femto

The DESY research magazine – Issue 01/18

EXTREME!

Physics under high pressure

Superstrong biomaterial
Artificial cellulose fibres outperform steel and spider silk

Edges against exhaust
Catalytic converters with many edges are more efficient

Four in one
Mini accelerator as "Swiss army knife" for electron beams

DESY.

How nanowires grow

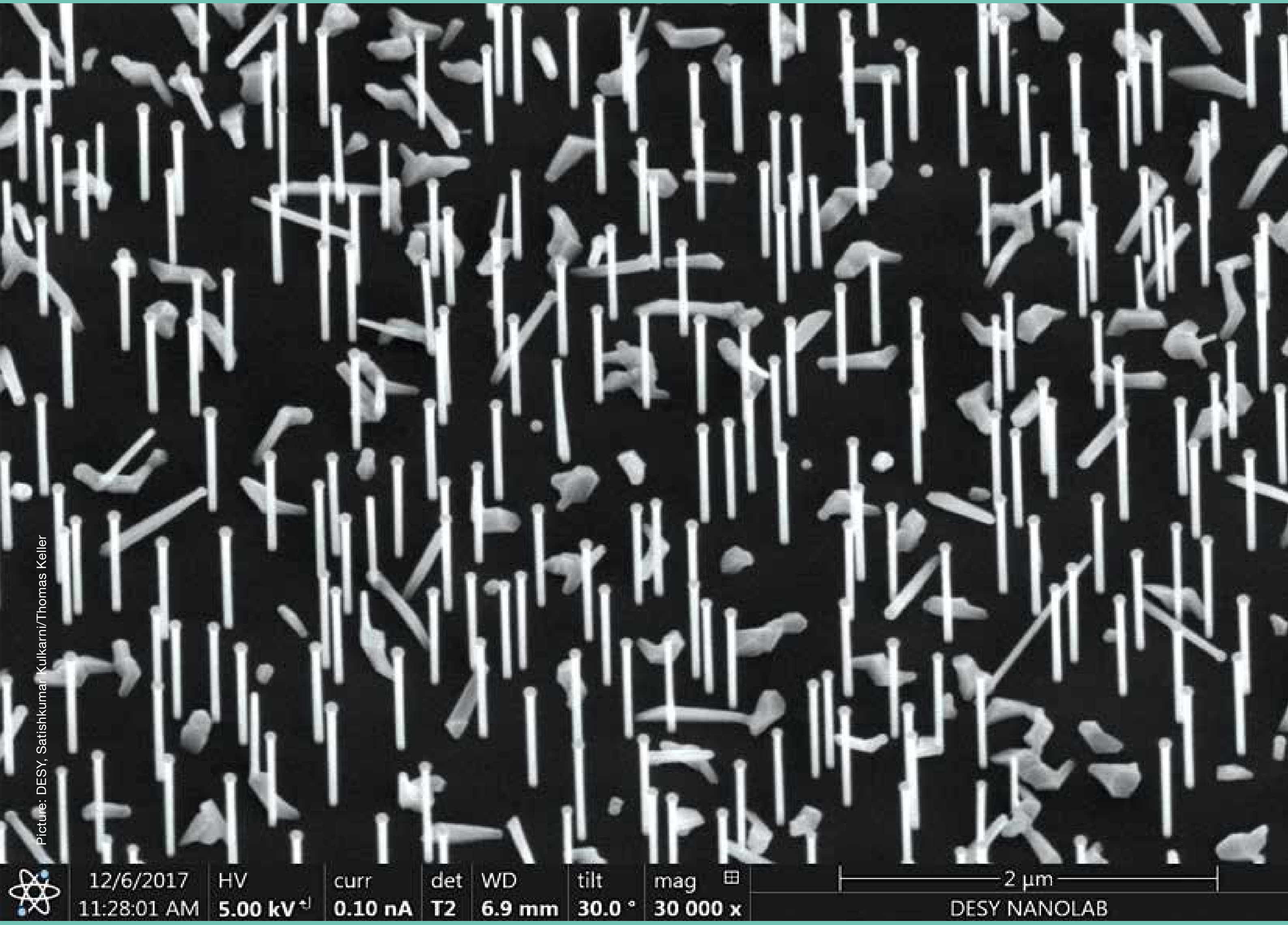
Tiny wires of gallium arsenide with dimensions of millionths of a millimetre were in the focus of an investigation at DESY's X-ray light source PETRA III. Researchers led by Philipp Schroth from the University of Siegen and the Karlsruhe Institute of Technology (KIT) followed in detail how such nanowires grow and form their special shape and crystal structure.

To fabricate the wires, the scientists used a procedure known as the self-catalysed vapour–liquid–solid (VLS) method, in which tiny droplets of liquid gallium are first deposited on a silicon crystal at a temperature of around 600 degrees Celsius. Beams of gallium atoms and arsenic molecules are then directed at the wafer, where they are adsorbed and dissolve in the gallium droplets. After some time, crystalline nanowires begin to form below the droplets, whereby the droplets are gradually pushed upwards. In this process, the gallium droplets act as catalysts for the longitudinal growth of the wires.

The aim of the researchers is to specifically control the crystal structure of nanowires produced in this way in order to tailor nanowires with special properties for specific applications in the future. The semiconductor material gallium arsenide (GaAs) is widely used, for instance in infrared remote controls, in the high-frequency technology for mobile phones, for converting electrical signals into light for fibre-optical transmission and in solar panels for deployment in spacecraft.

Nano Letters, 2018; DOI: 10.1021/acs.nanolett.7b03486

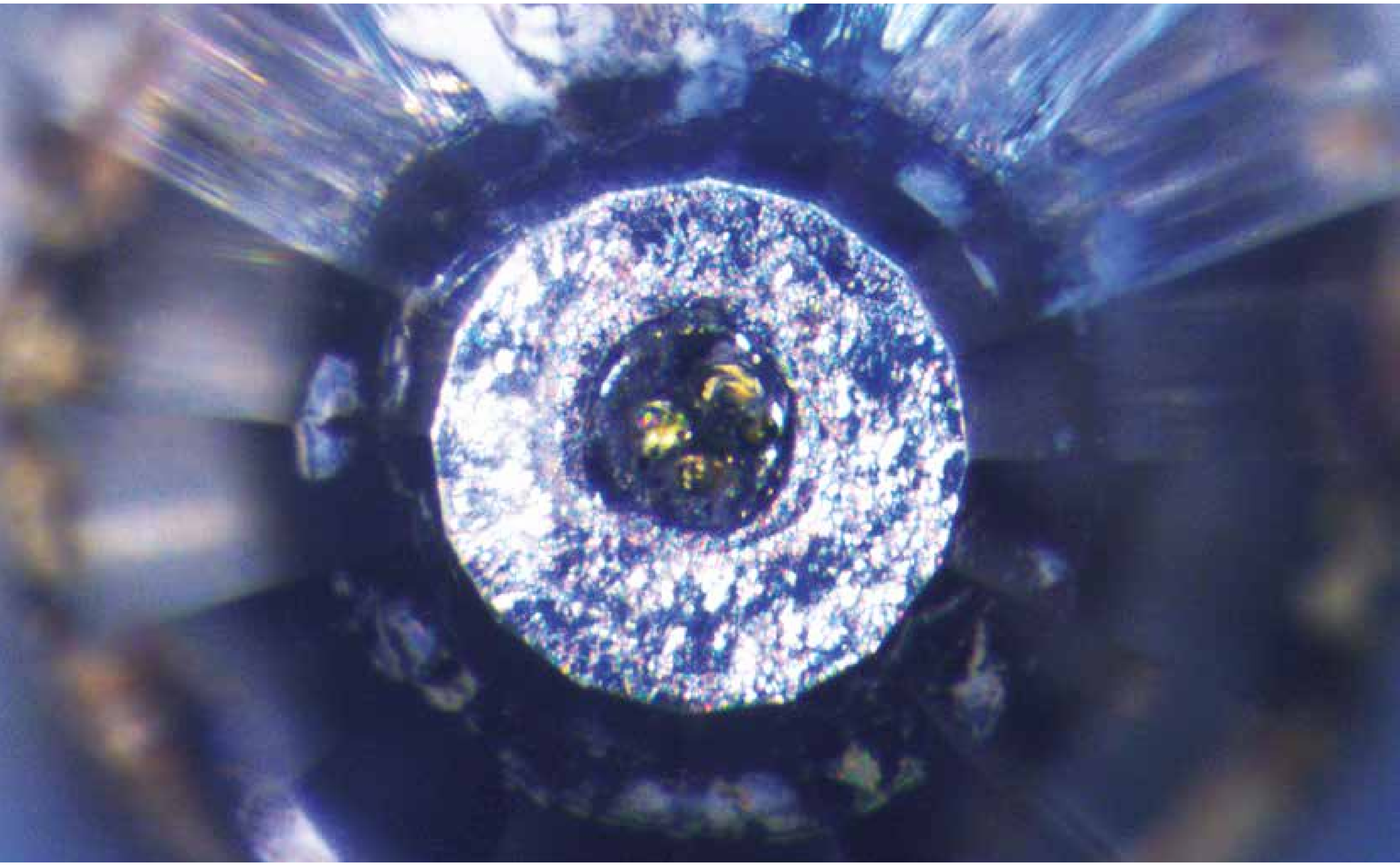
femtoscope



Nano forest

Nanowires growing on a silicon wafer, captured with a scanning electron microscope at the DESY NanoLab

Contents

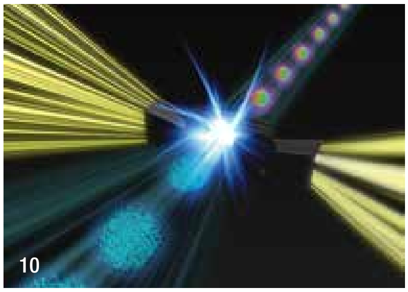


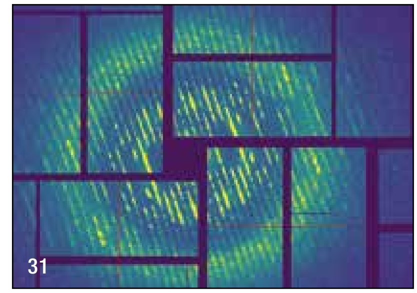
ZOOM

EXTREME!

Researchers generate conditions of high pressure and heat like those in Earth's interior

Polished facets, a symmetrical cut – the object sparkling under the microscope is a real diamond. The tiny jewel has an unusual purpose – it compresses very small samples of material extremely strongly, creating a pressure like that found in Earth's interior. Experts investigate these compressed samples at DESY using high-intensity X-ray light. Their studies provide important fundamental knowledge for geological and materials sciences, chemistry and even astrophysics.





CAMPUS

06 **An international port for science**
DESY's strategy for research and innovation

07 **The world's strongest biomaterial**
Artificial cellulose fibres outperform steel and spider silk

08 **Water with a spin**
Para- and ortho-molecules react differently

10 **Four in one**
Versatile miniature accelerator for electron beams

34 **Efficient corners and edges**
Nanoscale view into catalyst nanoparticles

36 **Top result**
LHC shows interaction of top quark and Higgs boson

37 **3D X-ray images of cells**
Novel microscope concept enables insight into intact biological cells

ZOOM

12 **Physics under high pressure**
When rocks become soft and pliable

22 **Water splitters and current converters**
An interview with John Parise, expert in high-pressure synthesis of novel materials

24 **Ice planets, gas giants and white dwarfs**
How the European XFEL will explore the interiors of distant celestial bodies

28 **Astrophysics in the lab**
FLASH focuses on exotic state of matter

SPECTRUM

30 **Science in brief**

- LEAPS – Light for research
- First X-ray light from plasma accelerator
- Collisions in the Belle II detector
- Amyloids in X-ray light
- Nickel in a carbon mantle
- New light sources at the European XFEL
- Liquid crystals form nanorings

SECTIONS

02 **femtoscope**
How nanowires grow

23 **femtopolis**
Why researchers are pulverising diamonds

33 **femtomenal**
0.000 000 000 000 075 seconds

40 **femtofinale**
Creative collisions

"An international port for science"

Helmut Dosch,
Chairman of the DESY Board of Directors

After a comprehensive process of strategy development, DESY is defining its focus areas in science and innovation for the years ahead and planning the further development of its large-scale research facilities. Helmut Dosch, the Chairman of the DESY Board of Directors, talks about the core elements of the new strategy.

femto: What lies ahead for DESY?

Dosch: We are developing the campus in Hamburg into an "international port for science" with new research centres and facilities, together with our partners from the German government, the City of Hamburg, the University of Hamburg and other research institutions. Our Zeuthen site near Berlin, which we are expanding into an international centre for astroparticle physics, is undergoing a similarly spectacular development.

femto: What does this mean in concrete terms?

Dosch: We are planning to build the ultimate 3D X-ray microscope, called PETRA IV, which will provide images of processes in the nano-cosmos that are 100 times more detailed than is possible today. First experiments at what will then be the world's best synchrotron could begin in 2026. They could yield revolutionary findings in fields such as electric mobility, energy production, information technology and infection research.

femto: How will this relate to the European XFEL X-ray laser facility?

Dosch: PETRA IV is the optimal complement for the European XFEL. DESY is the main shareholder of the European XFEL GmbH, with which it is cooperating closely in order to exploit the full potential of this new "superlaser". Together with our partners, we intend to significantly enhance our role as the world's leading centre for the investigation of matter using X-rays. Our aim is to tailor new high-performance materials and medical active ingredients at the molecular level in the future.

femto: What new technologies are on the agenda?

Dosch: One crucial technological advance for X-ray light sources could be the development of plasma accelerators, which can accelerate electrons 1000 times more efficiently than existing facilities. To this end, we will be testing new concepts in the years ahead. Moreover, we intend to specifically channel our technological excellence toward innovations. That's why we are significantly expanding our technology transfer activities. We want to become an "innovation accelerator" for the establishment of companies and start-ups in the Hamburg and Brandenburg regions.

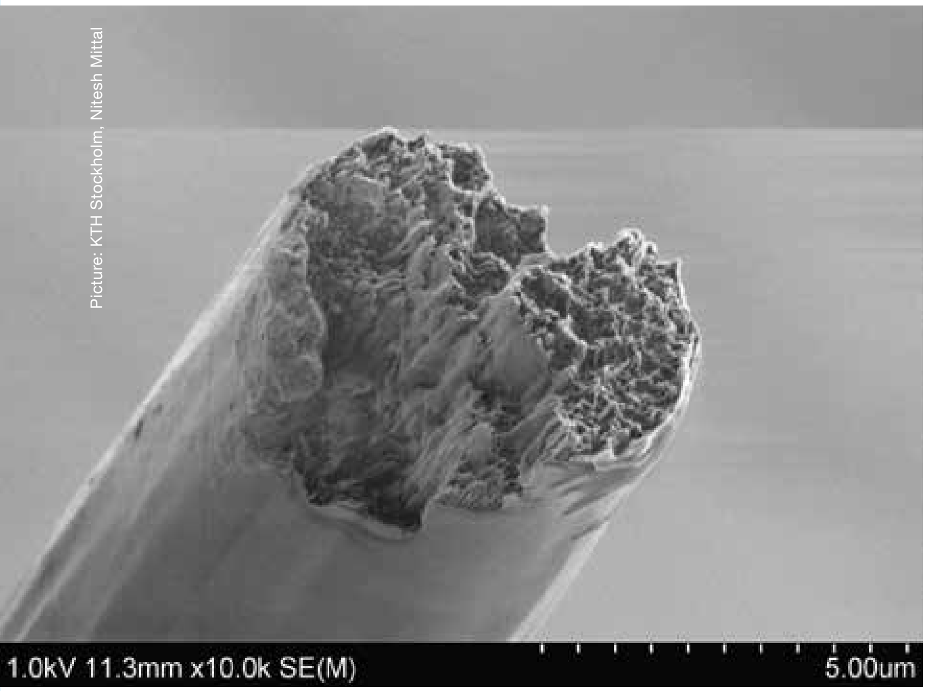
femto: What role will particle physics play in the future?

Dosch: DESY is Germany's most important centre for particle physics, and we intend to enhance our leading position as a key partner in international projects. We are searching for answers to fundamental questions about the quantum structure of our universe – specifically the origins of dark matter. Such answers can be found only through close cooperation of our particle and astroparticle physicists. Our work in particle physics enjoys an outstanding reputation all over the world. And our research campus in Zeuthen combines outstanding expertise in neutrino and gamma-ray astronomy as well as in theoretical astroparticle physics.

femto: And the campus in Hamburg?

Dosch: Together with the University and the City of Hamburg, we are planning an international science park and the targeted settlement of other interdisciplinary research centres. For example, the Wolfgang Pauli Centre brings together experts in theoretical methods, the Centre for Water Science focuses on new analytical questions concerning this vital fluid, and the new Centre for Data and Computing Science is dedicated to the topic of big data in order to meet the growing demands for data-intensive research. Last but not least, we are planning to set up a visitor centre in order to make the fascinating process of decoding matter accessible to everyone interested.

The world's strongest biomaterial



Scanning electron microscope image of the produced fibre

The world's strongest biomaterial ever produced outperforms even steel and spider silk. A team of researchers headed by Daniel Söderberg from the Royal Institute of Technology (KTH) in Stockholm has produced and studied the artifical, biodegradable cellulose fibres at DESY's X-ray light source PETRA III. The fibres are stronger than steel and even than spider silk, which is usually considered the strongest bio-based material.

The ultrastrong material is made of cellulose nanofibres, the essential building blocks of wood and other plant life. Using a novel production method, the researchers have successfully transferred the unique mechanical properties of these nanofibres to a macroscopic, lightweight material that could be used as an eco-friendly alternative for plastic in cars, furniture and airplanes. "Our new material even has potential for biomedicine since cellulose is not rejected by your body," explains Söderberg.

The scientists started with commercially available cellulose nanofibres that are just 2 to 5 nanometres in diameter and up to 700 nanometres long (a nanometre is a millionth of a millimetre). The nanofibres were suspended in water and fed into a small, just one millimetre wide channel milled in steel. Through two pairs of perpendicular inflows, additional deionised water and water with a low pH value entered the channel from the sides, squeezing the stream of nanofibres together and accelerating it.

This process, called hydrodynamic focusing, ensures that the nanofibres align themselves in the desired orientation, thereby self-organising into a tightly packed macroscopic thread. No glue or any other component is needed – the nanofibres assemble into a tight thread held together by so-called supramolecular forces between them, such as electrostatic and Van der Waals forces.

Using the bright X-ray beam from PETRA III, the scientists were able to follow the process in detail and optimise it. "The X-rays allow us to analyse the detailed structure of the thread as it forms as well as the material structure and hierarchical order in the superstrong fibres," explains Stephan Roth from DESY, head of the PETRA III beamline where the threads were spun. "We made threads up to 15 micrometres thick and several metres in length." A micrometre is a thousandth of a millimetre. According to the researchers, the threads can also be produced with greater thickness.

> *"The bio-based nanocellulose fibres are eight times stiffer and several times stronger than natural dragline spider silk fibres"*
>
> Daniel Söderberg, KTH Stockholm

Measurements showed a tensile stiffness of 86 gigapascals for the material and a tensile strength of 1.57 gigapascals. "The bio-based nanocellulose fibres fabricated here are eight times stiffer and several times stronger than natural dragline spider silk fibres," says Söderberg.

"If you are looking for a bio-based material, there is nothing quite like it. And it is also stronger than steel and any other metal or alloy as well as glass fibres and most other synthetic materials." The artificial cellulose fibres can be woven into a fabric to create materials for various applications. The researchers estimate that the production costs of the new material can compete with those of strong synthetic fabrics. "The new material can in principle be used to create biodegradable components," adds Roth.

The new method described in the study mimics nature's ability to assemble cellulose nanofibres into almost perfect macroscale arrangements, like in wood. It thus opens up the possibility of developing a nanofibre material that can be used for larger structures while retaining the nanofibres' tensile strength and ability to withstand mechanical load.

"The new material can in principle be used to create biodegradable components"

Stephan Roth, DESY

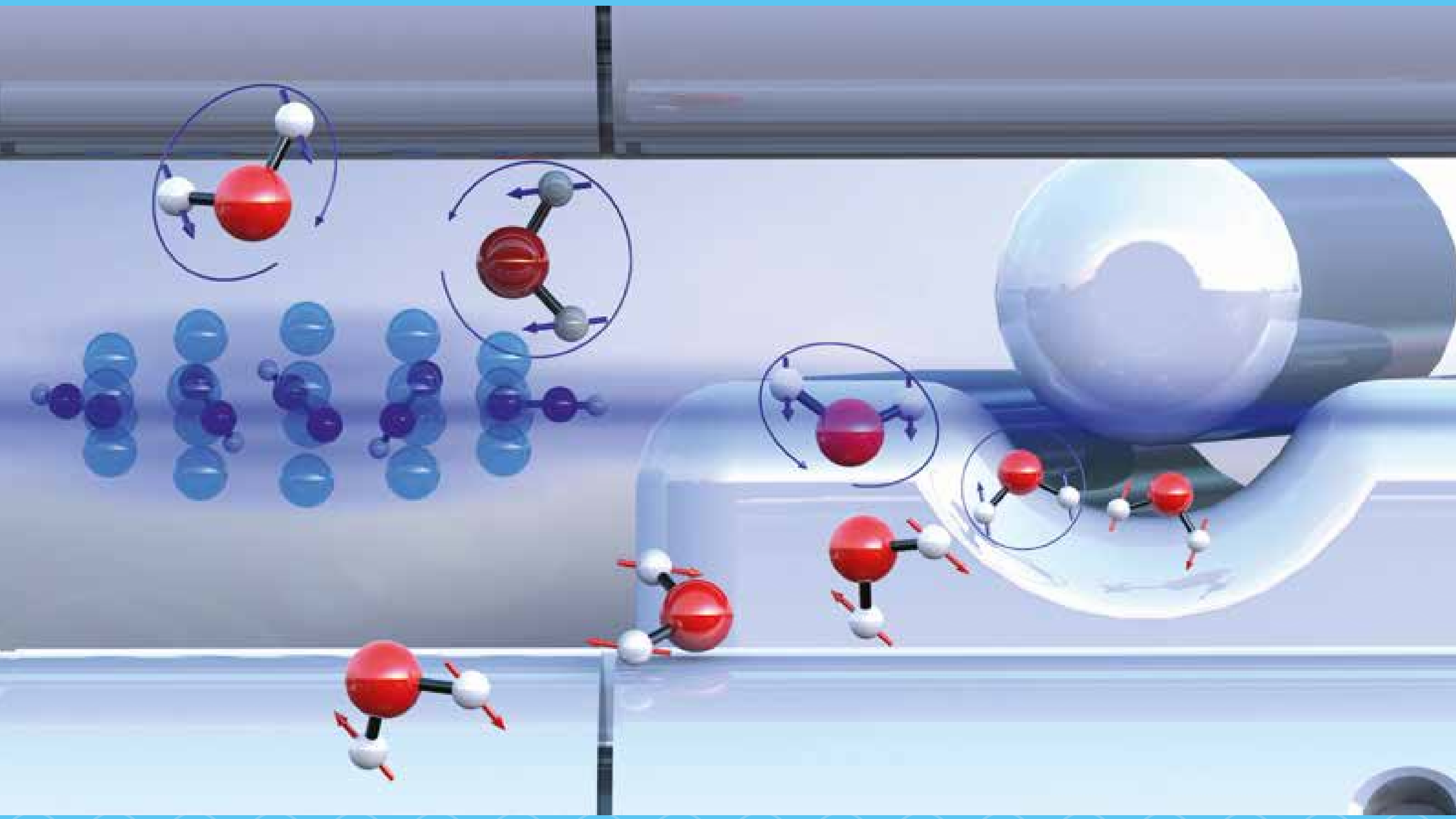
"We can now transfer the super performance from the nanoscale to the macroscale," says Söderberg. "This discovery was made possible by understanding and controlling the key fundamental parameters essential for perfect nanostructuring, such as particle size, interactions, alignment, diffusion, network formation and assembly." According to the researchers, the process can also be used to control the assembly of carbon nanotubes and other nano-sized fibres.

ACS Nano, 2018; DOI: 10.1021/acsnano.8b0108

Water with a spin

Water is not only the most important, but also one of the most complicated liquids on Earth. Without the special characteristics of water, life around us would not be the way it is. From a chemical perspective, water is a molecule in which a single oxygen atom is linked to two hydrogen atoms. It is less well known that, at the molecular level, water exists in two different forms. The difference lies in the relative orientation of the nuclear spins of the two hydrogen atoms. Depending on whether the spins of the two hydrogen nuclei in the molecule are aligned in the same or opposite direction, one refers to *ortho*- or *para*-water. These two so-called isomers exist in parallel and continuously transform into one another, for example through collisions with other molecules.

A research group headed by Stefan Willitsch from the University of Basel has now investigated how the two forms of water differ in terms of their chemical reactivity – their ability to undergo a chemical reaction. To test this



Picture: University of Basel, Ardita Kilaj

Pre-sorted *ortho*- and *para*-water molecules with differently oriented nuclear spins (blue or red arrows) react with diazenylium ions (centre left) at different speeds.

reactivity, however, the two isomers first have to be separated. "*Para*- and *ortho*-water have almost identical physical properties, which makes their separation particularly challenging," explains Ardita Kilaj of the Basel team.

The separation of the two forms of water was made possible by an "electric prism" developed by the group of DESY scientist Jochen Küpper. In the device, the scientists send an extremely thin jet of water molecules through a strong electric field. "*Para*- and *ortho*-water get deflected differently, allowing us to separate them in space and obtain nearly pure *para*- and *ortho*-water samples," explains Küpper.

The spin makes the difference

Using this approach, the Basel researchers and their Hamburg colleagues were able to initiate controlled reactions between the sorted water isomers and ultracold diazenylium ions ("protonated nitrogen") held in a trap. During this process, a diazenylium ion transfers a proton to a water molecule. This reaction is

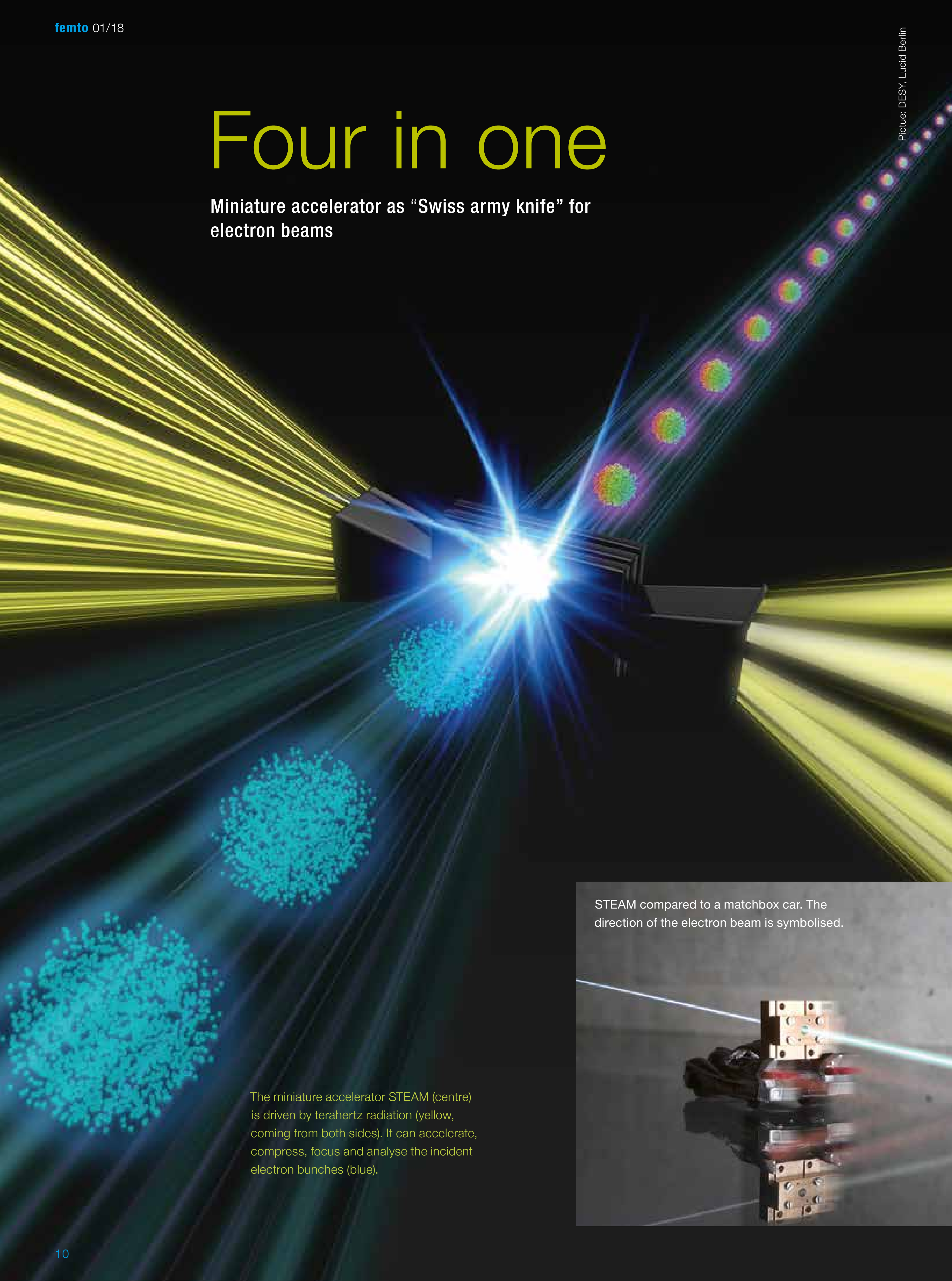
> *"We demonstrated that para-water reacts around 25 percent faster than ortho-water"*
>
> *Stefan Willitsch, University of Basel*

also observed in the chemistry of interstellar space. "We demonstrated that *para*-water reacts about 25 percent faster than *ortho*-water," says Willitsch, who led the research. "This effect can be explained in terms of the nuclear spin also influencing the rotation of the water molecules. As a result, different attractive forces act between the reaction partners. *Para*-water is able to attract its reaction partners more strongly than the *ortho* form, leading to an increased chemical reactivity." Computer simulations confirmed these experimental findings.

Nature Communications, 2018;
DOI: 10.1038/s41467-018-04483-3

Four in one

Miniature accelerator as "Swiss army knife" for electron beams



Pictue: DESY, Lucid Berlin

The miniature accelerator STEAM (centre) is driven by terahertz radiation (yellow, coming from both sides). It can accelerate, compress, focus and analyse the incident electron bunches (blue).

STEAM compared to a matchbox car. The direction of the electron beam is symbolised.

Scientists at DESY have created a miniature particle accelerator for electrons that can perform four different functions at the push of a button. The novel device, called STEAM, is driven by terahertz radiation and can accelerate, compress, focus and analyse electron bunches in a beam – even though its active structures measure just a few millimetres across. Terahertz radiation is located in the electromagnetic spectrum between microwaves and the infrared.

“The active structures are on a millimetre scale”

Dongfang Zhang, DESY

One of the central features of STEAM (Segmented Terahertz Electron Accelerator and Manipulator) is its perfect synchronisation with the electron beam. The scientists achieve this timing by using the same laser pulse to generate an electron bunch and drive the device. “To do this, we take an infrared laser pulse and split it up,” explains Dongfang Zhang from the Center for Free-Electron Laser Science (CFEL) at DESY. “Both parts are fed into non-linear crystals that change the laser wavelength: For the generation of an electron bunch, the wavelength is shifted into the ultraviolet and the laser is directed onto a photocathode where it releases a bunch of electrons. For STEAM, the wavelength is shifted into the terahertz regime. The relative timing of the two parts of the original laser pulse only depends on the length of the path they take and can be controlled very precisely.”

Electrons under control

In this way, the scientists can control with ultrahigh precision what part of the terahertz wave an electron bunch hits when it enters the device. Depending on the exact arrival time of the electron bunch, STEAM then performs its different functions. “For instance, an electron bunch that hits the negative part of the terahertz electric field is accelerated,” explains Zhang. “Other parts of the wave lead to focusing or defocusing of the bunch or to a compression by a factor of ten or so.” While compression means that the electron bunch gets shorter in the direction of flight, focusing means that it shrinks perpendicularly to the direction of flight.

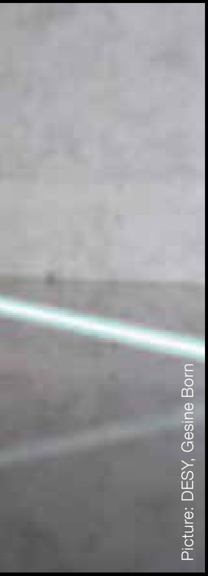
In addition, STEAM allows the scientists to analyse the structure of the electron bunch along the direction of flight. For this technique, called streaking, the incoming electron bunch is deflected sideways in such a way that it becomes smeared out perpendicularly to the direction of flight. When this smeared-out bunch hits a detector, it produces a profile of the bunch along its longitudinal axis. Streaking is regularly used to analyse the bunch structures in particle accelerators. In addition to its three other functions, STEAM can also smear out electron bunches for streaking. “STEAM is a kind of Swiss army knife for electron beams,” says Zhang. To perform multiple functions, such as compression and focusing, several units of the device can be combined.

A hundred times smaller

The use of terahertz radiation also allows for the compact size of the experimental manipulator. “Terahertz radiation typically has a hundred times shorter wavelength than the radio frequency radiation used in today’s big particle accelerators. Therefore, all the structures in the device can shrink accordingly,” explains Franz Kärtner, leading scientist at DESY and professor at the University of Hamburg. Measuring just about two centimetres on the largest side, STEAM easily fits into a matchbox. “And that’s just the size of the housing. The active structures are on a millimetre scale,” adds Zhang.

The STEAM technology is still at an experimental stage. The developers see STEAM as a first major step on the road to a future generation of compact, terahertz-driven particle accelerators. These could enable new applications and complement today’s accelerators. The pocket manipulator can already be put to good use today, however: Accelerator groups around the world are considering it for electron bunch characterisation, as Kärtner points out: “STEAM can be used for future table-top accelerators, but its various functions are also interesting for existing facilities.”

Nature Photonics, 2018; DOI: 10.1038/s41566-018-0138-zvvv



Picture: DESY, Gesine Born

The diamond anvils in a high-pressure cell need a special cut in order to be able to withstand the stresses.

Picture: Science Photo Library, Max Alexander

EXTREME!

Researchers generate conditions of high pressure and heat like those in Earth’s interior

Polished facets, a symmetrical cut – the object sparkling under the microscope is a precious stone. “It’s a real diamond,” says Hanns-Peter Liermann. “It has a special cut. There are only a few companies in the world who can make something like this.” The tiny jewel has an unusual purpose – it compresses very small samples of material extremely strongly, creating a pressure like that found in Earth’s interior. Experts such as Hanns-Peter Liermann investigate these compressed samples at DESY in Hamburg using high-intensity X-ray light. Their studies provide important fundamental knowledge for geological and materials sciences, chemistry and even astrophysics.

PHYSICS UNDER HIGH PRESSURE

Extreme conditions are normal in Earth's interior. The pressure increases to up to several million bar, and the temperature to several thousand degrees Celsius. The soft, pliable rocks are constantly in motion and change the face of our planet. Continents drift, mountains fold into the heights and trenches open up in the ocean. The turbulent motion triggers earthquakes and gives rise to volcanoes. A better understanding of these fundamental processes could conceivably lead to more precise forecasts of earthquakes and volcanic eruptions – a long-held dream of geologists.

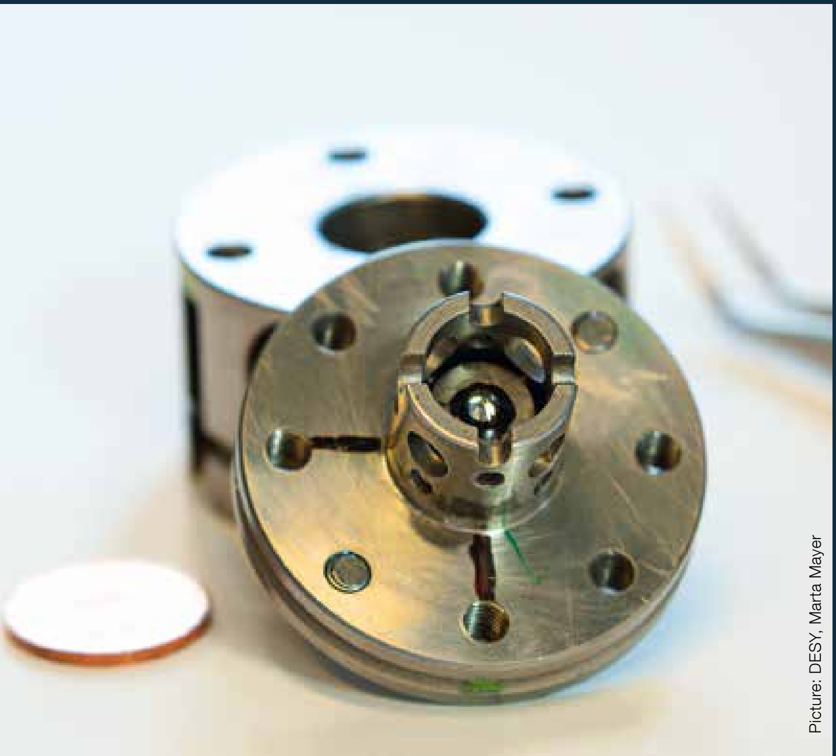
Bores are one direct way to investigate Earth's interior. The problem is that so far, the deepest borehole that people have drilled into the ground for research purposes is just 12 kilometres deep. "Earth's radius is 6370 kilometres, so we're just scratching the surface of our planet," says Hanns-Peter Liermann, a researcher at DESY in Hamburg. "We can't see into the interior of Earth that way." That's why the geoscientists turn to indirect methods. One of their approaches is to simulate the extreme conditions of Earth's interior using diamond anvils and to analyse the samples using intense, collimated X-rays generated by particle accelerators such as the PETRA III storage ring in Hamburg.

In the laboratory, Liermann shows a diamond anvil cell – a metal housing with about the same shape and size as a sweet tin. It contains two opposing diamonds with their points cut off to make the two pressure surfaces that will squeeze the sample. The smaller these surfaces are, the more pressure they can exert on a sample – in exactly the same way as the pressure from a high-heel shoe is greater than that from a slipper. The diamond surfaces are tiny, in some cases just a few tens of micrometres across. The samples that they compress are even smaller, frequently measuring just a few micrometres. One micrometre is a thousandth of a millimetre. These anvils can be used to create pressures as great as those in Earth's core – around 3.5 megabar, more than three million times the atmospheric pressure. Since a few years ago, it has been possible to reproduce the conditions in planets even bigger than Earth, thanks to a two-stage cell that was developed at the University of Bayreuth and which can achieve even higher pressures. This is made possible by an additional

"Deep bores are only scratching the surface of our planet"

Hanns-Peter Liermann, DESY

In high-pressure cells like this one, samples are generally placed on the diamond anvil underneath a microscope. The anvils are usually less than a tenth of a millimetre in diameter.



Picture: DESY, Marta Mayer

Picture: DESY, Marta Mayer

DESY's PETRA III X-ray light source gives a detailed view of the structure of matter. The individual beamlines specialise in different methods.

tiny hemisphere of nanocrystalline diamond mounted on the surface of the first, larger anvil. In 2015, an international research team headed by the University of Bayreuth used this technology to achieve an impressive world record: the highest static pressure ever attained in a lab up to that time. A double diamond anvil cell enabled a sample of the metal osmium to be compressed to 7.7 million atmospheres (nearly 7.7 megabar) – more than twice the pressure at Earth's core. Today, the technology is being used to achieve values as high as 10 megabar.

The measurements are made at the Extreme Conditions Beamline in the large experimental hall at PETRA III. The experiment setup is located on top of a huge low-vibration table. "It has to be as vibration-free as possible or we won't get a clear X-ray picture of the sample," says mineralogist Liermann. He then points to an arrangement of mirrors, lenses and shutters. They are parts of a special laser for generating powerful beams of infrared radiation. The experts use this laser to heat up the samples, because Earth's core features not only extremely high pressures, but also temperatures of several thousand degrees Celsius. Such a pulsed laser can achieve temperatures of up to 10 000 degrees Celsius. If only 2000 degrees are needed for an experiment, a simpler heating method can be used in which an electric current is passed through a small plate of graphite.

A simulated journey to the centre of Earth

In order to use the apparatus to simulate a journey to the centre of Earth, the researchers first carefully tighten several high-precision screws on the cell to align the two diamond anvils. Additional screws are then used to cautiously push the anvils against each other in order to increase the pressure between them in a controlled manner. "You don't even need strong forces for that," says Liermann. "If you tighten the screws too much, the pressure will get so high that the diamonds break." However, the precious stones don't last forever even without such an mishap. After 15 experiments at most, the diamonds are so damaged that they have to be repaired.

At the beginning of an experiment, the pressure on the sample is gradually increased. At the same time, the researchers heat the sample

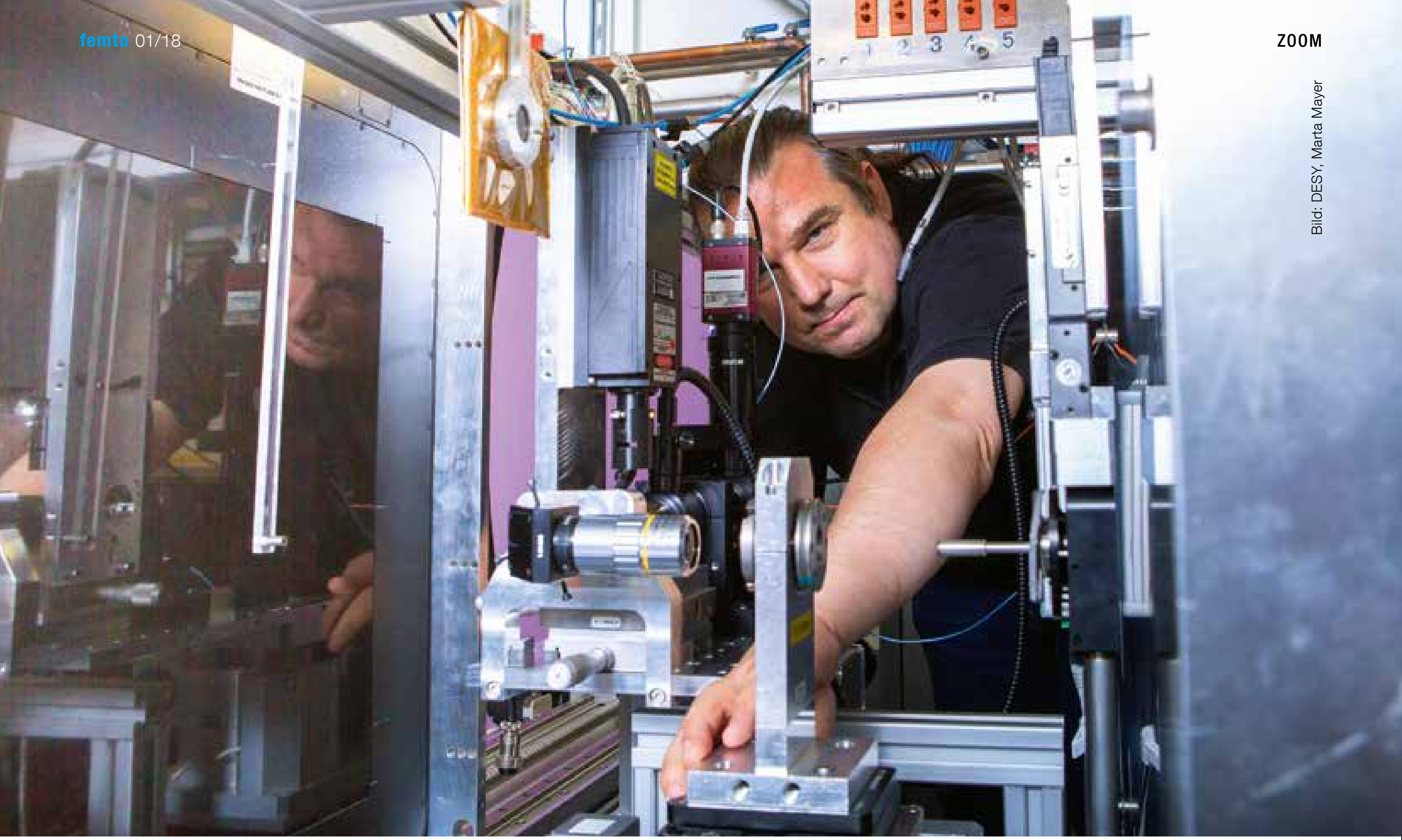


Bild: DESY, Marta Mayer

Hanns-Peter Liermann heads the Extreme Conditions Beamline at DESY's X-ray light source PETRA III.

"Because the samples are so small, we have to use a very fine beam of intense, short-wave radiation"

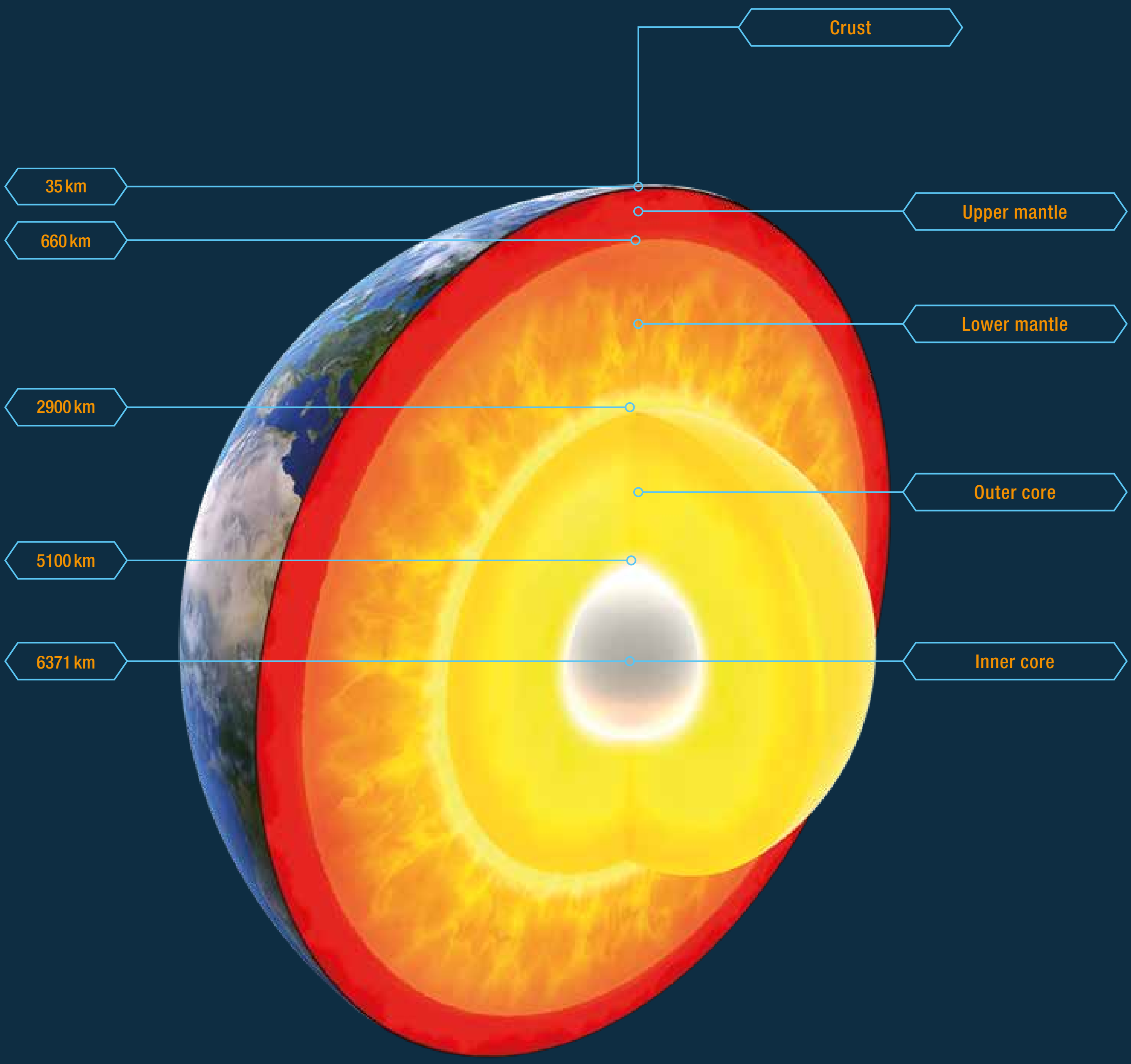
Hanns-Peter Liermann, DESY

up more and more, so that they can scan a broad range of pressures and temperatures. The material is examined with bright X-ray light in order to see how it changes under this torture. "Because the samples are so small, we have to use a very fine beam of intense, short-wave radiation," says Hanns-Peter Liermann. "PETRA III is ideal for this because it can generate beams of X-rays just micrometres in diameter."

The sample's atoms scatter the radiation, and a detector records the resulting diffraction pattern. These measurement data enable the researchers to reconstruct how the sample's density and crystal structure change at high pressures and temperatures. Although geoscientists roughly know the chemical composition of Earth's core, the crystal phases that are present there are only revealed through such high-pressure experiments. This information is important for seismologists, who measure the seismic waves that move through the ground after being triggered by earthquakes. These waves can serve as probes that provide information about the various types of rocks that they pass through and about the states of these rocks. To interpret the signals correctly, however, the scientists need to know what properties the rocks have at high pressures and temperatures. "That's where we come into play," says Liermann. "We can specifically study these physical properties in the lab."

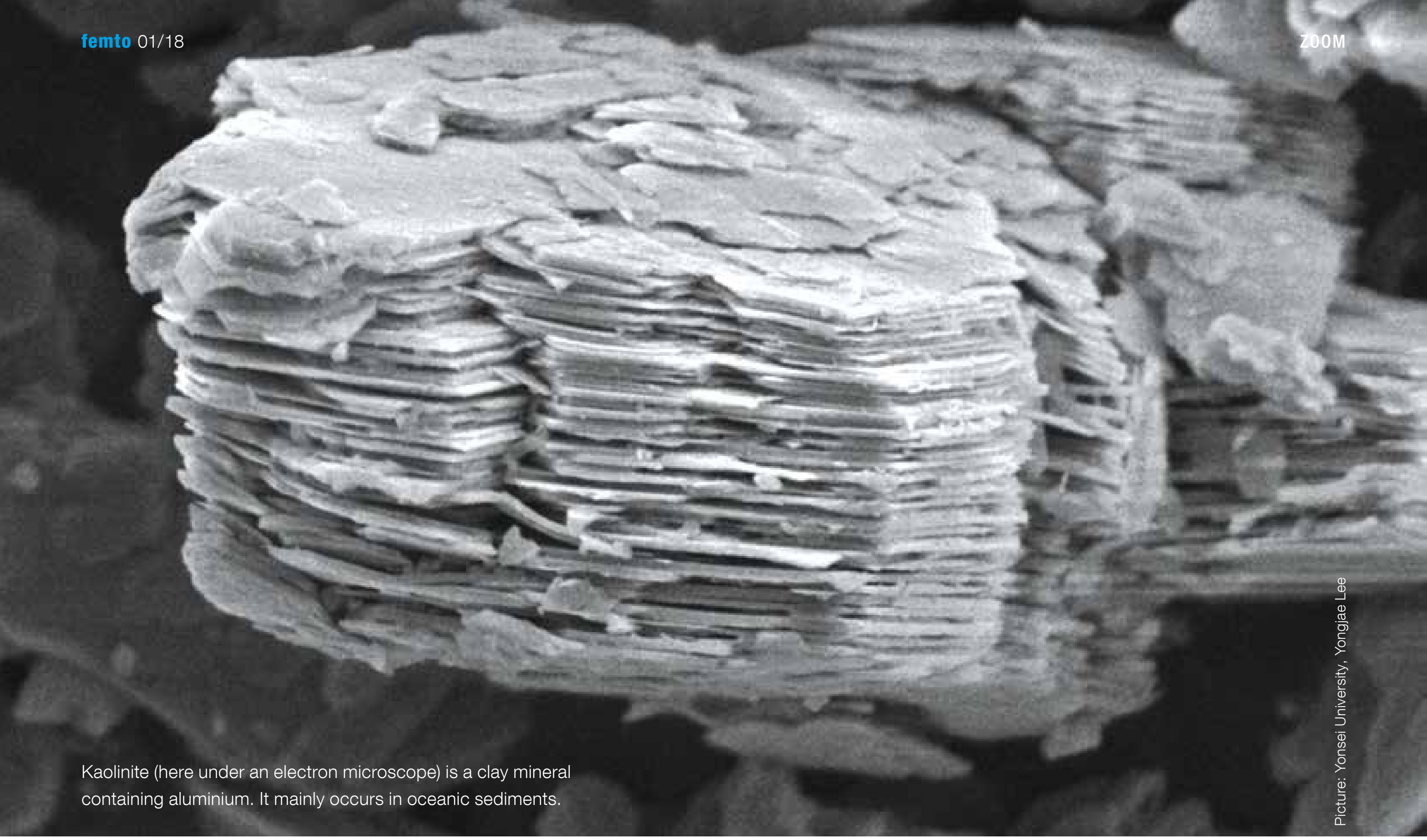
Oceans of magma

Researchers from all over the world perform experiments at the Extreme Conditions Beamline, where they have achieved impressive results over the years. Among other things, they found out that molten basalt changes its structure at a depth of 1500 kilometres in the lower mantle, taking on a denser and more rigid state. This result provides insights into the creation of our planet and supports the hypothesis that the young Earth's mantle contained two underground magma oceans separated by a solid layer. Although these prehistoric magma oceans have crystallised since then, there should still be local pockets of molten basalt.



An expedition into the depths of Earth

From a geological standpoint, Earth is like an onion consisting of several different layers. At the centre is the core, which has a radius of almost 3500 kilometres. It mostly consists of iron and has a temperature of up to 6000 degrees Celsius. Then comes the mantle, which is made of medium-density materials and has a temperature of up to 2000 degrees. Above that is Earth's crust, on the surface of which we live. It consists of lighter rocks and is on average around just 35 kilometres thick – a tiny fraction of Earth's radius of 6370 kilometres.



Kaolinite (here under an electron microscope) is a clay mineral containing aluminium. It mainly occurs in oceanic sediments.

Picture: Yonsei University, Yongjae Lee

Another team of researchers discovered a water-rich new variant of the clay mineral kaolinite, which probably plays a role in the creation of volcanism. Kaolinite is drawn down into the depths of Earth when an oceanic plate pushes underneath a continental plate in a subduction zone. In their experiments, the researchers were able to simulate the conditions in the subduction zones, thereby discovering a new crystalline form of kaolinite that can store unusually large amounts of water. This water-rich phase of kaolinite forms at depths of around 70 kilometres. Subduction then takes it down to greater depths until it breaks down at a depth of about 200 kilometres, where it releases much of its water. This water might promote the creation of magma and thus lead to the formation of eruptive volcanos.

"Until now, using dynamic anvil cells we've only been able to simulate the peripheral areas of an asteroid impact. At the European XFEL, starting in 2019 we will be able to push forward into the core area of an impact"

Hanns-Peter Liermann, DESY

Miniature meteor strikes

PETRA III even enables scientists to simulate meteor strikes – albeit only in miniature. In these experiments, the screws of the diamond anvil cell are not tightened gradually. Instead, special piezo actuators cause the pressure between the diamonds to suddenly increase within a few milliseconds. Geologists compare the types of crystal created in such "dynamic diamond anvil cells" with mineral samples taken from meteorites or from close to the sites of old asteroid impacts. The results can help scientists to better estimate the size and type of the impact.

At DESY, researchers examined, among other things, how quartz behaves during a hard impact. To the surprise of the scientific community, the experiments indicate that certain high-pressure crystal phases would not be formed at the edge of an impact crater. Meanwhile, a team from the University of

Bayreuth discovered why different types of quartz can exist in one and the same lunar meteorite. Scientists had previously assumed that the various types of quartz were created under very different conditions. However, the experiments at PETRA III clearly showed that the various types could also arise under similar conditions, provided that the compression of the materials during the impact was not even but uneven.

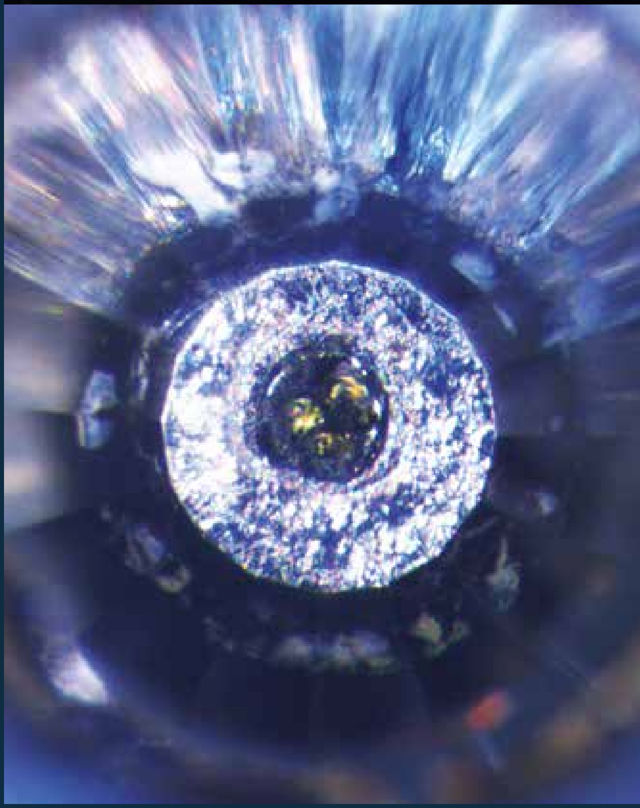
Liermann and his colleagues are now also building a dynamic diamond anvil cell for the European XFEL X-ray laser as part of the HIBEF (Helmholtz International Beamline for Extreme Fields) consortium. The new cell is needed because the huge new facility produces much shorter X-ray flashes than PETRA III. "It will enable us to analyse even faster compression processes than heretofore," says Liermann. "Until now, we've only been able to simulate the peripheral areas of an asteroid impact. At the European XFEL, starting in 2019 we will be able to push forward into the core area of an impact."

A massive block

At around the same time, another high-pressure beamline will go into operation at PETRA III. This Large Volume Press Beamline is currently being erected in the new Paul P. Ewald experimental hall. The huge anvil cell uses a massive block that is 4.5 metres tall and weighs 35 tonnes. The system's six hydraulic anvils can generate a pressure of up to one megabar. Although this is less than that produced by a diamond anvil cell, scientists will be able to compress much larger samples and examine them with X-rays. Instead of measuring just a few tens of micrometres, samples can have dimensions in the millimetre range. In some experiments, the samples will even measure centimetres across – comparable in size to a sugar cube. According to DESY researcher Robert Farla, the advantage here is that "we will be able to analyse real rock samples, which consist of several different phases. This will enable us to address questions that are almost impossible to answer using diamond anvils – for example, how a liquid or molten material is transported in a mineral mixture that is under high pressure."

Because all the six anvils of the press can be operated independently of one another, researchers can compress and deform a rock sample systematically. A laser positioning system ensures that all six anvils can be adjusted with a precision of less than one micrometre. The hydraulic anvils don't press the sample directly, but instead forward the pressure to several secondary anvils made from extremely hard tungsten carbide. These secondary anvils then compress a magnesium oxide mount, which holds the actual rock sample.

"It generally takes one to two hours to achieve the desired pressure," says Farla. "Moreover, we can heat the sample to as high as 2400 degrees Celsius by sending an electric



Pictures: University of Edinburgh, Chrystèle Sanloup

Artificial magma: A research team led by Chrystèle Sanloup from the University of Edinburgh (now Sorbonne University Paris) has used powerful infrared lasers shone through the diamond to heat basalt samples in an anvil cell (bottom) to thousands of degrees Celsius. The study supplied evidence for the existence of underground oceans of magma in the mantle of the young Earth. The three holes that can be seen in the sample (top) result from three heating and measurement cycles.

current through graphite or another heating material around the sample." The press can maintain the pressure indefinitely, making week-long synthesis experiments possible. As a result, it's possible to create highly pure rock samples without any natural impurities as well as samples to which selective elements have been added. Researchers can thus use the lab as a "kitchen" for synthetic crystalline materials.

Electron micrograph of cubic silicon nitride. The grain size is about 150 nanometres (millionths of a millimetre).

"We want to use our giant anvil cell to find out how minerals transform and how liquids or molten materials are transported in rock under extreme conditions"

Robert Farla, DESY

Squeezed samples

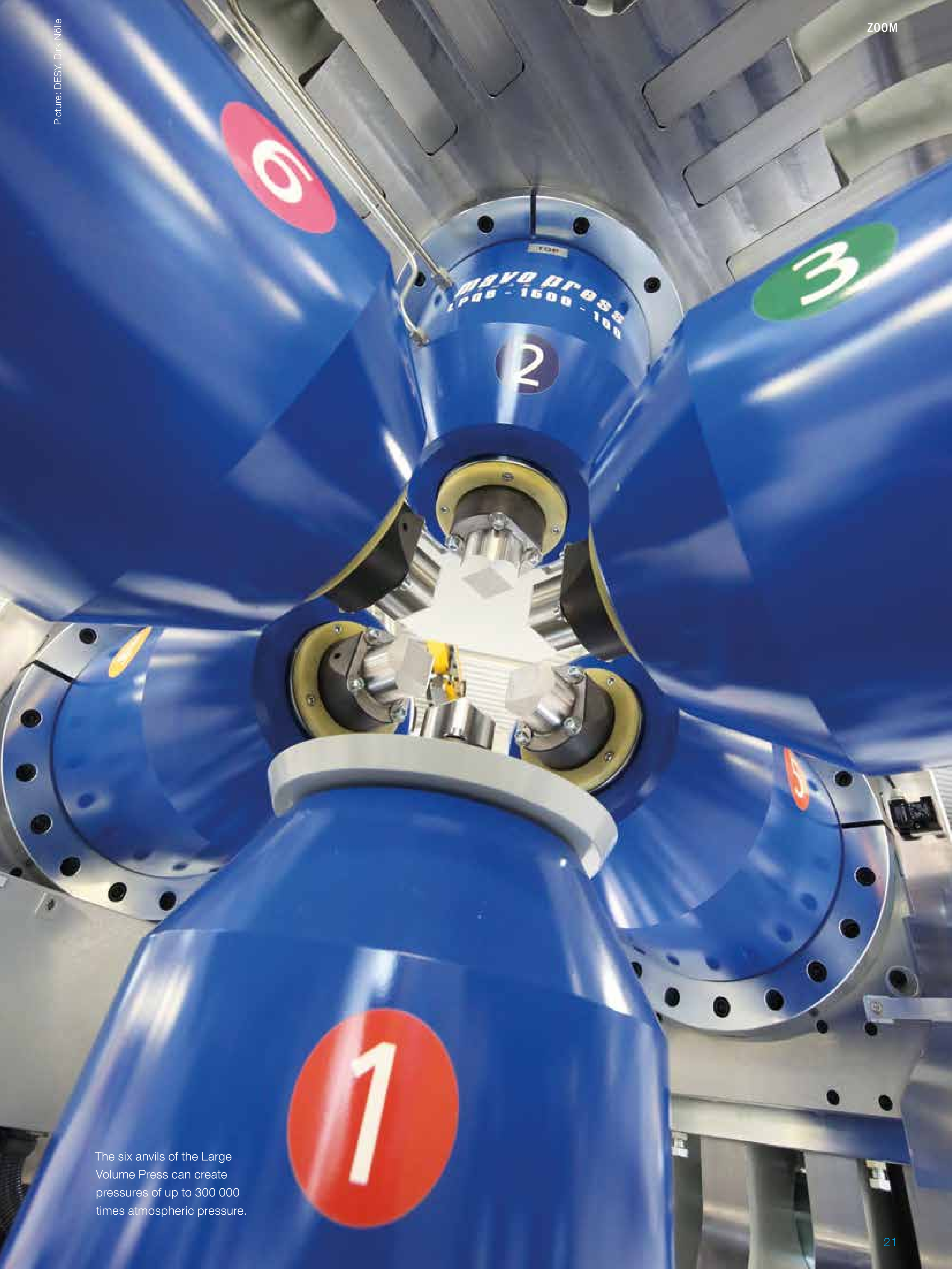
Although the press has been in operation since 2015, it has not yet used the X-rays from PETRA III for sample analysis. However, researchers have been able to conduct experiments even without a beam. Among other things, they have created a new kind of special material consisting of a transparent variant of cubic silicon nitride. This material isn't just transparent, it's also hard and temperature-resistant, which could make it interesting for special industrial applications.

Beginning in 2019, scientists from all over the world will be able to use the millimetre-scale, polychromatic X-ray beam from PETRA III to analyse the samples squeezed by the huge anvil cell. For the samples to be X-rayed completely, the radiation has to be very energetic and intense. To prevent it from getting outside, the experimental hutch has walls made of special concrete up to 50 centimetres thick.

"We want to use our giant anvil cell to find out, among other things, how minerals transform and how liquids or molten materials are transported in rock under extreme conditions," says Robert Farla. "For example, we'd like to know how the flow behaviour of a rock inside Earth is affected by its degree of melting and the size of its grains." The results should help to solve one of the most pressing questions in geoscience: how precisely Earth was created and what made it a habitable planet.

PETRA IV

PETRA III has been available to the international research community since 2010 – as the most powerful X-ray source of its type. However, DESY is already working on plans to upgrade the storage ring. PETRA IV is to deliver even finer beams with considerably greater coherence, i.e. with much more laser-like properties. PETRA IV will open up new horizons for high-pressure experiments. For example, it could be used to analyse mineral mixtures in diamond anvil cells, rather than just pure single phases as at present, and to substantially improve the quality of the images.



Picture: DESY, Dirk Nölle

The six anvils of the Large Volume Press can create pressures of up to 300 000 times atmospheric pressure.

WATER SPLITTERS AND CURRENT CONVERTERS

How high-pressure experiments help to develop new materials

High-pressure experiments such as those conducted at DESY in Hamburg are not only of interest to geoscientists and astrophysicists. Materials researchers also benefit from such investigations, because novel types of materials with interesting properties can be created at high pressures and temperatures. The classic example is the production of industrial diamonds from graphite. John Parise from Stony Brook University in the USA is a renowned expert in the high-pressure synthesis of innovative materials. His team is searching for catalysts that efficiently split water molecules.

femto: What could be done with the help of such water-splitting catalysts?

John Parise: Among other things, our catalysts could help to generate hydrogen as an environmentally friendly and climate-friendly fuel. The idea sounds simple: You put the catalyst into water, expose it to light – and out come hydrogen and oxygen.

femto: Why do you need high pressures for your experiments?

John Parise: The catalysts that we are developing are based on metal oxynitrides – compounds consisting of a metal, oxygen and nitrogen. If you make these compounds under normal pressure, the nitrogen tends to escape. By contrast, if you conduct this reaction in a pressure chamber at several tens of thousands of atmospheres, the nitrogen can be retained in the compound. In addition, the ratios of oxygen and nitrogen in the molecule can be adjusted more effectively under high pressure. As a result, we can control more precisely what kind of molecule is created.

femto: You conduct some of your experiments at a synchrotron, where you can observe the progress of reactions with intense X-ray radiation. What's the advantage of these studies?

John Parise: High-pressure experiments are difficult and time-consuming. A single experiment often lasts all day. But in most cases, a single experiment is not enough. In order to find out what pressure and what temperature are needed to generate the desired molecule, in the past one often had to tinker around for months and conduct time-consuming test series. Today, we can watch the reaction as it happens using the intense X-ray radiation from the synchrotron. As a result, we can find out in a few hours the pressure and temperature we need in order to generate the compound we want. After that, we know the reaction conditions, so we can systematically generate larger amounts back in our own labs and then find out how effectively the compound splits water. The use of synchrotron radiation is accelerating our research tremendously, by a factor of 30 to 40.

femto: Are the experiments at the synchrotron also helping to deepen your understanding of the catalysts?

John Parise: They certainly are. The theoreticians always have new ideas about what an effective water splitter could look like. With the help of synchrotron radiation, we can then say relatively quickly, "yes, these materials actually exist, but they have a somewhat different crystalline structure than predicted." That, in turn, helps the theoreticians to improve and refine their models.

femto: Are you still working on the fundamentals, or can we soon expect to see concrete applications?

John Parise: At the moment, we're still in the initial phase, and we're trying to improve the interplay between theory and experiment. We're making progress, but it's hard to predict if and when our work could be translated into market-ready products. High-pressure syntheses of this kind are expensive. That's why, when we find a promising material, we always look for possible ways to produce it at lower pressures. That applies not only to our work on catalysts but also to researchers who are using high-pressure experiments to search for new superconductors or thermoelectric materials that can efficiently convert heat into electricity.

Why researchers are pulverising diamonds

femtopolis

Picture: DESY, Gesine Born

Diamonds and graphite are two different forms of carbon that can be converted into one another. Researchers have now observed the graphitisation of diamonds in detail for the first time using an X-ray laser.

"Diamonds are forever," sang Shirley Bassey in the 1971 James Bond film of the same name. Today, diamonds are still regarded as the essence of hardness and durability – even though these sparkling jewels made of carbon can burn up under certain conditions. In an engagement ring, the diamond set in gold symbolises the indestructibility of love. Much less romantically, scientists use these robust gemstones in diamond anvil cells to squeeze material samples so hard that the samples yield up the secrets of matter under high pressure – for example, under the conditions in Earth's interior. This is only one of the multifaceted applications of diamonds in research.

But the precious stones are also themselves the objects of research. For example, a team of researchers at DESY's PETRA III X-ray light source has discovered that tiny inclusions of garnet in a diamond contain unusually strongly oxidised iron if the stones were generated at great depths. The researchers suspect that chemical reactions between iron and carbon are taking place in the transitional zone to Earth's lower mantle, and that these reactions may play an important role in Earth's carbon cycle. So diamonds are providing us with deep insights.

But why did another research team go to quite a lot of trouble to pulverise the precious stones into humble graphite – a material that can be found in every pencil lead? Even though this experiment drastically decreased the diamonds' material value, it helped the team to gain scientific knowledge. An X-ray laser enabled the researchers to observe the phase transition between diamond and graphite – both of which are nothing other than different forms of carbon – in detail for the first time. Understanding this graphitisation process is important for all diamond-based technologies, as diamonds are increasingly being used for industrial applications.

Diamonds and graphite differ in their internal crystal structures. Diamond is the high-pressure variant of carbon. It is formed in Earth's interior and is metastable under normal conditions at Earth's surface. This means that, under normal conditions, diamonds transform into graphite on their own if the process is initiated with a sufficient energy input. There are various ways to provide this energy input – for example, heating up the diamond in the absence of oxygen or even subjecting it to mechanical shocks. The process also works in the other direction. Through the use of heat and high pressure, graphite can be transformed into artificial diamonds – for which there is already a considerable worldwide market. So diamond lovers don't need to worry about a shortage!

ICE PLANETS, GAS GIANTS AND WHITE DWARFS

How the European XFEL X-ray laser will explore the interiors of distant celestial bodies

We are in the experimental hall of the European XFEL in Schenefeld near Hamburg. Carsten Bähtz, who is leading us toward the back of the hall, points to a hutch made of heavy concrete that is still surrounded by busy construction activity. "Inside this hutch, we will generate extreme states of matter," explains Bähtz, a physicist from the Helmholtz-Zentrum Dresden-Rossendorf. "We want to create the conditions that exist in the interiors of gigantic gas planets, for example." This hutch is part of HED, one of the six scientific instruments at the European XFEL. The name says it all: HED stands for "High Energy Density". The experiments, which are scheduled to begin in 2019, are expected to reveal new details about the origins of Jupiter, Saturn and distant exoplanets.

"We want to create the conditions that exist in the interiors of gigantic gas planets, for example"

Carsten Bähtz, Helmholtz-Zentrum Dresden-Rossendorf

"We want to generate pressures of up to ten megabar and temperatures of up to a million degrees Celsius," adds Ulf Zastrau, who is responsible for HED at the European XFEL. "Such conditions can be generated statically only with great difficulty by means of diamond anvil cells." The experts will rely on a different method instead, which involves firing ultrapowerful laser pulses at material samples. This process heats and compresses the samples so much that they enter a special exotic state – that of "warm dense matter".

This is the term experts use to describe the transition of matter from a normal solid body to a plasma. Warm dense matter has a structure similar to that of a crystal, but it is almost as energy-rich as a plasma, which is an electrically conductive hot gas. "Warm dense matter is present in the interiors of giant planets, for example," says Gianluca Gregori, a professor of physics at the University of Oxford. "However, we suspect that it also exists in white dwarfs." White dwarfs are old stars whose fuel has run out.

A million degrees

In order to generate warm dense matter in the laboratory, you need big, powerful lasers. These lasers are mounted on the roof of the HED concrete hutch – on the first floor, so to speak. They are being made available by HIBEF (Helmholtz International Beamline for Extreme Fields), an international user consortium led by the Helmholtz-Zentrum Dresden-Rossendorf. "We're setting up two lasers," says the project head from HIBEF, Toma Toncian. "One of them generates very short and intense light flashes with a power of up to 300 terawatts per pulse." The other laser has been designed to generate high-energy pulses with an energy of up to 100 joules. Both of these lasers should be able to deliver up to ten light flashes per second.

Such a 100-joule laser pulse will be able to heat up the surface of a material sample to a temperature as high as one million degrees Celsius within fractions of a second. "Metaphorically speaking, the laser delivers a hammer blow," explains Zastrau. "And this

Ulf Zastrau, European XFEL

Experimental chamber of the High Energy Density Science instrument at the European XFEL X-ray laser.


Picture: European XFEL, Jan Hosan

The 3.4-kilometer-long X-ray laser supplies a total of six scientific instruments with ultrabright X-ray flashes.

> *"Metaphorically speaking, the laser delivers a hammer blow"*
>
> *Ulf Zastrau, European XFEL*

hammer blow sends a shock wave through the material." This wave compresses and heats up the sample and thus produces a state of warm dense matter. However, the whole process lasts less than a billionth of a second – after that, the sample has evaporated and literally been pulverised. "So we have only a tiny time slot to investigate this phenomenon," says Zastrau. "We can do that only with the X-ray flashes of the European XFEL."

The European XFEL facility, which is 3.4 kilometres long, is the world's biggest X-ray laser. It is based on the world's longest superconducting particle accelerator, which speeds up electrons to almost the speed of light and sends them through special magnet structures called undulators. The undulators force the speeding electrons to fly along a slalom course. As a result, the particles emit short and extremely intense X-ray flashes that end up in the gigantic underground experimental hall in Schenefeld, distributed among six scientific instruments.

Ultrafast snapshots

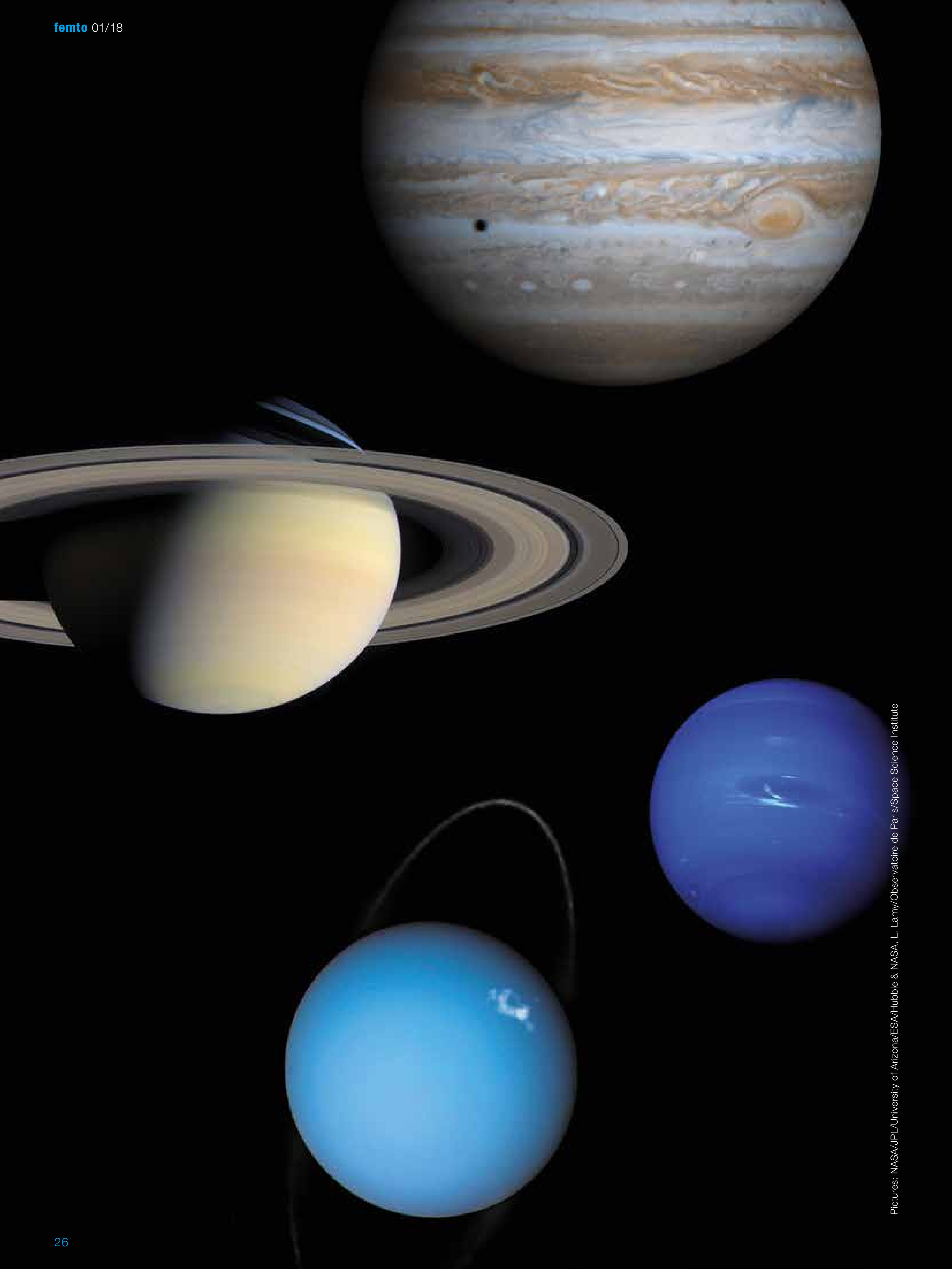
Synchrotron X-ray light sources such as PETRA III are ideal for continuously and non-destructively following chemical and physical processes, such as those in materials under high pressure, in space and time. By contrast, X-ray lasers such as the European XFEL deliver ultrashort X-ray pulses that are billions of times brighter and have laser properties, so that they enable snapshots of extremely fast processes. That's why X-ray lasers are ideal for studying warm dense matter in detail. "Because this state of matter exists for only very short periods of time, we need extremely short X-ray flashes in order to be able to analyse it," says Gianluca Gregori. "The European XFEL is the ideal tool for this purpose."

Among other things, the scientists want to investigate the processes occurring in the interiors of planets – ranging from worlds of ice like Neptune to gas giants like Jupiter, as well as distant "super-Earths". These are rocky planets outside our solar system, and astronomers are discovering more and more of them. The most intriguing question about them is: Could some of these worlds offer conditions that make the emergence of life possible?

One promising discovery might be a planet that, like Earth, has a magnetic field protecting it from cosmic radiation. "Whether a planet has a magnetic field or not might depend on the properties of warm dense matter," Gregori explains. "The magnetic field could then serve as a protective shield for the emergence of life." The experiments conducted at the European XFEL should provide more details about the properties of warm dense matter as well as crucial data for refining the theories of how planets develop.

Gas planets in the lab

In the case of ice giants such as Neptune and Uranus, the experts want to find out how water and methane behave at high pressures and temperatures. They suspect that methane splits into carbon and hydrogen in the planets' interiors. The carbon might even solidify into nano-diamonds – in a process that researchers have already demonstrated in the laboratory. Another interesting question is: What is happening to the water that is believed to exist in large quantities in the interior of Neptune? Does it turn into ice under high pressure, or does it change into a phase that has so far been hypothetical – that of "superionic", highly electrically conductive water?



Pictures: NASA/JPL/University of Arizona/ESA/Hubble & NASA, L. Lamy/Observatoire de Paris/Space Science Institute

Gas giants and super-Earths

With the help of the European XFEL X-ray laser, researchers are also venturing forth into distant worlds. The facility enables them for example to simulate and investigate the conditions in giant gas planets such as Jupiter, Saturn, Neptune and Uranus (left, top to bottom). This laboratory-based astrophysics research is also expected to answer questions about the formation of large rocky planets in other solar systems, which are known as super-Earths (right, drawings).

ASTROPHYSICS IN THE LAB

The FLASH free-electron laser focuses on exotic states of matter

Experts at the European XFEL are planning spectacular experiments in order to simulate the interiors of gigantic planets and certain types of stars. Important pioneering experiments in this area have already been conducted at DESY using FLASH, the prototype of all X-ray free-electron lasers. The FLASH facility generates intense laser pulses consisting of "soft", i.e. relatively long-wave X-rays.

"FLASH provides short laser flashes that we split into two halves by means of a special technology," explains DESY physicist Sven Toleikis. "With the first half, we create the warm dense matter. We can slightly delay the second flash so that we can use it to analyse this state of matter." The time interval between the "producer" pulse and the "observer" pulse can be varied as needed. As a result, the researchers can follow a kind of slide show that shows how the creation of the exotic state of matter proceeds.

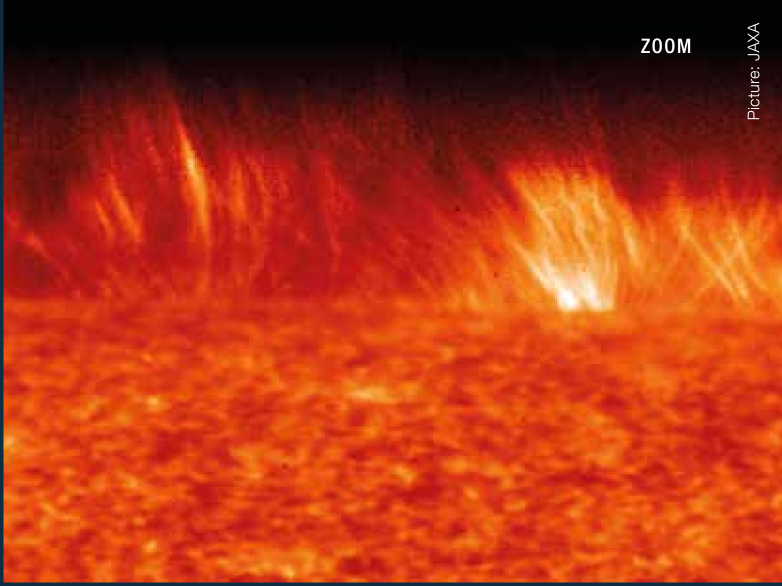
In one of their experiments, the experts fire their FLASH pulses at thin films of aluminium. As a result, a state of warm dense matter forms for a few nanoseconds at a temperature of many thousands of degrees Celsius. A tenth of a second later, it is followed by the next pulse at another spot. The aluminium film is literally scanned.

These experiments have delivered relevant basic knowledge: The scientists have found out how the energy of the laser pulses was transferred first to the electrons and then to the atomic nuclei of the aluminium. "Experimental data of this kind is important, because it enables us to improve the theories concerning warm dense matter," says Toleikis. "At the moment, our theories are still fairly erroneous."

In addition, the physicists shot the laser flashes at tiny droplets of liquid hydrogen at a temperature of minus 250 degrees Celsius. The gas is the main component of giant planets such as Jupiter and Saturn, and liquid hydrogen has a density similar to the one suspected to prevail in the lower atmospheric layers of these gas giants.

The experiments at FLASH showed, in a kind of super slow motion, how the cold hydrogen was suddenly heated up to 12 000 degrees. This enabled the scientists to draw conclusions about its thermal conductivity and certain energy exchange processes – factors that are important for planetary models.

Picture: DESY, Heiner Müller-Elsner



Picture: JAXA

The lower regions of the sun's atmosphere, photographed by the Hinode probe of the Japan Aerospace Exploration Agency (JAXA)

Yet another focus is on the interior processes of gas giants such as Saturn and Jupiter, which consist of hydrogen and helium. Jupiter is the largest celestial body in our solar system after the sun itself. It has a greater mass than all of the other planets put together. Its interior might be characterised by pressures of up to 50 million atmospheres and temperatures of up to 10 000 degrees Celsius – the conditions of warm dense matter.

In the interiors of such gas giants, hydrogen and helium become liquid below a certain depth – that's how great the pressure is. "Helium and hydrogen will readily mix if both of them are gaseous or liquid," says Zastrau. "That doesn't happen if only one of them is liquid and the other one is still gaseous." In the latter case, droplets of helium could form in a hydrogen atmosphere, for example – that's the theory, at least. In order to test it, the researchers depend on laboratory experiments. "A probe will never be able to fly into a gas giant to such a depth," says Zastrau. "It would never survive."

Reproducing the sun's atmosphere

That also applies to processes that take place at even greater depths. There, the gigantic pressure could turn hydrogen metallic – that is, capable of conducting electricity. Some time ago, several research teams claimed to have discovered experimental evidence of a metallic phase of hydrogen. However, these results have been disputed and have given rise to controversial discussions. "With the X-ray flashes of the European XFEL, we'll be able to take a much closer look and resolve this debate," says Zastrau.

"A probe will never be able to fly into a gas giant to such a depth"

Ulf Zastrau, European XFEL

The findings will help scientists gain a better understanding of how the gas giants came to be and to predict their future fate more precisely. For example, a mantle of metallic hydrogen, just like extensive demixing zones, could enable heat to be effectively transported outward from the planet's interior. As a result, the planet would cool off relatively quickly. That, in turn, would prevent nuclear fusion from taking place in its interior – so the gas giant would remain a planet rather than becoming a sun.

Researchers at the HED instrument will also be able to reproduce the conditions existing in the atmosphere of a star. One of the questions that interest them is how iron, traces of which exist in the sun's atmosphere, affects the dispersion of light on the sun's surface. "Iron atoms can store light, so to speak," explains Zastrau. "That means light takes longer to leave the sun." The physicists are planning to use the European XFEL to create an artificial solar atmosphere – a plasma made of highly charged iron. By means of the X-ray flashes, they want to measure how much light is absorbed by the iron as a function of its degree of ionisation – a detail that could refine our understanding of the sun.

Particles at full blast

Finally, the X-ray laser could help to solve a riddle of astrophysics. For quite some time, special telescopes have registered high-energy radiation emitted by sources including supernova explosions, whose origin is still unknown. The experts suspect that a special acceleration mechanism is involved. It could be that collision-free shock waves are accelerating electrically charged particles – similar to the way an ocean wave pushes a surfer along in front of it.

"To find out whether such a phenomenon actually occurs, we want to build a model of it at the HED instrument and investigate it by means of X-ray flashes," says Zastrau. The principle behind the model is as follows: A high-intensity laser is fired at a material sample, releasing vast numbers of electrons within the material. The electrons are accelerated in one direction – and should generate a kind of slow electric countercurrent in the other direction. According to the hypothesis, this could create the long-sought-after shock wave – a phenomenon that should be deteclable at the European XFEL.

LEAPS – Light for research

The recently founded League of European Accelerator-based Photon Sources (LEAPS) has drawn up its joint strategy for the next ten to fifteen years. The consortium presented the LEAPS Strategy 2030 to Jean-David Malo, Director with the Directorate General for Research and Innovation of the European Commission.

"Light from particle accelerators plays a crucial role in studies carried out in virtually every area of the natural sciences – from physics, chemistry and biology, through energy research, medicine and transport, to studies in cultural history," said DESY Director Helmut Dosch, who put forward the idea of LEAPS and who chairs the consortium. "National light source facilities in different countries have so far mostly been developed and operated independently of each other, yet they have much in common, because most of their scientific objectives are very similar."

Europe hosts 13 synchrotron radiation sources and six free-electron laser facilities, all of them are founding members of LEAPS. They represent a multi-billion euro investment, serving more than 24 000 direct users every year. "By bringing together the community of national and pan-European synchrotrons and free-electron laser facilities, the LEAPS initiative should be encouraged as it aims at structuring the European landscape of research infrastructures, coordinating strategic investments and facilitating transnational access," emphasised Malo.

Picture: LEAPS

Caterina Biscari, Director of the ALBA synchrotron in Spain and Vice Chair of LEAPS, presented the LEAPS Strategy 2030 to Jean-David Malo, Director at the Directorate General for Research and Innovation of the European Commission.

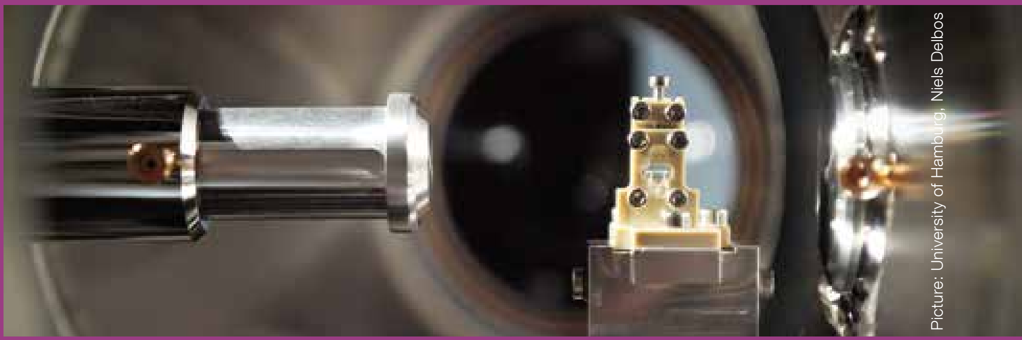
First X-ray light from plasma accelerator

A plasma accelerator at DESY has produced X-ray radiation for the first time. The LUX facility, which is headed by Andreas Maier of the University of Hamburg, created ultrashort pulses of radiation with a wavelength of nine nanometres (millionths of a millimetre), corresponding to so-called soft X-rays. "This is an important milestone in the development of novel, accelerator-driven X-ray sources," the head of accelerator physics at the University of Hamburg, Florian Grüner, pointed out. LUX (Latin for "light") is part of the LAOLA collaboration between DESY and the university.

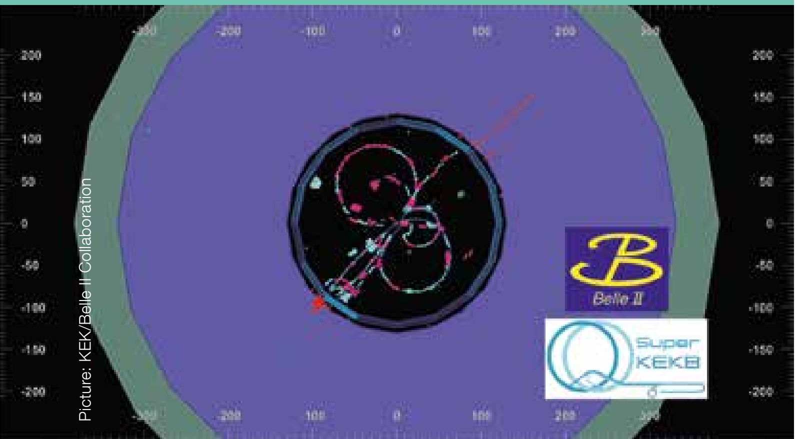
"I am very pleased that another important success could be achieved in these novel accelerator research activities, which were set up a few years ago," said the Director of the DESY Accelerator Division, Reinhard Brinkmann. "The development of the next generation of compact accelerators is an essential pillar of our strategy for the future at the research campus."

Physicists are hoping that the technology of plasma acceleration will lead to a new generation of high-performance particle accelerators with unique properties for a range of applications. In this technology, a laser or a beam of high-energy particles creates a plasma wave inside a fine capillary. Plasmas are electrically conductive gases. At the moment, the technology is at an experimental stage; a considerable amount of development work will be necessary before it can be put to practical use.

The plasma cell of LUX (centre) accelerates the electrons.



Picture: University of Hamburg, Niels Delbos



Picture: KEK/Belle II Collaboration

Event display of a collision in the Belle II detector

Collisions in the Belle II detector

After eight years of refurbishing, particles have collided in the SuperKEKB accelerator for the first time. SuperKEKB is located at the KEK research centre in Tsukuba, Japan, and is meant to produce more particle collisions during its operating life than any other accelerator ever before. The collisions between electrons and their antiparticles, the positrons, take place inside the particle detector Belle II, which has also been completely redesigned, a process in which DESY and other German research groups have been significantly involved.

Belle II is specifically designed to look for physical phenomena extending beyond the previously explored realms of physics. It specialises in measuring rare particle decays, for example that of so-called bottom quarks, charm quarks or tau leptons. The over 750 scientists involved in the project hope that the results will help them to unravel the mysteries of dark matter, track down new phenomena and explain the imbalance between matter and antimatter in the universe.

The first collisions are a milestone on the way to launching the research programme at Belle II. The accelerator has been fitted with a new system of focusing magnets and a new damping ring. Both of these ensure that the particle beams are extremely narrow and compressed, so that as many particles as possible collide with each other.

Amyloids in X-ray light

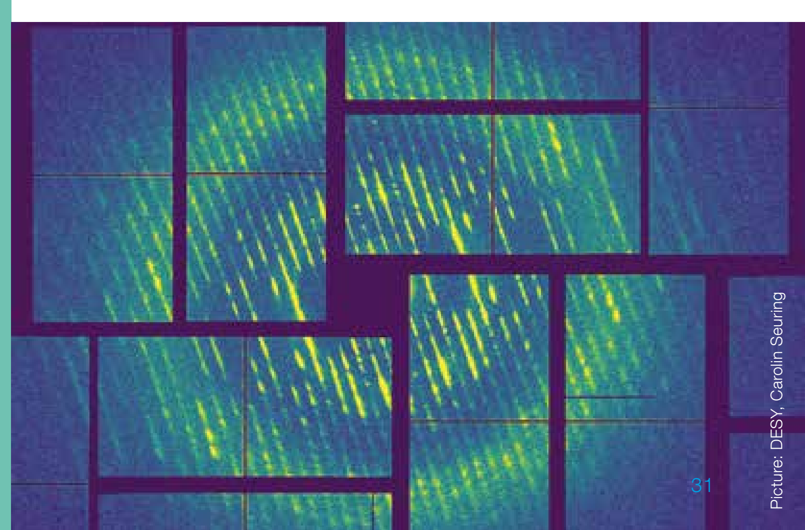
A new experimental method enables the X-ray analysis of amyloids, a class of large, filamentous biomolecules that are an important hallmark of diseases such as Alzheimer's and Parkinson's. An international team of researchers headed by DESY scientists has used an X-ray laser to gain insights into the structure of different amyloid samples. The study opens up a new way of analysing the structure of these protein filaments.

The scattering of X-rays by amyloid fibrils produces patterns similar to those obtained by Rosalind Franklin from DNA in 1952, which eventually led to the discovery of its now well-known double helix structure. The LCLS X-ray free-electron laser at the SLAC research centre in the USA, which was used for this study, is trillions of times more intense than Franklin's X-ray tube, thereby opening up the possibility to examine individual amyloid fibrils, the constituents of the amyloid filaments.

With such powerful X-ray beams, however, the signal of the tiny fibrils is easily lost in the radiation scattered by ambient material, such as the carrier liquid for the samples. The researchers solved this problem by storing their samples on an ultrathin graphene support, a film of carbon only one atomic layer thick. This thin sample carrier scattered so little that even extremely weak signals could be recorded. The method marks an important step towards studying individual molecules using X-ray lasers, a goal that structural biologists have long been pursuing. The researchers tested their method with amyloids and samples of the tobacco mosaic virus, which also forms filaments.

Nature Communications, 2018; DOI: 10.1038/s41467-018-04116-9

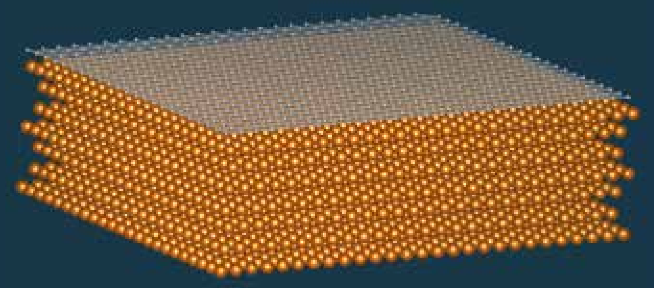
X-ray diffraction pattern of tobacco mosaic virus filaments, recorded with the LCLS free-electron laser at the SLAC National Accelerator Laboratory in the USA



Picture: DESY, Carolin Seuring

Nickel in a carbon mantle

Nickel soaks up carbon like a sponge and, due to the similar crystal lattice, forms graphene layers with particularly few defects on its surface.



Picture: DESY, Vedran Vonk

Scientists have been exploring a promising way of producing layers of graphene with particularly few defects. The coveted carbon material spontaneously forms on nickel surfaces on which carbon has previously been deposited. The extremely high quality of the graphene produced and the relatively low process temperature of around 400 degrees Celsius make the method interesting for practical applications, as the team of researchers, headed by Bernhard Klötzer from the University of Innsbruck and including scientists from the DESY NanoLab, reported.

Graphene consists of a single layer of carbon atoms, which are arranged in an atomic array resembling chicken wire. The material exhibits an astonishing chemical and structural stability and a high electrical conductivity, making it particularly interesting for electronic applications, such as transistors, transparent electrodes, photovoltaic cells and batteries. Moreover, its special mechanical properties mean that it can be used to build filters and seals on a subnanometre scale. Being impermeable even to gases such as helium and water, graphene can for example serve as a transparent electrode or membrane.

"In view of the many potential uses of graphene, there is a strong demand for optimised and cost-efficient ways of producing large sheets of it with few defects," said the head of research, Bernhard Klötzer.

Scientific Reports, 2018;
DOI: 10.1038/s41598-018-20777-4

New light sources at the European XFEL

Picture: DESY/European XFEL

The monitor in the accelerator control room shows the three X-ray laser lines of the European XFEL in operation.

European XFEL has successfully started operation of the third light source of the X-ray laser facility. This line of so-called undulators – special arrangements of magnets used to generate the X-rays – will provide light for the MID (Materials Imaging and Dynamics) and HED (High Energy Density Science) instruments, which are scheduled to start user operation in 2019. Altogether, the three light sources of the facility will eventually provide X-rays for at least six instruments. At any one time, three of the six instruments can simultaneously receive X-ray beam for experiments.

"The operation of the third light source, and the generation of light from all sources in parallel, is an important step towards our goal of achieving user operation on all six instruments," said European XFEL Managing Director Robert Feidenhans'l.

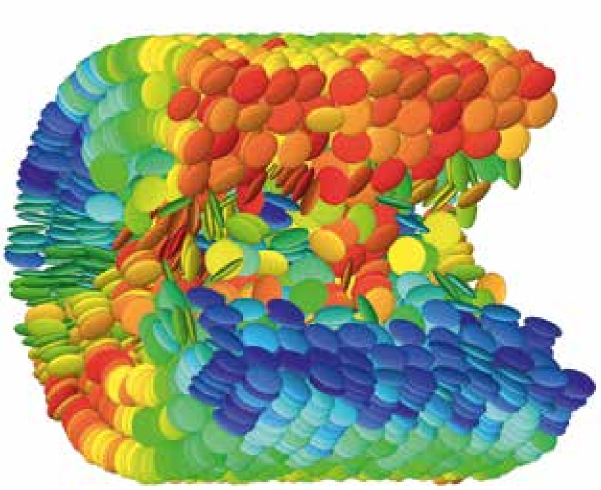
DESY and European XFEL staff have worked hard over the last year to ensure the timely start of operation of all three light sources and to continually improve the parameters of the X-ray beam and instruments. Since the first users arrived in September 2017, the number of X-ray pulses per second available for experiments has been increased from 300 to 3000 per second. At full capacity, the European XFEL is expected to produce 27 000 pulses per second.

Nanorings

At DESY's X-ray source PETRA III, scientists have investigated an intriguing form of self-assembly in liquid crystals: When the liquid crystals are filled into cylindrical nanopores and heated, their molecules form ordered rings as they cool – a condition that otherwise does not naturally occur in the material. This behaviour enables the production of nanomaterials with new optical and electrical properties. The team led by Patrick Huber from the Hamburg University of Technology (TUHH) had studied a special form of liquid crystals that are composed of disc-shaped molecules, called discotic liquid crystals. In these materials, the disk molecules can form high, electrically conductive columns by themselves, stacking up like coins.

As the opto-electrical properties of discotic liquid crystals change with the formation of molecular columns, the nanopore-confined variant is a promising candidate for the design of new optical metamaterials with properties that can be controlled stepwise through temperature. The investigated nanostructures could also lead to new applications in organic semiconductors, such as temperature-switchable nanowires.

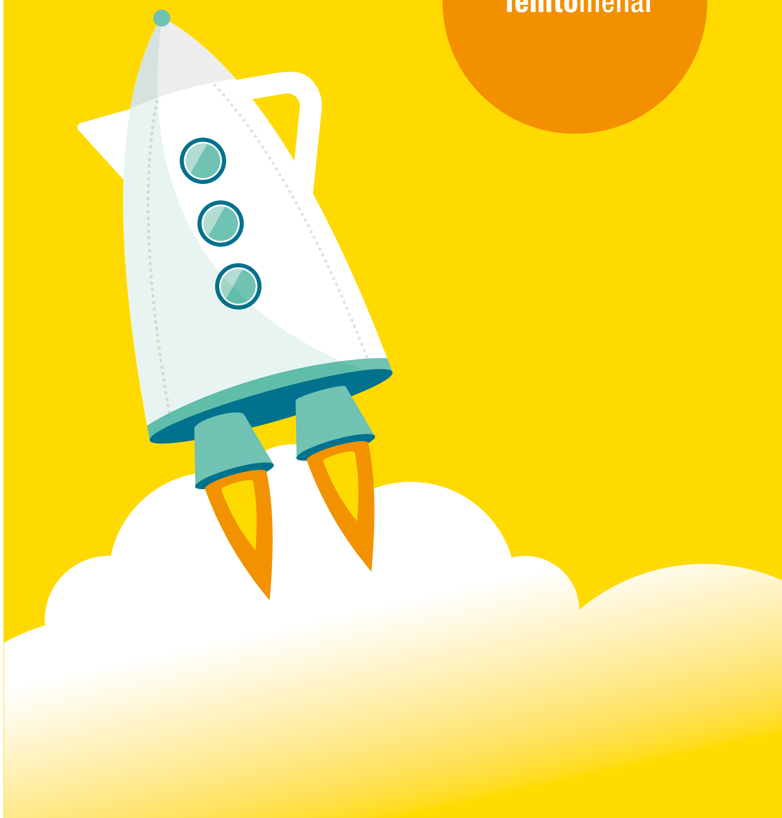
Physical Review Letters, 2018; DOI: 10.1103/PhysRevLett.120.067801



Cutaway view into a largely self-organised liquid crystal inside a nanopore

Picture: Max Planck Institute for Dynamics and Self-organization/Hamburg University of Technology (TUHH), A. Zantop/M. Mazza/K. Sentker/P. Huber

femtomenal



0.000 000 000 000 075 seconds

That's how long, or rather, how short, it takes for researchers to heat up water from room temperature to 100 000 degrees Celsius using an X-ray laser. The experiment, which is providing new insights into the specific properties of water, could be termed the world's fastest kettle. However, this hot droplet of water has a volume of just ten trillionths of a millilitre. To heat a cup of water (150 millilitres) from 20 to 80 degrees Celsius, you would need approximately nine billion drops of this size. The LCLS X-ray laser at the SLAC research centre in the USA, which was used for the experiment, flashes 120 times per second. That means it would need 75 million seconds – more than two years – to heat up the water for a cup of tea. The electric kettle in your home would be faster after all.

The research team led by Carl Caleman from the University of Uppsala and the Center for Free-Electron Laser Science (CFEL) at DESY was not interested in preparing a hot drink, however. With its experiments, the team was testing a model for the behaviour of water when it suddenly turns into a plasma.

Proceedings of the National Academy of Science, 2018; DOI: 10.1073/pnas.1711220115

More efficiency through corners and edges

Catalytic converters for cleaning exhaust emissions are more efficient when they use nanoparticles with many edges. This is one of the findings of a study carried out at DESY's X-ray source PETRA III. A team of scientists from the DESY NanoLab watched live as noxious carbon monoxide (CO) was converted into common carbon dioxide (CO_2) on the surface of noble-metal nanoparticles such as those used in the catalytic converters of cars. The results suggest that having a large number of edges between the nanoparticle sides (facets), which are covered with a nano-oxide, increases the efficiency of catalytic reactions.

"Here, we can really follow the reaction on an atomic scale"

Uta Hejral, University of Lund

Catalytic converters usually use nanoparticles – particles with dimensions of millionths of a millimetre – because these have a far greater surface area for a given amount of material on which the catalytic reaction can take place. The scientists at the DESY NanoLab grew platinum–rhodium nanoparticles on a substrate in such a way that virtually all the particles were aligned in the same direction and had the same shape of truncated octahedrons (double pyramids). The scientists then studied the catalytic properties of this sample under the typical working conditions of an automotive catalytic converter and with various gas compositions in a reaction chamber exposed to intense X-rays from PETRA III.

Emission test on nanoparticles

The efficiency of catalytic materials can be measured using a mass spectrometer that reveals the proportions of certain types of molecules in the exhaust emissions, here the relative concentrations of carbon monoxide, oxygen and carbon dioxide. "We carry out a kind of emission test on the nanoparticles," explains Uta Hejral, the first author of the study, now working at the University of Lund in Sweden. Thanks to the parallel alignment of the nanoparticles, the scientists were also able to determine where on the surface of the nanoparticles the reaction took place particularly efficiently. "Here, we can really follow the reaction on an atomic scale," Hejral points out.

Normally, the noble-metal nanoparticles in a car's catalytic converter are attached to tiny crumbs of substrate, which stick together forming complex structures. "These are difficult to examine using X-rays, because the noble metals only account for a few weight percent and in particular because the nanoparticles are aligned in all sorts of different directions," explains Andreas Stierle, leading scientist at DESY and professor of nanoscience at the University of Hamburg. "Under X-ray illumination, every particle produces a separate diffraction pattern and these overlap to create a blurred image. By having them aligned in parallel to each other, on the other hand, the diffraction patterns of all the nanoparticles are superimposed and amplify each other. This allows the different facets of the nanoparticles, in other words their individual surfaces, to be identified and specifically observed."

Reaction with oxygen

The investigation showed that the reactivity of the nanoparticles increases sharply at a certain oxygen concentration. "This happens when just enough oxygen is available to oxidise each carbon monoxide molecule and turn it into carbon dioxide," says Stierle. Beyond that concentration, the reactivity gradually drops again because ever larger oxide islands grow on the surface of the particles, impeding the reaction. The X-ray analysis reveals the atomic structure of the surface of the nanoparticles at the best resolution yet under the conditions at which the reaction occurs. This shows that once a certain oxygen concentration is

Picture: DESY, Lucid Berlin

“We would expect catalytic converters to be increasingly efficient the more edges the nanoparticles have for a given surface area”

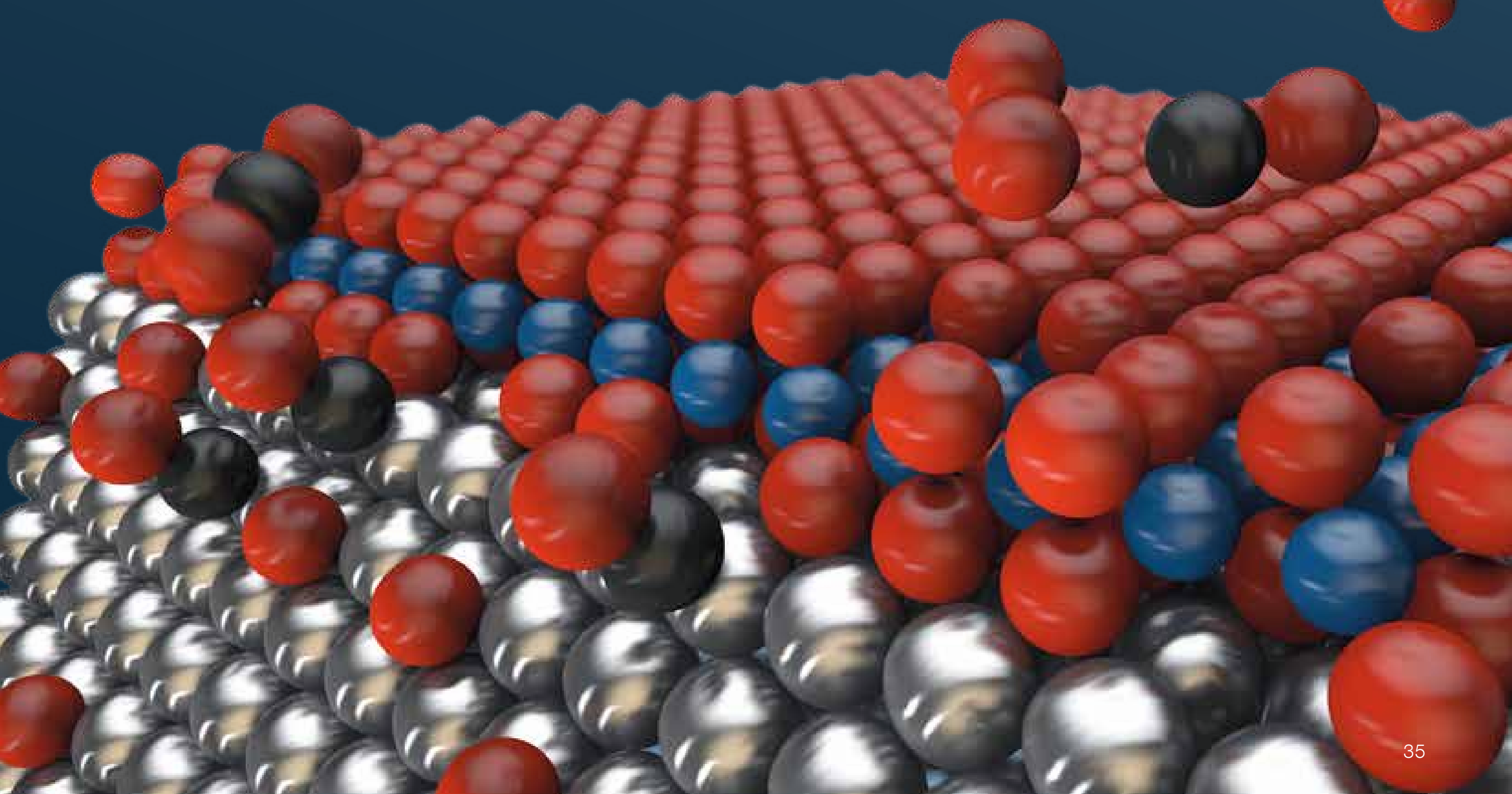
Andreas Stierle, DESY

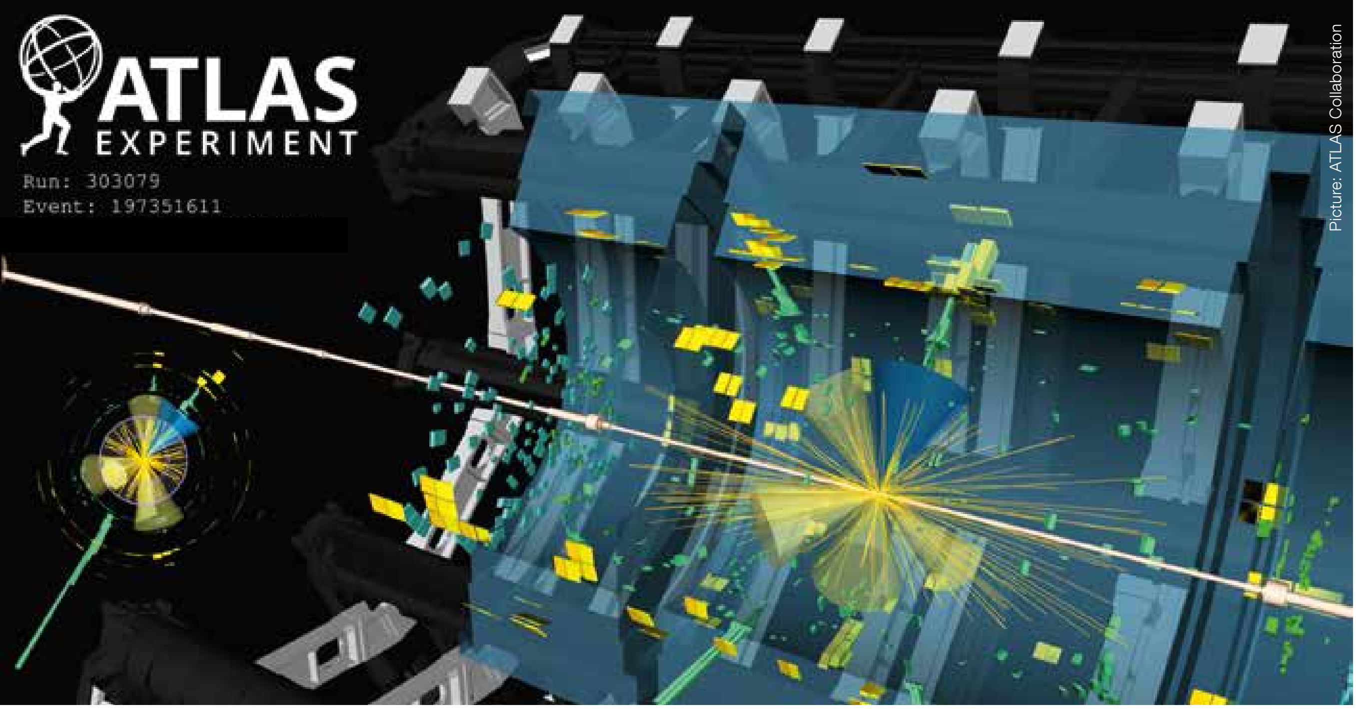
exceeded, the different crystal faces of the nanoparticles become coated with an oxygen–rhodium–oxygen sandwich, until eventually the surface of the metal is completely covered by this nano-oxide layer.

“The surface oxide eventually forms a closed layer over the nanoparticles,” reports Hejral. “This is unfavourable for the desired reaction at first, because it makes it difficult for carbon monoxide molecules to attach to the surface. However, the oxygen is unable to form a closed film along the edges between the facets of the nanoparticles, which means that the reactivity along the edges is higher.” This finding suggests a direct pathway to making catalytic converters more efficient: “We would expect catalytic converters to be increasingly efficient the more edges the nanoparticles have for a given surface area,” says Stierle. The finding can probably also be applied to many other catalytic reactions. Additional studies will have to show by how much the efficiency can be increased as a result.

Physical Review Letters, 2018;
DOI: 10.1103/PhysRevLett.120.126101

With increasing oxygen (red) concentration, an oxide sandwich made of oxygen–rhodium layers forms on the surfaces of the metallic nanoparticles, inhibiting the desired reaction of carbon monoxide (red–black) to carbon dioxide (red–black–red). At the edges between the facets of the nanoparticles, however, the oxide sandwich brakes up, leaving free active sites for catalysis. The more edges the nanoparticles possess, the more efficiently the catalytic converter can work.





Event display of a particle collision in the ATLAS detector in which top quarks and a Higgs boson are produced

Top result from the LHC

Particle physicists observe interaction between heaviest quark and Higgs boson

Scientists from the ATLAS and CMS collaborations at the Large Hadron Collider (LHC) at CERN near Geneva have for the first time directly observed the production of the heaviest of all known elementary particles, the top quark, simultaneously with the Higgs boson. The observation is a huge step for particle physicists in understanding the Higgs mechanism – the mechanism that gives elementary particles their mass.

The Higgs boson was discovered at the LHC in 2012. However, the discovery was only the first step in understanding all the properties of the newly found particle. Scientists are now busy unravelling how exactly the Higgs boson gives mass to the other particles by finding out how it interacts with them. This is especially interesting for the top quark, the most massive elementary particle observed so far, but it is also especially challenging because the top quark is very rarely produced in association with a Higgs boson – 100 times less often than other particles. Moreover, its interaction with the Higgs boson can only be observed and proven indirectly through the tell-tale particles produced in its decay.

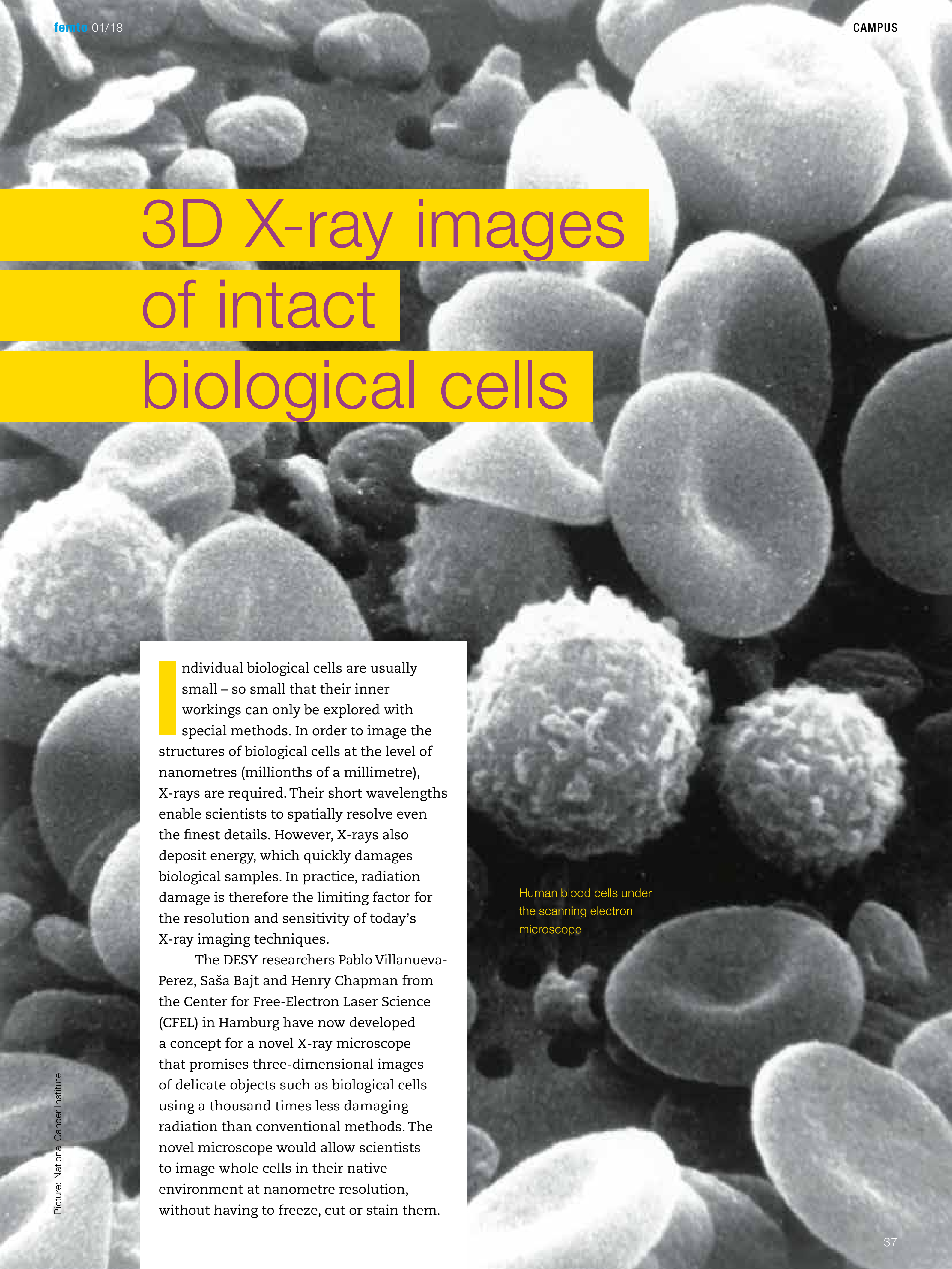
Because the top quark is so heavy, the Higgs boson cannot decay directly into a pair of top and anti-top quarks. Instead, the researchers are searching for events in which a pair of top and anti-top quarks is produced together with a Higgs boson, which all decay further into other particles.

The decay of the Higgs boson into a bottom quark and an anti-bottom quark occurs most frequently of all, but it is also hard to disentangle from the abundance of other particles that appear in the detector during a collision.

Together with researchers from other institutes, the DESY scientists Maria Aldaya (CMS) and Judith Katzy (ATLAS) and their groups concentrated on finding events in which two bottom quarks were produced in the final state. "The observation of the top quark together with the Higgs boson establishes this production mode of the new boson and enables us to study the direct interaction between the Higgs boson and the most massive quark. It marks another important milestone in the verification of the Standard Model of particle physics," explains Maria Aldaya, who also coordinates the top-quark group in the CMS collaboration.

CMS: Physical Review Letters, 2018; DOI: 10.1103/PhysRevLett.120.231801
ATLAS: Physics Letters B (submitted); Preprint: https://arxiv.org/abs/1806.00425

3D X-ray images of intact biological cells



Human blood cells under the scanning electron microscope

Picture: National Cancer Institute

Individual biological cells are usually small – so small that their inner workings can only be explored with special methods. In order to image the structures of biological cells at the level of nanometres (millionths of a millimetre), X-rays are required. Their short wavelengths enable scientists to spatially resolve even the finest details. However, X-rays also deposit energy, which quickly damages biological samples. In practice, radiation damage is therefore the limiting factor for the resolution and sensitivity of today's X-ray imaging techniques.

The DESY researchers Pablo Villanueva-Perez, Saša Bajt and Henry Chapman from the Center for Free-Electron Laser Science (CFEL) in Hamburg have now developed a concept for a novel X-ray microscope that promises three-dimensional images of delicate objects such as biological cells using a thousand times less damaging radiation than conventional methods. The novel microscope would allow scientists to image whole cells in their native environment at nanometre resolution, without having to freeze, cut or stain them.

Scattered photons

X-ray images can be obtained by a variety of means. The familiar radiographs of teeth or broken bones rely on X-ray absorption – the dense bones absorb more X-ray photons than the surrounding tissue and thus leave a shadow in the image. In contrast, an X-ray microscope built for imaging cells usually depends on the elastic scattering of X-ray photons in the sample to achieve images of much higher resolution. The principle is similar to that of an optical microscope. Although elastic X-ray scattering transfers no energy to the sample, in all X-ray microscopes built to date, such scattering processes happen much less frequently than actual absorption. "In reality, scattering cannot occur without a fraction of the photon's energy being deposited in the sample, producing radiation damage," says Villanueva-Perez.

High-energy X-rays were not considered useful for high-resolution microscopy since at high energies, elastic X-ray scattering decreases and inelastic scattering becomes predominant. In this process, also known as Compton scattering, the X-ray photon loses some of its energy to the sample as it ricochets off an atom and changes its wavelength. This usually produces an unwanted featureless background in the image, deteriorating the quality of sample and image.

> *"No one really thought of trying biological microscopy at such high energies"*
>
> Henry Chapman, DESY

The insight of the team was that at very high X-ray photon energies of 64 kiloelectronvolts (keV), there are many more Compton scattering events for a given amount of energy deposited into the cell than for elastic scattering at the conventional lower photon energies exploited by current techniques. A detailed image can then be built up by scanning a focused X-ray beam across the cell and mapping out the total scattering detected at each location.

Surprisingly, the analysis showed that the dose could be reduced by a factor of 1000 for a given resolution. "No one really thought of trying biological microscopy at such high energies," explains Chapman. "Bright enough X-ray sources didn't exist, there was no way to focus the beam, and there were no detectors."

Record resolution thanks to novel special lenses

The team has found solutions to these challenges. Bajt's group just recently developed an innovative X-ray lens from an artificial multilayer "metamaterial" that delivers the smallest X-ray focus yet achieved. "The efficiency of our multilayer lenses actually gets much better with increasing energy, and they generate even smaller focal spots," says Bajt. "So they are ideally suited to building our microscope."

> *"We produced the world's smallest X-ray focus using high-efficiency lenses"*
>
> Saša Bajt, DESY

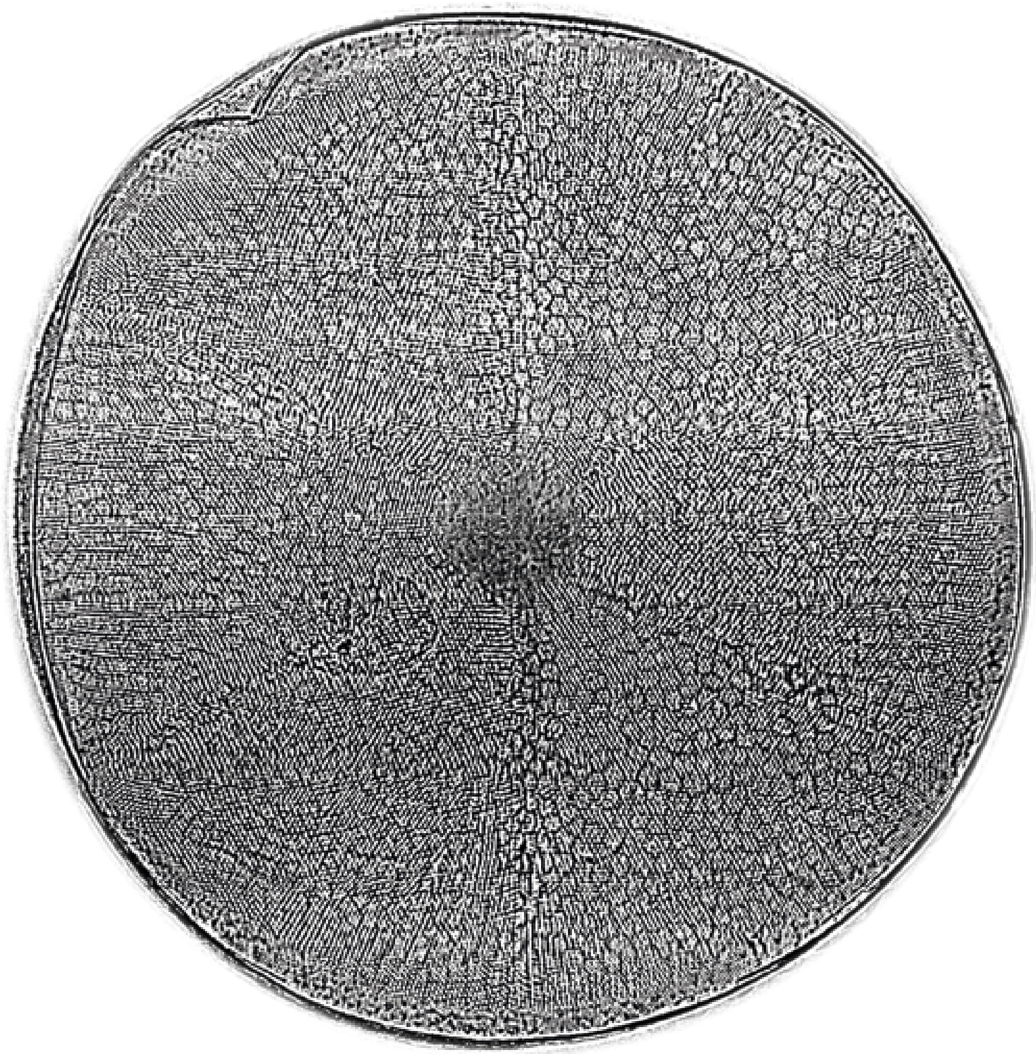
To achieve the required precision and special lens properties, Bajt's team developed a novel fabrication process and carefully investigated the properties of the lens material, which often vary with lens thickness. Using a new material combination of tungsten carbide and silicon carbide, the researchers produced lenses consisting of more than 10 000 alternating layers. "The selection of the right pair of materials was critical to success," emphasises Bajt. "That does not rule out other material combinations, but this one is definitely the best we know."

Due to their penetrating nature, X-rays would normally pass straight through the lens materials. One challenge therefore was to produce lens structures that generate the strongest possible interaction with the X-rays and that direct as much of the radiation as possible into the focal point. The new lenses have an efficiency of more than 80 percent. "We produced the world's smallest X-ray focus using high-efficiency lenses," says Bajt.

Brilliant perspectives

The novel X-ray microscope concept developed by Pablo Villanueva-Perez, Saša Bajt and Henry Chapman also provides a brilliant perspective for the planned expansion of DESY's PETRA III storage ring into a next-generation X-ray source. PETRA IV will deliver X-ray beams of much higher brilliance than possible today. This still leaves the detector. "The ideal detector should surround the sample, to collect all scattered photons in all directions," explains Villanueva-

The silica shell of the diatom *Actinoptychus senarius*, measuring only 0.1 millimetre across, is revealed in fine detail in this X-ray hologram recorded at 5000-fold magnification with the new lenses. The lenses focused an X-ray beam on a focal point with a diameter of only about eight nanometres – smaller than some viruses – before the X-ray beam expanded again, illuminated the diatom and generated the hologram.



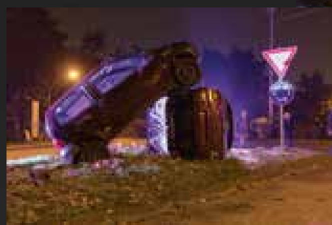
Picture: DESY/AWI, Andrew Morgan/Saša Bajt/Henry Chapman/Christian Hamm

Perez. Such a detector does not exist yet, but can be built using today's technology. Once realised, these various components will enable scientists to study whole cells and organelles at a resolution of a few nanometres in all three dimensions and in their natural environment, thereby fulfilling a widespread wish of biologists. Until then, the scientists plan to test their novel concept with biological samples using conventional detectors at today's best X-ray sources, such as PETRA III.

Optica, 2018; DOI: 10.1364 OPTICA.5.000450. Light: Science and Applications, 2017; DOI: 10.1038/10.1038/lsa.2017.162

ART MEETS SCIENCE

femtofinale



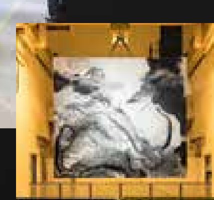
Creative collisions: Artists look at dark matter

Art Meets Science: In autumn 2017, 15 artists from all over Germany presented their works on the theme of dark matter at the DESY research campus in Hamburg – in test halls, in control rooms and inside a particle accelerator. The works are the result of an intensive series of contacts between science and art. The works on show included paintings, graphic art, photographs and films, sculptures, installations and interventions as well as sound and multimedia art. This was the first “Art Meets Science” project at DESY.

“Art and science are two essential pillars of our society,” says Helmut Dosch, the Chairman of the DESY Board of Directors. “Through the Dark Matter project, DESY aims to reveal and visualise the relationship between these two areas. After all, at DESY we’re always striving to push back the limits of what is known and to expand horizons – but we do it in line with our scientific and analytic approach. Seeing the artists’ perspective on the research topic of dark matter is not only very enjoyable but also gives us inspiration for our research activities.”

https://artmeetsscience.desy.de

dark matter



Imprint

femto is published by
Deutsches Elektronen-Synchrotron DESY,
a research centre of the Helmholtz Association

Editorial board address
Notkestraße 85, 22607 Hamburg, Germany
Tel.: +49 40 8998-3613, fax: +49 40 8998-4307
e-mail: femto@desy.de
Internet: www.desy.de/femto
ISSN 2199-5192

Editorial board
Ute Wilhelmsen (responsible under press law),
Till Mundzeck

Contributors to this issue
Frank Grotelüschen, Barbara Warmbein

Design and production
gutentag Hamburg

Translation
TransForm, Cologne
Ilka Flegel, Kapellendorf

Printing and image processing
EHS, Hamburg

Copy deadline
June 2018

FSC www.fsc.org MIX Paper from responsible sources FSC® C006225
EU Ecolabel www.ecolabel.eu

Cover picture
Using DESY's X-ray light source PETRA III, researchers led by Chrystèle Sanloup from the University of Edinburgh have for the first time peered into molten magma at conditions like those in the deep Earth mantle. The findings support the concept that the early Earth's mantle harboured two magma oceans, separated by a crystalline layer. Today, these presumed oceans have crystallised, but relics might still exist in local patches and maybe in thin layers in the mantle. The picture shows a basalt sample in a diamond anvil cell after probing.

Cover picture: University of Edinburgh, Chrystèle Sanloup

The DESY research centre

DESY is one of the world's leading particle accelerator centres. Researchers use the large-scale facilities at DESY to explore the microcosm in all its variety – ranging from the interaction of tiny elementary particles to the behaviour of innovative nanomaterials and the vital processes that take place between biomolecules. The accelerators and detectors that DESY develops and builds at its locations in Hamburg and Zeuthen are unique research tools. The DESY facilities generate the most intense X-ray radiation in the world, accelerate particles to record energies and open up completely new windows onto the universe.

DESY is a member of the Helmholtz Association, Germany's largest scientific organisation.

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

DESY.