro cameras.