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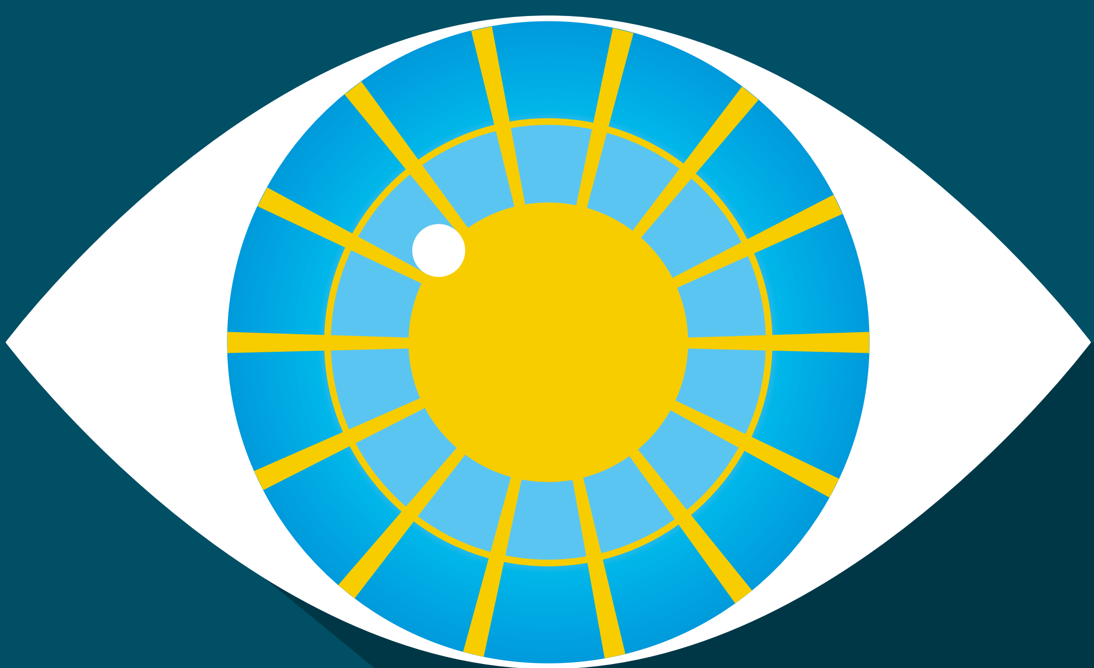
The DESY research magazine – Issue 02/21

ENGLISH EDITION



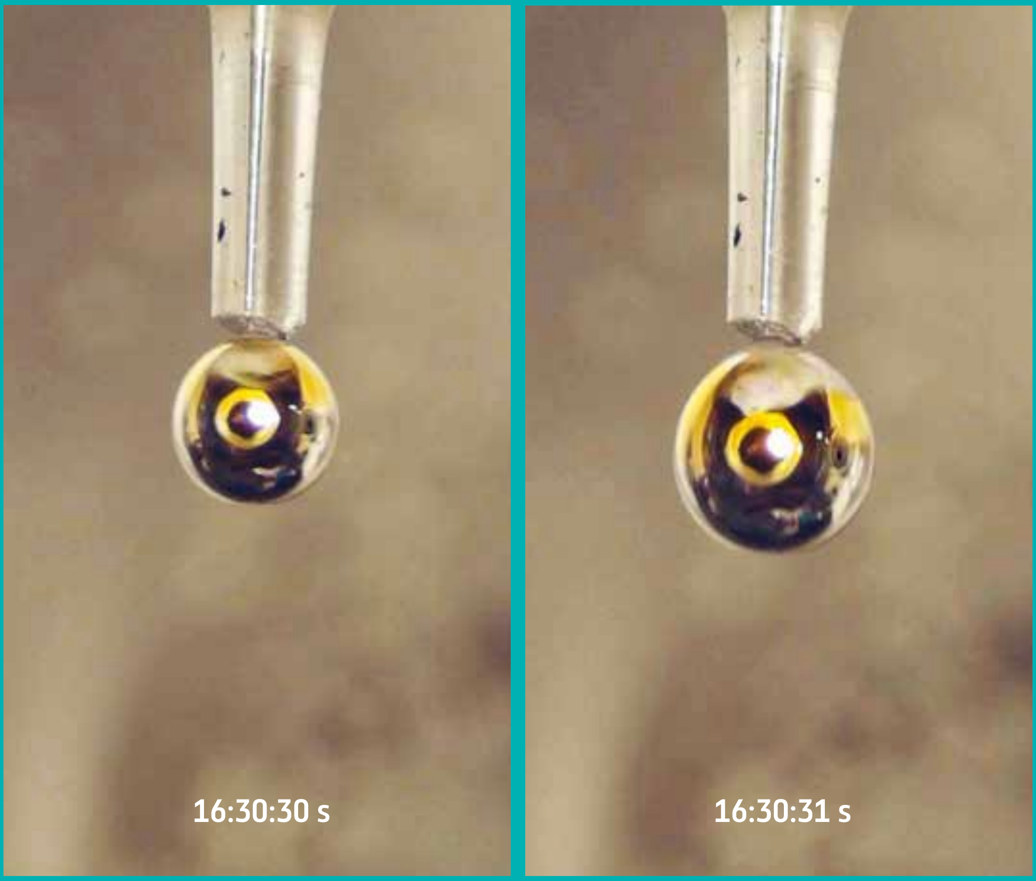
Research for the
ENERGY TRANSITION

Neutrino hunt in Greenland

The egg in the X-ray beam

Seeping oceans

DESY.



Water as a gold-shimmering metal

Many an alchemist would be envious of this feat: In a fascinating experiment, researchers led by Pavel Jungwirth of the Czech Academy of Sciences (CAS) have transformed ordinary water into a gold-shimmering, liquid metal.

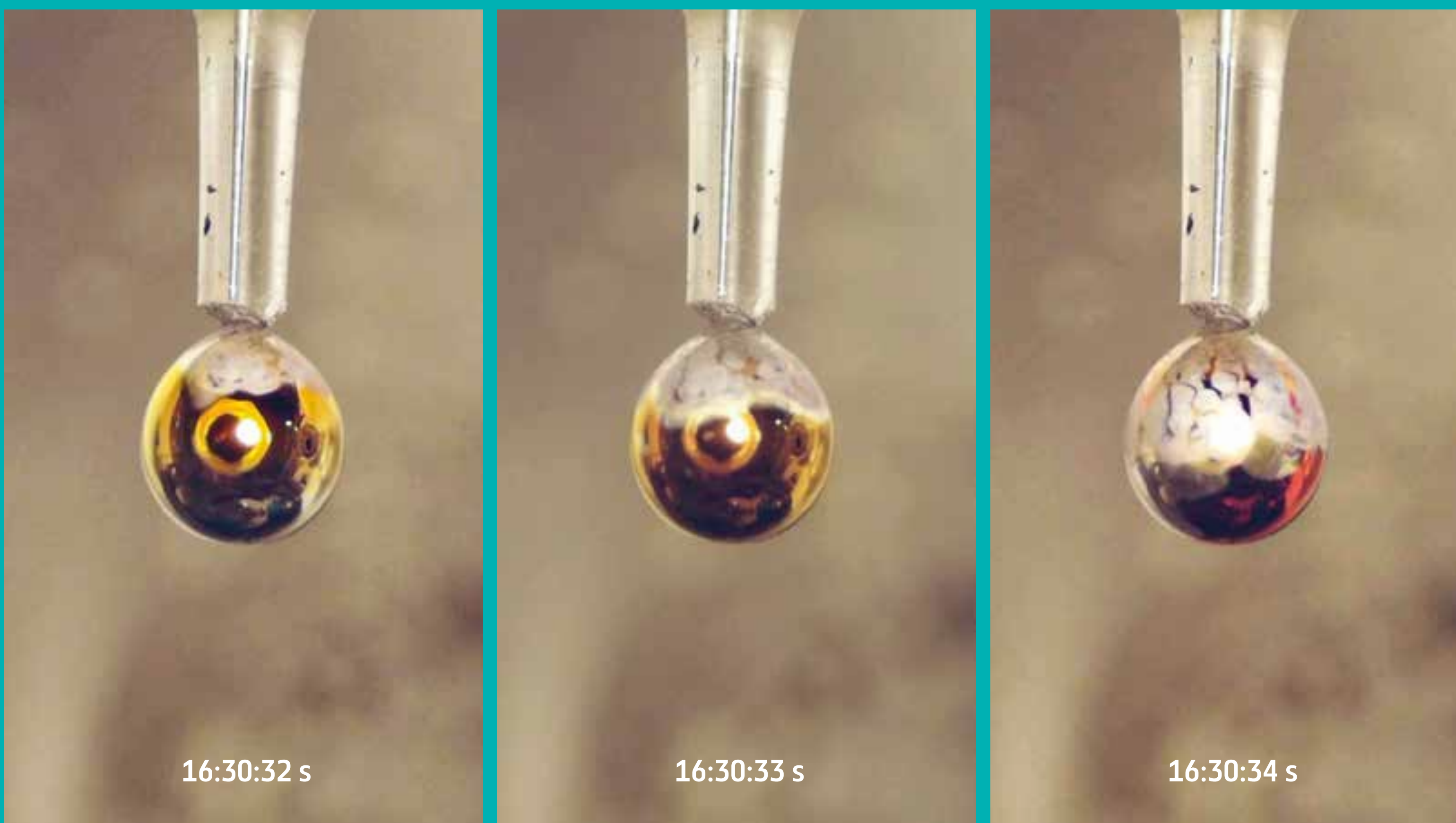
Pure water is normally an insulator. It only becomes electrically conductive when contaminated with salts. However, even pure water can develop metallic properties: Under extremely high pressure – conditions that prevail in the interior of large planets – any material can in principle become metallic. The necessary pressures are almost impossible to achieve in a laboratory, though.

Using a completely different approach, an international cooperation of 15 researchers from 11 institutes has now managed to produce metallic water at low pressure. The team allowed water vapour to condense on a droplet of sodium–potassium alloy in a vacuum chamber under carefully controlled conditions.

The vapour forms an extremely thin skin on the surface of the droplet, consisting of just a few layers of water molecules. In the process, electrons and metal ions migrate from the alloy into the water. "The migrated electrons can move around like free electrons in the conduction band of metals," explains Stephan Thürmer from Kyoto University.

Visible to the naked eye

"This transition to metallic water is visible to the naked eye," reports co-author Florian Trinter, who works at DESY among other places. "The silvery sodium–potassium droplet takes on a golden shimmer,



which is very impressive," adds Robert Seidel from Helmholtz Centre Berlin (HZB), where some of the experiments were carried out. The solution then reacts further and forms grey sodium and potassium hydroxide salt crystals.

The researchers, led by CAS lead authors Philip Mason, Christian Schewe and Tillmann Buttersack, used two different spectroscopic methods at the HZB X-ray source BESSY II and at the CAS Institute of Organic Chemistry and Biochemistry (IOCB) in Prague to demonstrate that the water is indeed in a metallic state.

Such surprising properties will be studied in future at the Centre for Molecular Water Science (CMWS), which is currently being set up at DESY as an international collaboration.

Nature, DOI: 10.1038/s41586-021-03646-5

Picture: IOCB, Philip Mason/Christian Schewe

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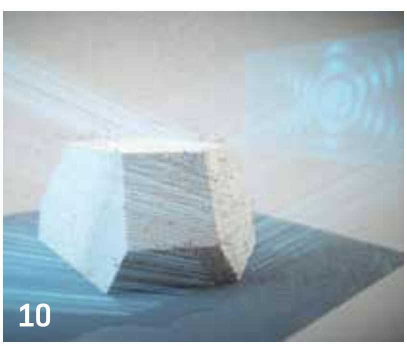

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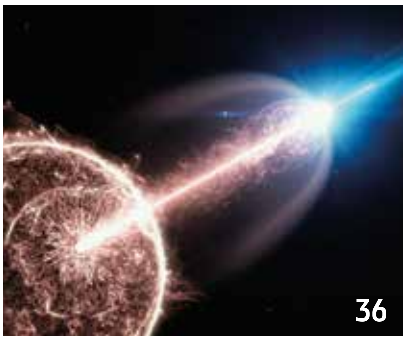


Dear Readers,

How can we achieve the energy transition towards renewable sources? Research alone cannot answer this question. Politics and literally each and every individual must make their contribution. However, fundamental research can help to open up new, innovative ways to produce green energy, store it more efficiently, distribute it better and use it more effectively. That's what this issue is about.
It focuses on two key aspects: Hydrogen is considered by many to play a central role as an energy carrier in a sustainable energy economy. However, the light gas is only as green as the energy used to produce it. Our most important energy source by far is the sun. It provides us with enormous amounts of energy for free. Making better use of it requires better and new types of solar cells – preferably made of cheap and sustainable materials. One interesting approach is based on ultrathin paper and polymers. However, innovations are only part of the answer. They must go hand in hand with behavioural changes, as economist Alexander Bassen from the German Advisory Council on Global Change (WBGU) emphasises. Last but not least, research itself can become more energy-efficient. A large EU project is investigating how to save a considerable amount of electricity in the operation of particle accelerators, for example.

We hope you enjoy reading this issue and find it enlightening, and we look forward to receiving your criticism, praise and suggestions at femto@desy.de.

Till Mundzeck
Editor

Antennas in the ice

A pioneering project listens for cosmic neutrinos in Greenland's glacier

In Greenland's ice sheet, a setup unlike any other in the world will in future be listening for extremely elusive particles from space. The Radio Neutrino Observatory Greenland (RNO-G) is a pioneering project that relies on a new method of detecting very-high-energy cosmic neutrinos using radio antennas, which are being installed on and in the ice.

"Neutrinos are extremely elusive, ultralight elementary particles," explains DESY physicist Anna Nelles, one of the initiators of the project. "These particles are created in vast quantities in space, especially during high-energy processes like those that take place in cosmic particle accelerators. But they are very difficult to detect because they hardly ever react with matter. From the sun alone, some 60 billion neutrinos pass completely unnoticed through a speck on Earth the size of a fingernail – every second."

The ultralight elementary particles are sometimes called ghost particles because they have no trouble passing straight through walls, the Earth and even entire stars. "This property makes them interesting for astrophysicists because they can be used to look inside exploding stars or merging neutron stars, for example, from which no light can reach us," explains Nelles, who is also a professor at Friedrich-Alexander Universität Erlangen-Nürnberg. "Also, neutrinos can be used to track down natural cosmic particle accelerators." These include, for instance, supernova remnants and gigantic black holes at the heart of distant galaxies.

Faster than light

On extremely rare occasions, however, a neutrino does in fact interact with matter when it happens to bump into an atom as it passes

> *"Neutrino research calls for patience"*
>
> ***Anna Nelles, DESY***

The first station of the Radio Neutrino Observatory on the Greenland ice. The red flags mark underground antennas powered by solar panels.

through – in the Greenland ice sheet, for instance. Such rare collisions produce an avalanche of secondary particles, many of which are electrically charged, unlike the neutrino. These secondary particles are so energetic that they travel through the ice faster than light can – though not faster than light in a vacuum, the absolute speed limit according to Albert Einstein. This creates a kind of optical equivalent to the sonic boom: the so-called Cherenkov light, which appears as a bluish glow.

At the other end of the world, at the South Pole, the IceCube neutrino detector is looking out for this blue glow in the Antarctic ice in order to detect neutrinos from the depths of space. An international consortium, including DESY, has installed around 5000 sensitive optical detectors to depths of several kilometres inside the ice. These so-called photomultipliers are distributed over an entire cubic kilometre of ice, hence the name of the experiment.

IceCube has already succeeded in making some spectacular observations of neutrinos arriving from the vicinity of a gigantic black hole or a shattered star, for example, and has thus opened a new window on the cosmos: In addition to electromagnetic radiation, such as light, and gravitational waves, neutrinos are a third, independent method of observing the cosmos.

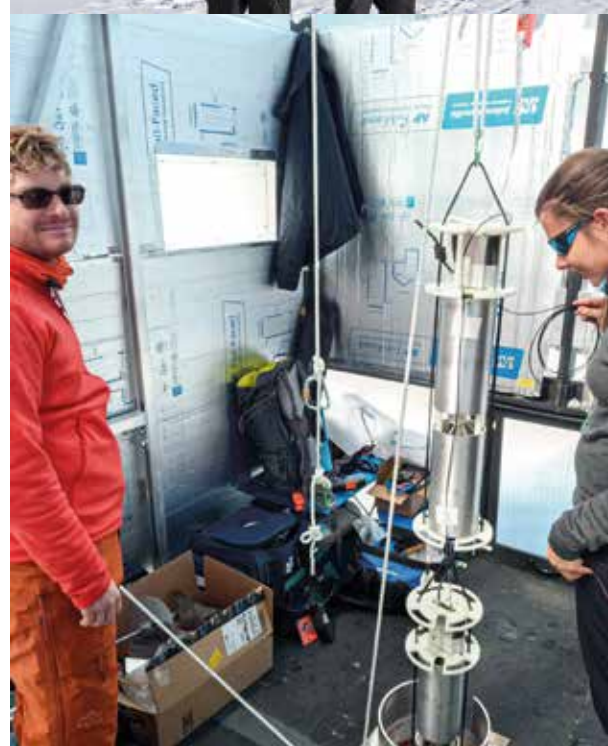
Pandemic challenges

In addition to Cherenkov light, however, the charged secondary particles of cosmic neutrinos also produce radio waves in the ice, which can be picked up by antennas. That is the goal of RNO-G. “The advantage of using radio waves is that ice is fairly transparent to them,” explains DESY physicist Christoph Welling, who set up the first antennas in Greenland with the pioneering team. “This means we can detect radio signals over distances of several kilometres.”

The greater the range, the larger the volume of ice that can be monitored, and the greater the chances of detecting one of the rare neutrino collisions. “RNO-G will be the first large-scale radio neutrino detector,” says Welling. Previous smaller-scale experiments have already shown that it is indeed possible to use radio waves to detect cosmic particles.

RNO-G comprises a total of 35 antenna stations, each 1.25 kilometres apart, around Summit Station on the mighty Greenland ice sheet. The individual stations can operate autonomously, powered ››

Installation in the glacier
DESY scientists Christoph Welling (l.) with a deep antenna and Ilse Plaisier (r.) with a surface antenna. The deep antennas are sunk through boreholes around 100 metres deep into the ice sheet. The stations operate autonomously with solar panels and are connected with each other via a wireless network.



Pictures: RNO-G, Cosmin Deaconu

> *"A very promising way of opening this new window to the cosmos even further"*
>
> ***Christian Stegmann, DESY Director in charge of Astroparticle Physics***

by solar panels, and are connected with each other via a wireless network.

The installation work was a particular logistical challenge in pandemic times: The members of the teams come from all over the world – in addition to DESY, more than a dozen partners are involved in the pioneering project, such as the University of Chicago, Vrije Universiteit Brussel, Penn State University and the University of Wisconsin-Madison – and people had to spend several weeks in quarantine at various locations before arriving at Summit Station to avoid introducing the coronavirus.

The energy of a squash ball

RNO-G will remain on the Greenland ice sheet for at least five years. In addition to providing new insights into the cosmos, the findings in the Arctic also offer interesting perspectives for the planned expansion of the Antarctic neutrino telescope into IceCube Generation 2 (IceCube-Gen2), for which, among other things, 12 000 additional detector spheres are to be sunk into the ice.

"Detecting radio signals from high-energy neutrinos is a very promising way of significantly increasing the energy range we can access and thus opening this new window to the cosmos even further," says Christian Stegmann, DESY's Director in charge of Astroparticle Physics. "We are pursuing this path with initial test setups in Greenland and will then go on to install radio antennas at the South Pole as part of IceCube-Gen2."

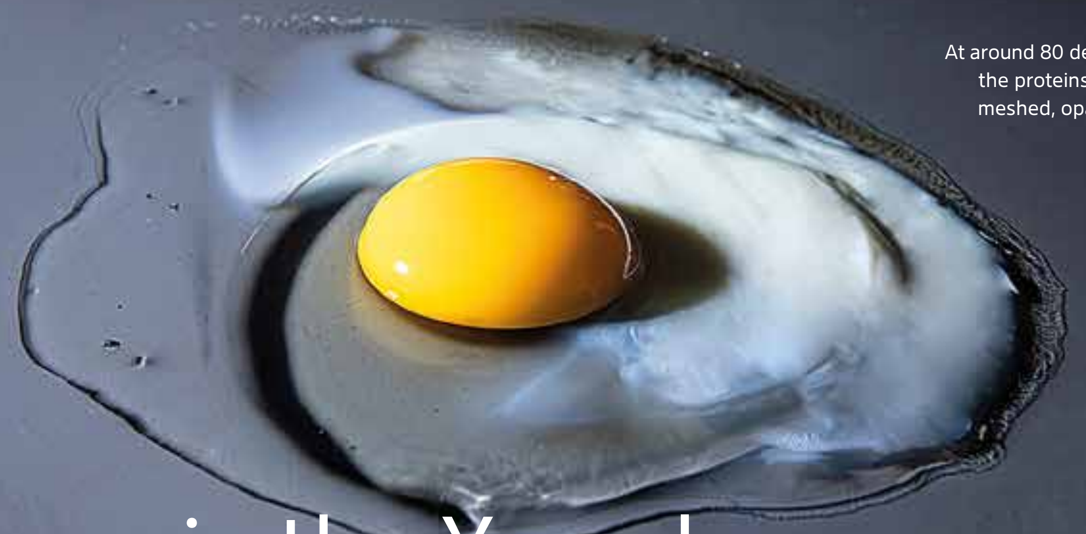
The glowing blue light from the secondary particles cannot be tracked over such long distances in the ice as the radio waves. However, the photomultipliers make up for this by responding to cosmic neutrinos with lower energies. "The higher the energy, the rarer the neutrinos become, which means you need larger detectors," explains DESY scientist Ilse Plaisier, who is also a member of the installation team in Greenland. "The two systems complement each other perfectly: IceCube's grid of optical detectors registers neutrinos with energies of up to about a quadrillion electron volts, while the array of radio antennas will be sensitive to energies from about ten quadrillion to a hundred quintillion electron volts." The electron volt is an energy unit widely used in particle physics. One hundred quintillion electron volts roughly corresponds to the energy of a hard-hit squash ball travelling at 130 kilometres per hour – but in the case of a neutrino, that energy is concentrated in a single subatomic particle that is a quintillion quintillion times lighter than a squash ball.

It could take months or even years, though, before the antennas in Greenland record a signal. "Neutrino research calls for patience," explains Nelles. "Capturing high-energy neutrinos is an incredibly rare event. But when you do catch one, it reveals an enormous amount of information."

RNO-G website:
https://radio.uchicago.edu

Summit Station is located in the middle of the Greenland ice sheet.

Pictures: RNO-G, Cosmin Deaconu; DESY, Gesine Born



At around 80 degrees Celsius, the proteins form a tightly meshed, opaque network.

The egg in the X-ray beam

Innovative time-resolved method reveals network formation by and dynamics of proteins

Eggs are among the most versatile food ingredients. They can take the form of a gel or a foam, they can be comparatively solid and also serve as the basis for emulsions. At about 80 degrees Celsius, egg white becomes solid and opaque. This is because the proteins in the egg white form a network structure when heated. Using DESY's X-ray source PETRA III, a team of researchers from the universities of Tübingen and Siegen has now investigated exactly how this happens.

The study reveals how the proteins in the white of a chicken egg unfold and cross-link with each other to form a solid structure when heated. The innovative method can be of interest to the food industry as well as to the broad field of protein analysis, as research leader Frank Schreiber from Tübingen points out.

Commercial chicken egg

Studying the exact molecular structure of egg white calls for energetic radiation, such as X-rays, which is able to penetrate the opaque egg white and has a wavelength that is no longer than the structures being examined. "To understand the structural evolution in detail, you have to study the phenomenon on the micrometre scale," explains lead author Nafisa Begam from Schreiber's team.

For their experiments, the scientists used a chicken egg from a supermarket and filled the egg white into a quartz tube with a diameter of 1.5 millimetres. "Inside, the egg white was heated in a controlled manner while we analysed it with the help of the X-rays," explains co-author Fabian Westermeier from DESY. "The X-ray beam was expanded to 0.1 by 0.1 millimetres to keep the radiation dose below the damage threshold of the protein structures."

Dynamics of biomolecules

The measurements reveal the protein dynamics in the egg white over a period of about a quarter of an hour. During the first three minutes, the protein network grew exponentially, reaching a plateau after about five minutes, after which hardly any more protein links were formed. At this time, the average mesh size of the protein network was about 0.4 micrometres (thousandths of a millimetre).

In a second study, the team investigated the self-organisation of protein solutions into domains with high and low protein concentration, respectively, as an example of structure formation in cell biology. In the process, the researchers were able to follow the temperature-dependent dynamics over time. "At high protein concentration, mobility decreases, which slows down the phase separation. This is important for the special dynamics of the system," reports lead author Anita Girelli from Schreiber's group.

The cooperation of the groups of Schreiber from Tübingen and Christian Gutt from Siegen used so-called X-ray photon correlation spectroscopy (XPCS) in a specific geometry for their studies, enabling them to determine the structure and the dynamics of the proteins in the egg white simultaneously.

These studies not only reveal new details about the structural changes occurring in egg whites, but also prove the experimental concept, which can be used for other samples too, as Schreiber explains: "The successful application of X-ray photon correlation spectroscopy opens up a new way to study the dynamics of biomolecules, which is essential if we are to understand them properly."

Physical Review Letters,
DOI: 10.1103/PhysRevLett.126.098001
and 10.1103/PhysRevLett.126.138004

Picture: DESY, Gesine Born

Catalyst at work

X-ray investigation provides unprecedented view of a single nanoparticle

The chemical industry would be inconceivable without catalysts: They save energy and make many production processes possible in the first place. From fertiliser manufacturing to the production of plastics, catalysts are of huge economic importance. “In spite of their widespread use and great importance, we are still ignorant of many important details of just how the various catalysts work,” explains DESY researcher Andreas Stierle, head of the DESY NanoLab. “That’s why we have long wanted to study real catalyst materials while in operation.”

This is not easy because, in order to make the active surface as large as possible, catalyst materials are typically used in the form of tiny nanoparticles, and the changes that affect their activity occur on their surface. Using high-intensity X-rays, a research team led by Stierle has been able to observe a single catalyst nanoparticle at work. The experiment has revealed for the first time how the chemical composition of the surface of an individual nanoparticle changes under reaction conditions, making it more active. The study marks an important step towards a better understanding of real, industrial catalytic materials.

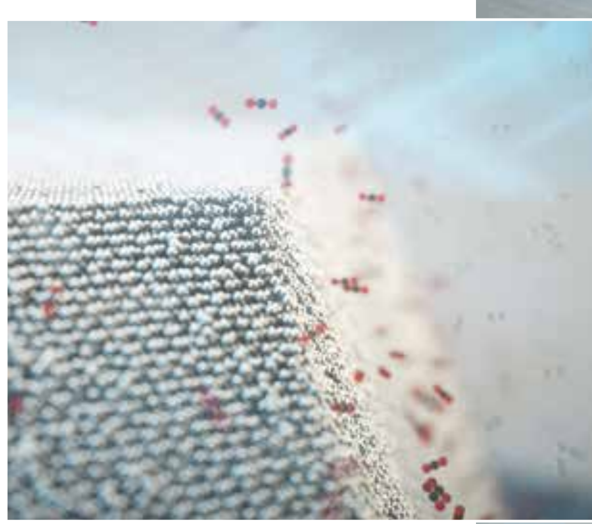
Catalysts are materials that promote chemical reactions without being consumed themselves. A very well-known example is the catalytic converters installed in the exhaust systems of cars. These contain precious metals such as platinum, rhodium and palladium, which enable the conversion of highly toxic carbon monoxide (CO) into carbon dioxide (CO_2) and the reduction of nitrogen oxides (NO_x). The team from the DESY NanoLab has developed a technique for labelling individual nanoparticles and thereby identifying them in a sample.

Detailed image

“For the study, we grew nanoparticles of a platinum–rhodium alloy on a substrate in the lab and labelled one specific particle,” says Thomas Keller from the DESY NanoLab. “The diameter of the labelled particle is around 100 nanometres, and it is similar to the particles used in a car’s catalytic converter.” A nanometre is a millionth of a millimetre.

Using X-rays from the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, the researchers were not only able to create a detailed image of the nanoparticle; they also measured the mechanical strain within its surface. “The surface strain is related to the surface composition, in particular to the ratio of platinum to rhodium atoms,” explains Philipp Pleßow from the Karlsruhe Institute of Technology (KIT). His group has developed a theory that describes the relationship between surface strain and chemical composition for the respective facets of the nanoparticle. The different surfaces of a nanoparticle are called facets, just like the facets of a cut gemstone.

When the nanoparticle is grown, its surface consists mainly of platinum atoms, as this configuration is energetically favoured. The scientists then studied the shape of the particle and its surface strain under different conditions, including



On the surface of the nanoparticle, carbon monoxide oxidises to carbon dioxide.

the operating conditions of an automotive catalytic converter. To do this, they heated the particle to around 430 degrees Celsius and allowed carbon monoxide and oxygen molecules to pass over it. “Under these reaction conditions, the rhodium atoms inside the particle become mobile and migrate to the surface because rhodium interacts more strongly with oxygen than platinum,” explains Pleßow. This is also predicted by theory.

Rhodium moves to the surface

“As a result, the surface strain and the shape of the particle change,” reports Ivan Vartaniants from DESY, whose team converted the shape and surface strain measurements into spatial images. “A facet-dependent rhodium enrichment takes place, whereby additional corners and edges are formed.”

The chemical composition of the surface and the shape and size of the particles have a significant effect on their function and efficiency. However, scientists are only just beginning to understand exactly how these are connected and how to control the structure and composition of the nanoparticles. The X-rays allow the researchers to detect changes of as little as 0.1 per mille in the strain, which in this experiment corresponds to a precision of about 0.0003 nanometres (0.3 picometres).

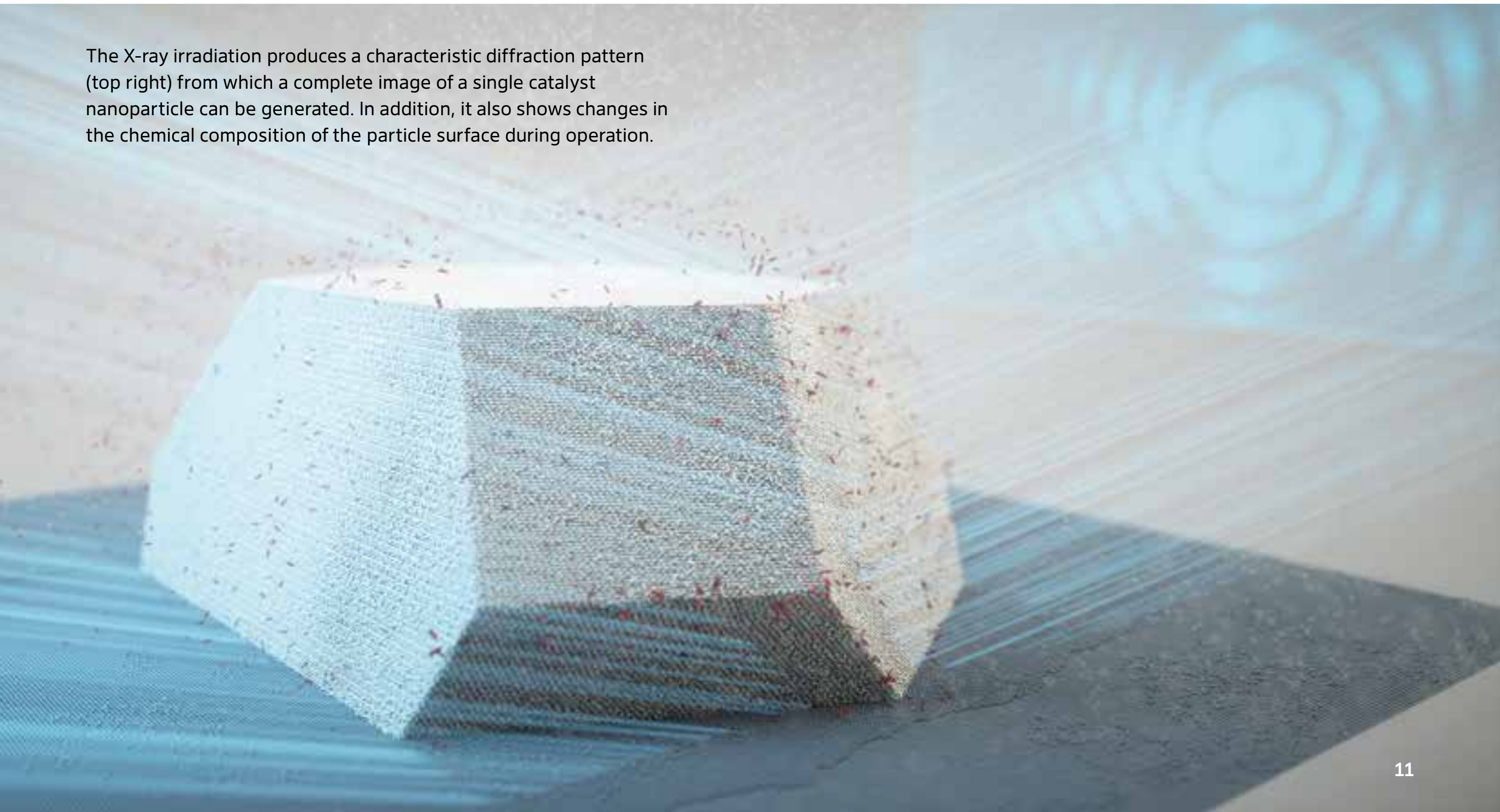
“We can now, for the first time, observe the details of the structural changes in such catalyst nanoparticles while in operation,” says Stierle. “This is a major step forward and helping us to understand an entire class of reactions that make use of alloy nanoparticles.” Scientists at KIT and DESY now want to explore this systematically in a new Collaborative Research Centre funded by the German Research Foundation (DFG).

“Our investigation is an important step towards analysing industrial catalytic materials,” Stierle points out. Until now, scientists have had to grow model systems in the laboratory in order to conduct such investigations. “In this study, we have gone to the limit of what can be done. With DESY’s planned X-ray microscope PETRA IV, we will be able to look at ten times smaller individual particles in real catalysts, and under reaction conditions.”

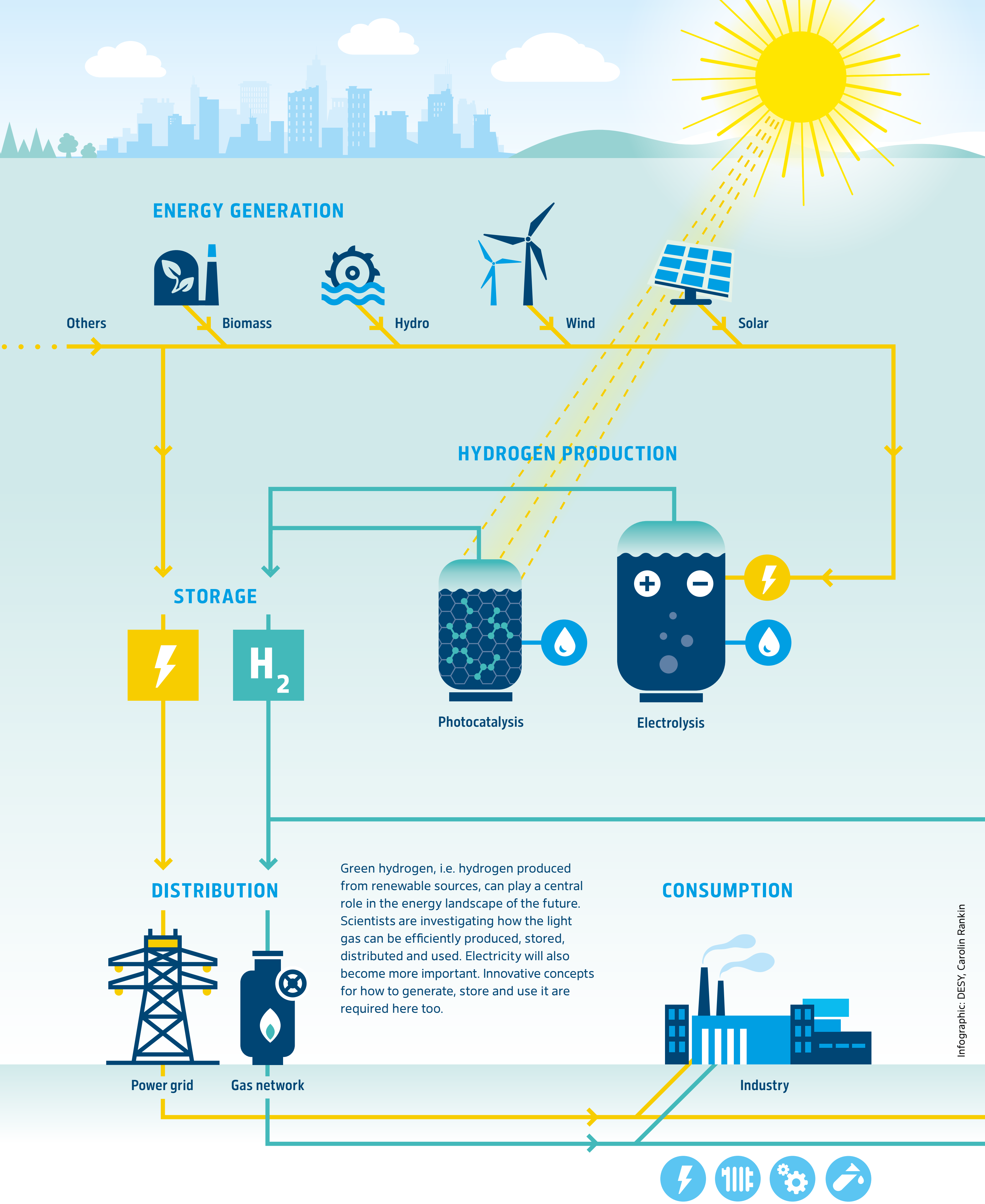
> *“Our investigation is an important step towards analysing industrial catalytic materials”*
>
> ***Andreas Stierle, DESY***

Science Advances,
DOI: 10.1126/sciadv.abh0757

Pictures: Science Communication Lab for DESY



The X-ray irradiation produces a characteristic diffraction pattern (top right) from which a complete image of a single catalyst nanoparticle can be generated. In addition, it also shows changes in the chemical composition of the particle surface during operation.



Green hydrogen, i.e. hydrogen produced from renewable sources, can play a central role in the energy landscape of the future. Scientists are investigating how the light gas can be efficiently produced, stored, distributed and used. Electricity will also become more important. Innovative concepts for how to generate, store and use it are required here too.

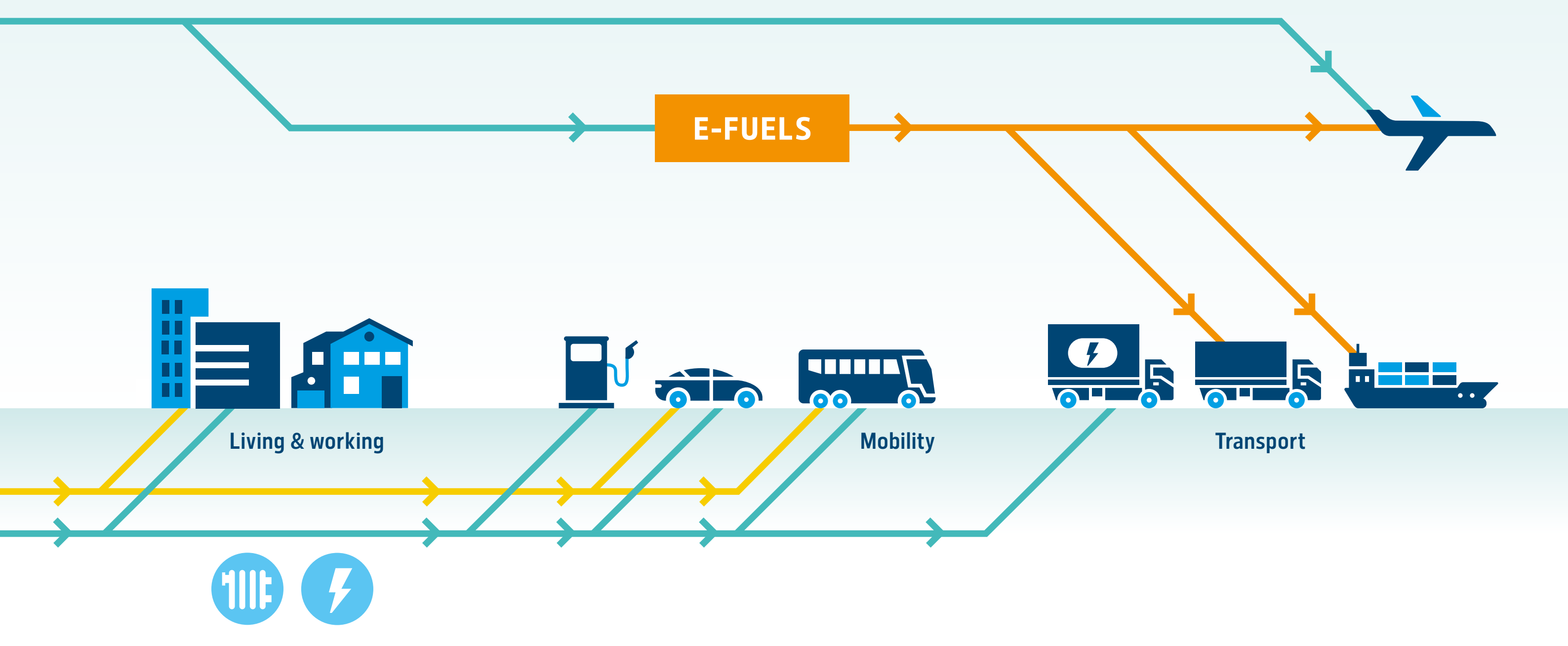
Infographic: DESY, Carolin Rankin

ZOOM

Research for the ENERGY TRANSITION

How fundamental research paves the way for green energy innovations

The energy transition is one of the greatest challenges for society of our time. Without a CO_2-neutral energy supply, climate change cannot be stopped. However, it is not the flick of a single big switch that will bring about the change. Instead, numerous developments and measures are required at various points in the energy landscape, and innovation and behavioural changes must go hand in hand. Hydrogen could play a central role in the future. But this energy carrier is only as green as its production. New and more productive methods for generating renewable energy are thus just as important as concepts for the efficient storage of different forms of energy. Saving energy also holds great potential, not least at the large-scale facilities used for research itself.



ZOOM

Hydrogen hope

The light gas has what it takes to become the energy carrier of tomorrow – but some research questions still need to be clarified

Hydrogen is regarded as a central element of the energy transition. In the future, it could power climate-friendly aeroplanes, ships and lorries and open the path to producing green steel and cement. But to do so, it must be produced without releasing carbon dioxide (CO_2), by electrolysing water using wind or solar power, for example. Researchers around the world are working on the foundations of a future hydrogen economy – from the efficient production of the gas to its storage and use.

"Over the next few years, we need to radically transform our economy, which consumes large amounts of energy and natural resources," says DESY physicist Simone Techert. "It is becoming increasingly clear that hydrogen will play a central role, especially in industry." Up until now, coal, oil and natural gas have been fuelling factories and emitting enormous amounts of carbon dioxide. Green hydrogen has the potential to decarbonise this sector sustainably. It is also likely to become important in the transport sector, especially in aviation and shipping – either directly or as an intermediate for synthetic fuels, also known as e-fuels.

Today, green hydrogen is produced using electrolysers: In containers full of pipes and valves, purified tap water flows into stacks consisting of dozens of special membranes. Here, electricity splits the water into its components, oxygen and hydrogen. The electricity might come from a wind or solar farm, for example, and is fed through cables into the electrolyser. For the electrolysis to work, a chemical catalyst is needed, which speeds up the reaction significantly. Experts are always on the look-out for better alternatives, i.e. catalysts that are more durable, more efficient and cheaper than the substances currently in use.

Picture: Istockphoto/peterschreiber.media

"Instead of using electricity, water is to be split apart using light"

Heshmat Noei, DESY

More economical catalyst

Certain electrolysers now use iridium, one of the rarest and most valuable metals in the world, whose annual production is just eight tonnes. In the future, the energy transition will require more and larger electrolysers – and therefore more iridium. "That is why we are trying to drastically reduce the amount of iridium in the catalyst," explains Vedran Vonk, a physicist at the DESY NanoLab. "Our approach is to combine the expensive metal with another material, ruthenium."

The metal ruthenium is also a viable catalyst and significantly cheaper than iridium, though less durable. Together with Herbert Over's group at Justus Liebig University in Gießen, Vonk is producing nanometre-sized blocks of ruthenium oxide. The team then spikes the edges of these blocks with iridium oxide, which has a stabilising effect on the ruthenium oxide. "This allows us to use small amounts of iridium, but still achieve a good catalytic effect," explains Vonk. "In our latest experiments, we have been able to show that our combined catalyst is really stable and does not break down even at high currents." Now the experts want to investigate the system in more detail and increase its efficiency, among other things.

Light splits water

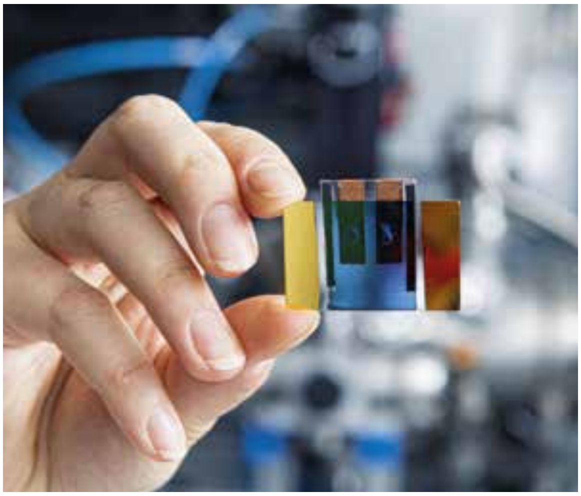
Looking further into the future, another idea for producing hydrogen is photocatalysis. "Instead of using electricity, water is to be split apart using light," explains NanoLab chemist Heshmat Noei. If this approach works, hydrogen could be produced along similar lines to solar power – the units would simply be placed in the sun. Here too, the catalyst plays a key role: Without it, the process of splitting the water molecule would simply not get going. In fact, reasonably good photocatalysts already exist, such as titanium oxide. "It's cheap and readily available," says Noei. "The disadvantage is that up till now titanium oxide only works for ultraviolet light; sunlight isn't enough."

The experts want to tackle this problem by modifying the shape of the nanometre-sized titanium oxide particles in specific ways. However, to do this they need a better understanding of just how catalysis takes place in this material. Experiments using high-power ultraviolet lasers such as FLASH at DESY are providing the necessary information. They can resolve the extremely rapid processes with great precision: What exactly happens on the scale of femtoseconds (quadrillionths of a second) when a water molecule docks onto a titanium oxide particle, reacts and is split apart? "In such experiments, we have found that certain forms of titanium oxide particles can also be active at a wavelength of 770 nanometres, that is in the visible range," says Noei. "Next, we plan to combine titanium oxide with some gold and see if that makes a better photocatalyst."

Thinner than a hair

A project being pursued by Simone Techert seems similarly visionary. The idea behind it is very original: "Just as the leaf of a plant converts light directly into chemical energy, we want to develop a solar cell that produces hydrogen directly." This means that the green electricity would not have to be generated by a solar farm and transported through cables to an electrolyser; it would be generated on site, more or less within the electrolyser itself.

Techert's group has already succeeded in building its first prototypes – tiny cells that are thinner than a human hair. They consist of several layers, like a ››



Green electricity for hydrogen production: The organic solar cell layer, which is only 200 nanometres (millionths of a millimetre) thin, converts light with an efficiency of almost 30 percent into electricity, which can be used directly to split water.

Picture: DESY, Gesine Born

DESY researcher Simone Techert uses artificial deep-sea minerals to produce hydrogen.

sandwich. A top layer serves as the solar cell, collecting light and converting it into electricity. Unlike most photovoltaic modules that are installed on roofs, it is made not of silicon but of light-sensitive molecules of organic polymers. The wafer-thin solar cell delivers the current directly to the layer underneath. This serves as a micro-electrolyser, splitting the water to produce hydrogen with the help of the electricity and small amounts of light.

The minute electrolytic layer consists of water-splitting oxides. These are mineral analogues that occur in the deep sea, among other places, as metabolites from bacteria that thrive on minivolcanoes beneath the sea. "These mineral analogues can be replicated in the lab and are excellent at splitting water," says Techert. "The solar and mineral layer are directly adjacent to each other, and their configuration allows special interactions to take place between them, ensuring the efficient conversion of solar energy into hydrogen." In numbers: The top solar layer is only 200 nanometres thick and converts light into electricity with an efficiency of almost 30 percent. The lower, equally thin layer has an efficiency of 70 percent – yielding an overall efficiency that is already on a par with commercial systems.

"Over the next few years, we need to radically transform our economy, which consumes large amounts of energy and natural resources"

Simone Techert, DESY

Like a tree

Some fundamental questions still need to be clarified, though. When light enters the cell, it creates a certain degree of disorder on the molecular level. Such disorder can be disruptive, obstructing the flow of current in the cell, for example. But by cleverly designing the materials, the disorder can be channelled in such a way that it actually enhances the flow of electrons and favours the conversion of sunlight to hydrogen.

"However, we still need to develop a better understanding of these processes," Techert points out. "The X-ray sources at DESY allow us to closely study the disorder and its dynamics and figure out which materials we need to use where to create the most efficient system." Experiments at the European XFEL X-ray laser, for example, allow the ultrafast motion of molecules inside the nanolayers to be observed – providing crucial input for developing a fundamental understanding. Experiments at the planned X-ray

Picture: DESY, Gesine Born

source PETRA IV should also give new impetus. It will be able to focus the X-rays much more narrowly than the current facility and hence allow the nanomaterials to be examined much more closely.

But even if some answers are still pending, do concrete ideas already exist as to what a green hydrogen factory made of nanocells might look like? "Perhaps something like a tree with leaves – surfaces that are arranged in a three-dimensional configuration," speculates Simone Techert. "They could then be integrated into urban architecture, for example in the façades and on the roofs of houses." One thing at least seems clear: The basic materials needed to make a nano-hydrogen cell are not particularly expensive. In that sense, nothing would stand in the way of their broad application.

New means of storing hydrogen

The cheap production of green hydrogen is only one research issue, however. "Another one is how to store the gas as efficiently and safely as possible," says NanoLab director Andreas Stierle. Today, there are two established methods: either in pressurised tanks, for which the hydrogen is compressed to 700 times atmospheric pressure, or else in cryogenic tanks, for which the gas must be cooled to minus 253 degrees Celsius and liquefied. However, both these methods are complex and cost energy, which is why experts are trying out alternatives.

Stierle's team is experimenting with palladium. It has been known for some time that this precious metal can absorb hydrogen like a sponge. "So far, however, getting the hydrogen out again has been a problem," explains Stierle. "That's why we're trying out palladium particles that are only a nanometre across."

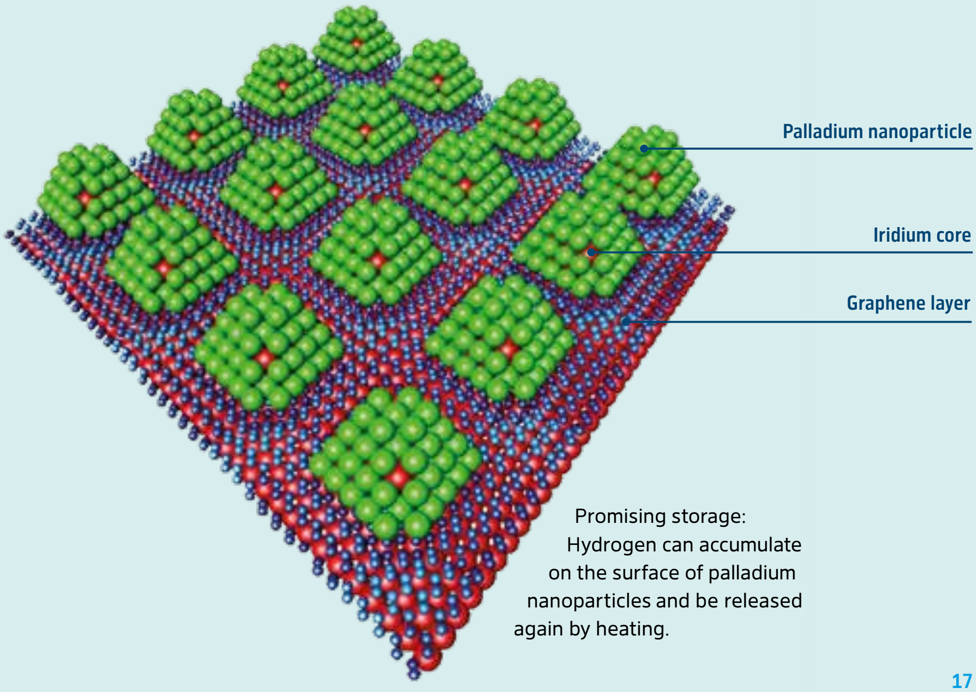
Such tiny objects can now be produced at the Centre for X-Ray and Nano Science, or CXNS for short. Stierle's team has only just moved into the brand new building; stray boxes from the removal still litter the corridors; and finishing touches are being applied to the building. Stierle opens the door to one of the laboratories and points to a long stainless steel tube. Numerous smaller tubes branch off from it, ending in a range of vacuum chambers, some thickly wrapped in aluminium foil. The whole structure is somewhat reminiscent of the model of some future space station. "In one of these chambers, we apply precious metals to special substrates by vapour deposition," the physicist explains. "In the process, the nanoparticles form by themselves in much the same way as a water droplet forms on a water-repellent surface."

In order to analyse these particles with the utmost precision, they then have to be manoeuvred through the evacuated tubes into the other chambers using a complex system: First, the experts use special grippers to transfer the samples to a small transport trolley. A conveyor belt moves this to the next chamber, where another gripper brings the sample into position. "It takes a great deal of skill," says Stierle. "If the sample holder gets lost somewhere in the vacuum tube, you have to open it up and allow air into the system – quite a lot of trouble. So it's better not to drop it!"

Praline with an iridium core

The palladium particles for storing hydrogen have a rather special feature: In order to stabilise them, they are given a tiny core of iridium. Afterwards, they are fixed to a surface made of graphene, i.e. an extremely thin two-dimensional layer of carbon. "The palladium particles can be attached to the graphene at intervals of only two and a half nanometres, resulting in a regular, periodic structure," explains Stierle.

Using sophisticated X-ray techniques, his team was able to follow in detail what happens when the clumps of palladium come into contact with hydrogen. The hydrogen adheres almost exclusively to the surface of the particles, as they are simply too tiny for any significant amount of gas to penetrate inside them. The resulting structures resemble a chocolate praline: with the nut in the middle made of iridium, coated with palladium rather than ››



Promising storage: Hydrogen can accumulate on the surface of palladium nanoparticles and be released again by heating.

The DESY NanoLab headed by Andreas Stierle is researching numerous aspects of a future hydrogen economy.

"How can the gas be stored as efficiently and safely as possible?"

Andreas Stierle, DESY

marzipan, and a chocolate coating made of hydrogen. To release the hydrogen and empty the storage again, moderate heating should be enough. The hydrogen should escape from the surface of the nanoparticles relatively quickly – after all, it does not have to make its way laboriously from the inside to the outside.

"We now want to find out what storage densities can be achieved using this technique," says Stierle. "But before we can think about technical applications, some problems still need to be overcome." Among other things, it is important to find a carrier that can be used in practical applications. One option is carbon sponges with tiny pores, in which the palladium particles could be housed in large numbers. "Something like that is already being tried out," says Stierle. "And I think it's quite promising for the future."

Better fuel cells

However, his lab is also looking into another issue: How can hydrogen be used most effectively? Some applications involve converting it back to electricity, to power vehicles, for example, or to compensate for fluctuations in the power grid. This is done using fuel cells. In them, hydrogen and oxygen react to form water, and the resulting flow of electrons produces a current. This reaction requires a catalyst too, and the precious metal platinum is often used for this. Platinum degrades over time, however, noticeably reducing the service life of the fuel cell.

"We are using various analytical methods to examine exactly what is going on in the fuel cell," explains NanoLab chemist Leon Jacobse. "The main problem is the oxygen that is inevitably produced during the reaction." This oxidises the surfaces of the platinum. At high electrical voltages, in particular, so much oxygen is bound by the surface that it can literally pull the platinum atoms out of the catalyst. "We were able to observe the platinum being removed layer by layer," Jacobse reports.

What happens to this vagabond platinum is largely unclear. Some of the atoms appear to return into the catalyst in a kind of healing process. The NanoLab researchers now hope to work out where the rest disappears to and what kind of compounds it forms. "We are planning new experiments for this," says Jacobse. "And hopefully we will be able to solve this puzzle over the next few years at PETRA III." Their findings could also be useful for industry in the long term, helping manufacturers to design future fuel cells so that they lose less platinum and thus last longer.

"We were able to observe the platinum being removed layer by layer"

Leon Jacobse, DESY

Picture: DESY, Gesine Born

"Innovation and changes in behaviour need to go hand in hand"

The economist Alexander Bassen teaches at Universität Hamburg. He is a member of the German Advisory Council on Global Change (WBGU) and the German Council for Sustainable Development (RNE). He believes that the transfer of research findings to innovative solutions needs even greater support.

femto: The energy transition is a task for society as a whole and poses enormous challenges. What role can fundamental research play in this process?

Alexander Bassen: On the one hand, there needs to be a change in behaviour. While we are well aware that we will need more wind turbines and power lines in the future, society is often not as willing to make its own contribution to this as one would wish. It is not unusual to hear the attitude: renewables yes, but please not in my backyard. We certainly still have a lot of convincing to do. But we will not achieve the energy transition through such changes in behaviour alone. I am firmly convinced that we also need technical innovations. Otherwise, the transformation will mean a marked decrease in our quality of life. That is why we need technological advances – as well as new ideas provided by fundamental research. All in all, in the energy transition, innovation and changes in behaviour must go hand in hand.

femto: Fundamental research certainly manages to keep bringing up new ideas. In recent years, a number of start-ups have been launched with visionary concepts for fusion reactors, for example. But by no means every idea makes it all the way to becoming a practical application. Is there perhaps a danger that fundamental research promises too much, which it later fails to deliver?

Alexander Bassen: I wouldn't say that. In my discussions with professionals working in fundamental research, when I ask them how their work might one day contribute to society, they often reply that they don't want to know. Because if they did, research might be guided in a specific direction too soon, preventing it from developing its true potential. As a business economist, it took me a while to understand and accept that. But today, I am convinced that this is the right approach. In fundamental research, we should first tackle the actual scientific questions and only afterwards think about which areas its findings might be applied to. Fundamental research needs this freedom in order to end up being successful.

femto: How then can ideas emerging from research be turned into tangible innovations that will help the energy transition?

Alexander Bassen: Once the research has reached a certain level of maturity, it is undoubtedly appropriate to provide impulses for innovation and think about the direction a project might take. This doesn't necessarily have to be done by the same people who drove the fundamental research. But scientists might also find it interesting to develop their ideas and turn them into implementations that can solve concrete problems. I would find it very exciting if established individuals were to pour their knowledge into products even more than before.

femto: It is repeatedly claimed that Germany is a leader when it comes to fundamental research, but then fails to implement this know-how in the form of applications and products. Is this a problem in energy research, too?

Alexander Bassen: Yes, I think so. The transfer works well in some areas, and some universities are really good at it. But we should be giving much more support to that transfer, by facilitating administrative processes, for example, and creating stronger incentives for researchers to develop their ideas and turn them into innovations. This is especially true of those who work within the relatively narrow framework of a civil service position. Here, we should allow greater flexibility and also offer financial incentives so that these experts can take entrepreneurial actions more often. I believe there is still a lot of potential at this interface.

Picture: Private

Tapping into the sun

Better and more environmentally friendly solar cells are a cornerstone of the energy transition

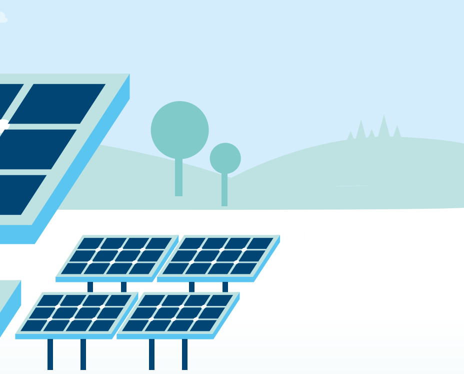
Solar cells turn sunlight into electricity. In the process, highly complex reactions take place inside them. Using sophisticated X-ray experiments, researchers are shedding light on the finest details of what goes on inside, providing manufacturers with clues as to how they can make their cells more durable and more efficient. Other research projects are going even further. Their aim is to develop solar cells that are ultimately made from natural materials and therefore sustainable.

> *"Industry has become steadily more interested in our work over time"*
>
> ***Michael Stückelberger, DESY***

Among other things, DESY physicist Michael Stückelberger is studying solar cells made of silicon – those silvery-blue solar panels that dominate the market today. Manufacturers have been trying for years to improve the efficiency and durability of their panels. One of the issues they are tackling is so-called crystal defects. Although industry tries to grow the most perfect silicon crystals possible for its solar cells, these crystals have certain flaws. These defects can then become gateways for elements like copper – troublemakers that cause the electrical charges separated by the sunlight to reunite prematurely, reducing the performance of the cell. "Some of these defects are less harmful than others," Stückelberger explains. "And that's where one would like to understand how such defects can be mitigated or eliminated."

DESY's X-ray source PETRA III can be used, for example, to determine precisely where copper has found its way into a solar cell. At the same time, it is then possible to measure how powerful the solar cell is at those specific locations. It turns out that solar cells typically perform worse in those areas where a lot of copper is present. "We are working directly with the manufacturers on these projects," says Stückelberger. "Industry has become steadily more interested in our work over time." Sometimes, the experts

Graphic: DESY, BUREAU BALD GmbH



come across problems in their experiments that the manufacturers had not even considered – after all, measurements of such great precision were not feasible until recently.

Production by printer

But the physicist is not only concerned with the cells that are available commercially; he is also studying a class of materials that holds great promise for the future, so-called perovskites. These minerals have a certain crystal structure that allows them to convert sunlight into electricity as efficiently as silicon, but should be much cheaper to produce, for example using something like an inkjet printer. “Perovskite solar cells can be very thin, yet powerful,” Stückelberger explains. “And the materials they are made of are ultimately available in unlimited quantities.”

There are still some drawbacks, however. Until now, moisture, heat and ultraviolet light have been detrimental to perovskites, causing them to age rapidly and thus forfeit a lot of their performance. Moreover, it is not yet possible to manufacture the cells with large surfaces – at least not in good quality. In some areas, the cells end up a little too thick, in others they are a little too thin.

Help for manufacturers

Stückelberger is using his metrological methods to search for causes and effects. “Initially, it was thought that perovskite cells would be unable to withstand the high-intensity X-rays we use for our measurements,” says the researcher. “But then it did work, and today, measurements like these are carried out routinely.”

For manufacturers, experiments like these provide information that tells them how to make their materials: What exactly happens, for example, when the layers that have been applied in a wet state dry and the perovskite crystals form in the process? The planned expansion to PETRA IV would allow Michael Stückelberger to take an even closer look at these events. “We would be able to analyse the relevant sites in the crystals in much more detail,” he says. “And we could make faster measurements, thereby taking a closer look at many more samples for the solar industry than before.”

Polymer solar cells

In addition to silicon and perovskite cells, there are also other types: polymer-based solar cells, for example, i.e. made of plastic. “These organic solar cells have the advantage of being very light and inherently flexible,” says DESY physicist Stephan Roth. This would allow the curved surfaces of buildings to be used to generate power too – an architectural advantage. It is true that organic solar cells have until now been less efficient than conventional silicon technology. On the other hand, they can be manufactured easily and cheaply using inkjet printers or spraying techniques.

So far, however, the technology has only become established ››

DESY researcher Michael Stückelberger uses X-ray light to investigate the inner structure of solar cells.

Picture: DESY

for niche applications. The reason for this is that the durability of the polymer solar cells often still leaves much to be desired, because ultraviolet radiation damages the materials over time, and water gets inside the cells. In addition, they are still essentially made from petroleum, and manufacturing them involves environmentally harmful solvents. Stephan Roth's group is hoping to change that. "Not only do we want to generate power sustainably, we also want to manufacture and apply the materials used to do so by sustainable means," he says. "That is the inclusive approach we are pursuing."

"Not only do we want to generate power sustainably, but also the materials used to do so"

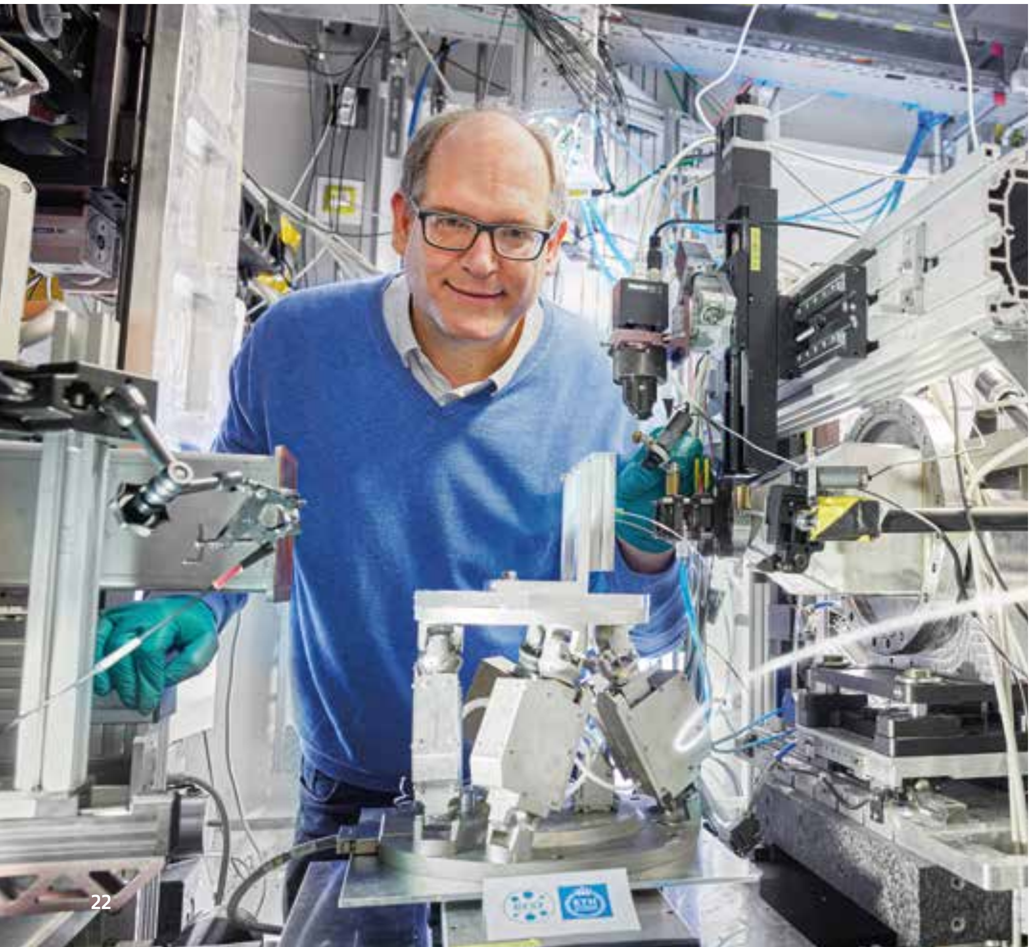
Stephan Roth, DESY

Simple trick

One of the weak points is the solvent. When manufacturing an organic solar cell, different layers need to be applied on top of each other to produce a film that turns sunlight into electricity. Some of these layers are made of polymers, including the solar-active material. To apply these polymers, they are dissolved in a solvent. When this evaporates, it leaves behind the polymers in the form of a solid layer. Up to now, the chemicals used as solvents have contained chlorine, which makes them potentially harmful. Together with experts from China and Munich, Roth's team was able to show some time ago that other, more environmentally friendly solvents can also be used by cleverly tweaking the parameters during the production process.

"It's based on a simple trick, but you have to come up with the idea first," Roth recounts. "Until now, only the base onto which you spray the polymer solution is heated; that allows it to dry more quickly. But we heated the solvent as well." X-ray measurements made at PETRA III revealed the result: Thanks to the "preheated" solvent, the microscopic structures of the solar cell turned out even better than before. In addition, efficiency increased and production time decreased. "This is a huge success," Roth is pleased to report. "You use a green solvent and end up with a solar cell that is at least as good as before." Together with the Munich group, he has now set up a team that wants to develop the technology to the point where it can be used in practical applications.

DESY researcher Stephan Roth is working with international colleagues on a solar cell made of sustainable materials.



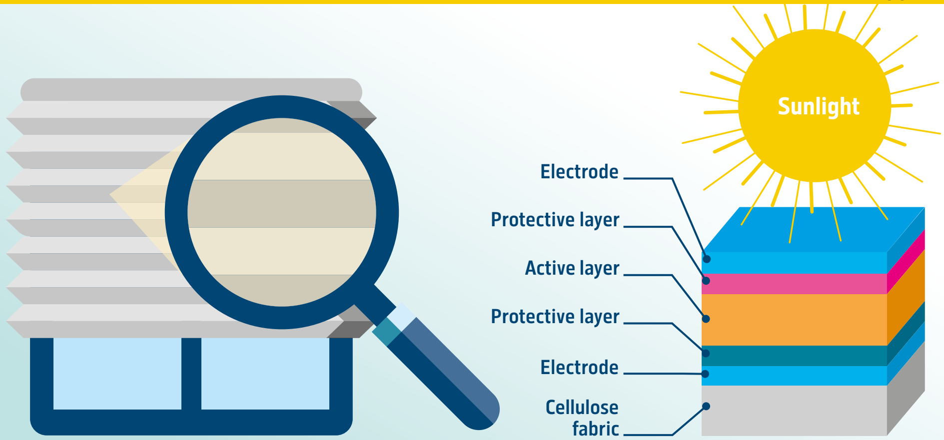
Paper instead of plastic

Another goal of the experts is to replace the carrier material on which the light-sensitive polymers are deposited by a sustainable material. At the moment, plastic films are used, i.e. petrochemical products. Roth's team is pursuing an alternative, known as nano-cellulose. This is produced by extracting tiny filaments from wood; these are just micrometres long and only five nanometres thick. These cellulose filaments can be used to make a special nanopaper, which the experts want to use as a carrier for organic solar cells.

"We can simply spray the polymer solutions onto the

Picture: DESY, Christian Schmid

nanopaper through a nozzle," explains Roth, who also works at the Royal Institute of Technology in Sweden. "This has several advantages over printing, which is the conventional method." Spraying is extraordinarily fast and, unlike printing, the liquid can be applied not only to a flat surface, but to objects of any shape, such as undulating roof tiles. This spraying method has already been found to work quite reliably in an experimental setup at PETRA III. It performs the various production steps automatically, while a high-intensity X-ray beam can be used at the same time to track precisely how the polymers are deposited and align themselves on the cellulose substrate.



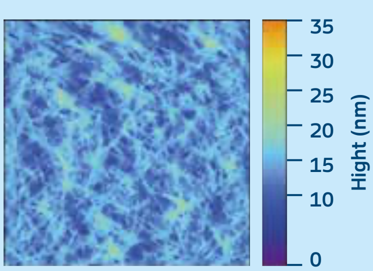
"Sunny Cellulose" – window blinds produce electricity

When the sun shines, the blinds are pulled down in many offices. In the future, a new type of paper sunblind will then produce electricity. It is based on an innovative material made of nanocellulose fibres that can be woven into a large tarpaulin, onto which a functionalised nanolayer of polymer solar cells is applied. When this functional blind is pulled down, electricity begins to flow. The product should be easily recyclable and provide impulses for construction and architecture. The joint project "Sunny Cellulose" of the Royal Institute of Technology (KTH) in Stockholm and DESY is funded by the German Federal Ministry of Building. The project partner is the Federal Association of German Garden Friends, in whose headquarters the novel high-tech blind will be used for the first time.

Compost instead of hazardous waste

Now Roth and his colleagues are taking the next step. They want to use nanocellulose not only as the carrier material, but also for other layers required for the solar cell to function properly, in particular the electrodes. These electrodes must be good conductors of electricity – a property that nanocellulose inherently lacks. A clever trick should get around this: The scientists are incorporating tiny metal particles, so-called nanowires, in the cellulose network, turning the insulating nanopaper into a conductive electrode. "We have already demonstrated that the principle works," says Roth. "Now we hope to produce a first prototype solar cell largely made of sustainable materials by 2022."

Afterwards,with the assistance of a company, they plan to integrate the technology into a building and to test it under practical conditions. But there are still various obstacles to be overcome. Resistance to water could become a problem, for example. Perhaps natural materials such as waxes or tree resins could be used to keep out the moisture – that's one idea. The durability of the cells and the stability of the thin cellulose carriers also need to be explored. But there is one thing that Stephan Roth is certain of: "We believe that these cells can be produced inexpensively," he says. "And, in principle, it should be quite easy to recycle them after use." Instead of having to dispose of them as hazardous waste, solar cells made of cellulose could end up on the compost heap or with the waste paper.



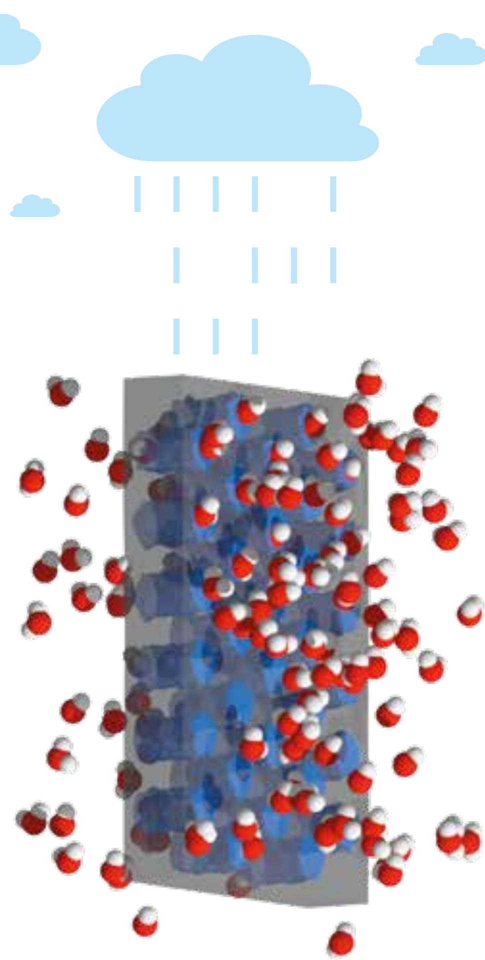
Nanocellulose fibres can be used to manufacture a paper layer into which a polymer solar cell could be sprayed.

An uncoated (top) and nanopaper-coated silicon wafer. The nanocellulose layer is only 200 nanometres thin. The wafers are each two centimetres wide and ten centimetres long.

Pictures: DESY/KTH Stockholm; Calvin Brett (nanopaper); Illustration: DESY, Rosen Dimitrovs; Graphic: DESY, Carolin Rankin

Porous sponge as a power plant

An EU project is exploring a new means of generating electricity



The wall of a quay in a seaport; its surface is coated with a fascinating material. At high tide, the wall becomes wet and electrical charges inside it are separated. When the water flows out with the ebb tide, the material dries again, becoming electrically charged and generating green, CO_2-free electricity. For now, this is only a vision: The miracle material does not yet exist. But an international research team has recently started tinkering with what it would require. The EU project EHAWEDRY is to build the first prototype of this new energy technology in a few years' time. It is based on electrically conductive materials that are riddled with tiny pores.

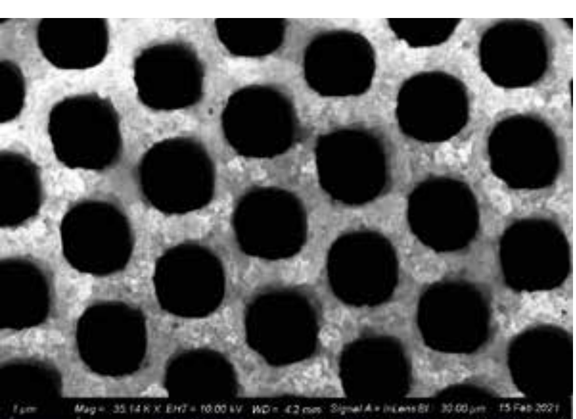
"We take carbon or silicon and use electrochemical etching to create nanometre-sized pores in them," says Patrick Huber, head of the Institute for Materials and X-ray Physics at the Hamburg University of Technology and of the DESY research group "High-Resolution X-ray Analytics of Materials". Seen under a microscope, the resulting material resembles a sponge. However, rather than being millimetres across, the pores are about a million times smaller. Fascinatingly, one cubic centimetre of such a material contains so many pores that its surface – if you unfolded it completely – would cover an entire football field.

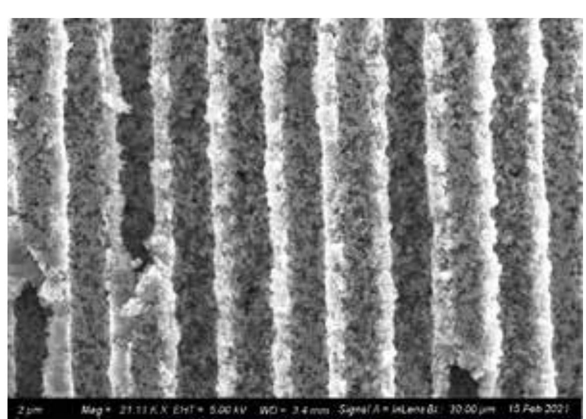
When this nanosponge is moistened with water containing common salt (sodium chloride), its pores are flooded with billions of molecules. If a small positive voltage is then applied to the sponge, the negatively charged chlorine ions migrate to the walls of the pores and attach themselves there. "The positively charged sodium ions remain in the water," explains Huber. "The resulting charge separation is similar to a capacitor being charged."

100 watts per square metre

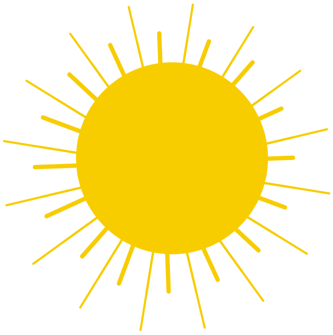
The crucial effect occurs if the material is then left to dry. The charges inside have to rearrange themselves and in the process they become concentrated, so to speak. This increases the electrical voltage within the material, which can be used to generate electricity. After that, the cycle starts all over again: The nanomaterial is rewetted and then dried again to generate energy.

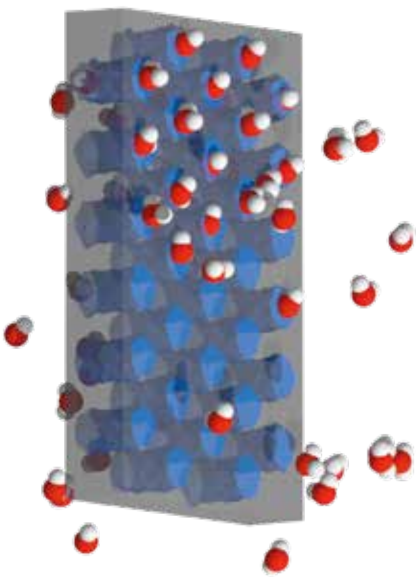
Due to the enormous number of pores and the huge resulting internal surface area, this process could well be effective. It is estimated that one square metre of the nanosponge's surface should produce about 100 watts of electrical power – the same order of magnitude as solar cells, except that





Top view (left) and cross-section (right) of the porous sponge under the electron microscope. The large cylindrical pores have a diameter of around one thousandth of a millimetre. They are separated by nanoporous walls, which are criss-crossed by pores with a diameter of only a few millionths of a millimetre.





“The energy used for the drying process could be waste heat from industrial plants or data centres”

Patrick Huber, Hamburg University of Technology and DESY

several layers of the porous sponge can be stacked, so that one cubic metre could produce 10 kilowatts of power.

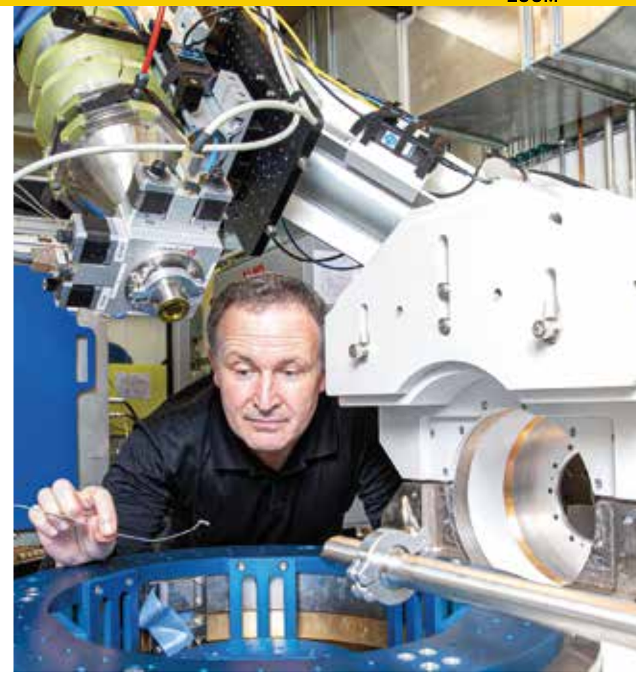
Coating a quay wall with this porous material to take advantage of the tides is only one way in which the idea could be applied. “An even more efficient approach might be to build generators from our material and pump liquid thorough them in a closed circuit,” according to Huber. “The energy used for the drying process could be waste heat from industrial plants or data centres that has previously gone unused.” Hot climates would also be suitable – the scorching sun could dry artificially moistened nanosponges integrated into façades in no time at all, producing a regular yield of electrical power.

Phase transitions in detail

Many research questions still need to be clarified, however, before this can happen. For example: “The salt threatens to crystallise during the drying process, which would literally blow apart our nanomaterial,” explains Huber. In addition, tiny bubbles could form through a process known as cavitation; these would severely disrupt the process. To analyse phenomena like these, the team wants to take a closer look at them at DESY in Hamburg using PETRA III, one of the world’s most powerful X-ray sources.

The narrowly focused, high-intensity X-ray beam produced by the accelerator will allow them to observe the precise details of the phase transitions in the nanosponge. Where exactly do the ions attach to the walls of the pores when the nanosponge is moistened? Where does it dry most quickly and where is some liquid left behind? And under what conditions do troublesome air bubbles form? The team led by Patrick Huber hopes to answer questions like these over the coming years in the context of the Centre for Integrated Multiscale Materials Systems (CIMMS), which is currently being set up in the Hamburg metropolitan region as a collaboration between the Hamburg University of Technology, Universität Hamburg, the Helmholtz Centre Hereon and DESY.

In addition, there are common areas of interest regarding the behaviour of aqueous solutions in nanoporous materials with the Centre for Molecular Water Science (CMWS). This interdisciplinary institution was initiated by DESY and studies fundamental questions about the behaviour of water at the molecular level, with partners from all over Europe. “Towards the end of EHAWEDRY, our team would like to present a first prototype,” the physicist outlines the goal of the project. “After that, we hope that industrial partners will join us in following up the technology.”

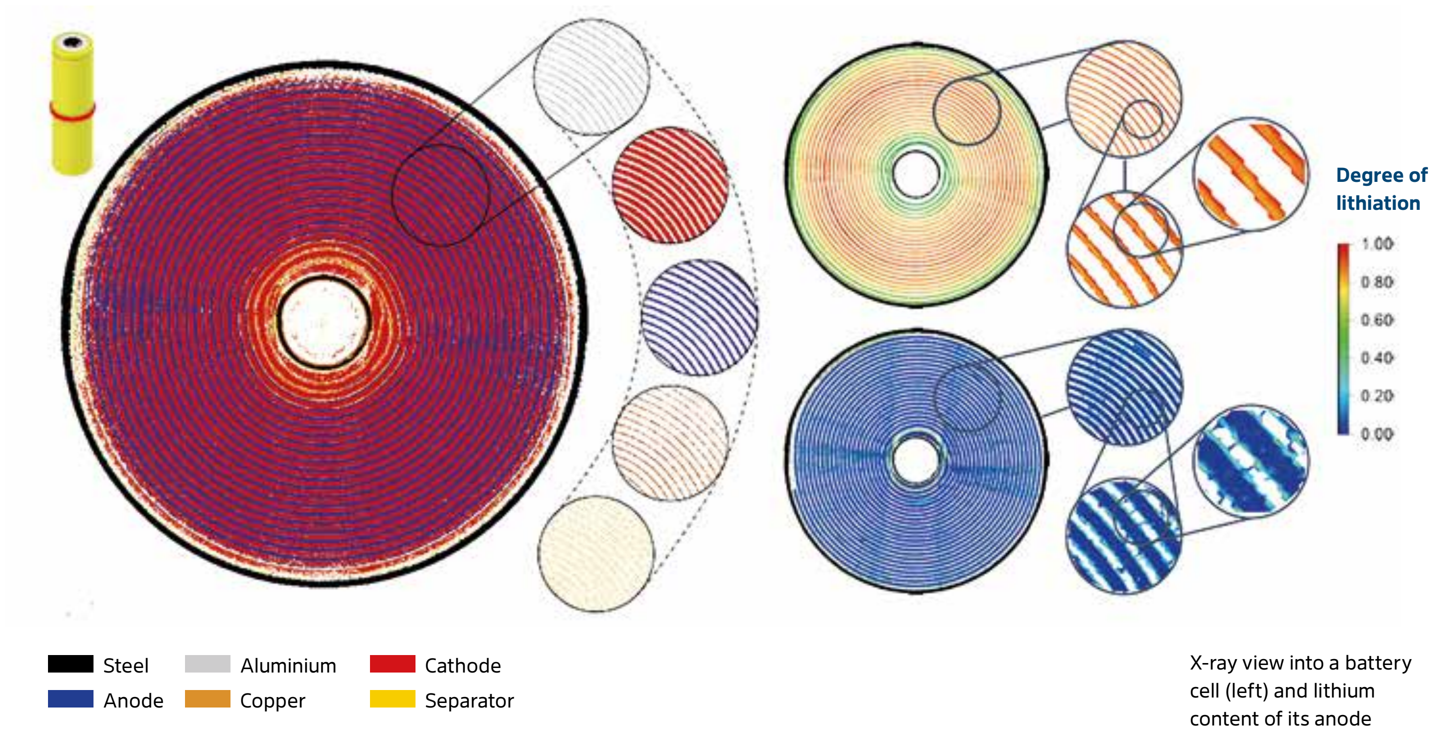


Patrick Huber researches customised multiscale materials.

INTERNATIONAL PARTNERS

EHAWEDRY stands for “Energy harvesting via wetting/drying cycles with nanoporous electrodes”. The project is receiving three million euros in funding from the EU, started in July 2021 and is due to run until the middle of 2025. Universität Hamburg and the Hamburg University of Technology are taking part, as well as partners from Spain, France, Italy and Ukraine, including an industrial company.
The vegetable world is an indirect source of inspiration: Certain seeds use tiny pores to bury themselves in the soil by making use of an interplay between the condensation and evaporation of water. The research group, on the other hand, wants to use this principle to generate electrical power directly, rather than kinetic energy.

Pictures: Hamburg University of Technology, Patrick Huber; DESY, Marta Mayer (portrait)



X-ray view into a battery cell (left) and lithium content of its anode (top right) and its cathode (bottom right)

Better electricity storage devices

Scientists are working on more efficient and sustainable batteries

Batteries are one of the core technologies for a sustainable electricity supply. No electric car can manage without them, and they are used to store electric power generated by wind turbines and solar cells, thereby stabilising the power grid. But these storage devices still have room for improvement. They need to become more efficient and more sustainable.

A research group led by DESY physicist Alexander Schökel is investigating a type of battery that is installed in laptops and electric drills, but also in some electric cars. The "18650" cell resembles an ordinary AA battery, only that it is a little thicker and longer. "In principle, the design of this battery cell is quite straightforward," explains Schökel. "However, the details of how the chemical elements are distributed in it when the battery is charged and then discharged remain unclear."

The behaviour of lithium is particularly interesting. In which

> *"In some regions, lithium accumulates and can no longer be removed properly"*
>
> ***Alexander Schökel, DESY***

areas of the electrodes do large amounts of it accumulate, and where does little collect? Details like these can significantly affect the efficiency of the cell, but also its durability. Together with colleagues from Munich, Grenoble and Geesthacht, Schökel used a combination of methods to record the activity of the lithium in the battery as precisely as possible. In doing so, the experts were able to observe to within 20 micrometres (thousandths of a millimetre) how the lithium content changes in different regions of the battery while it is charging and discharging.

Isolated islands of lithium

As a result, the group found out, among other things, that the lithium concentration is very uneven,

Pictures: Technical University of Munich, Dominik Petz especially around the contacts that carry the current away from the cell. “This can have an unfavourable impact on its efficiency and performance,” says Schökel. “In some regions, lithium accumulates and can no longer be removed properly.” As a result, that lithium is no longer involved in energy storage at all; figuratively speaking, the ions are stuck on an island and no longer take part in the journey between the charged and discharged states.

“That’s something you want to avoid, of course,” explains Schökel. “Lithium is an expensive raw material and, if possible, one would like all the lithium in the cell to participate in the reactions.” The results of the experiments provide manufacturers with clues as to how they can optimise their cells, for example by redesigning the contacts. “There’s definitely potential for improvement,” Schökel believes.

Currently, the experts are examining the durability of 18650 cells: What exactly happens inside them after they have been through a few hundred charging cycles? In future, they also want to apply their combination of methods to other common cell types. The problem is that some of these batteries are significantly larger and thicker than the types examined so far, which makes it more difficult to screen them. “That’s definitely a challenge,” says Alexander Schökel. “But we believe we can push our methods quite a bit further.”

“We use peptides – small protein snippets – as our starting material”

Simone Techert, DESY

Organic batteries from grain

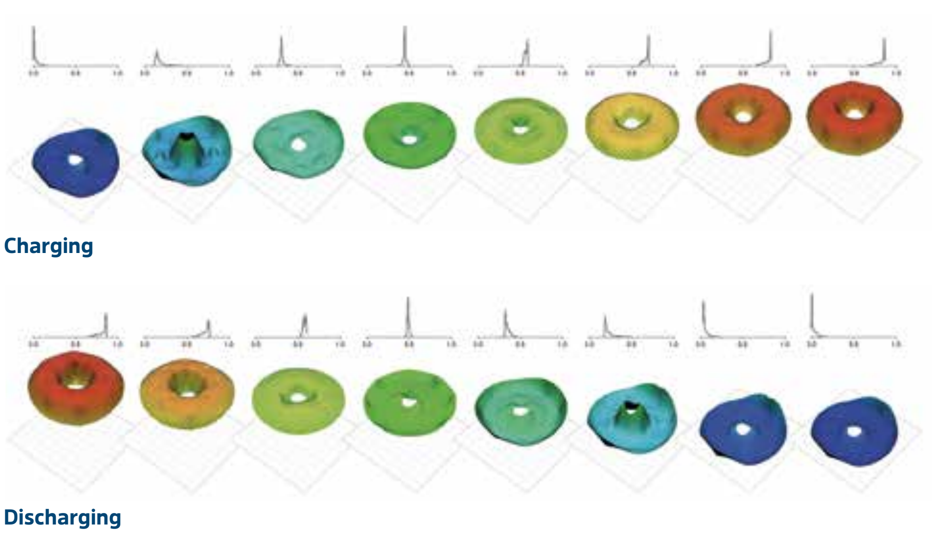
Today’s rechargeable batteries are made of materials that require special disposal – as everyone knows, batteries don’t belong in your normal household waste. The team of DESY physicist Simone Techert is working on a development that will change all this. The researchers are experimenting with a battery made of renewable natural materials, which can basically be thrown on the compost heap once it is spent. “We use peptides – small protein snippets – as our starting material,” says Techert. “They can be obtained from cereals, among other things.”

Her team is making use of the fact that the cereal peptides are electrically active. When an electric current is applied, sodium and potassium ions start moving about, and they accumulate at certain sites in the biomolecules, thereby storing energy. When the cell discharges, the particles migrate back, causing a current of electrons to flow – the battery supplies energy.

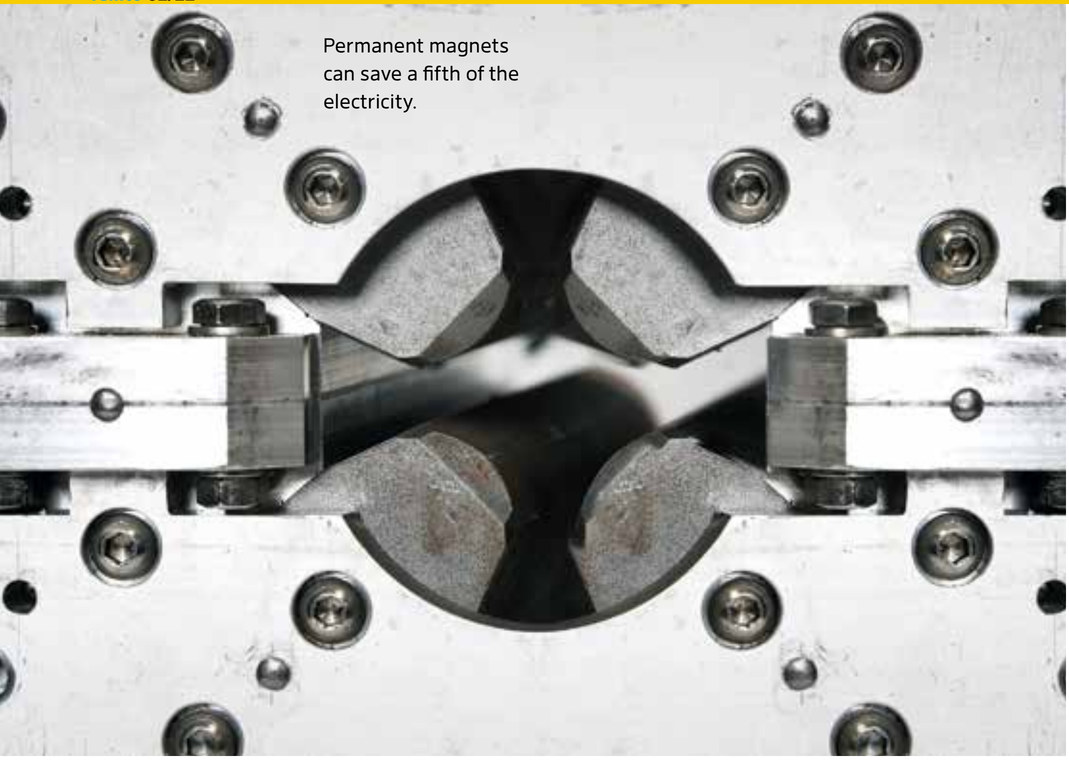
“In addition to doing the fundamental research that is and was necessary to determine whether and how peptides can be used to generate electricity, we have already built the first working prototypes,” says Techert. “Our research is still in its infancy, though, because we’re also looking into how X-ray methods can be optimised to study such systems in as much detail as possible in real time.” The aim is therefore not only to improve the batteries, but also to develop new methods for measuring and analysing the stability and efficiency of the biobattery.

Use in humans

If the research is successful, the peptide battery holds the promise of many exciting applications. Not only would it be sustainable, non-toxic and compostable, it would be made of a kind of gel, making it soft and pliable. It could therefore be manufactured in all kinds of shapes and forms. This would make it predestined for use in and on humans. In principle, biobatteries could be implanted inside the body to power pacemakers or brain implants. Or else they could power smart patches that are simply stuck on one’s skin and monitor vital parameters, such as body temperature or pH.



Lithium content of the anode during charging and discharging of the battery cell



Permanent magnets can save a fifth of the electricity.

Sustainable accelerator

The next generation of research machines is to run on less electricity

The energy transition is not just about wind turbines, hydrogen and electric cars. Developing more efficient technologies and thus consuming less energy is equally important. Research centres are no exception here. The large facilities used to do science, such as particle accelerators, consume considerable amounts of electrical power. To reduce their hunger for energy, Europe's leading research centres are working on more efficient accelerator technologies as part of the EU programme I.FAST.

"The issue of energy efficiency is becoming increasingly important for accelerator centres"

Denise Völker, DESY

"I.FAST is meant to advance the development of next-generation accelerators," explains Mike Seidel from the Paul Scherrer Institute (PSI) in Switzerland. "In one of the work packages, we are trying to make the facilities more economical and more sustainable." Apart from PSI, five other centres are also involved in the efforts: the European particle physics research centre CERN in Switzerland, the European neutron source ESS in Sweden, the UK Science and Technology Facilities Council (STFC), the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt and DESY.

Permanent magnets instead of electromagnets

One key focus of the I.FAST programme is developing more efficient accelerator components. An important starting point is the magnets that keep the electron beams travelling on a circular path in ring accelerators, such as DESY's PETRA III, and that focus them. At present, the Hamburg storage ring – one of the brightest X-ray sources in the world – runs on electromagnets, which by design work with electricity. However, some of these electromagnets could be replaced by permanent magnets. These maintain their magnetic field even without a power supply, so they don't consume any energy.

This would also have invaluable advantages in terms of the quality of the X-rays. Compact permanent magnets allow the magnets to be configured in new ways producing significantly more brilliant X-rays; this is extremely interesting for experiments aiming to examine the tiniest samples or sample sections in as much detail as possible. For this reason, DESY is planning a large-scale upgrade. In a few years, PETRA III is to become PETRA IV, which will be equipped with permanent magnets. Other facilities have already taken this step. The European Synchrotron Radiation Facility (ESRF) in Grenoble has been running with permanent magnets since 2020 – and, as a result, has consumed some 20 percent less electricity for accelerator operation.

Another key focus of I.FAST is developing more efficient klystrons. These specialised vacuum tubes generate the radio waves that accelerate the particles – much as surfers ride an ocean wave. "Today's klystrons have an efficiency of 50 to

60 percent; new technologies should increase this to over 70 percent," explains Mike Seidel. "We are working on a concrete development to replace the klystrons of the LHC accelerator at CERN by a more efficient type."

Slowing electrons and recovering their energy

In addition to developing efficient technologies, new, alternative accelerator concepts are also being considered, such as Energy Recovery Linacs (ERLs). In particle physics, accelerators are used to fire electrons head-on at their antiparticles, thereby uncovering clues to previously unknown elementary particles – indicating new, fundamental laws of nature. Unlike storage rings, particles in linear accelerators do not lose energy through synchrotron radiation and can reach higher energies. However, most of the high-speed electrons do not actually collide with each other at all, instead crashing into a kind of buffer after their first failed attempt at a collision.

The ERL concept seeks to recover this wasted energy. To do so, so-called resonators slow down the electrons travelling at close to the speed of light and extract a large part of their energy, which is then used to bring the next lot of electrons up to speed. "This type of accelerator would require significantly less power from the grid," explains Seidel. "However, the energy recovery principle would be more expensive and complex than a facility without energy recovery." Experts are currently investigating under what conditions the additional investment would pay off.

Sustainability certificate for rare-earth metals

"The matter of energy efficiency is becoming increasingly important for accelerator centres," as DESY's sustainability manager Denise Völker points out. "And other aspects of sustainability are also receiving more and more attention, such as water consumption, recycling and sourcing raw materials." For example, rare-earth metals such as neodymium and dysprosium are needed to manufacture the permanent magnets to be used in PETRA IV. "These elements are mined in countries such as China," says Völker. "But whether this mining is done in an environmentally and socially acceptable way is doubtful." A global certification would be desirable, to guarantee that these materials come from ecologically and socially acceptable sources. "Within the context of I.FAST, we are exchanging ideas with our industrial partners and looking for common ground," explains Völker. "And other industries, such as the manufacturers of wind turbines or electric cars, are also interested in this type of certification. We want to connect with them more closely."

https://ifast-project.eu

ON THE WAY TO A GREEN RESEARCH CAMPUS

DESY is not only conducting research for the energy transition; it also draws on climate-friendly technologies for its own energy supply. The long-term vision is a green campus that largely dispenses with CO_2 emissions. Today, the centre already obtains 60 percent of its electricity from renewable sources – a value well above the current electricity mix in Germany. DESY will be switching to 100 percent renewables by the beginning of 2023. From then on, its electricity needs, which, including those of the European XFEL X-ray laser facility, are equivalent to those of 150 000 people, will be covered exclusively by green power. This means that DESY will be responsible for 55 000 tonnes less in CO_2 emissions per year.

DESY is also gradually becoming greener in its heat supply. Already, one third of the campus is heated using waste heat from a helium liquefaction plant that is necessary for the operation of the European XFEL. In the future, the centre wants to tap into other sources of waste heat. Until now, the waste heat released by the accelerator magnets and the computer centre has gone unused. In a few years, it will feed the campus's own low-temperature local heating network. This offers considerable potential. An analysis carried out by the Hamburg University of Applied Sciences (HAW) suggests that this waste heat would be enough to heat the entire campus twice over. Plans are currently being considered to supply the additional heat to the neighbourhood, especially parts of the prospective Science City Hamburg Bahrenfeld.

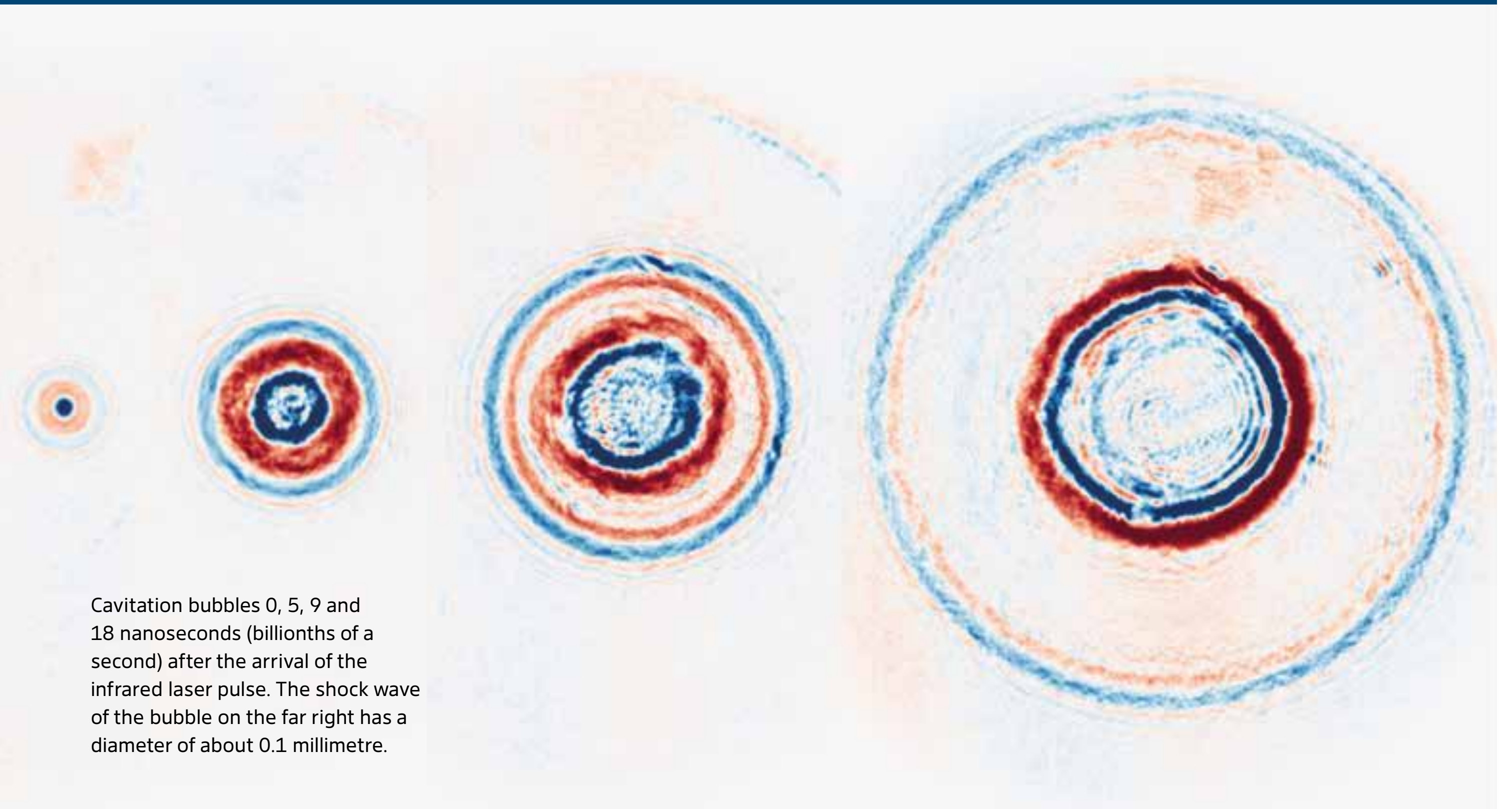
This is what DESY's Building 36 will look like in a few years' time.

These measures are flanked by better thermal insulation of existing buildings, detailed energy monitoring and plans to equip some of DESY's buildings with large areas of solar cells. And another, brand-new sustainability project should also help save energy. Greenery is currently being planted on the walls and the roof of one of DESY's research halls, covering a total area of 4600 square metres. The main objective of the project is to retain rainwater. In addition, the lush greenery should cool the building in summer and thus reduce the power consumed by the ventilation and air-conditioning system. And in winter, the plants will provide additional thermal insulation and reduce the need for heating.

Pictures: STFC; DESY, Marta Mayer (portrait); Luminousfields (DESY Building 36)

SPECTRUM

Science in brief



Cavitation bubbles 0, 5, 9 and 18 nanoseconds (billionths of a second) after the arrival of the infrared laser pulse. The shock wave of the bubble on the far right has a diameter of about 0.1 millimetre.

X-ray laser films cavitation bubbles in water

Everyone is familiar with tiny gas bubbles gently rising up in sparkling water. In fluid dynamics, this is called soft gas cavitation. A variant of this effect, hard cavitation, arises from the rapid movements of pumps, ship propellers and turbines and causes engineers a lot of headaches. Using the European XFEL X-ray laser, a research team led by the University of Göttingen has now filmed the propagation of such cavitation bubbles. The investigation offers hitherto unattainable insights into the phenomenon.

For the study, an infrared laser created cavitation bubbles in water. These are initially a few thousandths of a millimetre in size, but then spread explosively at supersonic speed, driven by an overpressure that exceeds normal pressure by a factor of about one hundred thousand. "In contrast to visible light, where refraction and scattering blur the image, X-ray imaging resolves not only the shape but also the density profile of the interior of both the bubble and the shockwave," explains Malte Vassholz, lead author from the University of Göttingen.

Thanks to the well-controlled time delay between the infrared laser pulse that created the effect and the X-ray pulse used to image the bubbles, the team could then record a kind of movie of the process. "In total, we recorded about 20 000 events and analysed more than 3000 bubbles," reports DESY lead author Johannes Hagemann.

The research not only provides new insights into the phenomenon, it also opens up interesting perspectives for applications. "Cavitation can be an undesirable effect in fluids in pumps or propellers, for instance, but it can be harnessed for use in laser processing of materials or to modify chemical reactions," explains co-author Robert Mettin from Göttingen.

"In laser surgery, shockwaves and compressed gases in tiny bubbles are created intentionally in tissue using laser pulses," adds research leader Tim Salditt from the University of Göttingen. "In the future, such processes could be 'filmed' in detail, using the methodology that we have developed, at a microscopic level and at high temporal resolution."

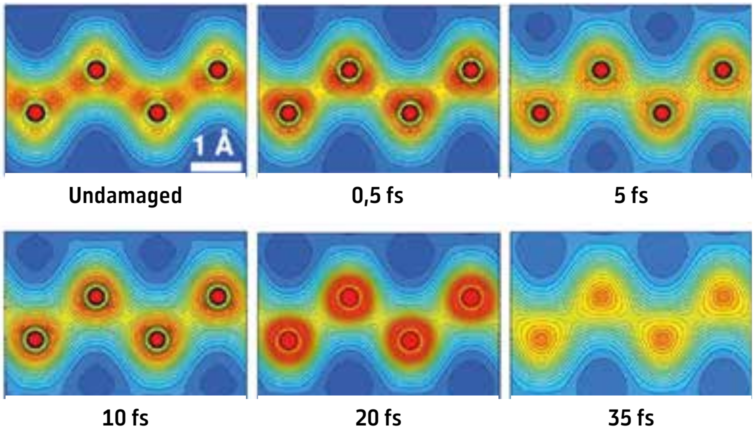
Nature Communications,
DOI: 10.1038/s41467-021-23664-1

Picture: University of Göttingen, Malte Vassholz

Unusual melting of diamond

An international team of scientists has found evidence of an unconventional melting process in diamond induced by an X-ray laser beam. While in conventional melting the atoms of a sample start moving stronger and stronger until their bonds break due to heating, the extremely intense X-ray laser pulses ripped the bonds apart straight away, and only afterwards did the atoms start to move due to heating, as the team around Ichiro Inoue from the RIKEN SPring-8 Center in Japan, Eiji Nishibori from the University of Tsukuba in Japan and DESY scientist Beata Ziaja reports.

The measurements reveal that the electron distribution around each atom becomes almost uniform in all directions (isotropic) within about five femtoseconds after the first pulse, followed by the onset of the atomic movement underway to the melting. "This femtosecond transition is called 'non-thermal' as it is not triggered by a much-longer-taking, 'thermal' heating of atoms in the crystal lattice," explains Ziaja.



About five quadrillionths of a second (femtoseconds) after the X-ray pulse, the electron distribution around each atom becomes almost uniform in all directions.

"The X-ray-induced non-thermal melting should be ubiquitous in many experiments with high-intensity X-ray laser pulses," comments Nishibori. "In particular, our finding can make a huge impact on the development of methodologies for structure determination with high-intensity X-ray laser pulses, as in this intensity regime, the X-ray-induced damage that occurs during the irradiation cannot be neglected."

Physical Review Letters,
DOI: 10.1103/PhysRevLett.126.117403

The Start-up Labs Bahrenfeld, a joint innovation centre of DESY, the City of Hamburg and Universität Hamburg

Pictures: Inoue, Ziaja, Nishibori et al.; Marta Mayer (Start-up Labs)

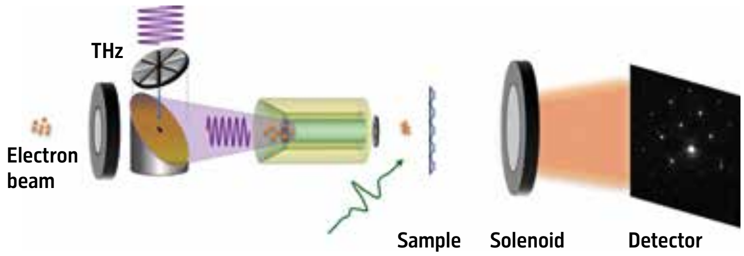
Entrepreneurship and innovation: Start-up Labs Bahrenfeld opened

Young companies and start-ups in the field of physics and biophysics have found a new home in western Hamburg: The Start-up Labs Bahrenfeld, a project jointly managed by DESY, Universität Hamburg and the City of Hamburg, have opened on the research campus at DESY. The innovation centre for deep-tech start-ups will also enhance the profile of the future Science City Hamburg Bahrenfeld.

"The future Science City Hamburg Bahrenfeld offers ideal conditions for scientific institutes, start-ups and innovative companies," said Hamburg's First Mayor Peter Tschentscher at the official opening. "With the Start-up Labs Bahrenfeld, we are creating a place in the neighbourhood of DESY where fundamental research and smart ideas can be turned into innovative products and applications."

Laboratories and workshops, offices and meeting rooms have been created covering an area of 2700 square metres. There is a strong need and high demand for them – almost all the premises at the Start-up Labs had been leased by the time they opened. The diversity of the various fields covered by the budding companies is huge, ranging from synchronisation systems to individualised tests for diagnosing cancer. The age of the companies also extends from absolute start-ups to companies that are already established on the market.

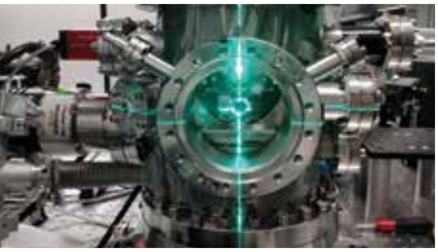
Table-top electron "camera" catches ultrafast dynamics of matter



A compact electron camera enables researchers to capture the ultrafast internal dynamics of matter. The system fires short bunches of electrons at a sample to take snapshots of its inner structure. It is the first such electron diffractometer that uses terahertz radiation to compress the electron bunches. The short wavelength of the terahertz radiation enables a compact design.

The development team around DESY scientists Dongfang Zhang and Franz Kärtner from the Center for Free-Electron Laser Science (CFEL) successfully validated the system by examining a silicon sample. To this end, they used the diffractometer to direct bunches of roughly 10 000 electrons each at a thin silicon crystal that was heated by a short laser pulse. The electron bunches were about 180 femtoseconds (quadrillionths of a second) long and clearly revealed how the crystal lattice of the silicon sample expanded within about a picosecond (trillionths of a second) after the laser hit the crystal.

On top of its reduced size, the terahertz electron diffractometer has another advantage that might be even more important to researchers: The system is perfectly synchronised, as it uses just one laser for all steps: generating, manipulating, measuring and compressing the electron bunches, producing the terahertz radiation and heating the sample.



The system fits on a lab bench and is adjusted with the help of an optical laser.

Ultrafast Science, DOI: 10.34133/2021/9848526

Pictures: European XFEL, Jan Hosian (experimental station); DESY, Timm Rohwer; DESY, Dongfang Zhang

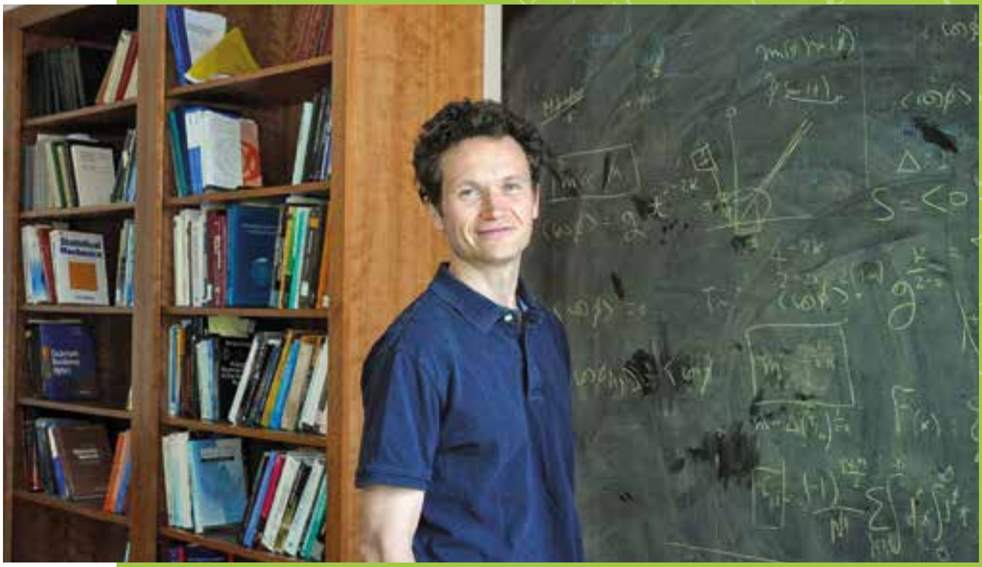
Beamline for extreme conditions inaugurated

The Helmholtz International Beamline for Extreme Fields (HIBEF) has officially gone into operation at the European XFEL X-ray laser. HIBEF combines the facility's X-ray radiation with two super lasers, a powerful magnetic coil and a platform for research with diamond anvil cells. Under the leadership of Helmholtz-Zentrum Dresden-Rossendorf (HZDR) in cooperation with DESY, the project pools equipment and expertise from various research institutions to make them available to the international scientific community.

The beamline is part of the High Energy Density (HED) experimental station at the European XFEL and enables deep insights into the structure of materials and into ultrafast natural processes in plasma physics. This will help researchers improve models of planet formation and simulate processes in plasma, for example, thus driving innovations in materials and accelerator research.

HIBEF was founded in 2013 by DESY and HZDR and involves a user consortium comprising more than 350 scientists at 60 research institutions in 16 countries. The total investment for the beamline, including operating costs for ten years, amounts to nearly 120 million euros.

The high-intensity laser ReLaX of the HIBEF user consortium can generate pressures of billions of bar.



Picture: Joachim Herz Foundation

Hamburg Prize for Theoretical Physics awarded to quantum physics researcher Demler

The Russian–American scientist Eugene Demler has been awarded the Hamburg Prize for Theoretical Physics 2021. Demler, who moved to ETH Zurich from Harvard University in the USA in autumn 2021, is working on a better understanding of so-called strongly correlated quantum systems. His research has a profound impact on fields such as magnetism, superconductivity and non-linear quantum optics. The prize is awarded by the Joachim Herz Foundation, in association with DESY, the Wolfgang Pauli Centre of DESY and Universität Hamburg, and the two Clusters of Excellence "CUI: Advanced Imaging of Matter" and "Quantum Universe" at Universität Hamburg.

"With Eugene Demler, we are this year honouring a scientist who has rendered outstanding services to the application of his theoretical work in experimental physics," notes Henneke Lütgerath, Chairman of the Board of the Joachim Herz Foundation. "His considerations have provided many important impulses for developing new materials, for energy transmission or data processing, for example."

Demler is a world-renowned expert in theoretical quantum physics, which describes how electrons, atoms and other tiny objects behave. Among other things, Demler's work has been instrumental in developing quantum simulators based on ultracold atoms.

In order to understand complex materials, theoreticians often use simplified mathematical models, analysing them and comparing the results with the properties of the materials that have been measured experimentally. The problem is that even simple mathematical models describing correlated quantum systems cannot be calculated precisely when strong interactions between particles are involved. So, when theoretical predictions and experimental findings contradict each other, it is often unclear whether this is because the mathematical equations can only be solved approximately or because the model has neglected important aspects.

Quantum simulators solve this problem using experimental systems that replicate fundamental models of condensed-matter physics – for example, by using laser beams to arrange ultracold atoms into periodic structures that form artificial crystals. Experiments with such artificial crystals can be used to study the properties of fundamental theoretical models in detail and to find out what is still missing in order to describe systems of condensed matter (more simply: complex materials) precisely. Quantum simulations with cold atoms have led to new insights into materials whose properties arise from the complex interactions of thousands of particles that obey the laws of quantum mechanics. These materials include quantum magnets as well as topological insulators and superconductors, which can transport electricity without losses.

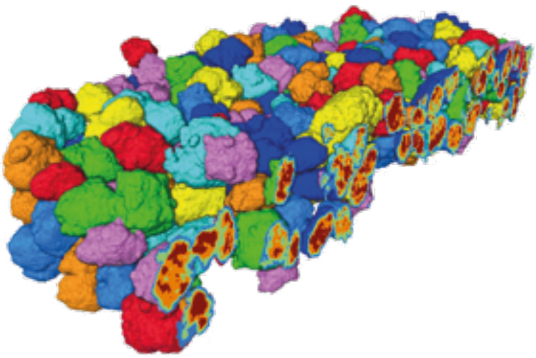
The Hamburg Prize for Theoretical Physics is endowed with 137 036 euros, the exact amount being an allusion to Sommerfeld's fine-structure constant, which plays an important role in theoretical physics. The prize has been awarded to internationally renowned scientists since 2010 and is linked to a stay in Hamburg as a visiting research fellow. It is one of the most highly endowed prizes for physics in Germany.

KAI Cooperation for Application and Innovation of HAW Hamburg and DESY

Hamburg's Science Senator Katharina Fegebank together with DESY Director Helmut Dosch (l.) and HAW President Micha Teuscher (r.) at the launch of the cooperation KAI

Educating, researching, developing and creating new perspectives – together: DESY and the Hamburg University of Applied Sciences (HAW Hamburg) have agreed on a new strategic Cooperation for Application and Innovation (KAI). The cooperative venture will focus on dual education programmes and teaching, research and development as well as innovation, technology and knowledge transfer. KAI is to strengthen the joint training of urgently needed highly qualified engineers and scientists, and it will help to shape Hamburg's structural transformation into a science and innovation metropolis in northern Germany, through applied research and the development of sustainable and digital technologies. The City of Hamburg supports the cooperation with start-up funding of 120 000 euros.

The list of concrete areas of cooperation ranges from real-time control technologies for highly complex accelerator facilities, through visual simulation and robotics, efficient energy systems, scientific computing, intelligent sensor systems, spectroscopy and measurement data processing, embedded electronics and electronics development, all the way to scientific illustration. There are plans to further extend this range of topics. Likewise, a joint site is planned in the Science City Hamburg Bahrenfeld, which is currently under construction, in order to expand and further develop the common activities in areas such as transfer-oriented research and start-ups.



A total of 434 particles were imaged simultaneously with a resolution of 74 nanometres and identified and characterised individually with respect to their geometrical properties and fragmentation behaviour. The displayed rendering shows a virtual cut through the tomographic data set where each identified particle is colour-coded for better visualisation. Most particles are about five to six micrometres in diameter. The data has further been segmented into regions of similar electron density to separate polymer from catalyst fragments within each particle: From blue through green and orange to red, the plastic content in the respective particle decreases. This fragmentation varies more from particle to particle than expected.

X-ray insights into plastics production

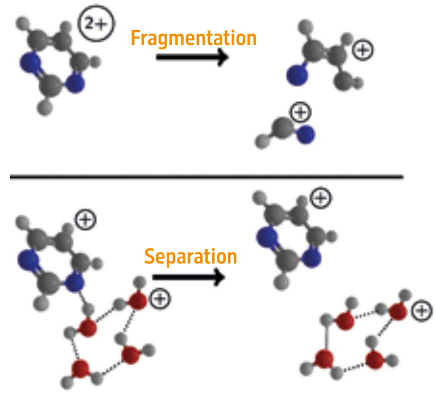
An X-ray study at DESY is pointing the way towards a better understanding of plastics production. A team led by Utrecht University, the Netherlands, has investigated so-called Ziegler-type catalysts, the workhorses in the world's polyethylene and polypropylene production, at DESY's X-ray source PETRA III.

Polyolefins, such as polyethylene (PE) and polypropylene (PP), play an important role in everyday life. Applications range from food packaging in order to increase the shelf life of the product, through the sterile packing of medical equipment, to the insulation of electrical cables. To prepare polyolefins tailored for these tasks on demand, a versatile class of catalyst materials including Ziegler-type catalysts is used, which consist of very small particles containing various metals such as titanium. As the scientists led by Bert Weckhuysen and Florian Meirer have now observed, the catalyst microparticles fragment into an astonishing variety of smaller particles during polymer production. "These spatial heterogeneities hint at differences in the accessibility of the catalytically active sites for ethylene, highlighting the importance of optimising the reaction conditions," explains Weckhuysen.

The analysis provides a better understanding of the overall industrial process and can help to specifically create desired polymer properties and further increase efficiency in production.

JACS Au, DOI: 10.1021/jacsau.1c00130

Water protects sensitive molecules from radiation damage



While a double positive charge induced by radiation causes pyrimidine to break quickly (top), the molecule can transfer a positive charge to water in an aqueous environment (bottom) and remain intact.

Water can protect small organic molecules from being damaged by X-rays. This is revealed by an experiment at DESY's X-ray source PETRA III led by the University of Kassel. Instead of being torn apart by the electrical charge induced by the X-rays, the molecules are able to transfer some of that charge to the water and so remain intact.

The researchers led by Andreas Hans studied the organic molecule pyrimidine ($C_4H_4N_2$), which is often used in research as a model system for fundamental biochemical analyses. They shone X-rays at pyrimidine dissolved in water and observed the molecular fragments that were produced. Without water, the pyrimidine breaks apart because the X-ray light creates a double electrical charge, and the molecule cannot withstand the resulting internal electrical repulsion.

In water, however, a significant part of the pyrimidine molecules remains intact after irradiation, as the experiments demonstrate. The reason is a weak bond with small clusters of just a few water molecules, as the theoretical analysis of the measured data by Nikolai Kryzhevoi's group at the University of Heidelberg shows. This can result in one charge in the molecule and one charge in the water cluster. "In the end, the pyrimidine and the water cluster each have a single positive electrical charge. This causes them to separate from each other, but the charge is not strong enough to tear the pyrimidine molecule apart," says co-author Florian Trinter from DESY and the Fritz Haber Institute in Berlin.

The Journal of Physical Chemistry Letters, DOI: 10.1021/acs.jpclett.1c01879

Pictures: University of Kassel, Andreas Hans

777 GRAMS OF DARK MATTER

The Earth contains Dark Matter with the same mass as two squirrels. This is revealed by models of the distribution of this enigmatic substance in our galaxy. Dark Matter is on average more than five times more abundant* in the universe than the ordinary matter we are familiar with. However, our solar system is dominated by conventional matter because it is highly concentrated here: in the form of the sun, its planets and other satellites. "Model calculations indicate that the local density of Dark Matter is about 720 picograms per cubic kilometre," explains DESY physicist Torben Ferber. A picogram is one trillionth of a gram. "With the Earth having a volume of around 1.1 trillion cubic kilometres, this means that it contains 777 grams of Dark Matter – enough for two squirrels**," calculates Ferber, who is now a professor at the Karlsruhe Institute of Technology (KIT).

femtomenal

* We cannot see Dark Matter because it only interacts very weakly with us. It makes itself felt through its gravitational force, however, which holds together rapidly spinning galaxies that would otherwise be torn apart by centrifugal forces. According to data from the "Planck" satellite, Dark Matter makes up just under 27 percent of the contents of the universe, while ordinary matter accounts for about 5 percent. The rest consists of the equally mysterious Dark Energy.

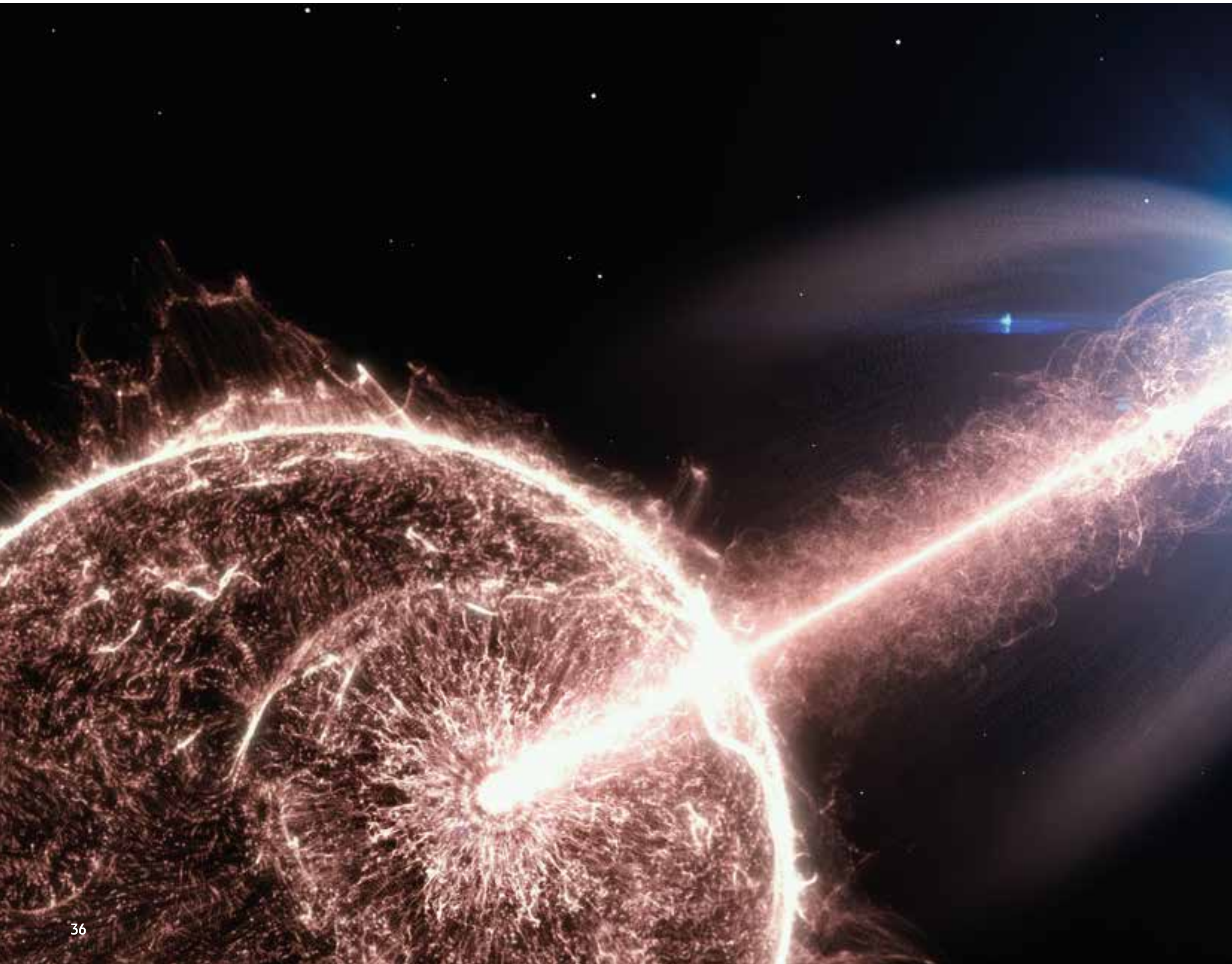
**According to the German Wildlife Foundation, a squirrel weighs around 300 to 400 grams.

Gamma flash from our cosmic neighbourhood

Detailed observation challenges theory of the most powerful explosions in the universe

Invisible to the human eye, flashes of cosmic gamma radiation regularly flicker across the firmament. These gamma-ray bursts (GRBs), which were discovered by chance in the late 1960s by nuclear test monitoring satellites, originate from enormous cosmic catastrophes in distant galaxies, such as certain supernova explosions, as we now know. Even after decades of investigation, there are still many unanswered questions about the nature of these colossal gamma flashes. The observation of a relatively close gamma-ray burst now provides unique new insights into these most powerful explosions in the universe.

Gamma-ray bursts (GRBs) may be even more powerful particle accelerators than thought: This is shown by the exceptionally detailed observation of such a gamma flash in the southern sky. Using the specialised telescopes of the H.E.S.S. observatory in Namibia, an international research team has registered the most energetic



radiation from a gamma-ray burst and tracked the longest gamma-ray afterglow of such an explosion to date. The analysis of the data now suggests that the X-ray and gamma-ray emissions from these powerful stellar explosions have the same origin and are not produced by separate processes, as was previously assumed.

"Gamma-ray bursts are bright X-ray and gamma-ray flashes observed in the sky, emitted by distant extragalactic sources," explains DESY scientist Sylvia Zhu, one of the authors of the paper. "They are the biggest explosions in the universe and associated with the collapse of a rapidly rotating massive star into a black hole." Part of the gravitational energy released in the process drives an extremely fast, ultrarelativistic shock wave through the surrounding gas. This accelerates subatomic particles, such as electrons, which in turn can produce gamma radiation. Gamma-ray bursts are divided into two distinct phases: an initial chaotic prompt phase lasting tens of seconds, followed by a long-lasting, smoothly fading afterglow phase.

"We were really sitting in the front row when this gamma-ray burst happened"

Andrew Taylor, DESY

On 29 August 2019, the satellites "Fermi" and "Swift" of the US space agency NASA detected a gamma-ray burst in the southern constellation Eridanus. The event, catalogued as GRB 190829A according to its date of occurrence, turned out to be one of the nearest gamma-ray bursts observed so far, at a distance of about one billion light years. For comparison: The typical gamma-ray burst is about 20 billion light years away. "We were really sitting in the front row when this gamma-ray burst happened," explains co-author Andrew Taylor from DESY. The team caught the explosion's afterglow immediately when it became visible to the H.E.S.S. telescopes. "We could observe the afterglow for several days and at unprecedented gamma-ray energies," reports Taylor.

Artist's impression of the relativistic matter jet of a gamma-ray burst (GRB), breaking out of a collapsing star and emitting very-high-energy gamma rays

Picture: DESY, Science Communication Lab

Unprecedented energy

The comparatively short distance to this gamma-ray burst allowed detailed measurements of the afterglow's high-energy spectrum, i.e. the distribution of "colours" or energies of the X-ray and gamma-ray photons. "We could determine GRB 190829A's spectrum up to an energy of 3.3 teraelectronvolts, that's about a trillion times as energetic as visible light," explains co-author Edna Ruiz-Velasco from the Max Planck Institute for Nuclear Physics in Heidelberg. "This is what's so exceptional about this gamma-ray burst – it occurred in our cosmic backyard, so its very-high-energy photons were not absorbed in collisions with background light on their way to Earth, as happens over larger distances in the cosmos." At very high energies, this process makes the universe increasingly opaque over large distances.

H.E.S.S. followed the afterglow of the gamma-ray burst up to three days after the initial explosion. The result came as a surprise: "Our observations revealed curious similarities between the X-ray ››

The High Energy Stereoscopic System (H.E.S.S.) observatory operated by an international cooperation in Namibia uses a total of five specialised telescopes to look for the bluish glow of high-energy particle showers triggered by cosmic gamma-ray photons in the Earth's atmosphere (artist's impression).

and the very-high-energy gamma-ray emission of the burst's afterglow," reports Zhu. Established theories assume that the two emission components must be produced by separate mechanisms: The X-ray component originates from ultrafast electrons that are deflected in the strong magnetic fields of the burst's surroundings. This "synchrotron" process is quite similar to how particle accelerators on Earth produce bright X-rays for scientific investigations.

Beyond the burn-off limit?

However, according to existing theories, the synchrotron process is not initially suitable for producing very-high-energy gamma radiation. This is due to a "burn-off limit" determined by the balance of acceleration and cooling of particles within an accelerator. Generating very-high-energy gamma rays requires electrons with energies well beyond the burn-off limit, which even the most powerful explosions in the universe cannot actually create. Instead, current theories assume that, in a gamma-ray burst, fast electrons collide with synchrotron photons that have already been produced, thereby boosting them to gamma-ray energies in a complicated process called "synchrotron self-Compton" (SSC).

Promising prospects

However, the observations of GRB 190829A's afterglow now show that both components, X-ray and gamma ray, faded in sync. Also, the gamma-ray spectrum clearly matched an extrapolation of the X-ray spectrum. Together, these results are a strong indication that X-rays and very-high-energy gamma rays in this afterglow were produced by the same mechanism. "Observing such remarkably similar spectral and temporal characteristics in the X-ray and very-high-energy gamma-ray energy bands is not something we would expect to see if the emission in these two energy ranges had different origins," says co-author Dmitry Khangulyan from Rikkyo University in Tokyo. This poses a challenge for the synchrotron self-Compton origin of the very-high-energy gamma-ray emission.

Whether the theory of gamma-ray bursts needs to be changed can only be clarified by further observations of the very-high-energy component of their afterglow. GRB 190829A is only the fourth gamma-ray burst detected at very high energies from the ground. However, the explosions detected earlier occurred much farther away in the cosmos, and their afterglow could only be observed for a few hours and not at energies above one teraelectronvolt. "Looking to the future, the prospects for the detection of gamma-ray bursts by next-generation instruments like the Cherenkov Telescope Array, which is currently being built in the Chilean Andes and on the Canary Island of La Palma, look promising," says H.E.S.S. spokesperson Stefan Wagner from Landessternwarte Heidelberg. "The general abundance of gamma-ray bursts in the cosmos leads us to expect that regular detections in the very-high-energy band will become rather common, helping us to fully understand the physics of these colossal cosmic explosions."

Science, DOI: 10.1126/science.abe8560

To illustrate the observation of the extraordinary gamma-ray burst, DESY scientists, together with the animation artists of the award-winning Science Communication Lab, have created a video set to music by the internationally acclaimed musician Alva Noto.

Picture: Science Communication Lab for DESY

Seeping oceans

More ocean water is carried deeper into Earth's mantle than expected

The global water cycle does not stop at the Earth's crust: Every year, around three cubic kilometres of ocean water disappear in the Earth's so-called subduction zones, where the tectonic plates plunge into the interior of our planet. In 10 000 years, this adds up to the volume of the Baltic Sea. Most of this water is spewed out again during volcanic eruptions. However, some of it migrates so deep into the Earth's mantle that its fate is uncertain. Several high-pressure experiments are now providing new insights into the behaviour of water inside the Earth and other planets.

A bigger volume of the world's oceans is seeping deeper into the Earth's mantle than expected: That is the result of a study investigating glaucophane, a water-bearing mineral abundant in the oceanic crust. High-pressure experiments at DESY's X-ray source PETRA III show that glaucophane is surprisingly stable up to 240 kilometres underground, which means it also carries water down to this depth.

Scientists attribute the unexpected stability of the mineral to the gradual cooling of the Earth's interior over geological time scales. The cooler temperatures let glaucophane and possibly other water-bearing minerals survive to greater pressures at greater depths, as the team headed by Yongjae Lee from Yonsei University in South Korea reports. The scientists estimate that, in about 200 million years, an additional volume equal to the Arctic Ocean could seep deep into Earth's mantle in this way.

Cooling mantle

"Under the ocean, there are so-called subduction zones with a total length of approximately 55 000 kilometres, much longer than the circumference of the Earth, where slabs from the crust and upper mantle dive into the interior of our planet," explains Lee. These slabs carry ocean water into the depths, mainly in the form of water-bearing minerals, such as amphiboles. "However, these minerals usually succumb to the high pressures and temperatures at depths of no more than about 100 kilometres," says Lee. When amphiboles such as glaucophane break down, their water is set free and drives earthquakes in the subduction slab and volcanism in the overlying mantle. These phenomena eventually deliver the water back to the Earth's surface.

However, the Earth's interior is slowly cooling by about 50 to 100 degrees Celsius per one billion years, and this cooling is getting faster. As a consequence, "cold" subduction zones have developed in many places on the globe in recent geological history. The temperatures in these zones are still sizzling hot compared to everyday standards, but significantly cooler than in "warm" subduction zones, as well as cooler than in the geologic past. "Using high-pressure, high-temperature equipment, we have simulated today's conditions in cold subduction zones in the lab and studied the behaviour of glaucophane under these conditions," explains co-author Hanns-Peter Liermann, head of the Extreme Conditions Beamline at PETRA III. "To our surprise, in cold subduction zones, glaucophane remains stable at conditions corresponding to much greater depths of up to 240 kilometres." ››

Picture: Dylan Sauerwein on Unsplash

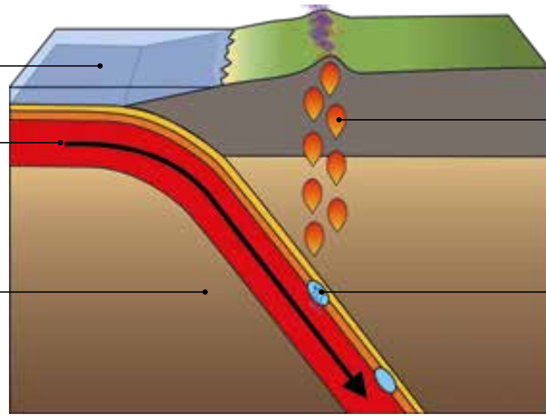


Plate tectonics
Along the subduction zones, slabs are diving into the Earth's mantle. They can carry substantial amounts of water downward in the form of water-bearing minerals.

Underground water reservoir

Previously, scientists had estimated that about a third of all the water carried underground in subduction zones reaches these depths in the mantle, from where it is not clear if and how it can return. "If we assume that all subduction zones eventually become 'cold', an additional volume equivalent to the Arctic Ocean could be stored in the mantle in about 200 million years," calculates Yoonah Bang from Yonsei University, the lead author of the study, which is part of the Early Science programme at the Centre for Molecular Water Science (CMWS) currently being established at DESY. "However, it would take five billion years until all oceans would be dried up assuming such a one-way process."

Since our sun will be slowly getting hotter and hotter, other scientists have previously estimated that the Earth's oceans might already evaporate in about a billion years. "It appears that the Earth may retain its surface water by storing it in the interior and thus preventing it from escaping into space," adds Lee.

The study – which also involved scientists from Seoul National University in South Korea, Lawrence Livermore National Laboratory, Argonne National Laboratory and the University of Chicago in the USA, the Center for High Pressure Science & Technology Advanced Research in China and Ehime University in Japan – has also other implications for the evolution of the Earth: Since underground water in the shallower depths is a major driver of volcanism and earthquakes, these phenomena are getting less frequent on geological time scales, as Lee points out. "As the Earth continuous to cool down, the transport of water to its interior is expected to extend to greater depths, thereby suppressing earthquakes and volcanism."

> *"There is no understanding of what happens in some icy planets where the hot, dense water of the subsurface oceans interacts with the underlying rocky crust"*
>
> ***Yongjae Lee, Yonsei University***

Extraterrestrial oceans

But it is not only the depths of our own planet that can be investigated with high-pressure experiments. Lee's team has also used such studies to simulate the conditions in extraterrestrial oceans on distant water planets. The analysis shows that the subsurface oceans of large water planets dissolve minerals from the rocky crust. At the high pressures and temperatures that are typical for such planets, the water washes magnesium out of the minerals.

"The mechanisms of water–rock interaction at the Earth's surface have been studied for many decades," says Lee. "However, there is no understanding of what happens in some icy planets where the hot, dense water of the subsurface oceans interacts with the underlying rocky crust." To investigate the issue, the team performed a series of high-pressure and high-temperature experiments at both DESY's X-ray source PETRA III and the Advanced Photon Source (APS) in the USA, which involved scientists from the University of Chicago, the University of Illinois, GFZ German Research Centre for Geosciences and Arizona State University.

The researchers created conditions like those found at the bottom of deep oceans in the sub-Neptune class of water planets. At pressures between 20 and 40 gigapascals, corresponding to between 200 000 and 400 000 times the atmospheric pressure at sea level on Earth, and temperatures above 1230 degrees Celsius, the water washes considerable amounts of magnesium oxide (MgO) out of the typical rock minerals ferropericlase (Mg,Fe)O and olivine $(Mg,Fe)_2SiO_4$.

Soluble like salt

"For the experiments, tiny pellets of either ferropericlase or olivine powder were loaded together with water in a submillimetric sample chamber drilled in a metal foil and

Picture: Yonsei Universiy, Yoonah Bang/Yongjae Lee (after Plank & Manning (2019)) squeezed between two gem-quality diamond culets using a so-called diamond anvil cell," explains Taehyun Kim from Yonsei University, lead author of the study, which is also part of the CMWS Early Science programme. "The samples were heated by shining an infrared laser through the diamond anvils."

By means of the X-rays, the team was able to observe when the minerals began to decay due to the interaction with the water. When illuminated with X-rays, the crystal lattice of each mineral produces a characteristic diffraction pattern. A sudden decrease in this diffraction signal announces the decay of the mineral. At the same time, the formation of new compounds, such as brucite (magnesium hydroxide) in this case, can also be observed in this way.

The X-ray investigation shows the onset of chemical reactions that dissolve the magnesium oxide component from the two minerals under study. The dissolution is strongest in the pressure range of 20 to 40 gigapascals and at temperatures between 1000 and 1750 degrees Celsius. The details of the reaction process and of the subsequent chemical segregation of magnesium oxide from the residual phases were confirmed by thorough measurements with a scanning electron microscope and by X-ray spectroscopy of the samples used. At these extreme pressures and temperatures, the solubility of magnesium oxide in water reaches levels similar to that of salts in the Earth's oceans at ambient conditions.

Astronomers have by now discovered evidence of subsurface oceans on numerous planets and moons in our own and other solar systems. Some are considered promising for extraterrestrial life.

Nature Communications, DOI: 10.1038/s41467-021-21746-8 (Bang et al.)
Nature Astronomy, DOI: 10.1038/s41550-021-01368-2 (Kim et al.)

femtopolis

HANDY HIGH PRESSURE

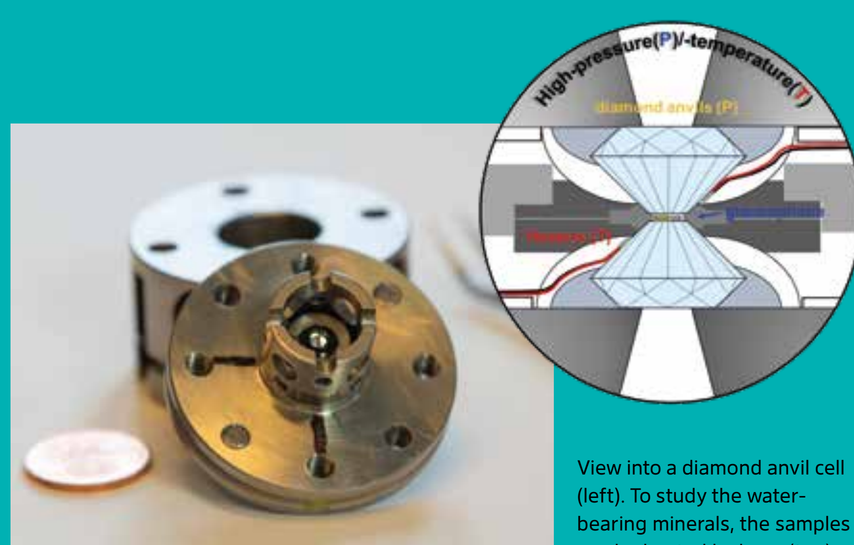
It may look like an inconspicuous flat metal tin, but the palm-sized device contains entire worlds. Scientists use the so-called diamond anvil cell to go on expeditions that take them deep inside our Earth and distant planets. With its help, they can generate the kind of high pressure that prevails hundreds to thousands of kilometres below the surface.

A brilliant trick is used to achieve this: As the name suggests, the cell contains two anvils made of ultrahard diamond. The sample – a piece of artificial rock from the Earth's mantle, for instance – is clamped between these two diamond anvils and put under pressure. The secret of the ultrahigh pressure is the tiny surface area of the anvils. They are typically only a tenth to a quarter of a millimetre in diameter. The sample has to be correspondingly microscopic, but it can still be examined in detail using the fine X-ray beam from facilities such as PETRA III at DESY.

Pressure is the amount of force per unit area. So the smaller the area, the less force is needed to produce a high pressure. Diamond anvil cells can often even be adjusted by hand using screws. "The trick here is not to exert a strong force," explains high-pressure expert Hanns-Peter Liermann from DESY. "The art is to design the diamond anvils in such a way that they withstand the pressure – if you tighten them too much, the diamond shatters."

The diamond anvils have special cuts that make them particularly durable. Nevertheless, now and then in the course of everyday research, anvils do turn into diamond shards. "Only about two-thirds of the loss is due to the value of the material itself; about one-third of its value is attributable to the special processing involved," explains Liermann.

The undisputed world champions of this type of high-pressure generation are Natalia Dubrovinskaia and Leonid Dubrovinsky from the University of Bayreuth. Using special anvils made of nanocrystalline diamonds, which are only 0.01 to 0.02 millimetres in diameter, in experiments at Liermann's Extreme Conditions Beamline among other places, they have succeeded in achieving a pressure around twice as high as that found in the Earth's core: 770 gigapascals, some 7.6 million times atmospheric pressure at sea level. In the meantime, they have even reached a pressure of 1000 gigapascals.

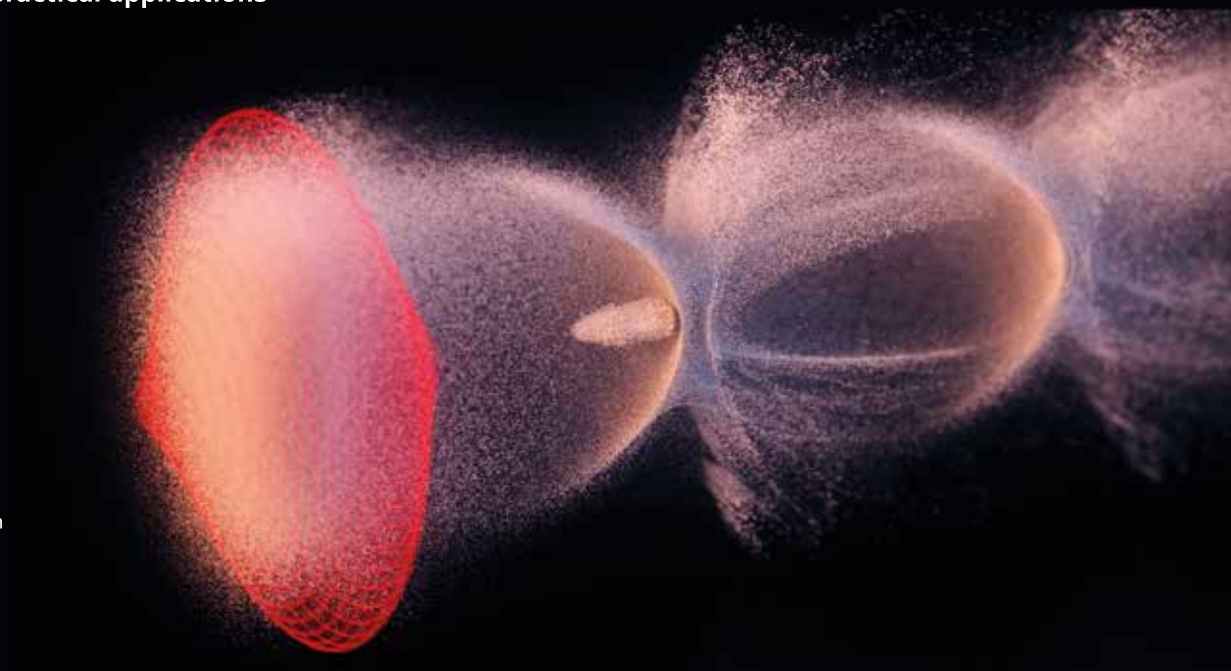


Pictures: DESY, Marta Mayer; Yonsei University, Yoonah Bang/Yongjae Lee

View into a diamond anvil cell (left). To study the water-bearing minerals, the samples can be heated by laser (top).

It’s all in **the mix**

A pinch of nitrogen and artificial intelligence are moving laser plasma acceleration a big step closer to practical applications



In laser plasma acceleration, an intense laser pulse (red) travelling through an ionised gas drives a bubble-shaped plasma wave consisting of electrons (white). An electron bunch (centre) riding this wave like a surfer is thus accelerated to high energies over very short distances. The rendering is based on real simulation data from the LUX experiment.

Plasma acceleration is an innovative technology that is giving rise to a new generation of particle accelerators, which are not only remarkably compact but also extremely versatile. The aim is to make the accelerated electrons available for applications in various fields of industry, science and medicine.

In their joint LUX project, researchers from Universität Hamburg and DESY have now achieved not just one but two milestones in the development of innovative plasma accelerators. The scientists used their accelerator to test a technique that allows the energy distribution of the generated electron beams to be kept particularly narrow, which improves the quality of the particle beams. In addition, they used artificial intelligence to get the accelerator to optimise its own operation.

“Like a surfer, the electrons are carried along by the plasma wave”

Manuel Kirchen, Universität Hamburg

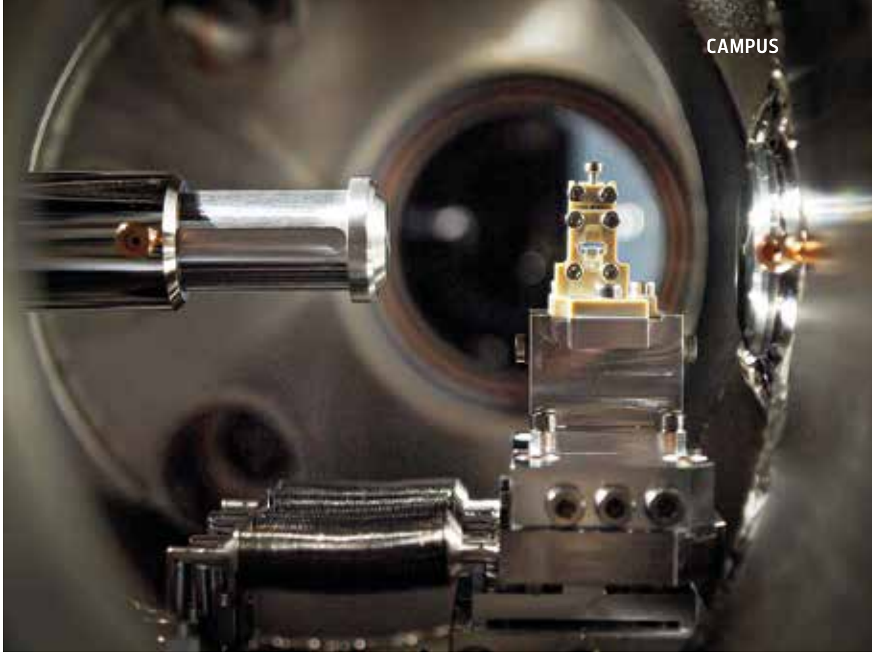
The acceleration takes place in a tiny channel, just a few millimetres long, filled with a plasma. This is a gas whose molecules have been stripped of their electrons, which are then moving freely. An intense laser pulse generates a wave within the channel that can capture and accelerate electrons from the plasma. “Like a surfer, the electrons are carried along by the plasma wave, which accelerates them to high energies,” explains Manuel Kirchen, lead author of one of the papers. “Using this technique, plasma accelerators are able to achieve accelerations that are up to a thousand times higher than those of the most powerful machines in use today,” adds Sören Jalas, lead author of the second paper.

Double cell improves quality

This compactness is both a curse and a blessing, however: Since the acceleration processes are concentrated in a tiny space that is up to 1000 times smaller than in conventional, large-scale facilities, the acceleration takes place under truly extreme conditions. As a consequence, a number of challenges still has to be overcome before the new technology is ready to go into series production.

The research team led by DESY accelerator physicist Andreas Maier has now found a way to

Picture: LUX, Sören Jalas and Manuel Kirchen / DESY, Science Communication Lab



The plasma cell of LUX (centre right) is only a few millimetres long.

significantly narrow the energy distribution of the accelerated electron bunches – one of the most essential prerequisites for many potential applications. The scientists conducted their experiments using a new type of plasma cell, specially developed for the purpose, whose plasma channel is divided into two regions. The plasma is generated from a mixture of hydrogen and nitrogen in the front part of the cell, which is about one centimetre long, while the rear part is filled with pure hydrogen. As a result, the researchers were able to obtain the electrons for their particle bunch from the front part of the plasma cell, which were then accelerated over the entire rear section of the cell.

"Being more tightly bound, the electrons in the nitrogen are released a little later, and that makes them ideal for being accelerated by the plasma wave," explains Kirchen. The electron bunch also absorbs energy from the plasma wave, changing the shape of the wave. "We were able to take advantage of this effect and adjust the shape of the wave so that the electrons reach the same energy regardless of their position along the wave," says the physicist.

"It's fantastic to see the speed with which plasma acceleration is reaching a level of maturity where it can be used in a wide range of applications"

Wim Leemans, DESY

Autopilot takes control

Based on this recipe for achieving high electron beam quality, the team then scored a second research success: Sören Jalas and his colleagues were able to use artificial intelligence (AI) to modify an algorithm that controls and optimises the complex plasma accelerator system. To do so, the scientists provided the algorithm with a functional model of the plasma accelerator and a set of adjustable parameters, which the algorithm then optimised on its own. Essentially, the system modified five main parameters, including the concentration and density of the gases and the energy and focus of the laser, and used the associated measurements to search for an operating point at which the electron beam has the optimum quality.

"In the course of its balancing act in five-dimensional space, the algorithm has been constantly learning"

Sören Jalas, Universität Hamburg

"In the course of its balancing act in five-dimensional space, the algorithm has been constantly learning and very quickly refined the model of the accelerator further and further," says Jalas. "The AI takes about an hour to find a stable optimum operating point for the accelerator; by comparison, we estimate that human beings would need over a week." A further advantage is that all the parameters and measured variables continue to train the AI model of the accelerator, making the optimisation process faster, more systematic and more targeted.

"It's fantastic to see the speed with which the new technology of plasma acceleration is reaching a level of maturity where it can be used in a wide range of applications," comments Wim Leemans, Director of the Accelerator Division at DESY. "The latest progress at LUX means we are well on the way to trying out initial applications for test purposes," says Andreas Maier. "Ultimately, we also want to use plasma-accelerated electron bunches to operate a free-electron laser."

Physical Review Letters, DOI: 10.1103/PhysRevLett.126.174801 (Kirchen et al.)
Physical Review Letters, DOI: 10.1103/PhysRevLett.126.104801 (Jalas et al.)

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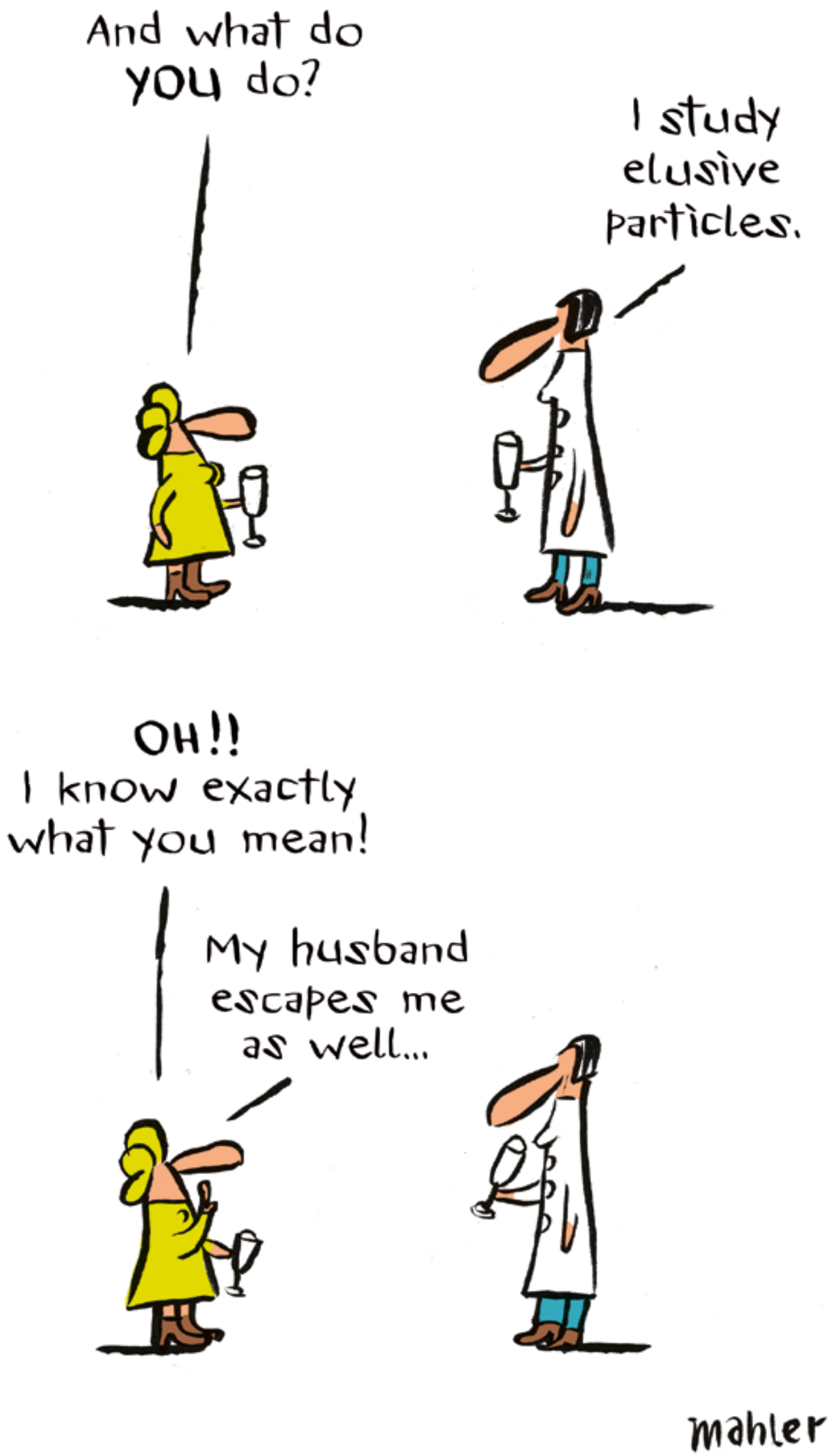

Cartoon: Nicolas Mahler

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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
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Contributors to this issue
Frank Grotelüschen, Carolin Rankin

Translation
Daniel Bullinger

Final editing
Ilka Flegel

Layout
Ulrike Darwisch

Art direction and production
Diana von Ilsemann

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EHS, Hamburg

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The DESY research centre

DESY is one of the world's leading particle accelerator centres and investigates the structure and function of matter – from the interaction of tiny elementary particles and the behaviour of novel nanomaterials and vital biomolecules to the great mysteries of the universe. The particle accelerators and detectors that DESY develops and builds at its locations in Hamburg and Zeuthen are unique research tools. They generate the most intense X-ray radiation in the world, accelerate particles to record energies and open up new windows onto the universe.

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