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The DESY research magazine – Issue 01/23

ENGLISH EDITION

LASER

LEGENDARY LIGHT AMPLIFIER

Asteroid impact in slow motion

Wall paint against coronaviruses

Rare appearance: four tops at the LHC

DESY.

Robots take to the pitch

Who are these little fellows who are wandering among the DESY campus? The answer might surprise you: they are the players in an international football tournament. And, as you can probably tell, they're also robots.

In spring, the GORE 2023 competition took place at the Center for Free-Electron Laser Science (CFEL) on the DESY campus in Hamburg. GORE (German Open Replacement Event) is part of the RoboCup competition, where teams either programme robots to play football autonomously or, in the case of the RoboCup Humanoid league, build the robots themselves from scratch. The robots operate on the rules and goals of the game, which are practically the same as traditional football with humans – just with fewer players.

The robots that toured the DESY campus before the games were from the Hamburg University of Technology.

The HULKs team of standardised robots and the Bit-Bots humanoid constructs were two of the eleven teams competing at CFEL, some coming from as far as Canada and Australia. "The tournament was arranged in a way so that some teams that couldn't be present on-site could still compete remotely," says Jonathan Hellwig, who helped with the organisation of GORE 2023 and who is part of the HULKs team.

In the end, the hometown HULKs won several matches and reached the quarter-finals. The victory at GORE 2023 was claimed by the nine-time world champions B-Humans from Bremen – fuelling the old football rivalry between the two Hanseatic cities.

https://gore-event.github.io

Pictures: DESY, Marta Mayer

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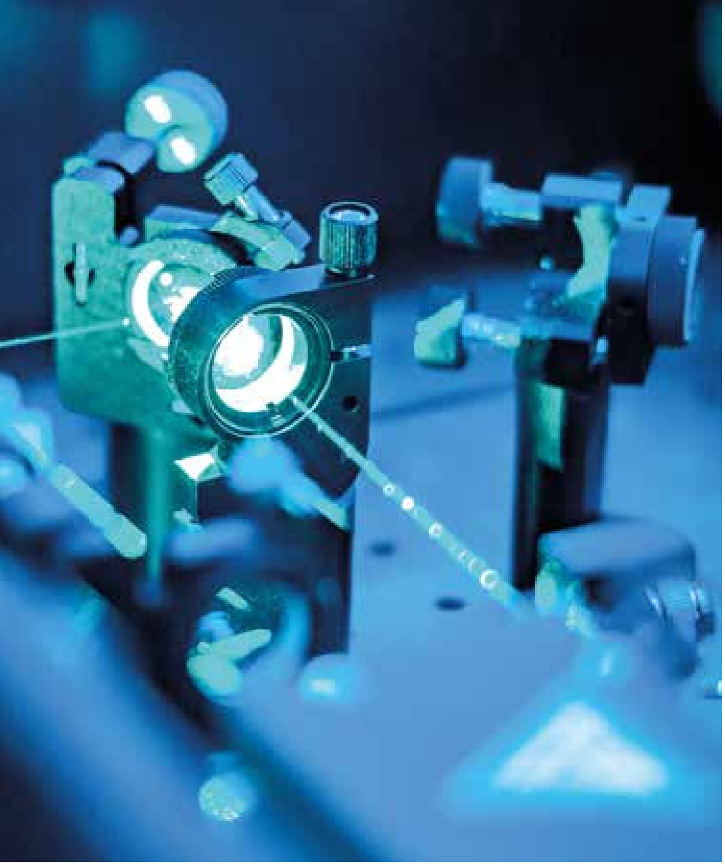


Picture credits: page 45

Dear Readers,

Even more than 60 years after their discovery, lasers still have a touch of science fiction about them: spaceship battles, light sabres, holographic worlds. Yet these universal tools have long since permeated our everyday lives in much more practical ways – from supermarket checkouts to dentist drills. Just count how many lasers you discover in your home (DVD player, laser printer, tools, etc.).

The lasers we report on in this issue, however, are anything but commonplace. They observe ultrafast processes in biomolecules, enable new compact particle accelerators and search for the mysterious dark matter. Some are tiny, some are gigantic – up to several kilometres long. They all have one thing in common: They cannot be bought off the shelf, because they are tailor-made for the respective purpose.

The demands of cutting-edge research, which seeks to discover new phenomena, are extreme. And so researchers often have to develop their own lasers before they can actually do experiments. Some also use them to provide solutions for other fields of application that no one has even thought of yet. Quite often, the result can be marketed. This development expertise is also interesting for industry, which therefore likes to network with research.

In this issue, we report on some of the spectacular lasers in research and the fundamental big questions they are designed to help answer. We hope you enjoy reading this issue and find illuminating insights, and we welcome your criticism, praise and suggestions at femto@desy.de.

Till Mundzeck
Editor

Asteroid impact in slow motion

High-pressure study solves 60-year-old mystery

For the first time, researchers have recorded live and in atomic detail what happens to the material in an asteroid impact. The team of Falko Langenhorst from the University of Jena and Hanns-Peter Liermann from DESY simulated an asteroid impact with the mineral quartz in the lab and pursued it in slow motion in a diamond anvil cell, while monitoring it with X-rays. The observation revealed an intermediate state in quartz that solved a decades-old mystery about the formation of characteristic structures in the material.

Impact indicator

Asteroid impacts are catastrophic events that create huge craters and sometimes melt parts of Earth's bedrock. "Nevertheless, craters are often difficult to detect on Earth, because erosion, weathering and plate tectonics cause them to disappear over millions of years," Langenhorst explains. Therefore, minerals that undergo characteristic changes due to the force of the impact often serve as evidence of an impact. For example, quartz sand (silicon dioxide or silica, SiO_2), which is ubiquitous on the Earth's surface, is gradually transformed into glass by such an impact, with the quartz grains then being crisscrossed by microscopic lamellae. This structure can only be explored in detail using an electron microscope. It can be seen in material from the relatively recent and prominent Barringer crater in Arizona, USA, for example. "For more than 60 years, these lamellar structures have served as an indicator of an asteroid impact, but no one knew until now how this structure was formed in the first place," Liermann says. "We have now solved this decades-old mystery." To do so, the researchers had spent years modifying and advancing techniques that allow materials to be studied under high pressure in the lab. In these experiments, samples are usually compressed between two small diamonds in a diamond anvil cell. It allows extreme pressures – as prevalent in Earth's interior or in an asteroid impact – to be generated in a controlled manner.

Characteristic lamellae

For its experiments, the team used a dynamic diamond anvil cell, in which the pressure can be changed very quickly during the measurement. With this device, the scientists compressed small silica crystals with a very regular crystal lattice ever more strongly, while shining intense X-rays from DESY's X-ray light source PETRA III through them to investigate changes to their inner structure. "The trick is to let the simulated asteroid impact proceed slowly enough to be able to follow it with the X-rays, but not too slowly, so that the effects typical of an asteroid impact can still occur,"

The simulated asteroid impact creates tiny glass lamellae in the quartz crystals studied, only tens of nanometres wide, which are only visible under the electron microscope.

Pictures: Science Photo Library, Van Ravenswaay / Detlev; University of Jena, Falko Langenhorst / Christoph Otzen

Barringer crater in Arizona was formed about 50 000 years ago by an approximately 50-metre iron meteorite.

Picture: US Geological Survey

Liermann says. Experiments on the scale of seconds proved to be the right duration.

"We observed that, at a pressure of about 180 000 atmospheres, the quartz structure suddenly transformed into a more tightly packed transition structure, which we call rosiaite-like," reports Christoph Otzen from the team. "In this crystal structure, the quartz shrinks by a third of its volume. The characteristic lamellae form exactly where the quartz changes into this so-called metastable phase, which no one has been able to identify in quartz before us." Rosiaite is an oxidic mineral and the namesake for the crystal structure, which is known from various materials. It does not consist of silica, but is a lead antimonate (a compound of lead, antimony and oxygen).

Collapse into a disordered structure

"The higher the pressure rises, the larger the ratio of silica with a rosiaite-like structure in the sample," Otzen explains. "But when the pressure drops again, the rosiaite-like lamellae do not transform back into the original quartz structure, but collapse into glass lamellae with a disordered structure. We also see these lamellae in quartz grains from deposits of asteroid impacts." The quantity and orientation of the lamellae allow conclusions to be drawn about the impact pressure. "But only now can we accurately explain and understand the formation of these lamellae," Langenhorst points out.

> *"No one knew until now how this structure was formed in the first place"*
>
> ***Hanns-Peter Liermann, DESY***

For the study, the researchers did not use the highest pressures technically feasible. "In the range of the highest pressures, so much heat is generated that the material melts or vaporises," explains Langenhorst. "Molten material that solidifies back into rock doesn't give us much useful information for now. What is important, however, is precisely the pressure range in which minerals undergo characteristic changes in the solid state, and that's what we studied in this case."

Relevance for other materials

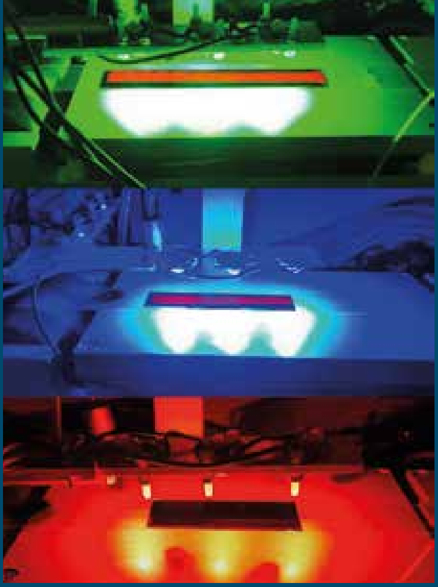
The results could have significance beyond the study of asteroid impacts. "What we observed could be a model study for the formation of glass in completely different materials, such as ice," Langenhorst points out. "It might be the generic path that a crystal structure transforms into a metastable phase in an intermediate step during rapid compression, which then changes into the disordered glass structure. We plan to investigate this further, because it could be of great importance for materials research."

With the planned expansion of PETRA III at DESY into the world's best X-ray microscope, PETRA IV, such studies will be possible even more realistically in the future. "A 100 times higher X-ray intensity will allow us to run these experiments 100 times faster, so we can simulate an asteroid impact even more realistically," says Liermann.

Nature Communications,
DOI: 10.1038/s41467-023-36320-7

Organic semiconductors like it dim

Coloured light can be used to control the construction of new electronics



In the experiments, the research team illuminated wet films of P3HT solution applied to silicon wafers with green (top), blue (middle) or red LED light as they dried.

Ambient light can have a major influence on the production of organic semiconductors. A group led by Jens Wenzel Andreasen from the Technical University of Denmark has observed that the semiconductors behave significantly differently during the coating process under red light or in darkness compared to under green or blue light. The experiments show a way to control the morphology of organic semiconductor devices.

Organic semiconductors have the potential to replace their silicon predecessors in many applications. Organic light-emitting diodes (OLEDs) are already used as standard in monitors, and organic solar cells already have efficiencies similar to their inorganic counterparts.

Electron flow slowed down

The Danish–German research team has now taken a closer look at the manufacturing process of a typical organic semiconductor (poly(3-hexylthiophene) or P3HT) used for flexible solar cells and organic electronics, for example. During the production of the active layer, the scientists excited the semiconductor polymer by shining visible light of different wavelengths onto it. While without illumination or under red light, the polymer chains showed a higher order, the structure was much less ordered when illuminated with green or blue light. The latter hampers a high electron flow and thus produces – depending on the application – a rather poor semiconductor material.

Stiffening polymer chains

Using DESY's X-ray light source PETRA III, the team was able to observe how the polymer chains in a solution very quickly begin to "sort" and form ordered domains when they are in the dark or illuminated with red light. Under green or blue light, on the other hand, the polymer chains stiffen. This hinders the formation of domains or even breaks up existing orders.

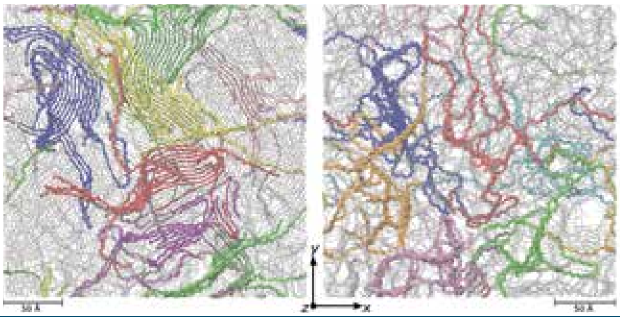
"We can show that visible light causes organic semiconductors in an excited state to prefer different arrangements of the molecules"

Matthias Schwartzkopf, DESY

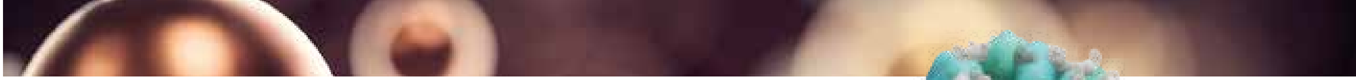
The researchers explain the result by the fact that green light or light with even shorter wavelengths excites the polymer in such a way that it interacts differently with the solvent during production and therefore cannot move as freely and arrange itself into domains during the drying process.

"We can show that visible light causes organic semiconductors in an excited state to prefer different arrangements of the molecules, and thus the morphology becomes manipulable," reports DESY scientist Matthias Schwartzkopf from the team. "In future, this could play a role in the processing of solar cells and organic electronics. For example, processing using red light similar to traditional photo processing might be recommended, depending on the behaviour of the materials."

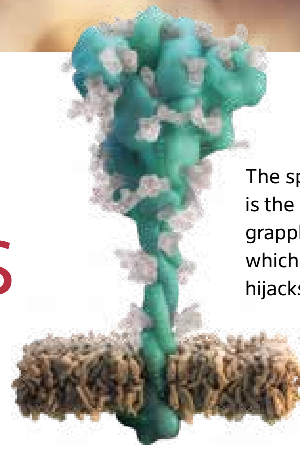
Advanced Functional Materials, DOI: 10.1002/adfm.202212835



Computer simulations show how the polymer chains can arrange themselves in relation to each other and form domains under red light or in darkness (left), while this does not happen with chains excited by blue or green light (right).



Wall paint against coronaviruses



The spike protein is the molecular grappling hook with which the virus hijacks the cell.

Investigation shows promising routes to surface and air disinfection

Technically optimised wall paint could possibly kill the coronavirus and many other pathogens. This is an important finding of a study on the virus-killing effect of titanium dioxide (TiO_2), a ubiquitous white pigment that is found in paints, plastic products and sunscreens. Titanium dioxide also has many other important applications relevant to environmental sustainability and renewable energy.

"Titanium dioxide is widely used as a pigment to whiten a wide range of products," explains DESY NanoLab researcher Heshmat Noei, who led the study. "But it is also a powerful catalyst in many applications, such as air and water purification and self-cleaning materials. Therefore, we saw it as a promising candidate for a virus-inactivating coating."

Spike protein makes contact

Teaming up with the group of virologists Ulrike Protzer and Greg Ebert from the Helmholtz Munich research centre and Technische Universität München, the scientists tested titanium dioxide's power against the coronavirus. "We were the first to apply coronaviruses on a titanium dioxide surface and investigate what happens," says Noei.

The international research team investigated the contact process on the surface using DESY's X-ray light source PETRA III. The scientists were able to clarify that the amino acids of the coronavirus spike protein attach to the titanium dioxide surface, trapping the virus and preventing it from binding to human cells.

Denaturation through dehydration

"We found that the virus adsorbs to the titanium dioxide surface and cannot detach again. Eventually, it will be inactivated by dehydration and be denatured," explains Mona Kohantorabi from the DESY NanoLab. "Moreover, we were able to observe that the titanium dioxide catalyses the inactivation of the virus by light. For our study, we used ultraviolet light, which triggered the inactivation of the virus within 30 minutes, but we believe the catalyst can be further optimised to accelerate the inactivation and, more importantly, work under standard indoor lighting. We believe it could then be used as an antiviral coating for walls, windows and other surfaces, for instance in hospitals, schools, airports, homes for the elderly and kindergartens." ››

> *"We were able to observe that the titanium dioxide catalyses the inactivation of the virus by light"*
> ***Mona Kohantorabi, DESY NanoLab***

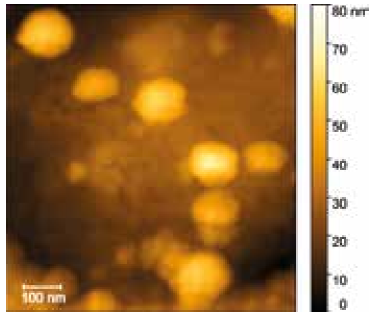
The spike protein attaches to titanium dioxide and is thus captured.

Pictures: DESY, Science Communication Lab / Coronavirus Structural Task Force, Thomas Splettstößer

Aerosols instead of solutions

Theoretical calculations by the group of Cristina Di Valentin at the Università degli Studi di Milano-Bicocca confirmed that the amino acids of the spike protein interact with the titanium dioxide surface. As these amino acids are present in the surface proteins of many other viruses, the NanoLab scientists expect the catalyst to also be effective against several other viruses as well; but this still needs to be tested.

Most coronavirus investigations to date look at liquid solutions. “But since corona and many other viruses spread through the air, it is important to look at aerosols,” says Noei. “If you create an antiviral coating, you have to put it where people are. Maybe you could even coat a fan to help purify the air.”



The atomic force microscope shows: The virus particles (light spots) adsorb to the titanium dioxide surface, where they are inactivated.

Optimisation potential

The team is now working on optimising the antiviral coating. “For instance, we found that the presence of palladium nanoparticles enhances the virus adsorption to the surface,” explains Kohantorabi. “Also, you want to avoid that water covers too much of the titanium dioxide surface, as less virus particles can be adsorbed.”

An optimal coating should be able to fully regenerate and self-clean to improve the longevity and sustainability of viral inactivation. The optimal mode of cleaning still needs to be determined. Complete oxidation of the virus on the surface would be a requirement for an efficient self-cleaning material. The scientists aim to test the optimised antiviral coating as soon as possible under conditions close to reality, such as in hospitals.

ACS Applied Materials & Interfaces,
DOI: 10.1021/acsami.2c22078

Picture: DESY NanoLab, Mona Kohantorabi

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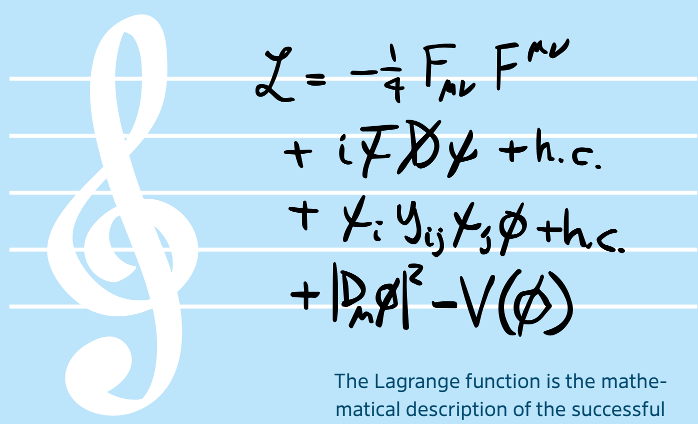
WHAT DOES THE THEORY OF EVERYTHING SOUND LIKE?



The Lagrange function is the mathematical description of the successful Standard Model of particle physics.

At the beginning, there is musical chaos. Timpani, strings, woodwinds and voices all sounding together in a wild mix. A chant slowly emerges from the tangle, like an incantation: “L uguale meno un quarto F mi ni...” – “L is equal to minus a quarter F mu nu...”: a physical formula! The choir recites several lines of the formula incantation, and slowly more order, harmony and interplay return to the music. In her opera “Creation”, the Hamburg-born composer and soprano Gloria Bruni has set a central formula of particle physics to music and, for the German premiere in Hamburg’s main church St. Katharinen at the end of April, even drummed up a volunteer choir of DESY employees to perform the work together with the Hamburg Symphony Orchestra and the International Choir Academy Lübeck.

The opera “Creation” examines the primordial beginning of humans and the universe, not only from a religious perspective, but also from a scientific and aesthetic one. “We witness how the universe could have come into being,” the composer explains in an interview with NDR. “From a tiny nothing to the huge everything up to the infinite universe!”

Bruni came across the formula – the Lagrange function, which describes the behaviour of the fundamental forces of nature – in conversations with DESY physicist Isabell Melzer-Pellmann. The two have been friends for a long time, and they often talk about the similarities and contrasts between music, physics, symmetry and spirituality. “We often discuss how physics interprets the big bang and how the universe develops, and also elementary particles and their interactions. At some point, we got to the Lagrange function, which describes three of the four forces between particles,” Melzer-Pellmann recalls. Bruni incorporated it into her opera as an organising element in the piece “Formula del tutto” (“Theory of Everything”).

Picture source: CERN

Under the influence of moisture, the special paper performs programmable movements.

Smart gifts will soon unwrap themselves

Cellulose-based materials can be programmed and repair themselves

A German–Swedish research group has developed a kind of special paper that can be animated by moisture to make specific movements. The cellulose–polymer mixture is thus an ideal base material for programmable actuators. In addition, the composite material is also very resistant to stretching and able to repair itself.

In nature, fascinating functions and mechanisms have prevailed over millions of years of evolution. In bionics research, scientists try to copy and reproduce these efficient methods from nature, for example in sensors or so-called bionic actuators, i.e. active elements that – controlled by a signal – can switch or move something. Modern actuators should be programmable, stimulable, very robust and able to cope with a wide range of working conditions.

The research team with members from the Royal Institute of Technology Stockholm (KTH), the Helmholtz Centre for Heavy Ion Research (GSI) and DESY produced a thin film of cellulose nanofibres with two types of polymers, following the example of biological tissue. To do this, they mixed polyvinyl alcohol (PVA) and polystyrene sulfonate (PSS) with the cellulose fibrils and poured the solution onto a glass plate. When it dried out, a circular film was created in which a tight network of chemical and physical bonds formed.

"It is the polystyrene sulphonate in particular that makes the film extremely stretchable and tough," says DESY scientist Qing Chen. "This ingredient of the solution can be broadened by mixing in food colouring agents, thus making it more colourful and diverse."

> *"In principle, we can make an active wrapping paper out of the material"*
>
> ***Stephan Roth, DESY and KTH Stockholm***

Application potential

Pieces up to several centimetres in size can be cut out of this film, which bend when exposed to moisture. "In principle, we can make an active wrapping paper out of the material," says Stephan Roth (DESY and KTH). "You just have to spray some moisture on it, and it unwraps itself."

But wrapping paper or sun awnings that roll up when it starts to rain are one thing; the novel cellulose–polymer film has much greater potential, for example as a moisture sensor or switch. In some ways, the devices are programmable: Bending direction, bending speed and curvature of the films can be tailored by controlling the geometry of the samples before they are cut.

X-ray control

Using DESY's X-ray light source PETRA III, the team gained particular insights into the tear resistance and self-repair of the material. For this purpose, the samples were stretched at KTH beyond the so-called yield point, and the inner structure of the resulting deformation was examined with X-rays.

The self-repair experiments were performed directly at PETRA III using a sample chamber in which the humidity could be adjusted. When the environment of the deformed samples was saturated with water vapour, the researchers could observe how chemical bonds formed again in the material, reducing the damaged area of the samples. "The self-repair mechanisms make this material truly unique," Chen emphasises.

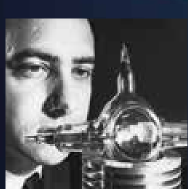
Advanced Functional Materials, DOI: 10.1002/adfm.202208074

LASER

FROM CURIOSITY TO INNOVATION DRIVER

1960

US physicist Theodore Maiman presents the world's first operational laser – the beginning of a technical revolution.



1962

The first semiconductor laser emits a beam of light. It is the ancestor of the laser diodes that are used in today's laser pointers, supermarket checkouts and fibre optic networks.

1965

A US team produces the first short laser pulses. They last less than a billionth of a second.

1967

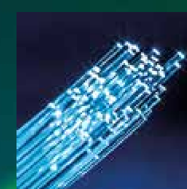
In England, a CO_2 laser cuts through a sheet of steel one millimetre thick – ushering in the use of lasers in industrial workshops.

1977

At Stanford University in California, John Madey's team builds the first prototype of a free-electron laser – the forerunner of DESY's large X-ray lasers.

1980

The first commercial fibre optic cables are installed. Laser pulses can carry huge amounts of data along them, and today they form the backbone of the Internet.



When the first laser went into operation in 1960 in Theodore Maiman's lab in California, it was considered a curiosity – interesting from a scientific point of view, but nobody really knew what to do with it. That has changed completely. Today, lasers are everywhere: from the laser scanners in supermarket checkouts to laser pointers and the laser drills used by dentists. In research and industry, this peculiar form of light has become a versatile tool. It cuts through steel, analyses the atmosphere and can even fuse atomic nuclei. But not only that. The demands placed on lasers in research are often extreme. As a result, laser technology is also a powerful driver of innovation, paving the way for new applications and techniques that would have been unthinkable just a few years ago.

Picture credits: page 45

ZOOM

1987

Ahmed Zewail invents the "pump-probe" method: A first laser pulse triggers a chemical reaction, and a second one measures what happens. In 1999, he is awarded the Nobel Prize in Chemistry.

1993

A team led by Wim Leemans, now Director of DESY's Accelerator Division, builds the first laser plasma accelerator. The concept promises significantly more compact facilities.

2001

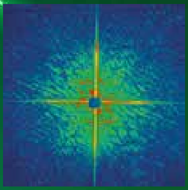
At TU Wien, Ferenc Krausz's team generates laser pulses in the atto-second range, lasting less than a quadrillionth of a second, for the first time. These can be used to track ultrafast processes.

1985

Donna Strickland and Gérard Mourou develop a method for generating ultrapowerful laser pulses. In 2018, they are awarded the Nobel Prize in Physics for their achievement.

1988

The first laser eye surgery is performed in the US state of Louisiana. Seven years later, the first commercial eye laser is approved.



2000

At DESY, a free-electron laser sets a world record: FLASH delivers high-intensity laser pulses in the VUV range.

2017

The European XFEL goes into operation in Hamburg. It is the world's largest and most powerful X-ray laser.

Graphic: DESY, Carolin Rankin

LEGENDARY LIGHT AMPLIFIER

The unprecedented success story of the laser

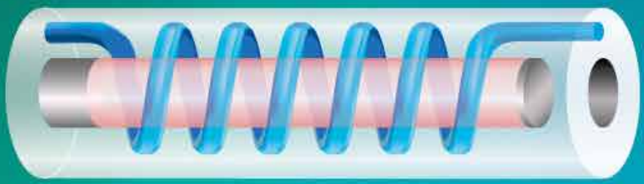
Whether in information technology, medicine or research laboratories – today, lasers are found everywhere. For a long time, experts had argued about whether such a magic lamp was even possible. Even physics genius Albert Einstein had speculated that it should in principle be possible to focus light to an astonishing degree. And in 1953, US researchers had succeeded in shaping microwaves into narrow beams. But it was far from clear whether the same trick would also work with visible light – until the late 1950s.

As Theodore Maiman, a physicist at the Hughes Research Laboratories in California, once remarked, “some people thought it was fundamentally impossible to build a laser.” At the time, he firmly believed in the concept and joined the race against other optimists. “Every day, I heard rumours that someone had already built a laser or was very close to doing so,” Maiman recalled.

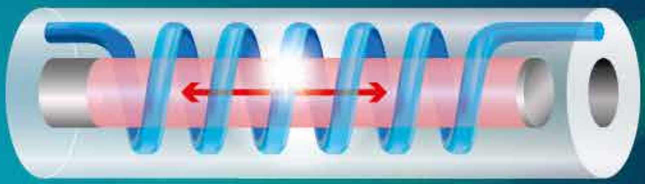
A pencil-sized ruby

The practical problem-solver tried a material that many thought to be hopeless: the ruby, a precious stone. He took a ruby rod the size of a pencil and attached tiny mirrors to its ends. Then he shone light at the arrangement using a screw-shaped flashlamp similar to a camera flash. The flash light pumped energy into the ruby crystal, raising certain atoms to an excited state. But the crucial effect only occurred once a sufficient number of atoms had been excited: Some atoms spontaneously dropped back to their ground state, emitting red photons in the process. These were reflected back and forth by the mirrors, sweeping other excited atoms along with them – triggering an avalanche. The mirrors focused this avalanche of

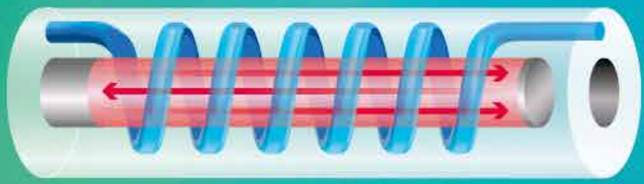
How does a laser work?



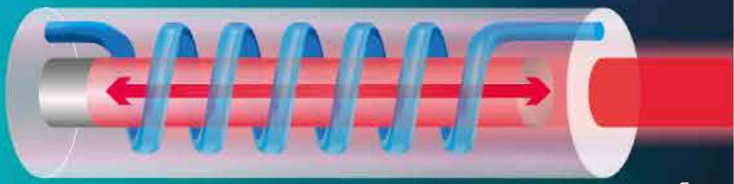
1 A simple laser, like this red ruby laser, consists of a rod of ruby crystal with a mirror at each end and a screw-shaped flashlamp wound around it.



2 A flash of light from the flashlamp supplies energy to the rod and excites chromium atoms in the ruby. Some chromium ions spontaneously release their energy in the form of particles of light (photons).



3 The spontaneously emitted photons are reflected back and forth many times by the mirrors and strike other excited chromium ions in the ruby, stimulating them to emit further photons.



4 These new photons in turn stimulate ions to emit photons. The process ramps up like an avalanche. One of the mirrors is slightly transparent, so that the light can leave the laser through it.

Graphic: DESY, Carolin Rankin

photons in the desired direction, producing an incredibly narrow, bright beam.

In July 1960, Maiman, then 32 years old, presented his invention to the public. This was the birth of the laser, an acronym for "light amplification by stimulated emission of radiation". "I simply ordered the ruby rods for my experiments from a catalogue, same with the flashlamp," Maiman recalled. "The rest was just a matter of technical workmanship."

Light in lockstep

It was not quite that simple, though. The physicist was the first to overcome two key hurdles. Firstly, he succeeded in pumping enough energy into the laser material using a flashlamp to create a surplus of excited atoms. Secondly, the two mirrors he used in his prototype reflected the light to and fro so well that it built up into an avalanche of light.

The bright narrow beam of light is not the only characteristic of a laser. The light is also usually monochromatic, a pure dazzling green or red, for example. In addition, the light is "coherent", meaning that the photons in a laser beam are locked in step with each other, as it were – in contrast to the light produced by a light-emitting diode, which scatters its photons randomly in all directions. This coherence is a prerequisite for certain techniques involving light, such as the creation of a hologram.

The public in 1960 was deeply impressed by Maiman's achievement, but the reaction of the experts was muted. A hastily written article, submitted by the physicist to the journal Physical Review Letters, was flatly rejected, for example. Maiman suspected a conspiracy on the part of the scientific establishment. After all, he had almost single-handedly achieved what great minds had been trying in vain to do for over two years. Initially, industry did not

"Some people thought it was fundamentally impossible to build a laser"

Laser pioneer Theodore Maiman of Hughes Research Laboratories

know what to do with the new light source either – lasers were generally regarded as a solution in search of a problem. Indeed, the first devices were of little practical use: Their power output was fairly modest, and they did not last long because the components stopped working too quickly.

A standard tool today

Over time, however, the teething problems were gradually overcome. In addition, more and more different types of lasers were invented, including semiconductor and gas lasers, each with specific strengths. Today, it is hard to imagine life without lasers: They weld and cut machine parts in industrial workshops. They send huge amounts of data through fibre optic networks – a prerequisite for the Internet. In medicine, they are used to operate on eyes and remove suspicious skin tissue. And in research, the laser has become one of the standard tools – in many laboratories, little would happen without it.

"Lasers are also used at DESY, in a wide variety of places," says Ingmar Hartl, head of the Laser Science and Technology group. The research centre operates several large-scale accelerators, such as the European XFEL, which accelerates short electron bunches to almost the speed of light. The particles are created by a laser firing at a metal plate at a rate of 27 000 pulses per second. Each time, electrons are ejected from the metal – a tailor-made bunch made up of a billion particles.

X-ray flashes

These are then brought to speed along a dead-straight, two-kilometre racing track, before being guided into an undulator – a kind of magnetic slalom course. There, they generate incredibly powerful X-ray flashes, which are used by research teams from around the world to study a wide variety of substances in great detail, including nanomaterials, plastics and proteins.

"Many of these experiments also use lasers," says Hartl. "Their light pulses trigger a chemical reaction, for example, which is then observed using X-ray pulses from the European XFEL." Different experiments require different types of lasers: Some ››

The components of the first ruby laser by Theodore Maiman emit pulses of infrared light, others produce ultraviolet radiation. It is also important to synchronise the triggering pulse with the observation pulse. The time difference between the two must be precisely controlled in order to follow the course of a reaction and record a sequence of images that can be assembled into a film.

"Once again, a laser is responsible for this high-precision synchronisation," Hartl points out. Ultimately, the X-ray pulses produced by the European XFEL also have certain laser-like properties – which is why it is referred to as an X-ray laser. The same applies to the FLASH facility on the DESY campus, a pioneering facility for all such X-ray lasers.

"This goes to the very limit of what is technically possible"

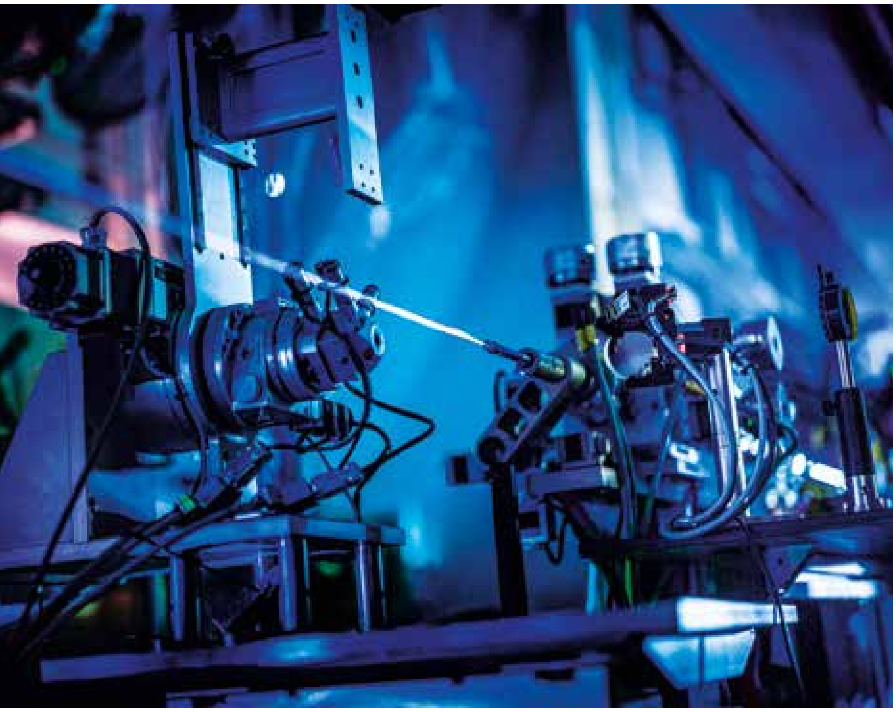
Ingmar Hartl, head of Laser Science and Technology at DESY

Holograms of molecules

Since many of the lasers used at DESY serve special purposes, they cannot be ordered from a catalogue. Instead, the research centre has to develop many components itself. "We often go to the limits of what is technically feasible," says Ingmar Hartl. His group is currently working on two projects that illustrate this quite well. At FLASH, for example, the electrons flying through the undulator are in future to be modulated by pulses from a UV laser. The X-ray pulses from FLASH could thus be optimised in such a way that, for example, holograms of molecules could be recorded – something that is not currently possible. "The laser we need for this must deliver a lot of power and, at the same time, we need to be able to tune it, in other words, to adjust its colour," explains Hartl. "We are currently developing such a laser, and we hope to be able to use it by 2025."

An even more ambitious project could one day further boost the performance of the European XFEL: At the moment, it generates X-ray pulses lasting less than 100 femtoseconds, well under a trillionth of a second. For certain experiments, however, it would be exciting if these pulses could be made a thousand times shorter – what experts call the attosecond range. Here too, laser pulses will be fired into an undulator through which fast electron bunches are moving. "To put it simply, these laser pulses are intended to manipulate the electron bunches so that they emit light only at a specific spot, thereby generating extremely short X-ray pulses," Hartl explains. The challenges facing the laser are enormous: It must emit powerful and extremely stable pulses, lasting just five femtoseconds, 200 000 times per second. "Nothing like this exists yet; this goes to the very limit of what is technically possible," says Ingmar Hartl. "But we believe we have now assembled the building blocks that are needed for such a laser."

Laser pioneer Theodore Maiman would probably have been impressed by such projects too. He died a wealthy man in 2007, having set up companies based on his invention and thus capitalised on his patent. Maiman also benefited from his invention in terms of his own health: In 2000, he successfully underwent prostate surgery at the University Hospital in Munich – with the help of a laser, of course.



The X-ray laser beam of the European XFEL is generated by sending fast particles (electrons) through a magnetic slalom track where they emit light in sync.

Pictures: European XFEL, Jan Hosan; DESY

"WE WANT TO INCREASE OUR **VISIBILITY** AS A LASER LABORATORY"

In industry and research, lasers are a technology of the future, and Wim Leemans, Director of DESY's Accelerator Division, expects their importance to continue to grow. This will also be a matter of making the best possible use of synergies.

femto: You have been Director of the Accelerator Division at DESY since 2019. Before that, you spent a long time doing research in California. What were your expectations when you came to Hamburg?

Leemans: I must admit that I had previously viewed DESY primarily as a leading accelerator centre. It was not on my radar as a laser lab. But once I was in Hamburg, I quickly realised that numerous top-class lasers were being developed here as well. Some produce ultrashort light pulses in the attosecond range. Others deliver very powerful laser flashes or run very reliably in continuous operation. The two large-scale accelerators FLASH and the European XFEL can also be regarded as lasers. Their X-ray pulses are far more powerful than anything produced by other types of lasers. DESY has also founded several exciting spin-offs, which are developing innovative laser technologies. So when I came to Hamburg, a whole new world opened up for me. And I believe that lasers will become even more important for DESY in the future.

femto: In what way, what is the plan?

Leemans: We are developing a laser, KALDERA, which will produce a thousand high-intensity light pulses per second. We want to use this to build a powerful laser plasma accelerator. This type of accelerator propels electrons to very high energies, but it is much more compact than conventional accelerators. This could one day make it possible to build X-ray sources that take up very little space, which would benefit a wide range of disciplines. That would be a huge advantage for research.

femto: For some time now, DESY has been a member of Laserlab-Europe AISBL, an association of 46 laser research institutions in Europe. What do you hope to gain from this membership?

Leemans: We want to increase our international visibility as a laser laboratory. We would like to draw attention to the many in-house developments and powerful laser systems that DESY has to offer today. As a member of Laserlab-Europe, we will use this network to invite experts from other member institutes, so they can get to know us better. This could also help us to attract new top talent to DESY.

femto: How important is the cooperation with the laser industry, and to what extent does DESY work with the industry?

Leemans: There are very strong laser manufacturers and optics companies in Germany, such as TRUMPF or ZEISS. These industrial partners are in the process of mass-producing lasers for research – devices that are manufactured according to industrial standards, and which are therefore cost-effective and operate reliably. Conversely, industry can also benefit from science. For example, ultrashort-pulse lasers were originally developed for research purposes, but can now process materials with much greater precision than ten years ago. We want to increase these synergies by means of the new HI-ACTS innovation platform. It brings together several Helmholtz centres and companies to advance the development of laser plasma acceleration, for example.

Picture: DESY, Werner Bartsch

FAR FASTER THAN THE BLINK OF AN EYE

Ultrashort laser pulses track the activity of molecules

“We generated UV pulses that were barely two femtoseconds long”

Francesca Calegari, DESY

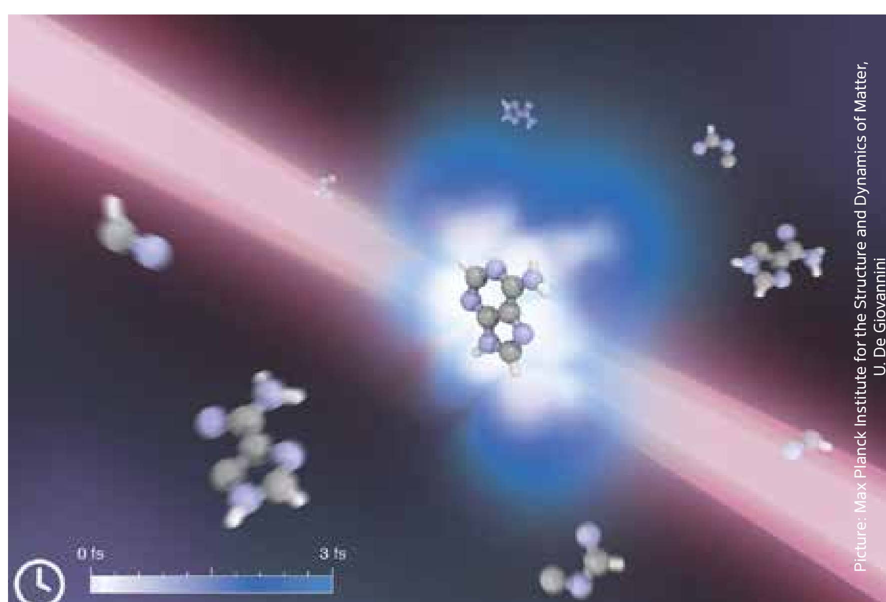
In the anteroom to her laboratory, Francesca Calegari reaches for a smock and overshoes and puts on a pair of clunky goggles. “We have to put these on to prevent any dust from getting on our lasers,” explains the physicist. “And the goggles are to protect our eyes from the intense beams.” She points to the floor – a massive slab of concrete, which forms the foundation of the experimental hall that houses Calegari’s apparatuses. “The solid concrete absorbs virtually all the vibrations,” she says. “That’s very important for our experiments.”

That’s because the experiments carried out by Calegari’s team require extreme precision. The experts are developing special lasers that can produce unimaginably short flashes of light – pulses in the femtosecond and even attosecond range, i.e. in the region of one quadrillionth of a second. “This is the time scale on which electrons move in atoms and molecules,” explains the Italian, who has been working as a lead scientist at DESY since 2017 and is also a physics professor at Universität Hamburg. “Our ultrashort-pulse lasers allow us to track these movements and gain a better understanding of how chemical bonds are formed and broken, for example in biomolecules.”

Molecular slideshow

This is relevant, for example, when studying natural processes that take place at enormous speed, such as the disintegration of the building blocks that make up DNA when they are bombarded with light. “To observe such processes, we need the laser,” says Calegari. “The first laser pulse stimulates a reaction, while the second one immediately afterwards allows us to observe the reaction as it unfolds.” The time between the first and the second pulse is then systematically varied. “Pump–probe” experiments like this allow the course of the reaction to be precisely tracked – producing a kind of molecular slideshow.

However, these experiments require special laser facilities – devices that cannot be bought off the shelf. So Calegari’s team has to build its own experimental setups and develop the new technologies it needs. The experts



Picture: Max Planck Institute for the Structure and Dynamics of Matter, U. De Giovannini

Artist’s impression of the ultrafast stabilisation of adenine against dissociation: When the molecule is ionised by XUV radiation, it undergoes dissociation. However, by properly timing a second infrared laser pulse and taking advantage of a charge migration mechanism, it is possible to stabilise the molecule through a second ionisation event.

One of the CFEL-ATTO group's unique attosecond beamlines generates both UV pulses of less than two femtoseconds duration and isolated attosecond pulses in the extreme UV range, which can be used to study ultrafast electron dynamics in matter.

have, for example, built a system that produces ultrashort UV pulses. "This is important because UV light from the sun is constantly reaching us and setting a whole series of biological processes in motion," says Calegari. "Among other things, it can promote skin cancer."

The group uses a tried and tested method to generate UV pulses with a laser: Intense pulses of infrared light are fired into a cell filled with a high-density noble gas; the electrons in its atoms are rapidly shaken back and forth, causing UV radiation to be emitted. The tricky part is getting really ultrashort UV pulses. To achieve this, Calegari's team takes advantage of the fact that infrared light transforms as it propagates through a gas cell, which significantly shortens the UV emission. "This allowed us to set a new world record in 2019," says Francesca Calegari. "We generated UV pulses that were barely two femtoseconds long."

Flash magnifier

The team can generate even shorter laser pulses – attosecond pulses in the extreme UV (XUV) or soft X-ray range – again based on ultrashort flashes of infrared light. In the lab, Calegari's colleague Gaia Giovannetti points to a commercially available laser, which produces pulses of infrared light. "These pulses are the starting point for our method," she explains, moving to the neighbouring laboratory, into which the infrared pulses are directed and where the actual apparatus is set up. She opens the lid of a box in which dozens of mirrors are arranged seemingly at random. "This setup increases the wavelength of the pulses and, at the same time, amplifies their intensity many times over," Giovannetti explains. "We then send these new pulses into a tiny glass cell, which is less than a millimetre long and filled with noble gas at high pressure." When the infrared pulse enters the cell, it knocks electrons out of the gas atoms. These electrons are accelerated in the laser field and then bounce back towards the gas ions – emitting ultrashort soft X-ray pulses.

"Our experiments can provide a better understanding of how radiation damage occurs"

Francesca Calegari, DESY

When the scientists used this technique to take a closer look at adenine, one of the building blocks of DNA, under their flash magnifier, they were in for a surprise: "When you bombard adenine with flashes of XUV radiation, it literally bursts apart," says Calegari. "But when we sent an infrared pulse closely behind, that stabilised the molecule and prevented it from breaking apart." This discovery could have implications for health research: When radiotherapy is used to treat cancer, the radiation knocks electrons out of the molecules in the tissue, which can then damage DNA building blocks, such as adenine. "Our XUV pulses have a similar effect," says Francesca Calegari. "So our experiments can provide a better understanding of how radiation damage occurs and perhaps even help to develop new mechanisms for protecting the tissue."

Portrait left, picture right: DESY, Marta Mayer

SUCCESSFUL **FLASH FORGE**

The start-up Class 5 Photonics builds innovative short-pulse lasers for research applications

In his laboratory, Robert Riedel opens the lid of a shallow, sleek aluminium box, not much larger than a regular parcel. Inside are lenses, mirrors and electronic components – parts that are needed to generate ultrashort laser pulses – all packed into a very small space. "In a typical research lab, these parts would be spread out on a large table," explains the physicist. "We have combined them all to create a compact, software-controlled system that can be operated even by people who are not certified laser specialists."

Riedel's spin-off is called Class 5 Photonics and is based at Start-up Labs Bahrenfeld, an innovation centre recently set up on the edge of the DESY campus in Hamburg. "Our company grew out of a Helmholtz Young Investigator Group at DESY," he explains. "Our mission was to develop a laser that fires short and powerful laser pulses in rapid succession." The idea was for this laser to trigger chemical reactions, for example, the course of which could then virtually be filmed using DESY's large facilities, such as the X-ray laser FLASH.

Helmholtz spin-off programme

The team developed a prototype, which worked so well that even experts outside DESY became aware of the technology. This gave Riedel and his team the idea of setting up a company to meet the obvious need for short-pulse lasers. To get off the ground, the team was supported by DESY's department for Innovation & Technology Transfer and a Helmholtz spin-off programme. This enabled the team to analyse the market and develop its first products.

The start-up company was launched in 2014. Its name alludes to a classification system commonly used in the professional world, whereby lasers are divided into four performance classes. Class 5 symbolises a new, even more powerful category. The first products generated short infrared pulses, but little by little the start-up expanded its range. "Our customers asked us whether we could also build lasers that produce other wavelengths," Riedel recalls. "We accepted the challenge, and today we have an entire portfolio of laser technologies at our disposal."

"Moving our growing team forward is a really wonderful challenge"

Company founder and CEO Robert Riedel

Close ties

Meanwhile, the range extends all the way from terahertz pulses, through flashes of visible light, almost to X-ray wavelengths – all of them lasers that serve as research tools in physics, chemistry and biology labs. The start-up sells around ten systems a year – from relatively small lasers for biological applications to large projects costing many millions for renowned institutions such as Stanford and Harvard Universities, Berkeley Lab and the Massachusetts Institute of Technology (MIT).

Class 5 Photonics started out as a team of two and now employs around 20 people, many with PhDs. "Moving our growing team forward is a really wonderful challenge," says Riedel. The company continues to maintain close ties with DESY. There are joint research projects for developing new technologies. These are partly funded by Class 5 Photonics, and the results can then be incorporated into the start-up's product portfolio.

Class 5 Photonics' high-power lasers have repeatedly won innovation awards, such as the PRISM AWARD at the Photonics West conference and the Laser Focus World Innovators Award.

Pictures: Class 5 Photonics GmbH, Mihail Petev

Lasers can be used to realise compact particle accelerators.

LASERS FOR TURBO-CHARGED PARTICLES

How KALDERA will facilitate the breakthrough of plasma acceleration

Particle accelerators are important research tools. Large-scale facilities such as the LHC in Geneva help scientists study the smallest building blocks of matter. And facilities such as the European XFEL in Hamburg generate incredibly powerful X-ray pulses, which can be used to peer inside a wide variety of materials. A new technology is set to significantly expand the range of applications for particle accelerators: So-called plasma acceleration promises to make facilities significantly more compact and hence more cost-effective.

In the future, this could make accelerators available in areas where they have previously been too complex and expensive – for example, in medical and industrial applications. Plasma accelerators can be based on different concepts. One concept centres on a new generation of short-pulse lasers. With the KALDERA project, DESY wants to advance into new dimensions and build one of the world's most powerful lasers for plasma acceleration.

Electrons surfing the wave

In the current accelerator technology, radio waves are guided into special metal tubes known as cavity resonators. These radio waves propel the particles, in most cases electrons, which ride the waves like surfers on the ocean. However, the maximum acceleration of a single cavity is limited by the underlying design. This means that a large number of cavities must be connected in series if the electrons are to reach high energies. Such facilities are therefore long and expensive.

Laser plasma acceleration is a very recent method that can take up much less space. The underlying principle is to fire brief but powerful laser pulses into a small cell containing an electrically charged gas, known as a plasma. Just as a boat forms a wake behind it, the laser pulse ››

Picture: DESY, Thomas Hülsenbusch

creates a wake as it passes through the plasma. This plasma wave is so strongly electrically charged that it can accelerate electrons tremendously – over a distance of just a few millimetres. This could allow accelerators to be made considerably smaller. A facility that is a hundred metres long today could be replaced by one that fits into the basement of a laboratory.

Laser-like X-ray pulses

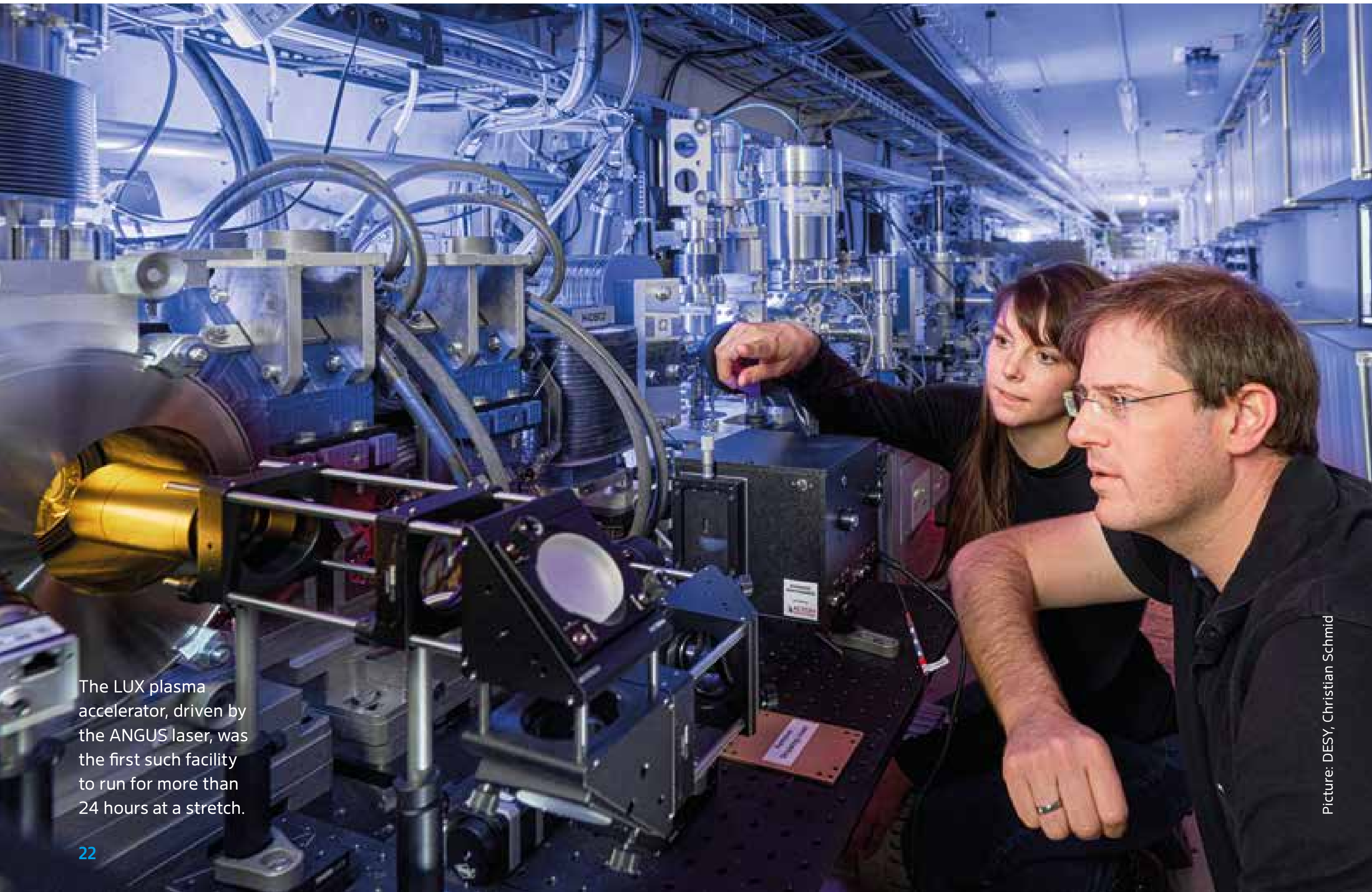
One exciting application will be to use bunches of plasma-accelerated electrons to generate laser-like X-ray pulses. Until now, such free-electron lasers (FELs) have all been based on conventional accelerators. As these are complex and expensive, only a few FELs currently exist around the world. Plasma technology, on the other hand, would allow facilities to take up less space and become more cost-effective. As a result, more FELs could be built, greatly expanding their potential applications.

A number of prototypes around the world have already demonstrated that plasma acceleration does work. "Using our ANGUS laser, we have for the first time in the world managed to operate a laser plasma accelerator for more than a day without interruption, as in routine operation," reports Andreas Maier, a lead scientist at DESY. "It was accelerating electrons once every second." However, prototypes like ANGUS are still some way from being ready for application. This is because one laser burst per second is simply not enough for FEL applications – these require several hundred or even thousands of laser pulses per second.

Nobel-Prize-winning technology

Until now, however, no laser exists that is capable of doing this. The pulse of light that ANGUS emits once a second is extremely short – 30 femtoseconds (quadrillionths of a second) – but enormously powerful, at 100 terawatts. So far, no one has managed to build a laser that produces a thousand such pulses every second. "That is what we are trying to do with KALDERA," explains Maier. "KALDERA is to accelerate up to a thousand electron bunches per second, at which point the technology would be competitive."

The challenges facing the project, which was initiated by the Director of DESY's Accelerator Division, Wim Leemans, are enormous, though. In order to generate short and powerful flashes of light at all, a Nobel-prize-winning technology is needed: chirped pulse amplification. The principle behind it is that a first laser produces a flash of light that is short but still weak. This is fed into special light



The LUX plasma accelerator, driven by the ANGUS laser, was the first such facility to run for more than 24 hours at a stretch.

Picture: DESY, Christian Schmid

amplifiers to give it more power. These consist of crystals that have been charged with energy, shortly before, by so-called pump lasers and then transfer this energy to the pulse of light passing through. Several such light amplifiers are connected in series to achieve the desired level of power.

Stretched pulses

However, as the light pulses pass through this cascade, they become so powerful that they would normally destroy the light

> *"KALDERA is to accelerate up to a thousand electron bunches per second"*
> ***Andreas Maier, DESY***

amplifiers. So the experts resort to a trick. Before amplifying a light pulse any further, they first pull it apart using special optical systems until it is a hundred thousand times longer than before. This reduces the amount of power so that it is safe to amplify the stretched pulse further. After the final amplification, a so-called compressor squeezes it back together again. In the end, it is far more powerful than before.

However, before being able to send a large number of pulses through the amplifier cascade every second, a variety of challenges need to be overcome. On the one hand, there are the pump lasers that supply energy to the amplifier crystals. "These lasers get very hot when they have to fire so frequently," says Maier. "The average power could reach five kilowatts, which is the kind of power used in industry for welding cars!" To solve this problem, the experts are working with partners in industry and research to develop new types of pump lasers that are more efficient and therefore produce less waste heat. Nevertheless, these lasers will also heat up, so the team will have to incorporate additional effective cooling techniques.

Crystals slice by slice

The second challenge is the amplifier crystals; they too would get quite hot at one thousand pulses per second. "This could deform them and interfere with the propagation of the laser pulses," explains Maier. "Eventually, it could even tear the crystal apart." It is therefore important to dissipate as much heat as possible from the crystal during operation. The experts are currently considering several potential concepts to achieve this. One possibility is to cut the crystal into a number of slices, positioning these one behind the other. This would provide a larger surface area through which the material could be cooled and heat could be removed.

Another hurdle is the compressor – the component that squeezes the stretched light pulse back together again at the end. Until now, this has been done using gold-coated materials with thousands of fine lines carved into them. In the case of KALDERA, the gold would absorb too much heat. The experts are therefore working on alternative coatings.

Correction signal

"Another improvement we are attempting to make at KALDERA is to shape the light pulses more specifically and thus to optimise their properties," says Andreas Maier. To achieve this, the team has to shield the sensitive equipment as well as possible from disruptive environmental influences. For example, to compensate for vibrations in the ground, the team plans to fit the laser with numerous sensors – including cameras that observe and measure the light beam, for example. If the resulting images indicate a deviation due to vibrations, software calculates a correction signal. This signal controls a motor-driven mirror in such a way that the laser beam continues to travel in the desired direction despite the vibrations.

The laboratory for KALDERA is already in place, and Maier and his team are assembling the first components. If everything goes according to plan, the facility should be completed by 2026 – then, for the first time, it will accelerate up to a thousand electron bunches every second.

iF Design Award for KALDERA web application

The interactive web application kaldera.desy.de has been awarded the prestigious iF Design Award 2023 for its outstanding presentation of laser plasma acceleration. The information service was conceived and designed for DESY by Science Communication Lab in Kiel, together with KALDERA scientists, and allows visitors to interactively explore the complicated process of plasma acceleration.

The iF Design Award is a world-renowned prize for outstanding design that has been presented annually by iF International Forum Design in Hanover since 1954.

https://kaldera.desy.de

LIGHT THROUGH A WALL

The ALPS II facility uses lasers to search for dark matter

Particle physicists are looking for the basic building blocks that make up the world. What does matter consist of at its core? What holds it together? To answer such fundamental questions, scientists mostly use particle accelerators, such as the huge LHC ring at CERN in Geneva. But in some projects, lasers play a key role.

A facility known as ALPS II has been installed in the underground tunnel of HERA, a decommissioned DESY accelerator. This 250-metre-long experimental apparatus is searching for a new, hitherto hypothetical particle, the axion: extremely light, volatile and exotic. If it exists, it might explain the mysterious dark matter. Although dark matter makes its presence felt throughout the universe through its gravitational effects, it is still unclear what it consists of. One candidate is axions – if they exist.

Laser in a magnetic field

An international team has designed a special experiment to detect these elusive particles. Theory predicts that axions should interact with light, though only weakly. So the scientists plan to send light from a laser into a magnetic field, in the hope that some of it will be converted into axions. These would then fly through a wall, like ghosts, behind which they could be turned back into light in another strong magnetic field – a "light shining through a wall" experiment, so to speak.

ALPS II is made up of two evacuated magnetic sections, each 120 metres long, separated by a wall that is opaque to light. "We fire the laser into one of the sections and hope that some of the light will be converted into axions," explains DESY physicist Aaron Spector. "The other side is completely dark. If we were to register a faint glow there, it would have to have come from an axion that has turned back into light."

One photon per day

This calls for special types of lasers, though. The laser that is meant to produce the axions sends out a powerful, continuous infrared beam. This has to be perfectly matched to the mirror system in which the light travels back and forth. This means the 120-metre-long system must be controlled to within a billionth of a millimetre. Also, the laser must be able to maintain its frequency with extremely high accuracy. "We are benefiting from the technological developments that have been made in gravitational wave detectors, such as LIGO in the USA," says Spector. "Our system is very similar to the laser used there."

A frequency-stabilised laser also operates on the other side of the opaque wall. This is used to check the mirror system behind the wall and at the same time to detect the axions. If one of the ghost-like particles were to change back into a photon, it should interfere with the laser beam. This would produce characteristic interference patterns, which would be registered by sensitive sensors. However, the light signals are likely to be extremely weak – the scientists expect at most a single infrared photon to appear in their apparatus per day. "Because of this, we have to do everything we can to ensure that no light gets through from the other side of the wall," explains Spector. "Otherwise, we will not be able to see the signal we are after against the background."

femtoweb

Through the tunnel by speed drone

Speed drone pilot Christina Krywka, a full-time physicist at the Helmholtz Centre Hereon outstation at DESY, has captured a high-speed glimpse of the unusual ALPS II experiment underground. Her exciting six-minute video shows the entire facility and explains the principle behind the measurements. Unlike the hypothetical axions the team is looking for, however, her speed drone was unable to penetrate a solid wall...

https://www.youtube.com/watch?v=qwbGDRTQG48

Picture: DESY, Science Communication Lab

MATTER OUT OF NOTHING

Can particles be created in a vacuum using a laser?

Beate Heinemann is puzzling over a question that sounds rather strange: Can matter be created out of a vacuum, out of nothing, as it were, with the help of light? "We usually think of the vacuum as being a completely empty space," explains DESY's Director in charge of Particle Physics. "But that isn't true in quantum physics; here, the vacuum is full of virtual particles." These particles pop up abruptly out of nowhere, in pairs, only to disappear again immediately afterwards – that's why they are called virtual. It has long been possible to detect them indirectly, for example in the way they slightly weaken electrical charges.

The theory that describes such processes is called quantum electrodynamics. It makes a spectacular prediction: If a vacuum could be literally brought to the boil by supplying enough energy, pairs of virtual particles could manifest themselves and turn into real, actual particles. Out in space, this is likely to happen in extreme environments. The physicist Stephen Hawking, for example, once speculated that the gravitational field in the immediate vicinity of a black hole ought to be strong enough to give birth to real particles as a result of erratic vacuum fluctuations.

Heinemann and an international team now want to initiate and observe a similar process – in an experiment called LUXE. The scientists are planning to have the high-energy electron beam from an accelerator collide with pulses from a powerful laser. "This should allow us to generate extremely intense electromagnetic fields," explains Heinemann. "These fields, in turn, should be strong enough to convert the virtual particles in the vacuum into real particles."

> *"The vacuum is full of virtual particles"*
> ***Beate Heinemann, DESY***

High-energy electron bunches

More specifically, the team wants to use the accelerator of the European XFEL in Hamburg – a facility with a total length of more than three kilometres, which has been the world's most powerful X-ray laser since 2017. The laser is to be installed in one of its halls. It will deliver pulses that are only 25 femtoseconds (quadrillionths of a second) long, yet have a power of 300 terawatts. "We want to focus these pulses on a tiny spot, three micrometres across," says Heinemann. "This is the only way we can achieve the field strengths we need." The high-energy electron bunches from the accelerator are then to fly into this focal point – or else high-intensity gamma quanta that were previously produced by the fast-moving electrons.

The idea is that pairs of electrons and their antiparticles, called positrons, might materialise during these collisions – which could be recorded by detectors. The construction plans are ready, and applications have been written for the approval of the experiment, which is expected to cost about 15 million euros. "We hope to begin construction in 2025 and to launch the experiment two years later," says Beate Heinemann. If the team does indeed manage to create matter out of light at the rate predicted, this would be impressive confirmation of the theory for the first time at such enormously high field strengths. However, if deviations from the theory were to emerge, this would be even more exciting. They might hint at new, hitherto unknown laws of physics.

Picture: DESY, Angela Pfeiffer

At the HED measuring station, Ulf Zastrau's team can examine samples under extreme conditions.

INSIDE A PLANET BY LASER

Experiments at the European XFEL X-ray laser study extreme conditions

Two scientists sit in the control room, fully concentrated, their eyes glued to one of the countless monitors. The camera image displayed there shows a magnified view of a wafer-thin sheet of copper in the experimental hutch next door, shielded by thick concrete walls. One of the researchers begins to carefully align the copper sheet by clicking with the mouse: position, angle, distance – everything has to be just right.

The procedure is taking place in the underground hall of the European XFEL in Schenefeld, the most powerful X-ray laser in the world. The alignment is part of the preparations for a spectacular experiment that is due to take place here in a few hours. A high-power laser will fire an ultrashort pulse of light at the copper foil, burning a small hole in it. A fraction of a second after the laser hits the foil, it will be followed by a powerful X-ray pulse from the European XFEL. This will shed light on the events that are taking place, revealing in great detail how the laser pulse burns its way through the copper foil. “We will repeat the experiment dozens or even hundreds of times,” explains Ulf Zastrau, lead scientist at the European XFEL. “Each time, we will vary the interval between the laser pulse and the X-ray pulse, so that we will end up with an overview of the entire process.”

Precision cutting

The experiment is interesting because the laser does not simply melt holes in the metal. Instead, the pulses are so short and intense that they abruptly ionise the material at the point of impact. In other words, they tear away a large proportion of the electrons orbiting the copper atoms. As a result, the

Picture: European XFEL, Jan Hosan

region becomes so highly charged that everything flies apart in an instant. Unlike melting, however, this phenomenon is confined to a tiny spot – the surrounding material remains largely untouched.

That is why industry is increasingly turning to short-pulse lasers, in order to process materials as precisely as possible. The method allows silicon wafers or smartphone displays to be cut with much greater precision than with previous lasers. "Our experiments allow us to observe in detail how the laser pulse interacts with the material," explains Zastrau. "How exactly does a hole form? How does it spread?" The results provide important fundamental information for manufacturers who want to improve their industrial lasers and tailor them to specific applications.

Exotic states

However, carrying out this type of experiment requires considerable effort. On the one hand, they need the X-ray pulses from the European XFEL, a 3.4-kilometre-long large-scale facility based on a superconducting particle accelerator. On the other hand, the laser pulses striking the copper foil must be extremely short and intense. They last just 25 femtoseconds (quadrillionths of a second), but have a power of 300 terawatts. Pulses like these can generate extreme energy densities and put matter into exotic states. For this reason, the measuring station used by Zastrau and his team is aptly named High Energy Density Science, or HED for short.

The superlaser is located directly above the control room and the experimental hutch. Ulf Zastrau slips on a lab coat, unlocks the door and reveals the inside of an air-conditioned laboratory the size of a classroom. Massive boxes with auxiliary lasers stand alongside stainless steel vacuum chambers and tables full of screens and mirrors. The aisles between them are so narrow that it is difficult to squeeze through. "This is really tightly calculated," says Zastrau. "We had to plan very carefully to be able to accommodate all the components."

"A space probe could never penetrate that far inside a gas giant"

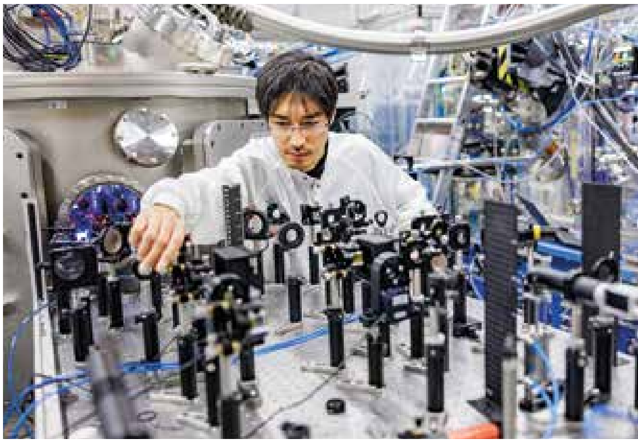
Ulf Zastrau, European XFEL

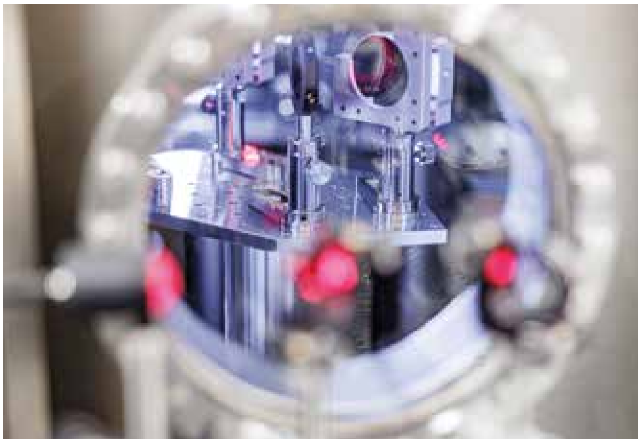
Shock wave

He points to the device in the other half of the room – a second superlaser. Its pulses last ten nanoseconds, significantly longer than those of the other laser, but they contain far more energy: up to 100 joules. Both lasers are among the most powerful of their kind in Germany and can emit up to ten pulses per second. They are funded and operated by the international user consortium HIBEF (Helmholtz International Beamline for Extreme Fields), which is coordinated by the Helmholtz Centre Dresden-Rossendorf.

This high-energy laser, which is due to go into operation this year, will also allow spectacular experiments to be carried out. "When its laser pulses strike a sample, they can trigger a veritable shock wave in the material," explains Zastrau. "The shock wave is associated with enormously high temperatures and pressures." To put that in numbers: The laser pulses can generate temperatures of up to one million degrees and pressures of up to ten million bar, or ten million times atmospheric pressure. However, these conditions only persist for a billionth of a second – before the sample is pulverised. In order to analyse such short-lived events nonetheless, the short X-ray pulses of the European XFEL are needed.

The fascinating thing is that the extreme conditions created by laser are similar to those found deep inside Earth or giant planets, such as Jupiter and Saturn; in other words, they can simulate the inner workings of these celestial bodies. That allows many exciting research questions to be tackled. What phenomena govern events inside Earth's core, which consists partly of solid and partly of liquid iron? And what do the inner layers of Saturn look like in detail – presumably a honey-like mixture of hydrogen and helium? "A space probe could never penetrate that far inside a gas giant," Zastrau points out, "it wouldn't survive. But our laser experiments allow us to simulate what is going on there – even if only for a tiny moment."





The measuring station has two sample chambers, in which high-power lasers can be used to create conditions such as those that prevail in the interior of planets.

Pictures: European XFEL, Axel Heimken

IN **TERAHERTZ** TIME

Special lasers for triggering molecular experiments

Sometimes a big laser needs a smaller one – to make certain experiments possible. In this case, the big laser is the European XFEL in Hamburg. With a length of more than three kilometres, it is considered the world's most powerful X-ray laser. Its X-ray pulses are so short and intense that they can be used, for example, to track ultrafast processes on a molecular scale with very high precision. To set those processes into motion, a smaller, specialised laser is needed, which can generate short trigger pulses, for example in the terahertz range. A research team at DESY's Zeuthen site is developing such a radiation source.

In the electromagnetic spectrum, terahertz radiation lies between microwaves and infrared light. This radiation has the property of transforming matter and individual molecules into new, otherwise inaccessible states. These states can then be studied with the X-ray pulses from the European XFEL to reveal how they evolve over time. However, generating short and intense terahertz pulses that are ideally suited for such experiments is far from easy.

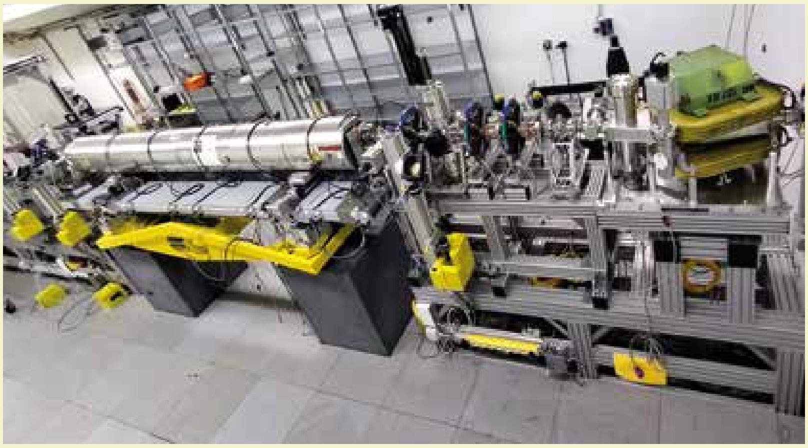
A high-brilliance electron source for the accelerator of the European XFEL is currently being developed at DESY's photoinjector test facility PITZ in Zeuthen. It seemed an obvious choice to use a prototype of this injector for a laser that delivers short terahertz pulses. The device produces short bunches of electrons, which are propelled almost to the speed of light by electric fields and a small accelerator, and then directed into an undulator. This is a complex arrangement of magnets that forces the electron bunches to follow a slalom course, causing them to emit the required terahertz laser pulses.

Perfectly tuned

"Our technology allows us to pack an extremely large number of electrons into one bunch," says DESY physicist Mikhail Krasilnikov. "This can then be used to generate quite powerful terahertz pulses." Another important feature is the number of pulses that the new laser will produce. "It should generate the same number of terahertz pulses as the European XFEL produces X-ray pulses," says Krasilnikov. "Because each X-ray pulse has its own terahertz pulse, the two would be perfectly matched, and that would allow very high-contrast images to be recorded." The device will also be tunable, producing different terahertz frequencies, which is important for triggering a range of different processes.

> *"Our technology allows us to pack an extremely large number of electrons into one bunch"*
> **Mikhail Krasilnikov, DESY**

An initial feasibility test was successfully carried out in 2022 at the PITZ test facility – so the concept works in principle. The next step is to develop the technology to application maturity. "We hope to build a compact terahertz source, based on our photoinjector, close to a measuring station of the European XFEL," explains the physicist. "In that case, the terahertz pulses would not have to be transported very far, and the losses would be minimal." This would make it possible to carry out so-called "pump–probe" experiments, which are suitable for a wide range of applications. Among other things, materials for faster and smaller data storage, more efficient solar cells and novel catalysts could be studied.



View inside the PITZ extension with the terahertz laser. The undulator that generates the laser radiation is mounted on the yellow frame, the electron beam enters the beamline from the right.

Picture: DESY, PITZ group

PERFECTLY SYNCHRONISED

How a start-up ensures that different lasers work in sync

Lasers can generate extremely short and uniform light pulses, making it possible to measure ultrafast processes in the microcosm, such as chemical reactions. Often, several different laser systems must work hand in hand and be precisely coordinated. This requires extremely accurate synchronisation. The technology required for this is being developed by Cycle, a DESY start-up.

The experiments with which molecular movies can be made are called “pump–probe” experiments: A first laser initiates a reaction with its light pulses, and a second laser fires a tiny bit later to analyse how the reaction unfolds. Then it starts all over again. The reaction is repeated again and again, and sampled at different times. The result is a series of still images that can be combined to form a kind of flip-book, a “molecular movie”.

Femtosecond accuracy

This process requires the two lasers to be precisely synchronised. For the measurement to work, the time interval between the two pulses must be defined to within a few femtoseconds – a femtosecond is a quadrillionth of a second. If the two lasers are located close to each other in a lab, this synchronisation is not too much of a problem. At huge facilities like the European XFEL in Hamburg, the world’s most powerful X-ray laser, the situation is different.

Here, the pump laser that triggers the reaction is located in an experimental hall in Schenefeld, Schleswig-Holstein. The accelerator-based probe laser, on the other hand, originates a good three kilometres away, on the DESY campus in Hamburg-Bahrenfeld. There, a laser blasts bunches of electrons out of a piece of metal, which later produce the X-ray laser pulses.

Laser metronome

“To synchronise the two lasers, in Schenefeld and on the DESY site, they are connected by a fibre optical system,” explains Franz Kärtner, lead DESY scientist and founder of Cycle. “This optical fibre allows them to exchange highly stable light signals and thus work in precise synchronicity.”

One hurdle remains, though. The glass fibre reacts to its environment – to vibrations and temperature fluctuations. If temperatures are significantly lower at night than during the day, the fibre can contract by up to 20 centimetres. That also changes the transit time of the synchronisation signal – and the precision of the synchronicity. To compensate for such fluctuations, Kärtner’s team has come up with a clever device. They bounce highly stable laser pulses back and forth inside a resonator – a metre-long path between mirrors. This creates an ultraprecise laser metronome.

Space communication

The crucial point is that its signals can be precisely correlated with the pulses bouncing back and forth in the kilometre-long glass fibre between Bahrenfeld and Schenefeld. If a change in temperature alters the length of the glass fibre and thus the transit time of the pulses it carries, this can be detected with an accuracy of less than a femtosecond by comparison with the laser metronome. “We can then react by adjusting a mechanical actuator to lengthen or shorten the flight path,” explains Kärtner, who is also a professor at Universität Hamburg. “This compensates for the fluctuations, so that the lasers are once again precisely synchronised.” At the European XFEL, this was implemented by the DESY Beam Controls group.

In the meantime, Kärtner’s company offers techniques like this for other scientific applications too, such as the radar stations of ESTRACK, an antenna network operated by the European Space Agency (ESA). These radar systems communicate with space probes such as “Gaia” or “BepiColombo”, which are travelling in the depths of our solar system. Cycle’s laser technology ensures that the control centres are reliably synchronised with the remote radar antennas.

Picture: Heiner Müller-Elsner, Agentur Focus

"IMPORTANT **INTERFACE** WITH THE ACADEMIC WORLD"

The physicist Max Kahmann is head of Advanced Development Laser Application at the Baden-Württemberg-based high-tech company TRUMPF. This leading global laser manufacturer has been collaborating with DESY for quite some time. The cooperation is now to be stepped up.

femto: How did this research collaboration come about?

Kahmann: One of the seeds for it was our Munich subsidiary. The purpose of this spin-off is to specifically serve the scientific market, including research centres such as DESY. The lasers manufactured by this subsidiary contain new, innovative components that are very suitable for use in a laboratory setting. This gives us valuable insights into how such components can best be used and how we can develop them further to be employed in industry. The collaboration also serves as an interface with academic research. That is often several steps ahead of current developments, so we have potential new technologies on our radar early on.

femto: Can you give us an example? In which area of laser technology have you specifically benefited from cooperating with basic research?

Kahmann: Researchers have been able to generate ultrashort laser pulses for decades. A good ten years ago, TRUMPF was one of the first manufacturers to transfer the technology to an industrial setting. This has advantages when processing materials. Essentially, these are: an insensitivity with regard to material properties, so that materials that are normally transparent to light can still be processed, for example. The technology can also be used to ablate, or remove, material without heating it. This helps to avoid a build-up of molten material, for instance.

femto: What trends are you looking at right now? Which technologies could make the leap from the lab to the business world in the future?

Kahmann: The generation of so-called secondary light, for example. The idea is to use laser pulses to generate other types of radiation. DESY is working on using high-intensity laser pulses to create a plasma, that is ionised matter. In this plasma, the laser could accelerate electrons on very short distances, for example, and we believe there is huge potential here, for example in medicine. That is why we are participating in HI-ACTS, a new innovation platform coordinated by DESY, which brings together industry and research. We hope to jointly develop components that are still some way from being ready for application so they can be used in practical settings.

femto: DESY has powerful X-ray sources, such as PETRA III, with which materials can be analysed in great detail. To what extent are such research opportunities of interest to TRUMPF?

Kahmann: We have regular projects going on. At DESY, for example, we can investigate certain details of 3D laser printing, a promising technology for manufacturing metal components. And, together with the Fraunhofer Institute for Laser Technology (ILT), TRUMPF has been investigating how a laser can weld copper onto a ceramic–metal substrate. This is an important step in the construction of electric cars. The X-rays from PETRA III have allowed us to look deeper than ever before into the internal workings of laser processing. This has shown us how the welding process can be specifically optimised by modifying the laser parameters.

Picture: Michael Frick

TRUMPF and the Fraunhofer ILT have been using DESY’s X-ray light source PETRA III to investigate the laser welding of copper joints in the high-performance electronics of electric cars.

X-RAY VIEW OF LASER WELDING

Every electric car contains high-performance electronics, a key technology that ensures the best possible performance of the battery and the motor. An interdisciplinary collaboration between research and industry has now been studying the laser welding processes used in the production of electric cars at DESY’s X-ray light source PETRA III. They found that using a laser with a green wavelength leads to far less wastage than other laser welding processes. Car makers can thus save raw materials and contribute to more sustainable manufacturing.

Electromobility poses major challenges for laser technology. Copper is the most important material in manufacturing some of the basic components needed for e-mobility. This non-ferrous metal absorbs only about 5 percent of the laser radiation in the near infrared range (NIR) and is a very good conductor of heat. These two properties lead to considerable problems when it comes to welding. That is why such processes are coming under close scrutiny.

The high-tech laser company TRUMPF from Baden-Württemberg and the Fraunhofer Institute for Laser Technology (ILT) have been using the measuring station of the Helmholtz Centre Hereon at PETRA III to take high-speed pictures at several thousand to ten thousand frames per second. “We wanted to know exactly what makes the difference when welding copper,” says Marc Hummel, a scientist at the Fraunhofer ILT. “A stable welding process is important, because the manufacturers of electric vehicles have to weld several billion joints while maintaining top quality.”

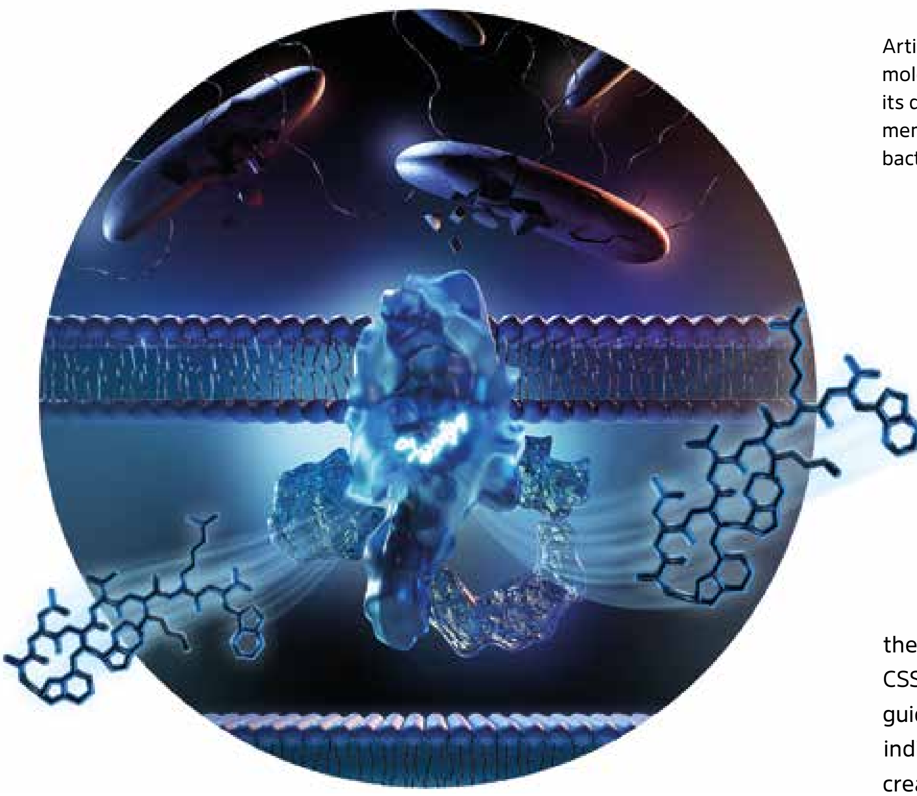
The team investigated laser welding using two different laser systems: an NIR laser and a green laser. “For us, this is a great opportunity to study the welding of industrial parts. How do spatters and pores arise, for example? And how does the heat from the welding process affect sensitive components, such as electronic parts?” says Mauritz Möller, Industry Manager Automotive at TRUMPF.

Copper absorbs the green wavelength much better than the infrared. The material therefore reaches its melting point faster, which means that the welding process also starts earlier and less laser power is required. “More stable welding processes mean less wastage and therefore more sustainability, which is a big issue in electromobility,” explains Möller.

Picture: TRUMPF

SPECTRUM

News from research



Artist's impression of the molecule darobactin 22, its docking site in the cell membrane and the target bacteria

Scientists engineer new potent antibiotic

In the constant arms race with bacteria, scientists at the Centre for Structural Systems Biology (CSSB), together with colleagues from the Helmholtz Institute for Pharmaceutical Research Saarland (HIPS), have engineered a new, promising antibiotic in the laboratory. The molecule called darobactin 22 shows the potential to fight even difficult-to-treat infections. So far, it has only been tested in the laboratory.

Darobactin is a naturally produced antibiotic derived from the bacterium *Photorhabdus khanii*, which lives in symbiosis with threadworms. In Gram-negative bacteria, darobactin binds to the outer membrane protein BamA, which is essential for the bacteria's function. After the darobactin binds to BamA, the bacterium is no longer able to survive. To understand why darobactin is so potent, the researchers investigated this binding mechanism in more detail.

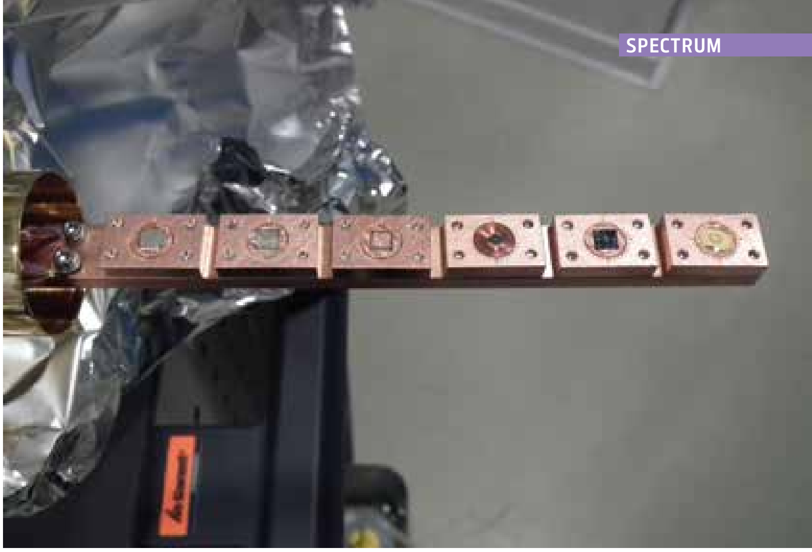
"Unveiling the detailed molecular structure of the darobactin–BamA binding site helped us understand why the bond is so strong," says Biao Yuan, who analysed the complex with the cryo-electron microscopes at CSSB. "This allowed us to develop a guided approach in order to modify individual parts of darobactin and create an even stronger version."

This structural information was then used to specifically produce 20 new biosynthetic derivatives of darobactin in order to optimise binding as much as possible. Of these, darobactin 22 (D22) turned out to be the strongest. "D22 surpasses the antibacterial activity of all identified native darobactins," explains Carsten Seyfert from HIPS, who synthesised the variants.

"We have demonstrated that modifying the binding sites of antibiotics can result in stronger, more potent antibiotic activity," states DESY group leader Thomas Marlovits, who is also a professor at the University Medical Center Hamburg-Eppendorf (UKE). Future studies will look at improving D22's binding strength even further and at developing efficient ways to mass produce D22 synthetically for pharmaceutical use.

Angewandte Chemie, 2023; DOI: 10.1002/anie.202214094

Surprising behaviour of quantum material



The samples with the tiny vanadium dioxide squares are mounted on this holder.

Picture: DESY, Jan Schunck

A research team at DESY's X-ray light source PETRA III has uncovered a surprising behaviour of the quantum material vanadium dioxide (VO_2). It is a promising candidate for future IT applications, for example in customised functional devices. This is because it can transform from an insulator to a conductive metal at a temperature of around 70 degrees Celsius, which is comparatively suitable for everyday use. For example, vanadium dioxide has been applied in novel transistors to mimic the behaviour of the human brain. The material could possibly also serve as a transparent window cover that turns into a dark film to block sunlight at elevated temperatures.

The team led by DESY researcher Jan Schunck now used X-ray microspectroscopy to examine the structures of thin vanadium dioxide layers in detail. They found that the transition temperature in the 30 by 30 micrometre squares studied was not the same everywhere: The edges became conductive at a temperature 1.2 degrees lower than the centres.

"If one wants to use these materials in micro-electronic devices in only tiny amounts, different behaviour at different bulk sizes and geometries has to be expected," says Schunck. "We therefore need careful studies of such size effects."

Scientific Reports, DOI: 10.1038/s41598-022-13872-0

Tempering glasses without heating

For thousands of years, people have been experimenting with different properties of glass. These usually depend on how the glass is melted and then cooled again. A team led by scientists at the University of Padova in Italy have used DESY's X-ray light source PETRA III to achieve an effect similar to this so-called annealing of glass by means of X-rays. To do this, the researchers exposed thin slices of silicon dioxide or silica (SiO_2), the "raw material" of glass, to X-rays and tracked the movements of the atoms within the sample.

As the study shows, the effect of X-rays is fundamentally different from simply heating and melting the glass: Instead of the atoms flowing around one another at a consistently faster rate, in the irradiated sample some of the atoms tended to make comparably giant leaps within the material. The X-ray process occurred without the glass changing temperature.

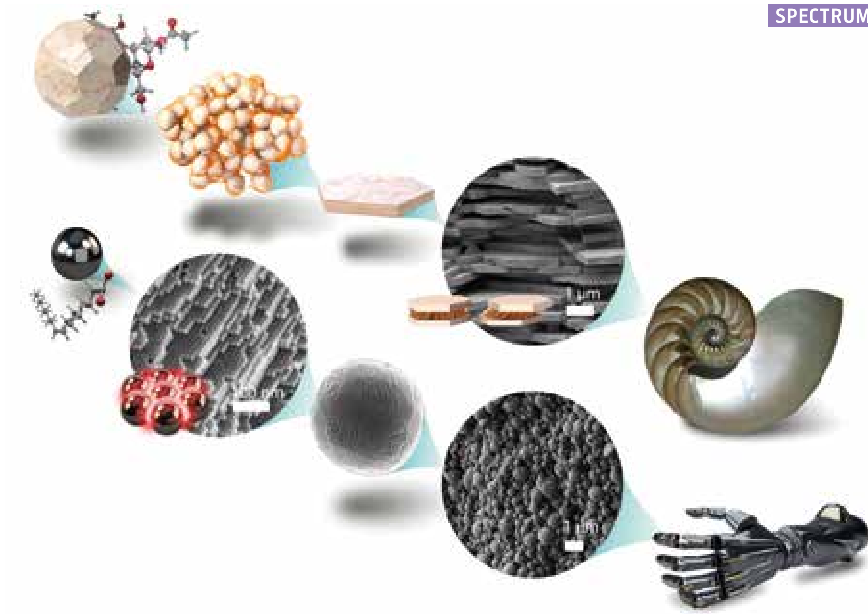
Understanding the effect of X-rays on glass could enable many new and heretofore unknown properties of glasses. "Depending on the application, glasses might need to be cooled or quenched quickly," explains DESY scientist Francesco Dallari, one of the main authors of the study. "Using X-rays would be like superfast quenching." Exactly what properties this could create still needs to be investigated.

Proceedings of the National Academy of Sciences, DOI: 10.1073/pnas.2213182120

Picture: University of Padova

Thin slices of silica glass were used as samples for the experiment. The team used X-rays to melt the glass without heating it and was able to observe the unusual stochastic acceleration of the atoms inside the glass.

North German Science Prize for materials research



In the collaborative project CIMMS, researchers are investigating how principles from nature can be used to produce materials with integrated functionalities.

Picture: CIMMS

The collaborative materials research project CIMMS has been awarded the North German Science Prize. The Centre for Integrated Multiscale Materials Systems (CIMMS) connects scientists from the Hamburg University of Technology, Universität Hamburg, Helmholtz Centre Hereon and DESY in a research approach that is unique in Germany.

The aim of CIMMS is to produce a novel material base using 3D printing in order to develop more cost-effective and durable products with novel functions. The project is funded by the Hamburg Science Authority (BWFGB) with a total of four million euros from 2020 to 2024.

The North German Science Prize is awarded every two years by the North German Conference of Science Ministers (NWMK). CIMMS received the first prize of 150 000 euros. The second prize of 100 000 euros was awarded to the Homeo-Hirn collaborative project at the Technical University of Braunschweig.

"Both prize-winning projects impressively demonstrate how much scientific work can benefit when the brightest minds join forces – and that, across the boundaries of departments and institutions," Hamburg's Science Senator Katharina Fegebank said at the award ceremony. "It is precisely these innovative cooperation models that now need to be further strengthened and expanded in the North German region."

Savings potential in plastic film production

Film packagings for medication (blisters) are often made of PET plastic.

Picture: Pixabay

Consider the humble plastic food wrapper. It may look like a simple clear film that wraps a loaf of bread or fruit gums, but these films are not as simple as it seems. They are usually composed of several layers, and each individual layer must be chemically treated so that it adheres well to the next. Using DESY's free-electron laser FLASH, a team of scientists from DESY and the Leibniz Institute for Plasma Science and Technology in Greifswald has examined the surfaces of individual layers made of PET (polyethylene terephthalate) in detail.

Manufacturers usually treat the individual thin plastic layers with electrical plasma discharges to change the chemical composition of the plastic surface in such a way that bonding or printing becomes possible. The team led by DESY researcher Elke Plönjes compared the surface structures of films treated with two different plasma processes. One sample had undergone the process most widely used in the industry, known as corona treatment; the other a newly developed process that treats the films with plasma almost a hundred times more intense, but for a shorter time.

In combination with further laboratory tests in Greifswald, the analysis showed that, with the same energy input, adjusting the treatment process leads to even more of the desired surface changes, which can improve the adhesive properties of the film layer. This in turn opens up the potential to save on additional chemical treatments of the film surface, which are often still necessary today. "Taken together, the result is the opportunity to produce better films with less effort," explains Plönjes. "This can be of great interest to industry."

Polymers, DOI: 10.3390/polym14132528

The FASER detector is located deep underground in a side tunnel at the LHC near the ATLAS detector.

Neutrinos from particle collider detected for the first time

An international research team at the FASER experiment at the Large Hadron Collider (LHC) in Geneva has for the first time detected subatomic particles called neutrinos created by a particle collider, i.e. an accelerator in which particles are brought to collision. Neutrinos are the most abundant particles in the cosmos and key participants in the process that makes stars burn. The neutrinos now registered by FASER are the most energetic ever produced in a laboratory.

"Neutrinos have been known for several decades and were very important for establishing the Standard Model of particle physics," says DESY theorist Felix Kling, one of the four scientists who proposed the FASER experiment in 2018, and who also conducted the simulations of how many neutrinos could be expected from the experiment. "But previously, no neutrino produced at a collider had ever been detected by an experiment, and even today the larger experiments at the LHC are unable to detect neutrinos directly."

The experiment FASER (Forward Search Experiment) is a novel particle detector designed and built by an international group of physicists. Compared to other detectors at CERN such as ATLAS or CMS, which are several storeys tall and weigh thousands of tonnes, FASER weighs only about one tonne and fits neatly into a small side tunnel at the LHC. It took only a few years to design and construct it, using spare parts from other experiments.

Together with astroparticle experiments such as IceCube, which are measuring neutrinos of a wide energy range showering on Earth from deep space, FASER will help us to better understand the role of these mysterious particles.

Picture: CERN

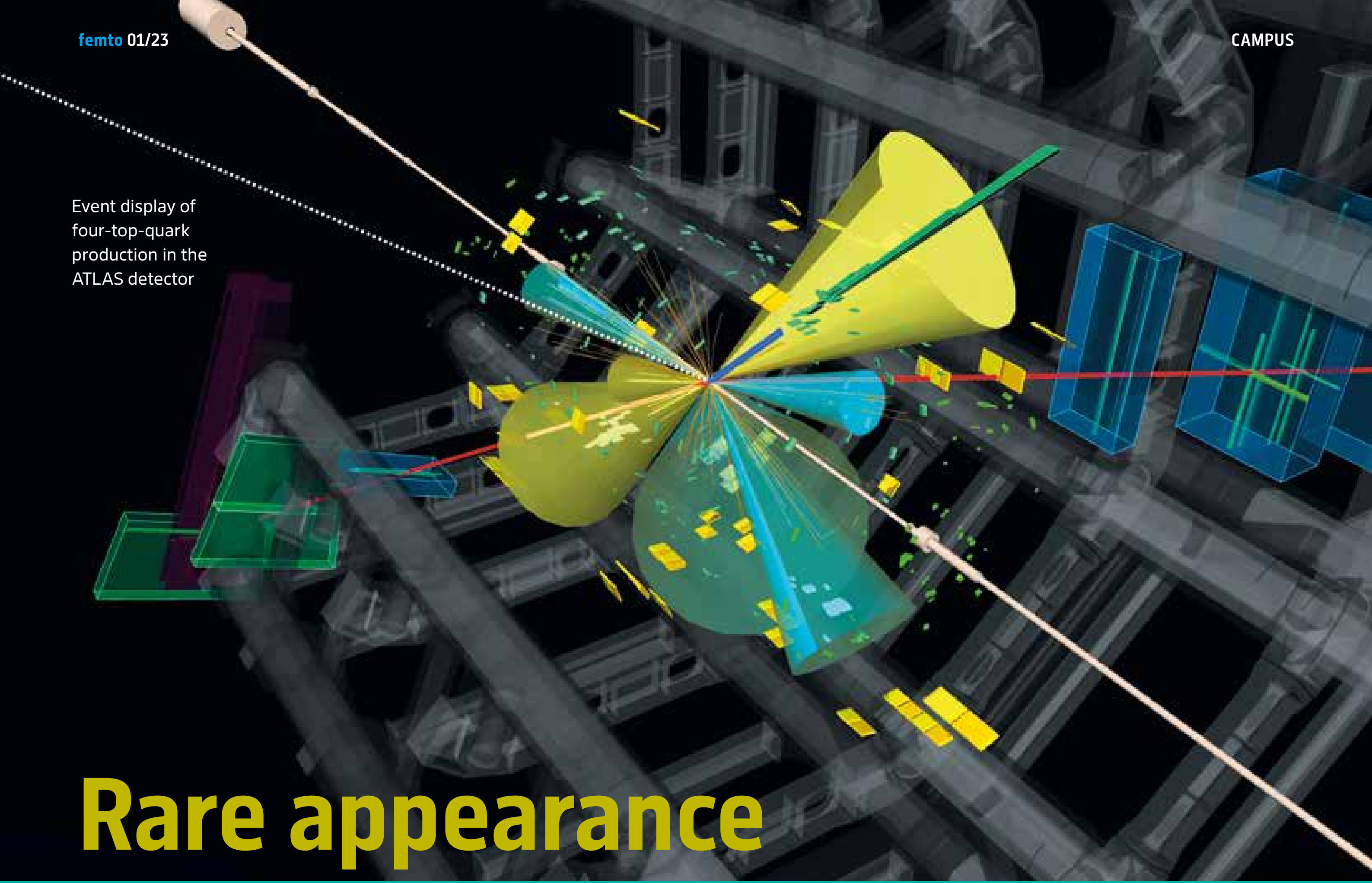
femtomenal

1 000 000 000 000 particles of light (photons)

are found on average in each flash of the European XFEL X-ray laser. One trillion, that's a difficult number to imagine. By way of illustration, let's compare it with sand: A grain of sand weighs about 0.0002 grams. One trillion grains of sand thus amount to 200 tonnes of sand – about 15 truckloads or a small private beach, as Harald Sinn, head of the Instrumentation Department at European XFEL, calculates. The European XFEL can generate 27 000 such flashes per second. This makes it the brightest X-ray laser in the world.

By the way: At the same power, radiation of lower energies, such as visible light, has even many more photons. However, the high-energy X-ray photons are much more difficult to produce.

Picture: iStock, draganab



Event display of four-top-quark production in the ATLAS detector

Rare appearance of four tops at the LHC

Evidence of a novel way of producing top quarks

The observation of a very rare process at the world's largest particle accelerator, the LHC, is making the particle physics community take notice: The big detectors ATLAS and CMS at the Large Hadron Collider have for the first time provided tangible evidence for the production of four so-called top quarks in one go. The rare appearance of the "four tops" at the CERN research centre near Geneva offers the chance to learn more not only about the top quark itself, but possibly also about the Higgs boson and perhaps even about new physics beyond the known Standard Model of particle physics.

Quarks are, among other things, the basic building blocks of atomic nuclei. The top quark is the heaviest of all known elementary particles; it alone weighs about as much as a whole gold atom. It is not stable, though, and decays in unimaginably short fractions of a second. For this reason, it can only be observed if it is specifically produced. And this requires a lot of energy because of the particle's high mass. Therefore, top quarks are only generated in the most powerful particle accelerators and by high-energy cosmic rays, where, however, they are hardly observable because of their short lifetime.

70 000 times rarer

The LHC, which fires hydrogen atomic nuclei (protons) at each other with high energy, produces top quarks about once per 100 million of these collisions. They almost always occur as a pair, a top quark and its antiparticle, the antitop quark. About 70 000 times more rarely than the top quark pairs, particle physicists expect the simultaneous production of four top quarks, in the form of two pairs. Up to now, there had been indications that this process actually takes place, but reliable proof was still lacking. The two detectors have now provided this evidence.

"The search for events with four top quarks is a challenge, but it is worth it," says Freya Blekman, lead scientist at DESY and a professor at Universität Hamburg. Blekman has been studying the production of four top quarks since the LHC started up

Picture: CERN

in 2010. Each top quark decays into a W boson and a bottom quark, and each quark produces a distinctive jet of particles called a quark jet. The W boson, in turn, can produce either a charged lepton and a neutrino or two quark jets. Leptons are a class of particle that includes the electron. For the researchers, this means that a multitude of measurements can point to the decay of four top quarks – events with zero to four charged leptons and with up to twelve jets. So finding four-top-quark events is very complicated.

Methods of machine learning

That is why all ATLAS and CMS analyses that look for four top quarks use artificial intelligence algorithms to distinguish the four-top-quark events from the uninteresting "background" of other top quark events. Blekman and her team worked on the most challenging final states with zero, one or two leptons. "We managed to reach evidence of 3.9 standard deviations, or a chance of one in 10 000 that this is a statistical fluctuation, in one of the most technically demanding signatures studied at the LHC. This would not have been possible were it not for the machine learning experts who worked on making the analysis the best it could be."

Because of its high mass, the top quark is the elementary particle with the strongest relationship to the Higgs boson, the particle that gives all the others their mass. As Blekman explains, deviations of the four-top-quark abundance of production from the theoretical prediction could indicate new, undiscovered particles or a slightly different interaction between the top quark and the Higgs boson. This could also provide clues to physical forces and particles beyond the Standard Model of particle physics.

"The search for events with four top quarks is a challenge, but it is worth it"

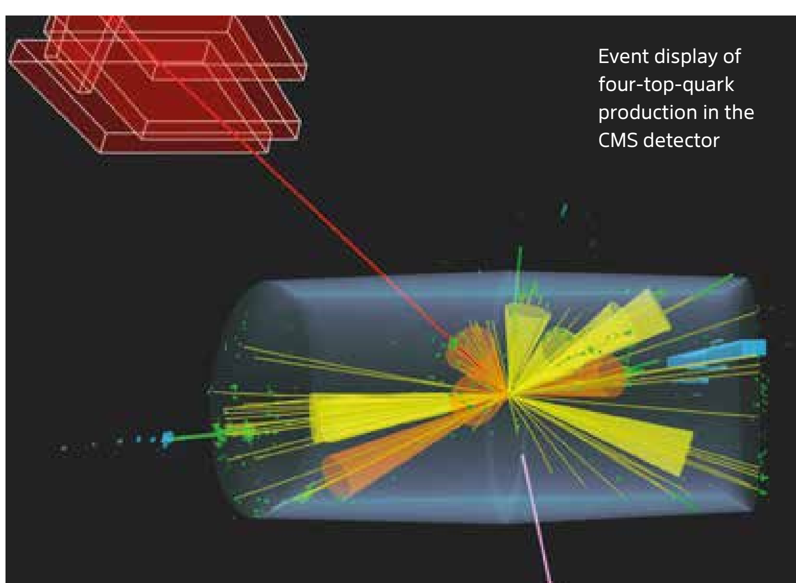
Freya Blekman, DESY and Universität Hamburg

Search for new physics

The Standard Model is an extremely successful theory framework that describes the world we are familiar with very well. Today, however, we know that the familiar particles and forces only make up about five percent of the universe. Particle physicists are therefore intensively searching for a gateway to the remaining 95 percent, which is divided into an enigmatic dark matter and a mysterious dark energy.

Interestingly, the number of collisions consistent with the production of four top quarks exceeds the prediction of the Standard Model in the measurements of both ATLAS and CMS. However, within the present large measurement uncertainties, the values are still fully consistent with the model. The accuracy of the analysis will improve significantly as more data is added. Therefore, the production of four top quarks remains one of the exciting topics to be studied during the LHC's third measurement period, which started in 2022, and especially in the so-called high-luminosity phase of the LHC, which will begin in the late 2020s and in which the particle accelerator is expected to deliver around 20 times as much data as it does today.

arXiv: https://arxiv.org/abs/2303.03864



Event display of four-top-quark production in the CMS detector

Pictures: CERN, M. Lithmaath

Tiny tunnelers

Silver nanoparticles carve tunnel systems in silicon

Silver nanoparticles can drill nanochannels into macroporous silicon and thus endow silicon with a hierarchical pore network. The visualisation shows the real porous material combined with an illustration of chemical etching and thus pore formation along the paths of the silver particles under the development of hydrogen bubbles in aqueous solution.

Visualisation: DESY/TUHH, Huber group

In road networks, the method is common practice: While large motorways provide fast connections for long-distance traffic, small roads and lanes can be used to reach even the remotest corners of the country – albeit much more slowly. Researchers call this a hierarchical network. Nature often does the same thing, for example in the lungs or in plants: Bronchial tubes or networks of large capillaries in leaves allow air or water to be transported rapidly across tissues, and then the channels branch out and become narrower until they reach the tiny alveoli or pores, where important local functions take place, such as supplying oxygen to the blood or carrying out photosynthesis. These highly efficient structures are known as hierarchical porous systems, and – divided into large and small units – they can take care of extensive distribution or local functions.

A Hamburg-based research team has developed a method for producing a network of large to very fine pores in silicon and glass. At DESY's X-ray light source PETRA III, scientists led by Stella Gries and Patrick Huber from the Hamburg University of Technology and DESY were able to analyse the porosity of silicon using X-ray tomography. The innovative method for producing micro- and nanochannels is easy to control, extremely variable and even works for large volumes of materials. This makes it ideal for use in industrial applications.

Fascinating propulsion

The research team led by Gries coated silicon wafers, which already had straight channels one micrometre (thousandth of a millimetre) in diameter passing through them, with silver nanoparticles. The 20 to 60 nanometre (millionth of a millimetre) particles were deposited on the surface of the wafer. The scientists then exposed the wafers to a corrosive solution of hydrofluoric acid and hydrogen peroxide, triggering a fascinating process: The nanoparticles bore into the silicon, dissolving the silicon crystal at the surfaces where the silver particles were in contact with the silicon.

"The etching process systematically perforates the entire crystal with nanopores"

Stella Gries, TU Hamburg and DESY

In this way, the silver particles burrow further and further into the solid, leaving behind a fine network of tunnels along the way. The kinetic energy for the directed propulsion of the particles comes from a chemical decomposition reaction, i.e. the conversion of hydrogen peroxide into water and hydrogen and the "eating up" of the silicon. The silver particles behave like small, autonomous agents, catalysing the reaction and thus enabling their own propulsion through the silicon crystal. The resulting system of tunnels self-organises to create the desired three-dimensional hierarchical porous structure.

The research team used a number of different methods to investigate the porosity of the silicon. With the help of X-ray tomographic images taken at PETRA III, they were able to resolve the inner structure on a nanometre scale. "We see that the etching process systematically perforates the entire crystal, creating nanopores that are smaller than 100 nanometres," says Gries, who developed this method in Patrick Huber's group in the course of her master's thesis and is now conducting further research as part of her doctorate.

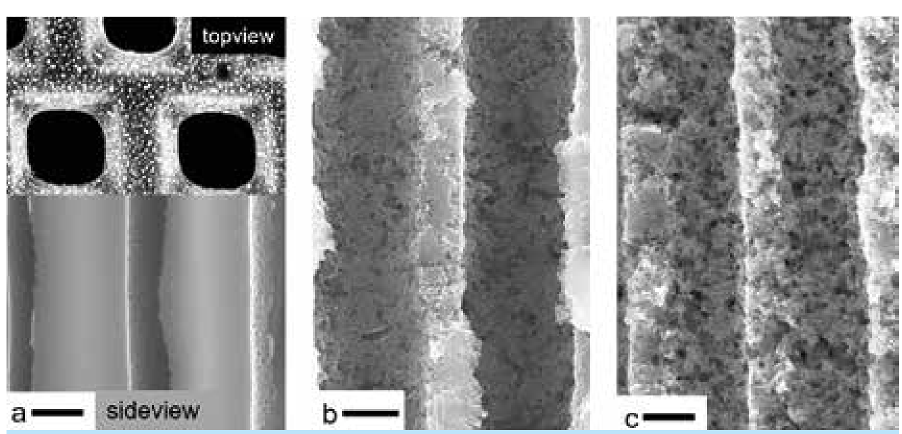
Nanometre precision

"By adjusting the size of the nanoparticles and the duration of the procedure, we can precisely control how deep the hierarchical porous system extends," adds co-author Manuel Brinker, a member of the group. Longer exposures produce pores that penetrate to the parallel main channels in the silicon wafer, connecting them with each other. For the time being, the exact mechanisms that lead to the movement of the particles and thus to the formation of the network of channels are only partially understood. Sometimes, for example, the particles travel along spiral paths, leading to spiral-shaped nanochannels in the silicon, and sometimes they change direction abruptly, suggesting that the particles are rotating. The network of pores produced has a sponge-like structure and thus no preferred orientation, unlike the large main channels. "We suspect that the geometric shape of the silver nanoparticles has a strong influence on the way the particles eat into the silicon," says Gries.

In a further step, the scientists heated the perforated silicon to over 800 degrees Celsius in an atmosphere containing oxygen. The walls between the tunnels are so thin that the silicon was completely oxidised to form silicon dioxide, colloquially known as glass. To the scientists' great surprise, the structure of channels was not destroyed despite the considerable rearrangement of the atoms and the expansion of the walls when the oxygen was incorporated.

Switchable glass

This means that the open-pored structure allows the wafers to be transformed into hierarchical porous glass. While this material originally has a milky appearance due to the way its pores reflect white light, the team was able to make it transparent by infiltrating ››



Electron micrograph of the one micrometre macropores before etching and after 20 and 45 minutes of etching

Pictures: DESY/TUHH, Huber group

it with water. The amount of light absorbed by the glass can thus be very easily controlled by moistening and drying the material, an effect that could be used, for example, for simple functions in windows, which could be switched by the humidity in the air. Such smart glasses could be switched comparatively quickly, because wetting and drying can take place rapidly throughout the entire volume thanks to the multiscale transportation routes.

Overall, the scientists anticipate a wide range of potential applications, including in energy technology. “Silicon still has the highest potential to serve as an electrode material for lithium–ion batteries,” says Huber. “Our new etching technique may form the basis for a new generation of battery cells with a high charge density and a large number of charging cycles, if it turns out that not only vitrification – that is the incorporation of oxygen – but also the incorporation of lithium preserves the internal structure thanks to the hierarchical porosity of the silicon crystals. In non-porous silicon, this lithiation usually destroys the material.”

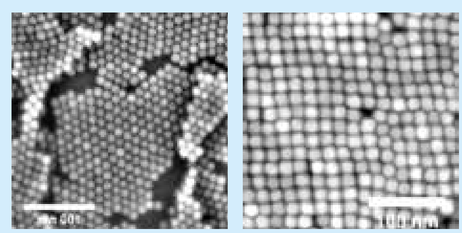
“Our new etching technique may form the basis for a new generation of battery cells”

Patrick Huber, DESY and TU Hamburg

The procedure, for which the researchers have applied for a patent, was developed within the framework of the Centre for Integrated Multiscale Materials Systems (CIMMS) and the Collaborative Research Centre “SFB 986: Tailor-Made Multiscale Materials Systems”, which is based at the Hamburg University of Technology. In the next step, the researchers want to explore how the manufacturing parameters influence the porosity and what exactly drives the silver particles as they perforate the material. The lithiation of the hierarchically porous silicon will also be investigated with cooperation partners.

Small, DOI: 10.1002/smll202206842

SOLVENT CONTROLS STRUCTURE OF NANOCOATINGS



The solvent controls the structure and thus the properties of the coating: on the left a hexagonal arrangement of nanocubes, on the right a cubic one.

The choice of solvent can control the specific structure of nanoparticle coatings, as has been demonstrated in a study headed by the DESY NanoLab. The researchers investigated how nanocubes of magnetite (Fe_3O_4) arrange themselves during so-called spin coating. This process is used in the semiconductor industry, among other places, and allows very uniform layers to be applied to a substrate by spraying the coating liquid onto a rotating substrate.

In this technique, nanoparticles have to be suspended in a solvent to be sprayed, which then evaporates during the coating process. The analysis using a scanning electron microscope shows that different structures are left behind, depending on the solvent used. **“With the solvent toluene, for example, the nanocubes arrange themselves in a hexagonal pattern, whereas chloroform leads to a cubic arrangement,”** explains NanoLab director Andreas Stierle. This structure has direct consequences for the properties of the coating. For example, the more densely packed hexagonal structure is generally harder than the cubic lattice.

The nanoparticles are usually surrounded by a film of oleic acid. This standard treatment ensures that the particles bond better. Chloroform interacts more strongly with oleic acid, meaning that the oleic acid molecules spread out more and better mimic the shape of the nanoparticles. This creates a cubic layer. With toluene, the interaction is weaker, so the nanoparticles adopt a more spherical appearance in their oleic acid mantle and form a hexagonal layer.

The different structures are reminiscent of those formed by atoms in a crystal lattice, except that the nanoparticles are themselves tiny crystals. “This method of construction is typical of the way in which nature produces hard coatings, such as mother-of-pearl or dental enamel,” says Gerold Schneider from the Hamburg University of Technology. “Our method now means that we are able to create coatings with specific desired properties.”

Nanoscale, DOI: 10.1039/D2NR03043H

Pictures: DESY, Arno Jeromin

Salty **ice moons**

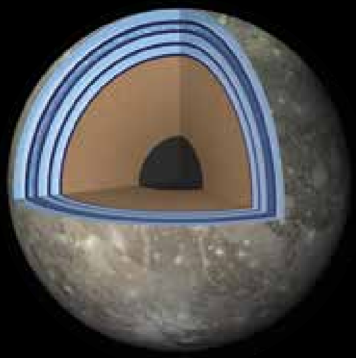
Newly discovered salt hydrate could point the way to search for extraterrestrial life

Jupiter's moon Ganymede is the largest moon in our solar system and even larger than the planet Mercury.

Pictures: NASA/JPL-Caltech/SwRI/MSSS/Kevin M. Gill; NASA/JPL-Caltech

Is there life beyond Earth? The icy moons of the giant planets Jupiter and Saturn are considered promising locations in our solar system for the search for extraterrestrial life forms. This is because some of them have large oceans under their icy shells, as measurements by space probes have shown. The satellites of the gas giants in the outer solar system are therefore of particular interest for research. An international team of scientists led by Baptiste Journaux from the University of Washington has now recreated the conditions on the icy moons in the laboratory and discovered two new forms of salty ice. The discovery could also benefit the search for extraterrestrial life.

Icy moons like Europa and Ganymede from Jupiter or Enceladus and Titan from Saturn are ››



Ganymede may even have several ocean layers inside it, separated by layers of ice.

thought to have formed by collecting gas and ice particles from their home planets. “These are the only planetary bodies other than Earth where liquid water is stable at geological time scales, which is crucial for the apparition

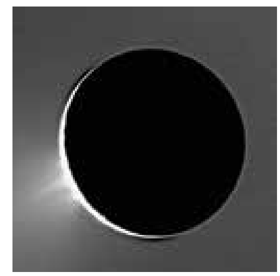
> *“This will permit us to identify where the best places on the surface of the moons are to look for signs of life”*
>
> ***Baptiste Journaux, University of Washington***

and development of life,” explains Journaux. “They are, in my opinion, the best places in our solar system to discover extraterrestrial life, so we need to study their exotic oceans and interiors to better understand how they formed and evolved, and how they can retain liquid water in cold regions of the solar system, so far away from the sun.”

Natural antifreeze

Presumably, the water in these oceans contains table salt (sodium chloride, NaCl), which acts as a natural antifreeze, lowering the freezing point of water and allowing it to remain liquid at temperatures that would normally freeze pure water. However, planetary scientists had, until now, not been able to clearly identify the salt at the surface, despite using the space missions’ surface reflectance infrared spectroscopy. None of the compounds known would match the infrared spectra from the surface of the icy moons.

Journaux explains the challenges: “Salt and water are very well known in common conditions. However, beyond that, we are totally in the dark. Now we have these planetary objects, which probably have compounds that are very familiar to us, but in very exotic conditions. We have had to redo all the fundamental mineralogical science done in the 19th and early 20th century, but at high pressure and low temperature.”



On Saturn’s moon Enceladus, ice volcanoes have been discovered, which are probably fed by a subterranean ocean and create one of Saturn’s rings.

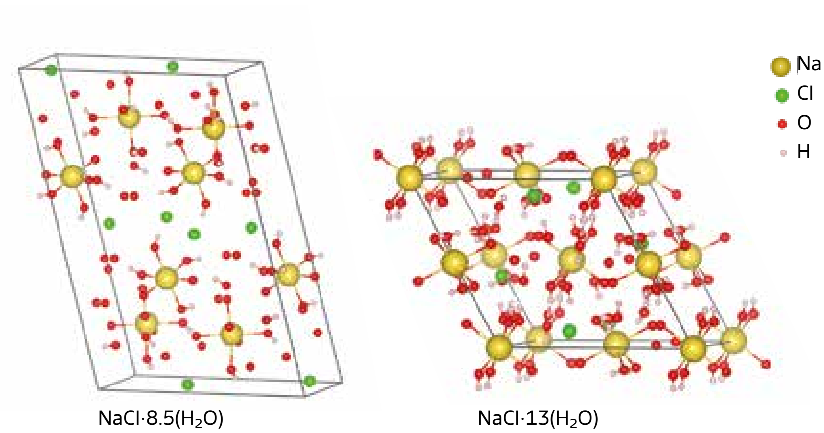
The temperature on the surface of Jupiter’s moon Europa is only a frosty -130 degrees Celsius. However, measurements by the space probe “Galileo” indicate that there is a 100-kilometre-deep ocean beneath a kilometre-thick ice sheet.

Inner structure

In these conditions, the water with the salts dissolved in it crystallises and forms so-called hydrates. At the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, and at DESY, the team studied these crystals using X-ray diffraction. This method allows the internal structure of crystallised materials to be determined by illuminating them with X-rays and observing how the radiation is diffracted by the sample.

“Our goal was to understand which compounds form in the high pressure and low temperature conditions of the icy moons,” says co-author Anna Pakhomova. “In our experiments, we used single-crystal X-ray diffraction to understand how the new hydrates are organised on

Pictures: NASA/JPL-Caltech/SETI Institute



Internal structure of the two newly discovered salt hydrates

the atomic scale. It is a superior and unique technique to get unambiguous information on a solid's crystal structure."

25 000 times atmospheric pressure

At the Extreme Conditions Beamline of DESY's X-ray light source PETRA III, the researchers recreated the conditions on the icy moons by compressing the samples of water and table salt in a so-called diamond anvil cell between two tiny diamonds to up to 25 000 times atmospheric pressure, while keeping them cooled in a cryostat, a kind

> *"Our goal was to understand which compounds form in the high pressure and low temperature conditions of the icy moons"*
>
> ***Anna Pakhomova, DESY and ESRF***

of scientific deep freezer. In these conditions, the samples crystallised, forming previously unknown forms of salt hydrates.

Until then, the scientific community had knowledge about the presence of just one salt hydrate – a compound that has very few water molecules trapped within its crystal structure. Its composition is a simple structure with one salt molecule for every two water molecules. The new experiments unveiled two new, different forms at different pressures and temperatures, both with a much higher amount of water in the structure. One has two salt molecules for every 17 water molecules; the other one salt molecule for every 13 water molecules. This observation would explain why the infrared signatures from the surface of Jupiter's moons are more "watery" than expected.

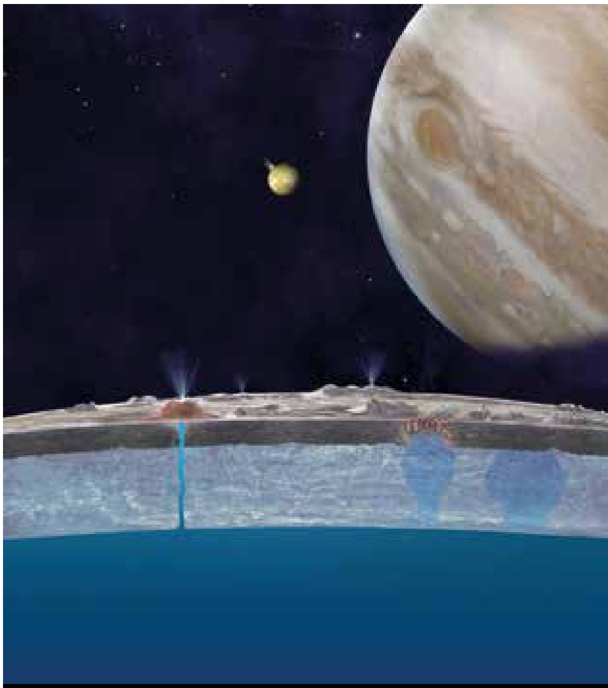
Stable at the moons' surface

"These new phases are fascinating because they demonstrate a new diversity of water–salt crystal structures at high pressure and low temperature that wasn't expected and remains to be explored for other compounds," says Journaux.

The team was also able to show that one of the new salt hydrate, NaCl·8.5(H_2O), is stable at the surface conditions of icy moons and should be the most common type of salt hydrate on icy worlds. "It has the structure that planetary scientists have been waiting for to explain the mysterious surface spectra of icy surfaces. This will permit us to identify where the best places on their surface are to explore and eventually land and dig to look for signs of life," explains Journaux.

Next, the scientists plan to study other types of salt relevant for icy ocean worlds and measure their spectral properties to make sure they can be detected in upcoming space missions, such as the European Space Agency's recently launched "JUpiter ICy moon Explorer"(JUICE) and the planned "Europa Clipper" of the US space agency NASA, both of which are scheduled to enter Jupiter orbit in the early 2030s.

Proceedings of the National Academy of Sciences, DOI: 10.1073/pnas.2217125120



Researchers assume that chloride salts bubble to the surface from the underground ocean on Jupiter's moon Europa.

Pictures: NASA/JPL-Caltech

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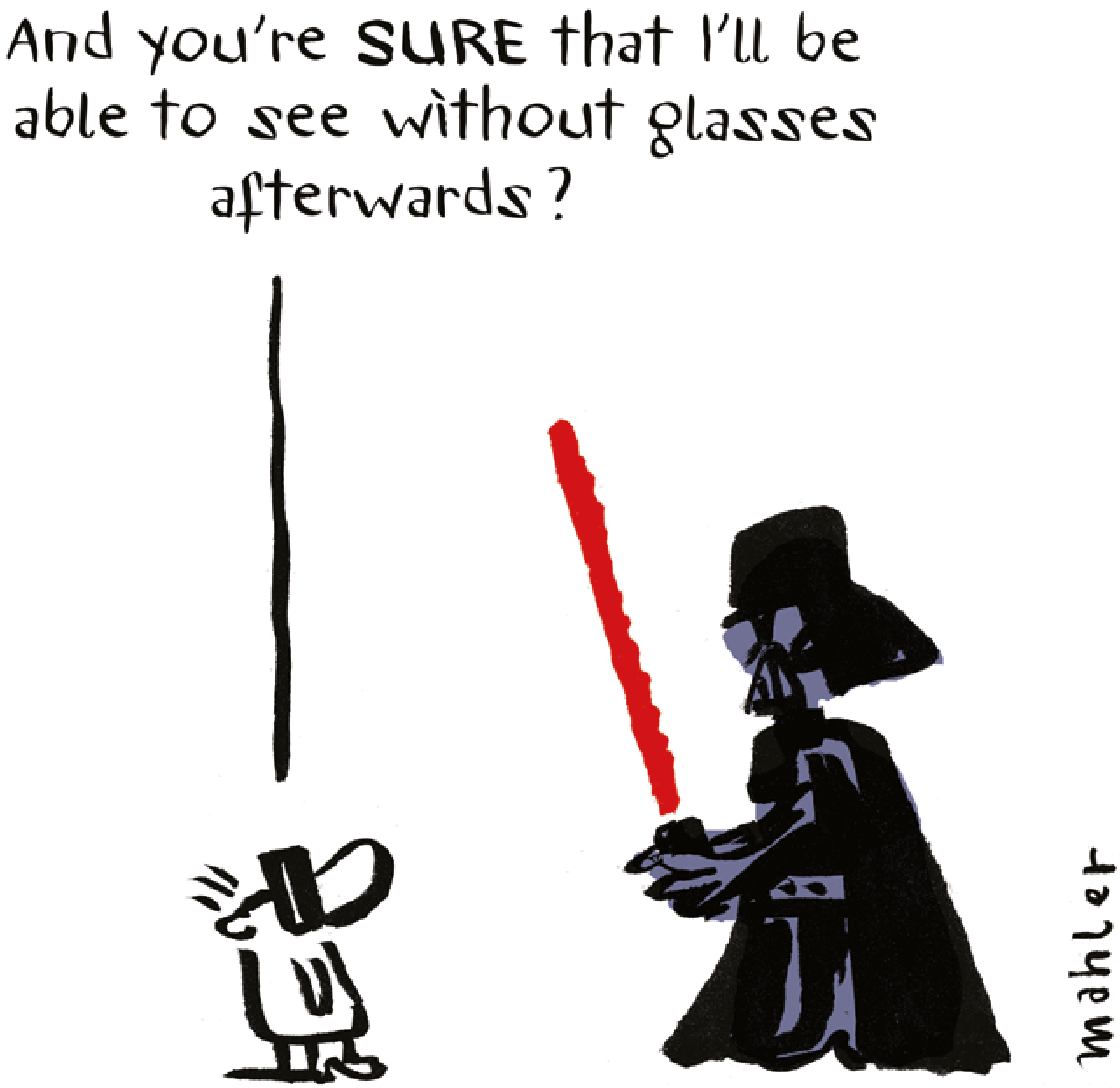

Cartoon: Nicolas Mahler

Imprint

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

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ISSN 2199-5192

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Art direction and production
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Image processing and printing
EHS, Hamburg

Copy deadline
May 2023

Picture credits
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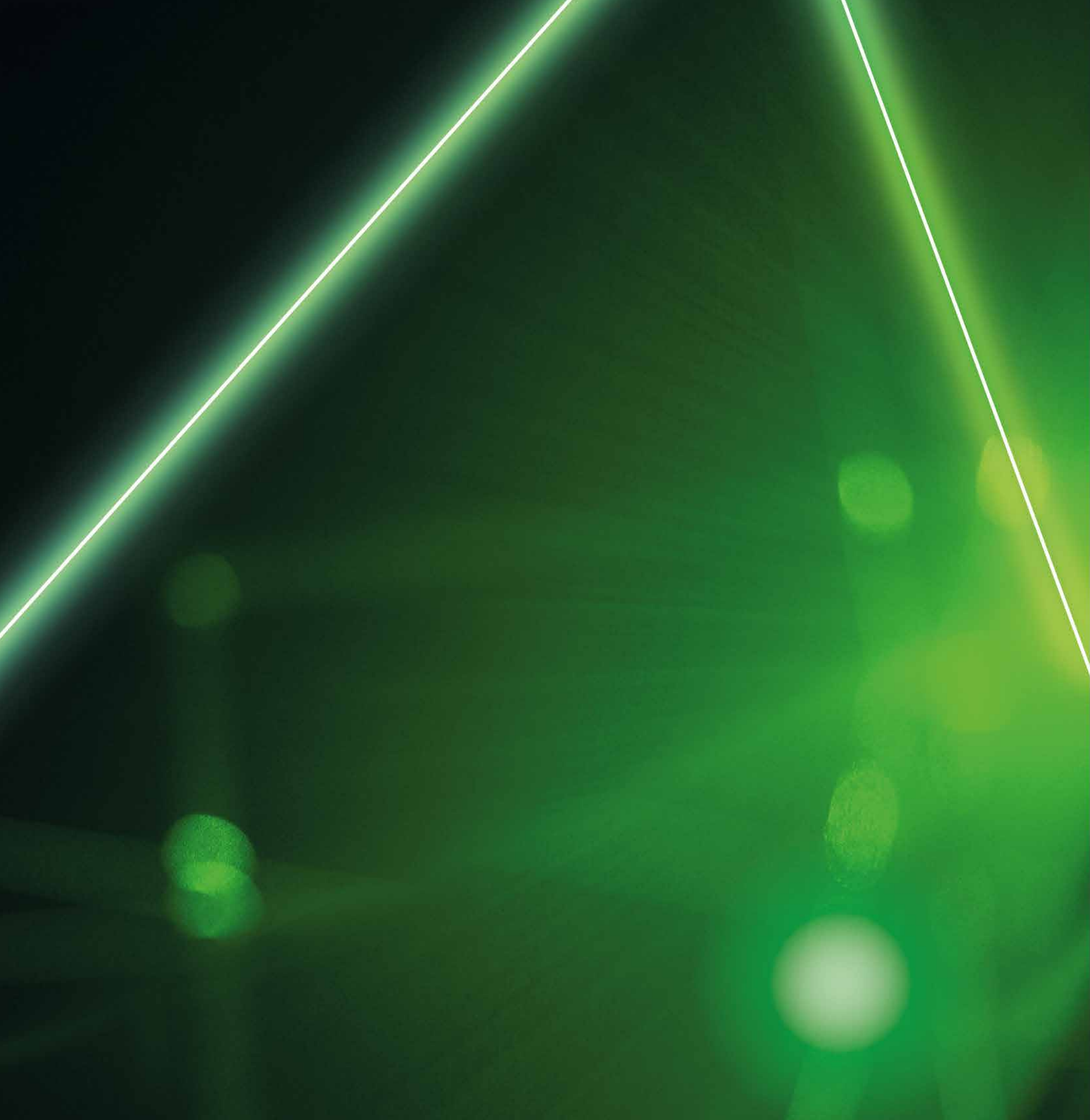

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