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The DESY research magazine – Issue 01/17

ZOOM

ULTRA *FAST PHYSICS*

When a wingbeat lasts forever

Artificial silk from whey protein

Five big questions in particle physics

Spectacles for X-ray lasers

Codling moth virus cocoon

The codling moth is a butterfly whose caterpillars infest apples, thereby damaging the harvest. The pest can be contained by means of a special virus used as a biological pesticide. This granulovirus infects and kills the caterpillars of the codling moth, and is then left stranded inside its decaying host. To protect itself against adverse environmental conditions, the virus wraps itself in a cocoon made of protein crystals, which an international research team recently analysed using the X-ray flashes of the LCLS free-electron laser at the SLAC research centre in the USA.

"These virus particles provided us with the smallest protein crystals ever used for X-ray structure analysis," explains Cornelius Gati from DESY. The occlusion body (the virus cocoon) has a volume of around 0.01 cubic micrometres, about one hundred times smaller than the smallest artificially grown protein crystals that have until now been analysed using crystallographic techniques. The picture shows the fine details of the building blocks that make up the viral cocoon down to a scale of 0.2 nanometres (millionths of a millimetre) – approaching atomic-scale resolution.

PNAS, 2017; DOI: 10.1073/pnas.1609243114

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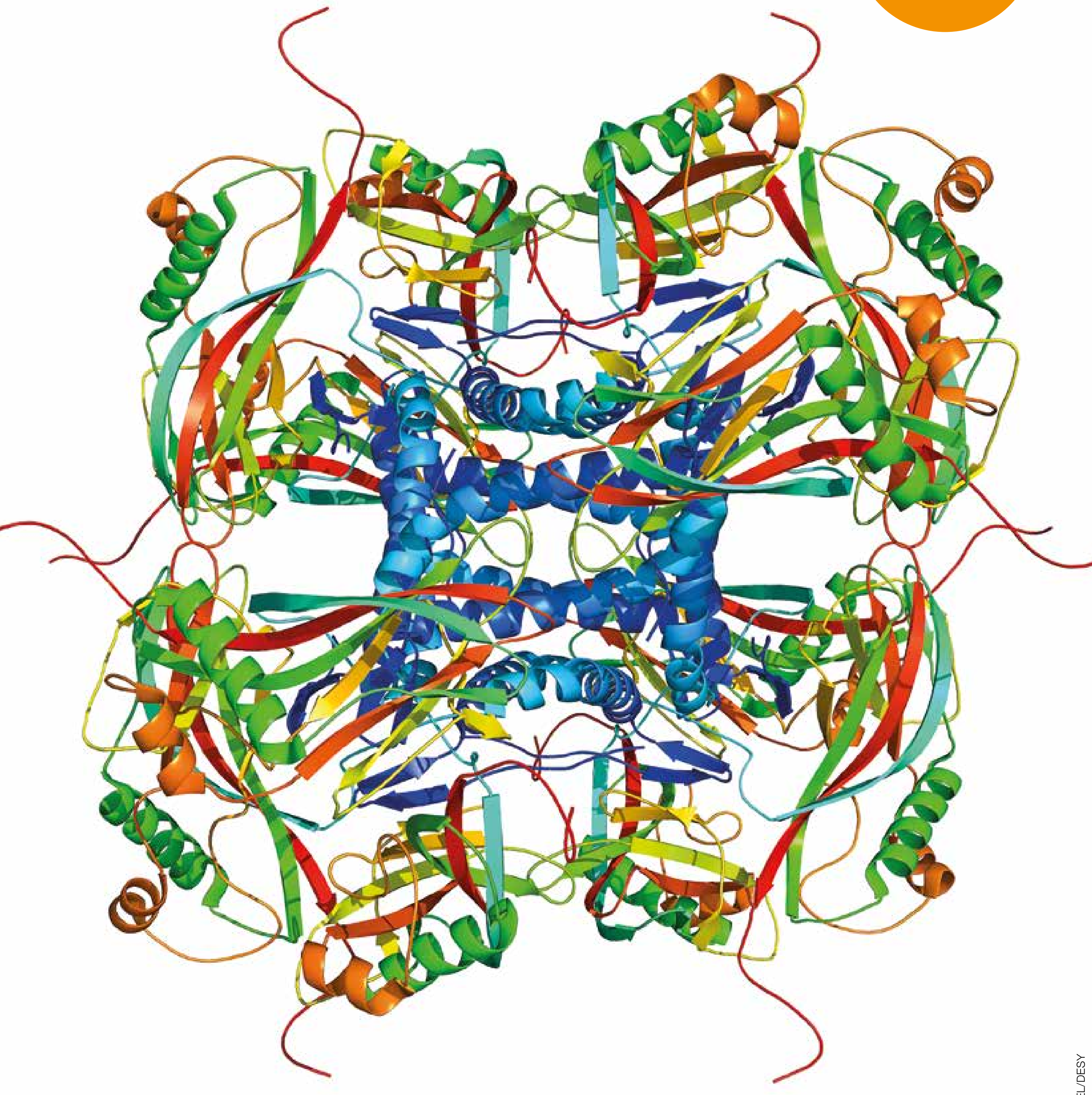

Picture: Dominik Oberthür, CFEL/DESY

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When a wingbeat lasts forever

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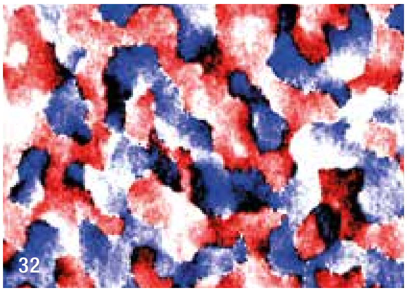
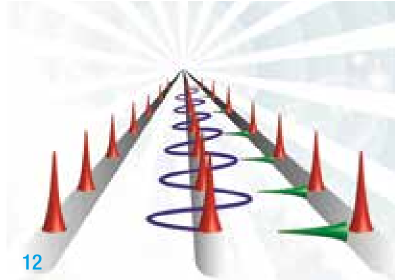
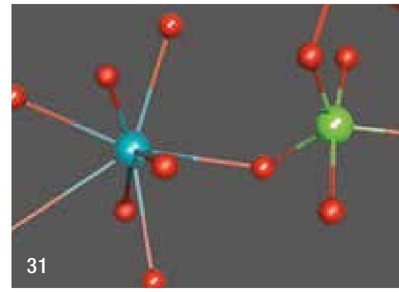






CAMPUS

ZOOM

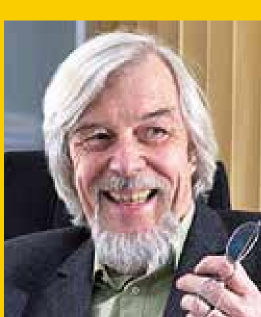
SPECTRUM

SECTIONS

A ray of hope for the Middle East

The SESAME X-ray source is meant to strengthen scientific and political cooperation

Sometimes it takes a particle accelerator to bring people together. In international politics, cooperation is often achieved only after great effort, but in science it doesn't seem to be a big problem. In the SESAME project, countries such as Israel, Iran, the Palestinian National Authority, Turkey and Cyprus are working as partners to reach a shared goal, in spite of all the political tensions between them. In Jordan, they have set up a research centre that houses the first synchrotron radiation source in the region. After it is opened in mid-May, SESAME (Synchrotron-light for Experimental Science and Applications in the Middle East) will enable scientists from a variety of research areas to conduct structural investigations by means of X-rays, ranging from studies of new materials to analyses of biomolecules.



Rolf-Dieter Heuer, president of the SESAME Council

The aim is to strengthen the region's research sector, especially by keeping young scientists in the region so that their know-how is retained over the long term. A second aim of SESAME, which is at least equally important, is to improve the interaction between the member countries. "Our goal is not only to build up a research centre. This is also a project in which many countries are working together to promote peace. The project includes many challenges, but it will also create huge opportunities if it is successful," says Wolfgang Eberhardt, an expert in photon science who is a member of the SESAME Council as an observer representing Germany.

The path to a finished research centre was not an easy one, and it included several phases of downtime. The researchers Herman Winick from the SLAC accelerator centre in the USA and Gustav-Adolf Voss, who was then director of the accelerator division at DESY, had conceived the idea for the project back in 1997. They proposed that the BESSY I accelerator in Berlin, which was to be replaced by a newer machine, be donated for a facility in the Middle East. The German government approved this plan. SESAME was founded with the support of UNESCO. In 2004, it became an intergovernmental project between Jordan, Israel, Iran, Egypt, Bahrain, Turkey, Cyprus, the Palestinian National Authority and Pakistan. For a long time, work on SESAME proceeded slowly, primarily because of a shortage of funding.

But over the past three years there has been great progress, partly because a new storage ring could be built thanks to a contribution of millions of euros from the European Commission. Today, SESAME is a third-generation synchrotron radiation source for which an improved version of BESSY I serves as an injector. The commissioning of the facility began at the end of 2016, and in January 2017, the first electron beam circled the storage ring. In the second half of 2017, experiments will begin at the two initial measuring stations. Additional stations will be added over time. "Many critics believed that the difficulties were too great and that the possible yield would be too small. When the first research results are published in the near future, it will really be great," Eberhardt says.

Diverse experiments

As of the opening of the facility, the SESAME Council – the project's highest decision-making body – has a new president, Rolf-Dieter Heuer. After serving as research director at DESY for many years, he was appointed director general of CERN, the European particle research centre near Geneva, in 2009. Heuer will now lead SESAME into the operation phase. "SESAME offers diverse scientific opportunities ranging from physics to the life sciences and archaeology, which is unique in this region. But that's not all. We want this research facility to also serve as a bridge for promoting understanding between nations that have different political, cultural and religious world views. CERN served the same function after World War II. The natural sciences know no national, political or ideological boundaries. We have to seize this opportunity!" says Heuer.

SESAME is also meant to intensify the interaction with countries in Europe and other regions. Many countries are sitting on the SESAME Council as observers and supporting the project with funding or through machines and expertise. Many European research centres are cooperating closely with SESAME. Gustav-Adolf Voss at DESY was a strong supporter of the project from the very start. "Gustav-Adolf Voss was extremely helpful in creating the structure of SESAME," says Frank Lehner from DESY, who today organises the cooperation between DESY and SESAME. "Together with other institutes, there was an extensive capacity-building programme in which scientists and technicians from the region were trained at the research centres. A number of these people also came to DESY at the beginning of 2000."

"The natural sciences know no national, political or ideological boundaries"

Rolf-Dieter Heuer

Open SESAME! The international research centre will be open to scientists from the entire region.

At the moment, the commissioning of the SESAME accelerator is still under way. But the first experiments should begin in the second half of the year.

International understanding through research

One of them was Hossein Delsim-Hashemi. He was one of seven Iranians who came to a SESAME workshop in Jordan in 2000. At the time, he was researching cosmic radiation at Sharif University of Technology in Iran. He was slated to receive a place in the SESAME injector group, and he came to DESY to receive the necessary training. "SESAME shows that the countries in the region can work together and pursue shared goals," he says. "As a result, the project could enable scientists to get together and maybe even return to their home countries afterward. There's tremendous potential in the participating countries." In fact, he would have liked SESAME to open its doors a few years earlier.

Even now that Gustav-Adolf Voss has retired, DESY still supports the project in a variety of ways. Among other things, Lehner is trying to attract funding for an additional SESAME measuring station that could be financed from sources in Germany. "We should clearly demonstrate that Germany has the will to create future-oriented projects in the countries of the Middle East. SESAME is a project of this kind. It could build up research capacities in the region that remain there over the long term," he says. In addition, together with nine other European research centres, DESY is part of the EU-funded OPEN SESAME project, which aims to train scientists and personnel for SESAME.

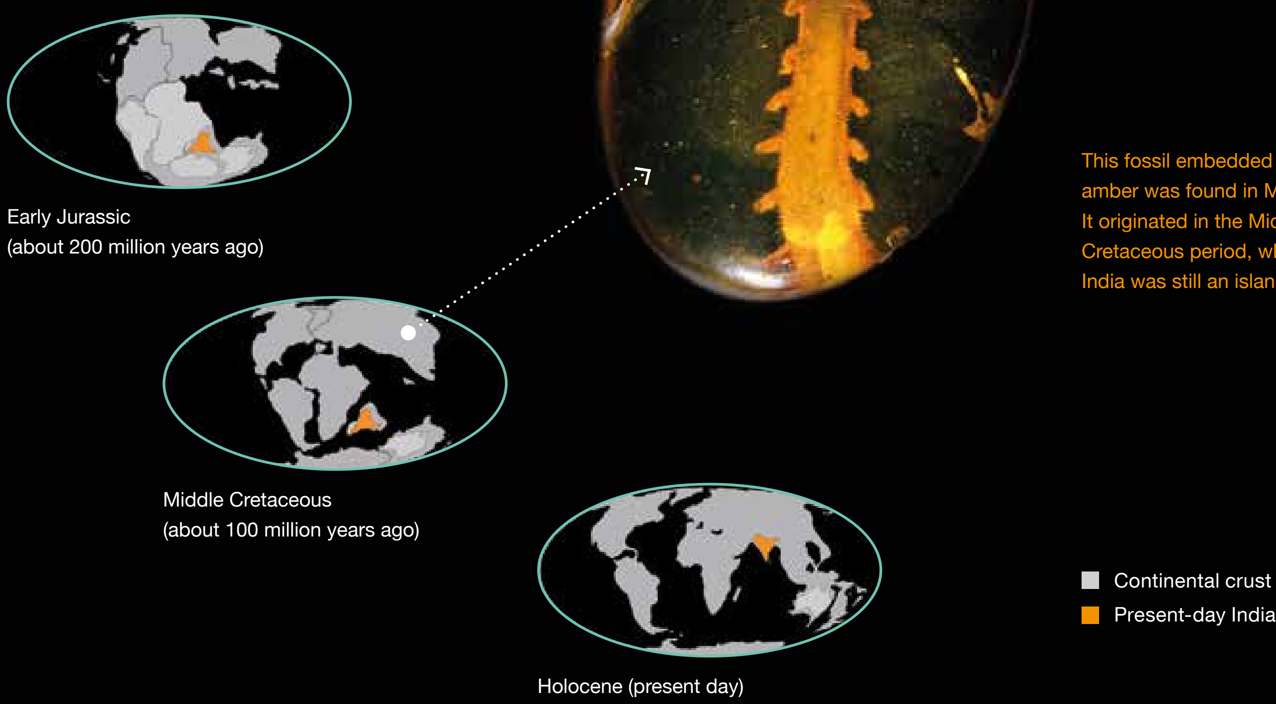
Other research centres could also learn from SESAME, because it may soon become a pioneer in at least one area. There are plans to cover the storage ring's electricity consumption entirely through solar energy. The government of Jordan has designated land for the project, and photovoltaic systems are being constructed there thanks to funding from the EU. There will also be a cooperative project with the local power suppliers in order to solve the problem of electricity storage. Excess electricity will be fed into the grid during the daytime, and energy will be drawn from the grid at night. SESAME will thus be the first particle accelerator that is powered entirely by sustainable energy sources.

Evidence in amber

100-million-year-old fossil solves mystery of velvet worm spread

Pictures: Ivo de Sena Oliveira, University of Kassel

This fossil embedded in amber was found in Myanmar. It originated in the Middle Cretaceous period, when India was still an island.



Besides providing pretty jewellery, amber serves as a valuable archive of primitive animal and plant species that were conserved in tree resin millions of years ago. This includes an animal that looks inconspicuous and worm-like only at first glance: a velvet worm that was almost perfectly encased in amber around 100 million years ago and was discovered by scientists in modern-day Myanmar. Velvet worms (*Onychophora*) are a primitive phylum that is situated somewhere between annelids and arthropods. Velvet worms are distinguished from true worms, which are legless, by their stubby legs, which have a pair of claws at the end. Other characteristics of these tiny animals also offer some clues as to how annelids, whose bodies are organised along relatively simple lines, may have evolved into crustaceans and insects – a good reason for the scientists to investigate the velvet worm fossilised in the piece of amber using sophisticated tomography technology.

With the help of intense X-rays from DESY's PETRA III light source, the researchers from the Chinese Academy of Sciences in Beijing, the University of Kassel and Helmholtz-Zentrum

Geesthacht were able to examine the rare amber fossil with extremely high precision, using microtomography, without damaging it. The study not only revealed extremely tiny details of the creature's anatomy, but also provided the solution to a decades-old mystery regarding the spread of velvet worms during the Cretaceous period.

Today, this animal phylum is primarily found in areas that used to be part of the supercontinent Gondwana, which united South America, Africa, India, Australia, Antarctica and other areas until about 150 million years ago. However, some velvet worms also live in Southeast Asia, which was never part of Gondwana. Until recently, there were two hypotheses as to why this is the case: Velvet worms either colonised Southeast Asia from Africa via Europe during the time when these land masses were joined to one another in the supercontinent Pangaea (the Eurogondwana hypothesis), or continental drift enabled velvet worms to spread through Southeast Asia by causing India to collide with Asia (the "out of India" hypothesis). The amber fossil has now provided the final proof that the "out of India" hypothesis is incorrect.

The fossil comes from the Southeast Asian country of Myanmar, which borders Thailand, China, India and other countries. More than 100 million years ago, when velvet worms lived in the region that is now known as Myanmar, India was not yet part of Asia. This means that the current subcontinent could not have been used as "conveyance". The age of the fossil, as well as its impressive morphological similarities with the velvet worms that live in India today, led the scientists to the conclusion that velvet worms must have migrated to Southeast Asia via the land mass of Europe before India collided with Asia. Only after the collision could they have spread to India.

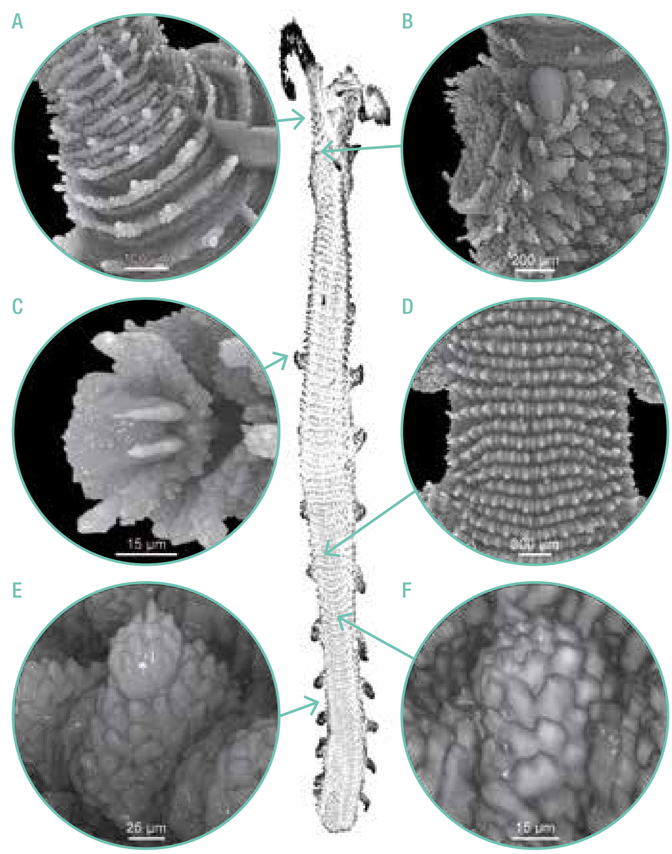
"We can now exclude the 'out of India' hypothesis," says team leader Georg Mayer, head of the Department of Zoology at the University of Kassel in Germany. "Unlike India, Myanmar was not isolated from the rest of the Southeast Asian plate and was therefore not affected by the continental drift. However, the velvet worm from Myanmar is most closely related to the Indian species. Moreover, it clearly existed long before India collided with Asia."

As Mayer explains, the examination of the fossil has also enabled the researchers to provide more detailed information about the evolution of velvet worms. "For example, you can very clearly see that this fossil creature had eyes," he says. "In the course of evolution, the velvet worms from India lost their eyes. Another interesting finding is that this fossil animal clearly had claws. None of the previously found fossils shows any claws." One reason why this study is so important is that velvet worms are rarely found in amber. Only three such fossils have been found to date, each one at a different location.

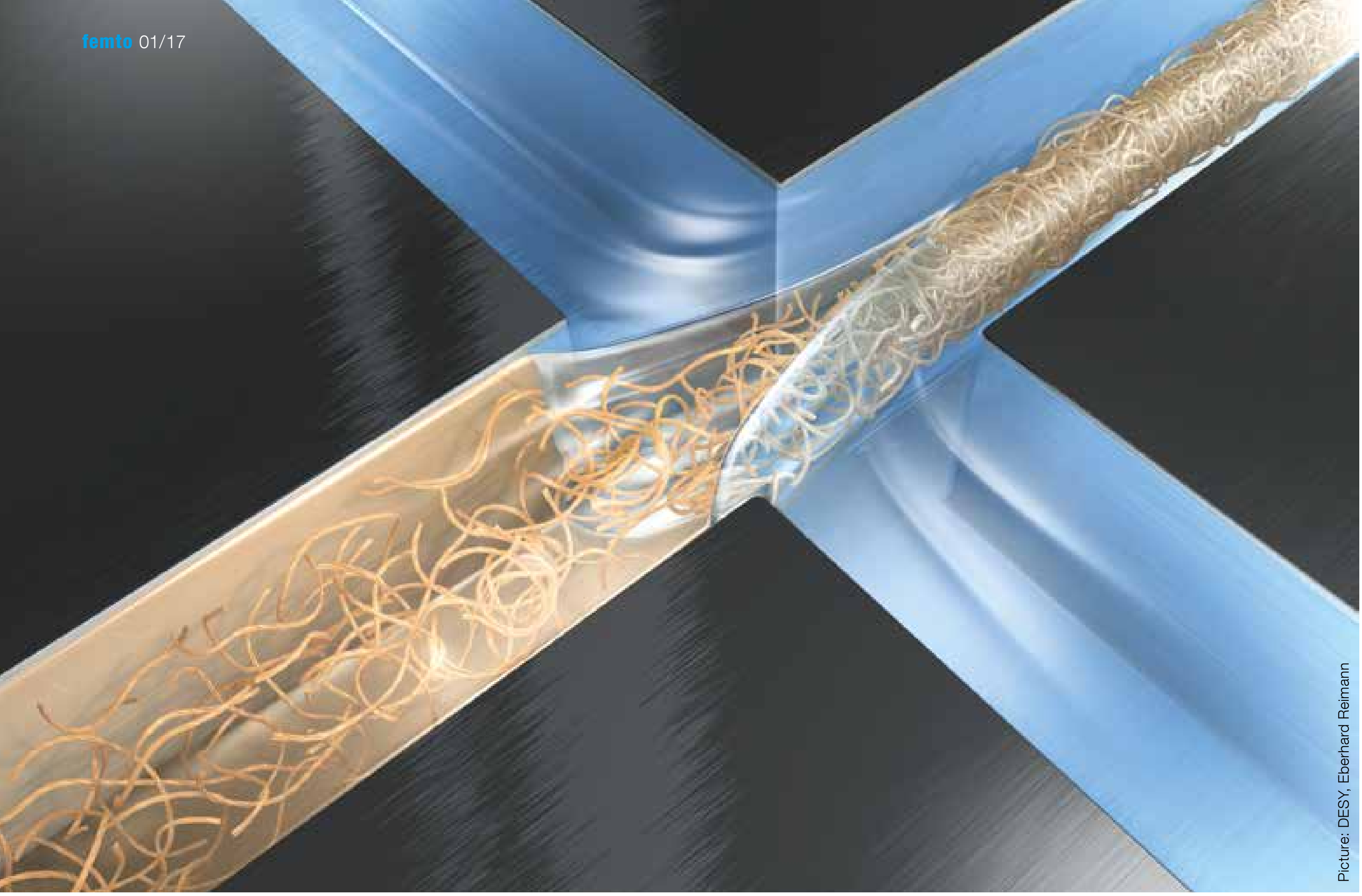
Current Biology, 2016; DOI: 10.1016/j.cub.2016.07.023

"We can now exclude the 'out of India' hypothesis

Georg Mayer, University of Kassel



X-ray microtomography reveals details of the amber fossil's anatomy.



The hydrodynamic focusing by means of perpendicular water streams makes the nanofibrils lock together in a microfibre.

Artificial silk from whey protein

X-ray study throws light on key production process

A Swedish–German team of researchers has cleared up a key process for the artificial production of silk. With the help of the intense X-rays from DESY's research light source PETRA III, the team around Christofer Lendel and Fredrik Lundell from the Royal Institute of Technology (KTH) in Stockholm were able to observe how small protein pieces, called nanofibrils, lock together to form a fibre. Surprisingly, the best fibres are not formed by the longest protein pieces. Instead, the strongest "silk" is won from protein nanofibrils with seemingly less good quality.

Due to its many remarkable characteristics, silk is a material high in demand in many areas. It is lightweight, yet stronger than some metals, and can be extremely elastic. Currently, silk is harvested from farmed silkworms, which is quite costly. "Across the globe, many research teams are working on methods to artificially produce silk," says Stephan Roth from DESY, who is also a professor at KTH. "Such artificial materials can also be modified to have new, tailor-made characteristics and serve for applications like novel biosensors or self-dissolving wound dressings, for example."

However, imitating nature proved especially hard in the case of silk. The Swedish team focuses on self-assembling biological materials. "That's a quite simple process," explains Lundell. "Under the right conditions, some proteins assemble themselves into nano-fibrils. A carrier fluid with these

"Such artificial materials can also be modified to serve for applications like novel biosensors or self-dissolving wound dressings"

Stephan Roth, DESY

protein nanofibrils is then pumped through a small canal. Additional water enters perpendicular from the sides and squeezes the fibrils until they stick together and form a fibre." The latter process is called hydrodynamic focusing, and Lundell's team has used it before for producing artificial wood fibres from cellulose fibrils. "In fact, the process has several similarities with the way spiders produce their silk threads," says Lendel.

The optimal whey fibre

In the new study, the nanofibrils were formed by a protein from cow's whey under the influence of heat and acid. The fibrils' shape and characteristics strongly depend on the protein concentration in the solution. At less than four percent, long, straight and thick fibrils form. They can be up to 2000 nanometres (millionths of a millimetre) long and 4 to 7 nanometres thick. But at an only slightly higher protein concentration of six percent or more in the initial solution, the fibrils remain much shorter and thinner with an average length of just 40 nanometres and a thickness of 2 to 3 nanometres. Also, they are curved, looking like tiny worms, and 15 to 25 times softer than the long, straight fibrils.

In the lab, however, the short and curved fibrils formed much better fibres than the long and straight fibrils. Using the bright X-ray light generated by PETRA III, the researchers were able to find out why: "The curved nanofibrils lock together much better than the straight ones. The X-ray diffraction patterns show that the fibrils largely keep their rather random orientation in the final fibre," says Roth, who heads the beamline where the experiments took place.

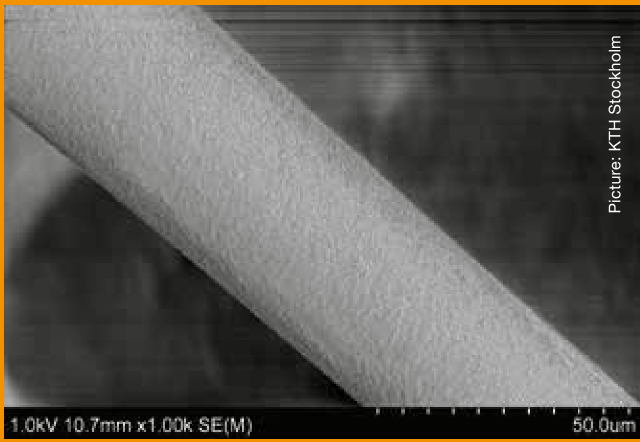
"The strongest fibres form when a sufficient balance between ordered nanostructure and fibril entanglement is kept," adds Lendel. "Natural silk has an even more complex structure with evolutionary optimised proteins. These assemble in a specific way with both highly ordered regions – called beta-sheets – that give the fibre strength and regions with low order that give it flexibility. However, the fibre structures of artificial and natural silk are essentially different. In particular, the protein chains in natural silk have a larger number of intermolecular interactions that cross-link the proteins and result in a stronger fibre."

In their experiments, the researchers obtained artificial silk fibres that were roughly five millimetres long and of medium quality. "We used the whey protein to understand the underlying principle in detail," explains Lendel. "The whole process can now be optimised to obtain fibres with better or new, tailor-made properties." In this way, the results of the study could help to develop materials with novel features, for example artificial tissue for medical applications.

PNAS, 2017; DOI: 10.1073/pnas.1617260114

"The whole process can now be optimised to obtain fibres with better or new, tailor-made properties"

Christofer Lendel, Royal Institute of Technology (KTH) Stockholm



Scanning electron microscope image of an artificially produced microfibre

ZOOM

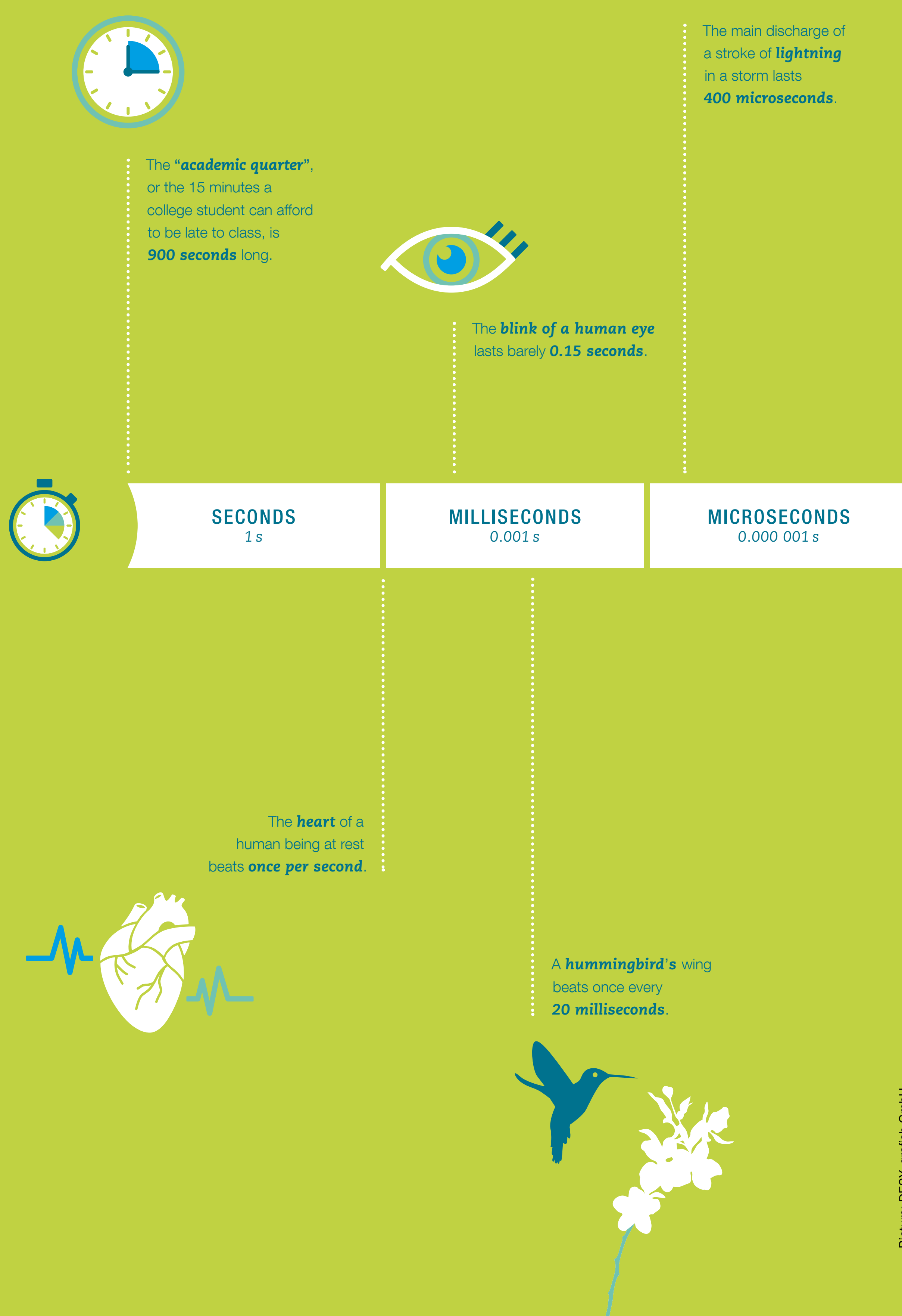
ULTRA FAST PHYSICS

When a wingbeat lasts forever

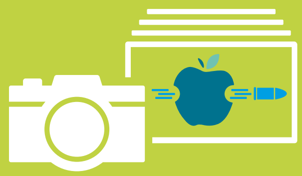
The whirring flight of hummingbirds is legendary. It propels them through the air with 50 wingbeats per second, faster than the human eye can see. But even the fastest wingbeats by far in the world of birds look sluggish compared to the temporal dimensions that are currently being investigated in the field of ultrafast physics. Thanks to sophisticated laser technologies, researchers are able to make snapshots on the scale of femtoseconds and attoseconds – incredibly short time intervals, some of which last less than 0.000 000 000 000 001 seconds. That's shorter than a millionth of a billionth of a second – and trillions of times shorter than a hummingbird's wingbeat. It's on these incredibly short time scales that the fundamental processes of matter are taking place: the reaction chain of photosynthesis in green plants, the chemical processes in catalytic converters and the movements of electrons in atoms and molecules. Francesca Calegari, an expert in ultrafast physics at DESY, explains the dimensions the researchers are exploring as follows: "An attosecond to a second is as a second to the age of the universe!"

Picture: DESY, grafish GmbH

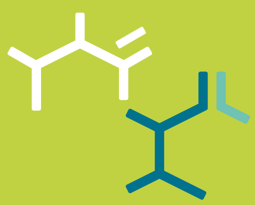
Even the proverbial blink of an eye is a trillion times slower than the molecular machinery of photosynthesis. This graphic shows some typical processes that take place within a time frame between a quarter of an hour and an attosecond. With every step, the time frames become a thousand times shorter: A millisecond is a thousand times shorter than a second, a microsecond is a thousand times shorter than a millisecond, and so on.



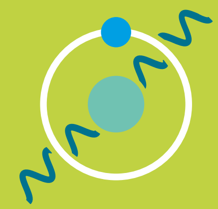
Picture: DESY, grafish GmbH



The shutter speed of modern ***high-speed cameras*** is ***one microsecond.*** They can capture up to one million images per second.



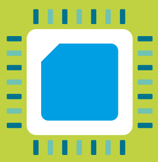
Chemical reactions occur in ***picoseconds***.



In approximately ***one attosecond***, light travels a distance corresponding to the size of a hydrogen atom.

NANOSECONDS	PICOSECONDS	FEMTOSECONDS	ATTOSECONDS
0.000 000 001 s	0.000 000 000 001 s	0.000 000 000 000 001 s	0.000 000 000 000 000 001 s

The clock cycle of a modern ***PC processor*** is shorter than ***one nanosecond***.



During photosynthesis, biomolecules change their shape within ***femtoseconds***.

A GALLOP THROUGH ULTRAFAST PHYSICS

Back in 1872, in the recently established State of California, the railroad operator Leland Stanford was a key figure. He would later spend part of his considerable fortune founding one of the most important centres of learning in the USA, Stanford University. Yet his real passion was for horses. One question in particular exercised him: When a horse trots quickly, does it ever have all four hooves in the air at once? The answer was provided by an innovative photographer by the name of Eadweard Muybridge. He devised a technique for capturing a spectacular sequence of images that showed in detail how a horse actually moves its legs when trotting. This series of images is also regarded as the birth of what would become ultrafast physics – now a highly topical branch of research.

Since then, researchers have succeeded in capturing ever shorter time intervals. Today's equipment is capable of taking snapshots in the femtosecond and even attosecond range, i.e. a time span of less than 0.000 000 000 000 001 seconds – or shorter than a millionth of a billionth of a second. It is on such time scales that the fundamental processes of matter are taking place: The sun's rays act upon chlorophyll in a plant and thereby trigger a lightning-fast series of reactions, known as photosynthesis. In individual atoms, electrons jump from one energy level to the next – quantum leaps can now be measured.

Sophisticated techniques are required to produce such extreme slow-motion sequences. They include the use of special laser equipment to generate pulses of light so short that they can be used to "freeze" even ultrafast processes, such as electron movement within atoms. Special imaging methods are then used to capture these high-speed processes. In addition, kilometre-long accelerator facilities that generate intense, ultrashort flashes of X-ray light can provide measurement data with an extremely high temporal and also spatial resolution. DESY operates a number of these super microscopes at its premises in Hamburg. Its campus is a major centre for ultrafast physics, where DESY works in close cooperation with the Max Planck Society and the Universiy of Hamburg.

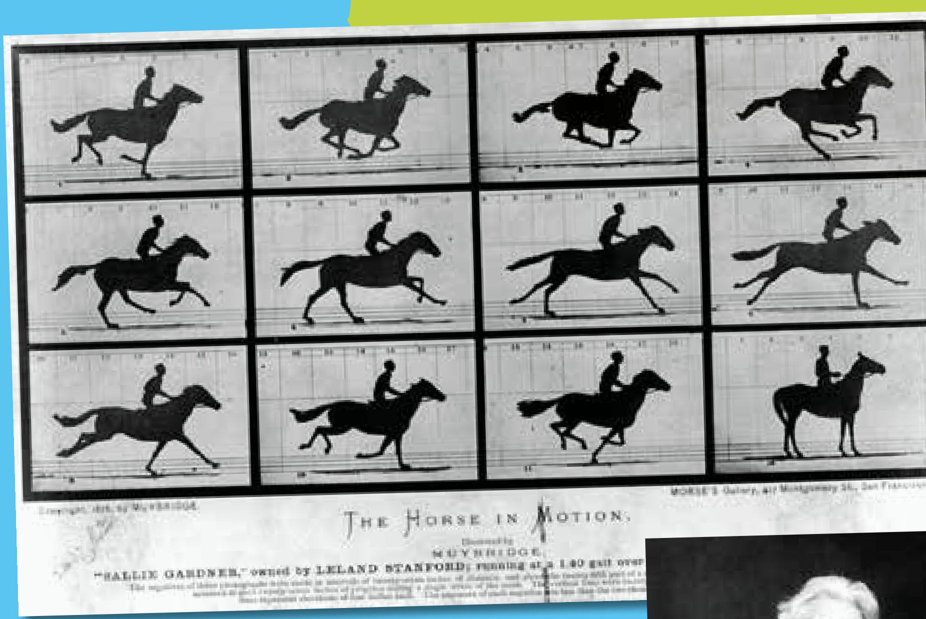
The borders of our perception

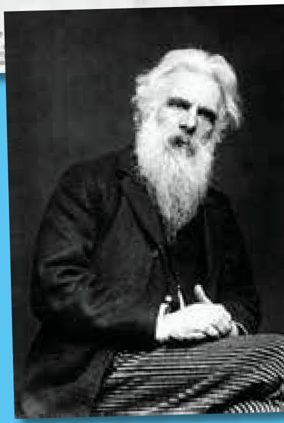
Our senses are nowhere near acute enough to register high-speed processes in nature. The human eye can distinguish at most 30 light stimuli per second. Anything more, and it merely registers a continuous image. Television exploits this fact: 50 images a second are enough to create the illusion of a moving picture. It takes sophisticated high-speed techniques to overcome the limitations of human perception.

The foundations for these technologies were first laid in the Wild West almost 140 years ago, when Stanford promised Eadweard Muybridge a substantial sum of money for solving the puzzle of the trotting horse. The problem was that, with the cameras of the day, it was impossible to capture such rapid movements on a photographic plate. Muybridge, a colourful character, was ambitious and soon obsessed by the challenge. His first innovation was to devise a shutter with a fast exposure time. He then placed 12 cameras in a line, each one triggered by a kind of tripwire that Muybridge had laid in the sandy ground over which the horse would pass. As the animal trotted along the track, it successively tripped the wires, thereby setting off each camera as it passed.

The result was the world's first sequence of images, a precursor of the cinema picture. When Leland Stanford saw the pictures, he was confounded, for the actual position of the horse's ››

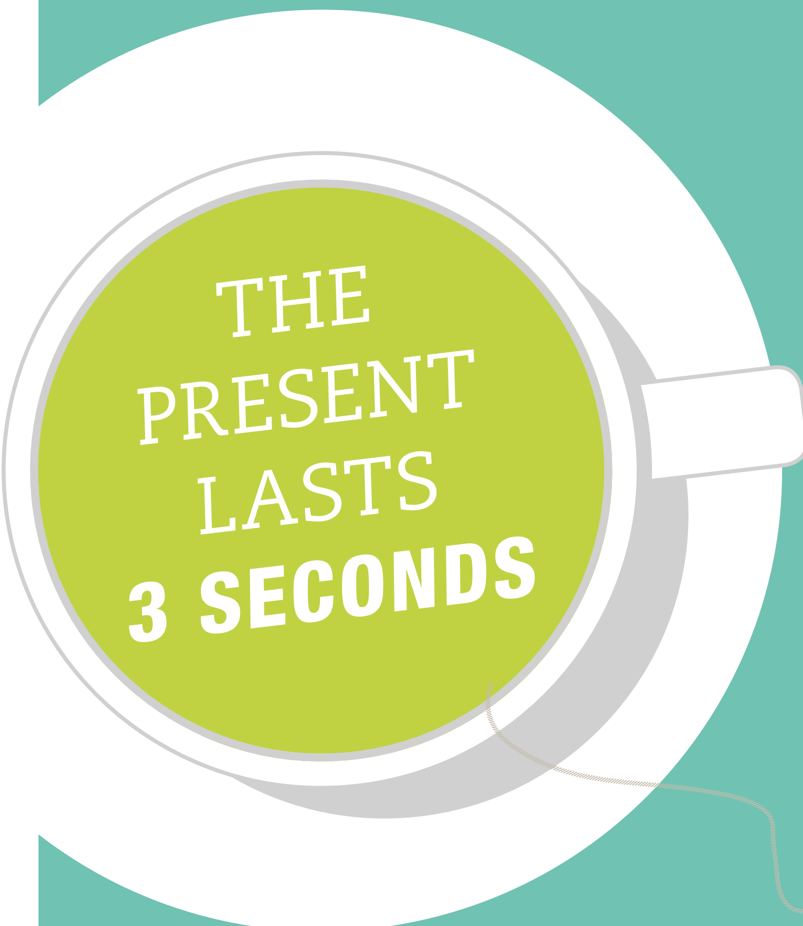
1872





Pioneering photographer Eadweard Muybridge developed a way of showing how a trotting or galloping horse moves its legs.

THE PRESENT LASTS 3 SECONDS



For a femtosecond researcher engrossed in an experiment, time just seems to fly by – so quickly, in fact, that before she's even blinked, another three hours have passed. There's just time for a quick sandwich and a cup of tea before the next meeting begins. But doesn't it take an age for the kettle to boil? And the three minutes for the tea to brew seem to last almost longer than the previous three hours spent in the lab.

That's because time is more than just a physical quantity. We also perceive it in very human and capricious ways. Between our subjective perception of time and its objective measurement, there is often a big difference. For example, when we experience a lot of new things at once, time can pass very quickly. But when we look back and remember all the many different events, the same period of time seems much longer.

By contrast, waiting for something can take forever. But looking back, this uneventful period appears very short. In retrospect, what determines our subjective perception of the passing of time is the amount of different experiences that we recall from memory for the period in question. In other words, the more experiences we had and the more of them we can remember, the longer the period in question seems to have lasted.

In her daily life, our femtosecond researcher also experiences the entire spectrum of subjective time perception, despite working with extremely precise time measurement in the lab. She can take her time, give time to others, yet also steal time. She can gain or lose time, mark, save or even kill time. Her perception is limited by the capabilities of the human senses. In order to be perceived as distinct from one another, optical impressions must lie at least 20 to 30 milliseconds apart. For acoustic stimuli, by contrast, three milliseconds suffice.

And even for our researcher, the present lasts three seconds at most. This is the maximum period during which our brain can process and integrate events such as the succession of individual notes in a tune. Any longer, and the brain's ability to integrate is exhausted. Even across cultural boundaries, it seems that language and movement, for example, are structured into three-second blocks. Biologists name this universal brain mechanism "the three-second phenomenon".

legs was not as expected. However, they did show that a fast trotting horse has all four hooves off the ground. Soon afterwards, Muybridge showed that this is the same for a horse in gallop. These ground-breaking sequences of images marked the birth of freeze-frame photography. Since then, the technique has been progressively refined, enabling the resolution of ever shorter time intervals.

Over the decades, engineers thus developed faster and faster mechanical shutters, with the best of them reaching shutter speeds of as little as 1/8000 of a second. Then came electronic shutters, which electronically control the length of time the camera chip is exposed to light. Unlike mechanical shutters, there is no mass to be moved, which makes the process substantially faster. Modern high-speed cameras can capture as many as one million images a second. Speeds this fast enable spectacular slow-motion sequences, such as a bullet penetrating an apple. They represent the pinnacle of the Muybridge principle. However, as physicist Markus Drescher from the University of Hamburg explains: “In the realm of science, time intervals on the microsecond scale are pretty long. Many processes in nature are millions or even billions of times faster.” In the nanocosmos in particular, the clocks tick decidedly faster, for example when substances react with one another chemically.

In the blink of an eye

A paradigm shift was needed to be able to capture these kinds of processes in detail. Conventional photography uses a mechanical or electronic shutter to “chop up” the light from a continuous light source such as the sun. Now, however, the shutter remains open, while the process under investigation is illuminated for an instant by extremely short flashes of light. In this technique, the achievable temporal resolution depends on the duration of the flashes. Conventional electronic flashes generate light pulses of a few microseconds in duration – which is already significantly faster than a mechanical shutter.

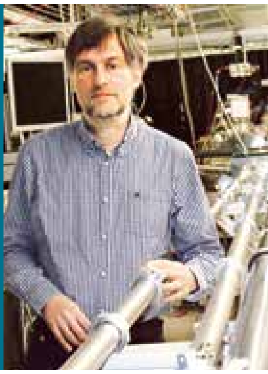
Yet the real breakthrough occurred in 1960, when the US physicist Theodore Maiman unveiled the world’s first laser. The device used a ruby crystal to generate pulses of extremely collimated red light. “After that, the pace of development just took off,” Drescher explains. “With each passing decade, pulse duration has decreased, on average, by an order of magnitude.” It was around the year 2000, working on a team led by physicist Ferenc Krausz in Vienna, that Drescher succeeded in producing pulses on the attosecond time scale, i.e. billionths of a billionth of a second. Drescher demonstrates how the technology works in one of his labs on the Hamburg campus – a long windowless room, filled with the whir and hum of pumps and air conditioners. Mounted on a massive bench cushioned against vibration are a wide array of optical equipment as well as diverse heavy-duty housings. “A high-performance gigawatt laser,” he explains. “Each of its infrared pulses has a power of around 100 gigawatts.”

“With each passing decade, pulse duration has decreased, on average, by an order of magnitude”

Markus Drescher, University of Hamburg

These highly intense pulses are fired into a nondescript metal cylinder containing a few cubic centimetres of noble gas, such as argon, neon or xenon. What then occurs is a special, “non-linear” interaction between the laser pulses and the gas atoms. The electromagnetic field of the laser pulse tugs at the electrons of the atoms, disengages them slightly and excites them with part of its energy. Then, however, the field of the laser pulse changes direction, thereby kicking the electron back towards the atom. This results in the emission of energy in the form of a flash of shortwave light. Crucially, the kick is so fast that the flash is extremely short – on the attosecond scale. ››

Markus Drescher is a specialist in ultrafast physics and a professor at the University of Hamburg.



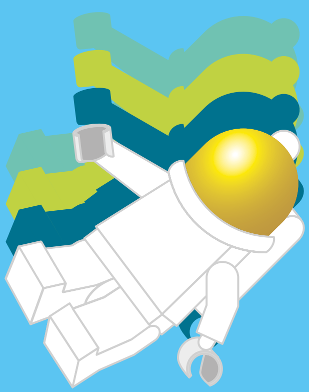
A DO-IT-YOURSELF SUPER SLOW-MOTION CAMERA

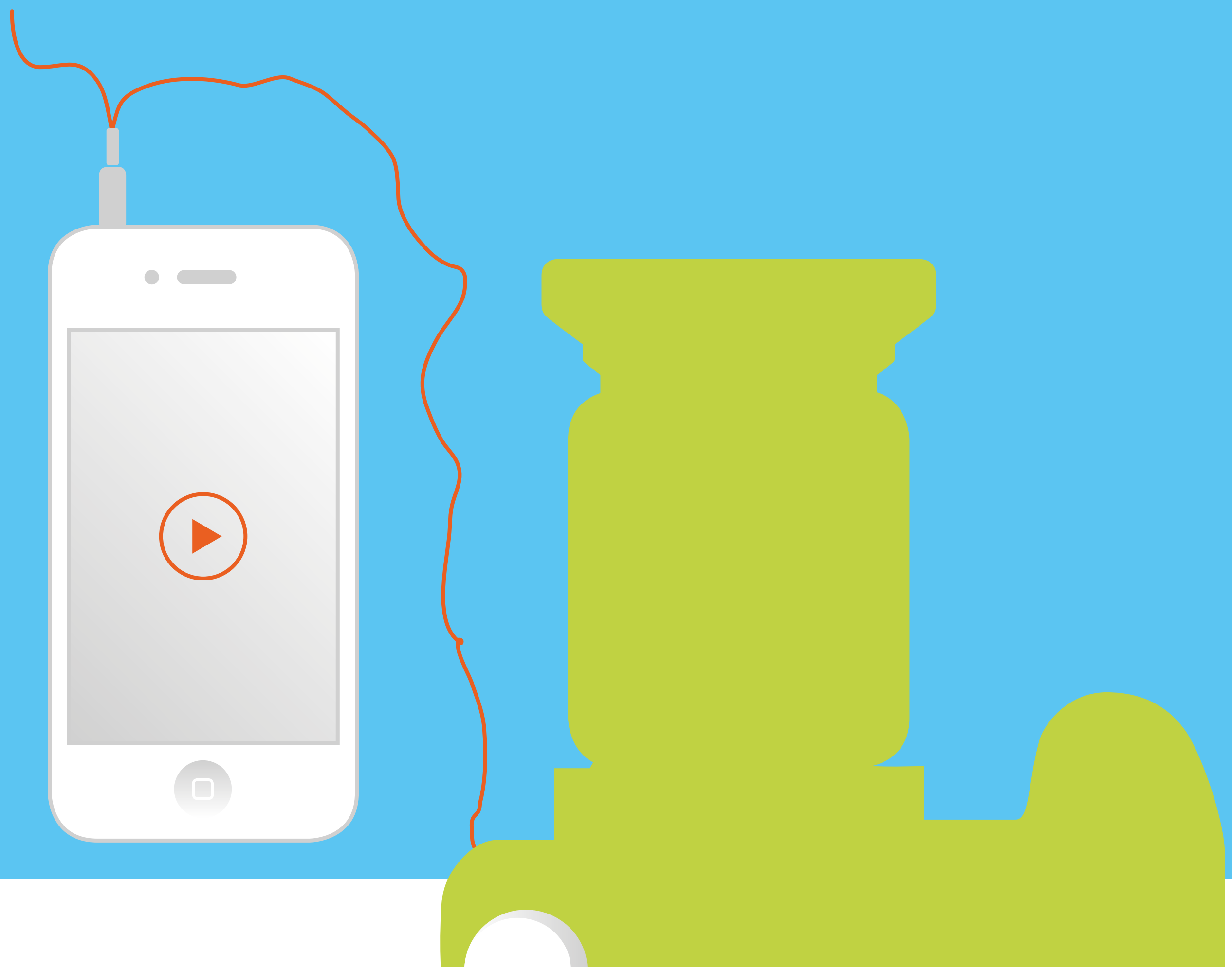
It doesn't take much more than a smartphone, a digital camera, LEDs and a few electronic components to get an idea of how researchers are able to image ultrafast processes. "Flashmotion" – a project launched by the team of Markus Drescher at the University of Hamburg – aims to illustrate the so-called "pump–probe" method.

The results are astounding: spectacular super slow-motion images of a Lego astronaut tumbling through the air or being catapulted back up. Normally, such images are only achievable with expensive high-speed cameras.

For those who'd like to have a go themselves, instructions can be found at:

https://dynamix.desy.de/





Atoms at work

Scientists around the world now make use of this method to generate pulses of less than 100 attoseconds in duration. This is the time scale on which a number of fundamental processes in nature take place, including the movement of electrons within an atom. “Attosecond physics means we can observe electrons at work in atoms, as it were, and check the basic principles of quantum mechanics,” enthuses Drescher, who is one of the coordinators of the Centre for Ultrafast Imaging (CUI), a cluster of excellence in Hamburg. What, for example, happens in detail during ionisation, when an electron departs from its atom, leaving behind a charged ion? Or how do electrons move during a chemical reaction?

“Attosecond physics means we can observe electrons at work in atoms”

Markus Drescher, University of Hamburg

In Drescher’s lab on the DESY campus, various experiments are under way to investigate ultrafast processes on the femto- and attosecond scale. How fast do magnets switch their polarity? How long does it take for a chemical bond in a molecule to break? And what exactly takes place when UV radiation splits a water molecule, a process that occurs continuously in Earth’s upper atmosphere?

Francesca Calegari, leading scientist at DESY, is interested in ultrafast processes in biomolecules. With the help of attosecond pulses, she has been able to investigate how amino acids – the basic building blocks of proteins – react to light. “In the long term, we’re hoping not only to observe biochemical reactions but also to control them,” she explains. The vision is that one day, ultrashort laser pulses may be used to develop and even produce pioneering new drugs.

Other researchers are mainly interested in processes that take place on the surface of crystals and nanostructures. “Solids are not yet fully established in attosecond physics,” says Thorsten Uphues, junior professor at the Center for Free-Electron Laser Science (CFEL), a joint research institution of the Max Planck Society, the University of Hamburg and DESY. As Uphues explains: “With the established methods of attosecond physics, it’s difficult to follow almost any of the ultrafast processes on a surface.” Among other samples, Uphues and his team are investigating tiny nanostructures which they emboss on the surface of crystals in an artificial process that produces chip-like patterns on the nanometre (millionth of a millimetre) scale.

Computer simulations suggest that when bombarded with short flashes of light, the nanostructures would respond with laser-like oscillation patterns that behave in a manner similar to ultrafast transistors. “This field, in which ultrashort pulses of light are used to induce a charge displacement, is known as nanoplasmonics,” Uphues explains. “It may well represent the future of information technology.” In principle, it could enable faster data transfer and data processing. Unlike today’s technology, components would be controlled optically rather than electrically, which would pave the way for much faster switching processes.

Physicist Adrian Cavalieri from the Max Planck Institute for the Structure and Dynamics of Matter in Hamburg is interested in a different class of solids: materials that can suddenly mutate from electrical conductor to insulator and vice versa. “We know that these transitions occur extremely rapidly, within just a few femtoseconds,” he explains. Using lasers, his team is trying to trace these ultrafast phase shifts in detail. They hope one day to be able to perfectly control this process and to switch at will between conductor and insulator. “The result would be an extremely rapid switch that is operated by means of light,” Cavalieri explains. “Such mechanisms would be of great interest to the electronics industry, since they would enable ultrafast switching operations.”

Short laser pulses also look to have promising applications in medicine. Researchers are currently investigating the use of light to activate cancer drugs. The idea is that the drug is already present throughout the body, but is not active until exposed to ultrashort pulses of light. This activation is only carried out where the drug is supposed to act, in the tissue of the tumour. ››

“In the long term, we’re hoping to control biochemical reactions”

Francesca Calegari, DESY

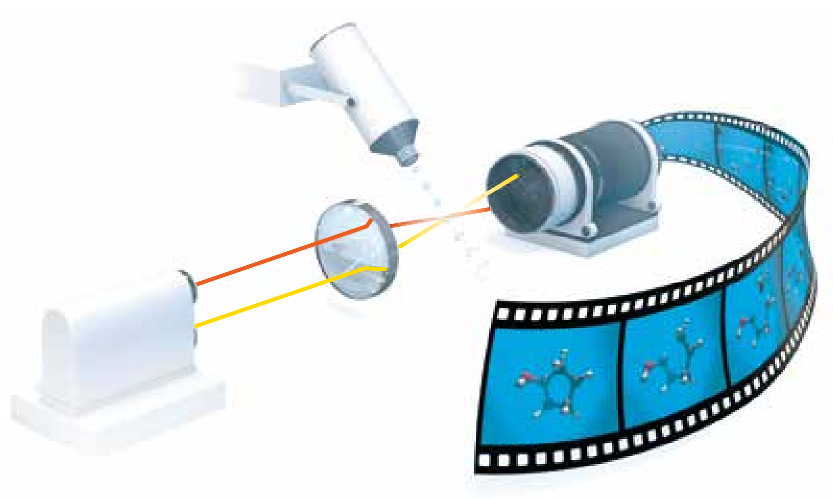
The aim is that the drug achieve maximum effect with minimal side effects. The light pulses are to be conducted directly to the tumour via optical fibres. The use of short pulses will prevent the tissue from heating, making the therapy more patient-friendly.

Physicists such as Markus Drescher, Thorsten Uphues and Adrian Cavalieri tend to work with bench-top lasers, even if the bench in question can run to a dozen metres in length. DESY, however, is also home to research equipment of a totally different order of magnitude: the two free-electron lasers FLASH and European XFEL, a new X-ray laser in which DESY is strongly involved. Both facilities are based on long linear particle accelerators and generate pulses of radiation that are significantly more powerful and have a much shorter wavelength than those from laboratory lasers, making them ideal for investigating individual atoms in crystal structures. This combination of laboratory laser systems and large free-electron lasers offers unique research opportunities.

Chemical reactions in super slow motion

The pulses from the huge free-electron laser facilities are likewise extremely short, lasting for just a few dozen femtoseconds. They thus enable measurements with an extremely high spatial and temporal resolution – high enough, in an ideal case, to observe in super slow motion how individual atoms react chemically. The X-ray flashes provide unequivocal information, showing in detail how chemical bonds form and break down.

Simone Techert, leading scientist at DESY, is hoping to use the high-intensity X-ray flashes generated by the accelerators to unravel the ››

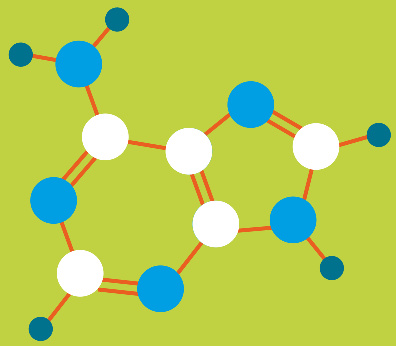


Two laser pulses are fired at a material sample in rapid succession. The first pulse triggers a reaction, the second enables observation of what happens. This process is repeated, each time varying the delay between the two pulses. The result is a series of snapshots that form a film when viewed in sequence.

STOPWATCH FOR ATOMS

Using short-pulse lasers, a research team in California led by chemist Ahmed Zewail achieved a decisive breakthrough in 1987. They developed what amounted to an ultrafast stopwatch for use in the world of atoms and molecules. The process is as follows: First, the molecules have to be brought into position, then an initial laser pulse triggers the reaction. Very shortly afterwards, a second laser pulse is fired at the molecules. This enables scientists to observe what has happened. By varying the delay between the first and the second laser pulse, it is possible to capture a snapshot of each stage of the reaction. In combination, these snapshots will yield a slide show of how the reaction progresses through all its different phases.

In 1999, Zewail was awarded the Noble Prize in Chemistry for his development of this “pump–probe” technique. His pioneering work founded a new branch of research, femtochemistry.



THE **DYNAMIC** WORLD OF BIOMOLECULES

Francesca Calegari, world-renowned expert in attosecond physics, comes to Hamburg

“An attosecond to a second is as a second to the age of the universe!” When Francesca Calegari conjures up an image of the dimensions in which her research takes place, it’s impossible not to hear a certain awe: an awe at the incredibly short time spans that can be imaged with the help of today’s sophisticated laser technology. It is this technology that enables her to investigate a crucial type of sample central to life itself: organic molecules. The 36-year-old Italian physicist is now moving from Milan to Hamburg, where she has taken up a position as leading scientist at DESY.

“An attosecond to a second is as a second to the age of the universe!”

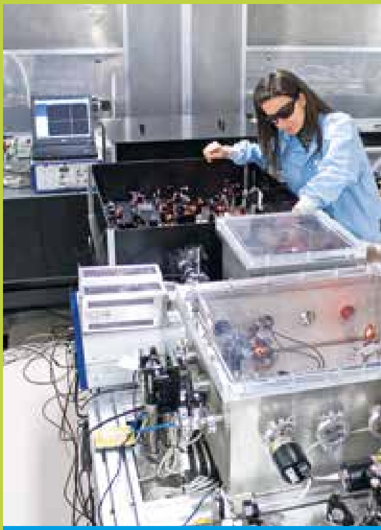
Francesca Calegari, DESY

One focus of her research is amino acids, the basic building blocks of proteins. “Amino acids such as phenylalanine are very efficient at absorbing light,” she explains. “Our experiments have shown, among other results, how the electrons in this molecule reorganise themselves after one of them has been stripped off by an extreme-ultraviolet laser pulse.” In a matter of femtoseconds, the electrical charge in the molecule begins to oscillate back and forth between two important “ends” of the amino acid. Fundamental knowledge of this kind could prove important for biological research.

Calegari now intends to continue this work in Hamburg, where she has also been appointed professor at the university. “My plan is to use ultrashort laser pulses to investigate molecules such as adenine or thymine, which are the building blocks of DNA,” she says. The results could well be useful for medical research. For example, what exactly takes place when skin cells are damaged by extensive time in the sun? Is it the initial, extremely rapid interactions between UV light and biomolecules that trigger a fatal reaction cascade? “There’s a gap in the research here that I would like to fill,” Calegari explains. “And maybe this knowledge can one day be used to control the processes that are at the beginning of the reaction chain. That might be useful in the production of new drugs.”

At present, Calegari is concluding her research projects at the Institue for Photonics and Nanotechnologies in Milan. She intends to move permanently to Hamburg at the beginning of 2018 in order to set up an ultra-modern attosecond lab. “DESY offers an extremely attractive, interdisciplinary research environment,” she says. “Here, I can collaborate with groups from a range of fields and investigate my samples using different light sources, such as FLASH and the European XFEL.” Her aim is to study the biomolecules from various points of view – complementary information produces a rounded picture.

And the move north? “Well, Hamburg isn’t an international fashion centre like Milan, but it’s a very pretty place,” she says. “It’s a lot greener here than in Milan, and I really like that.”



Francesca Calegari studies attosecond physics at DESY and is a professor of physics at the University of Hamburg.

structure of random coil proteins – i.e. proteins without a fixed structure whose functions include controlling the transport of DNA molecules. "We also use these facilities to investigate processes that are important for developing more efficient solar cells and new kinds of photocatalysts," says Techert. Photocatalysts, when exposed to light, accelerate chemical reactions and may well have therapeutic applications in medicine.

Meanwhile, the development potential of the large free-electron lasers is far from being exhausted. Here too, the trend is towards increasingly shorter X-ray pulses that are nonetheless of high intensity and still possess the desired laser properties. "In our machine studies, we've already achieved pulse lengths of well under ten femtoseconds at FLASH," explains Juliane Rönsch-Schulenburg, accelerator physicist at DESY. "This involves manipulating the electron beam so as to produce ultrashort electron bunches." These are the crucial input for producing laser pulses from the accelerator which are so short that chemical reactions can effectively be followed live.

"We investigate processes that are important for developing more efficient solar cells and new kinds of photocatalysts"
Simone Techert, DESY

A key challenge with large-scale facilities such as FLASH and the European XFEL, which is over three kilometres in length, is to ensure the precise synchronisation of the various components. To film a chemical reaction, researchers must know as precisely as possible the time delay between the laser pulse that triggers the reaction and the X-ray pulse that enables the observation of this reaction.

To this end, a team led by DESY scientist Cezary Sydlo has developed a high-precision synchronisation system. Radio frequency signals, which are otherwise used, no longer suffice to achieve the requisite accuracy on the femtosecond scale. Instead, at the European XFEL, for example, a laser acts as clock generator, repeatedly emitting optical pulses 200 femtoseconds in duration along 21 kilometres of special optical fibre installed throughout the entire facility.

Sophisticated mechanisms are in place to offset the effect on the fibres of ambient factors such as temperature, humidity and vibration, thereby ensuring that the clock signals arrive consistently on time. For this purpose, a small portion of the signals is returned from the end of the optical fibres, so as to enable the propagation time to be measured and stabilised. "We use variable optical delay lines," Sydlo explains. "This means motorised mirrors and, to balance out rapid changes, a piezoelectric element to stretch an optical fibre."

At the end of the fibres, the optical reference pulses are used to synchronise various time-critical systems. These include, in particular, the optical lasers that are used for experiments at the end of the 3.4-kilometre-long European XFEL.

To ensure that the X-ray pulses arrive at the experiment at exactly the right moment, the researchers measure the arrival time of the electron beam at a number of points. Fluctuations are unavoidable and can only be corrected at the start of the accelerator by means of extremely rapid adjustments. "This way, we're able to synchronise the X-ray pulses with the optical laser pulses to within less than ten femtoseconds. And we can do that even in facilities that are many kilometres in length," emphasises Holger Schlarb, accelerator expert at DESY.

Terahertz acceleration

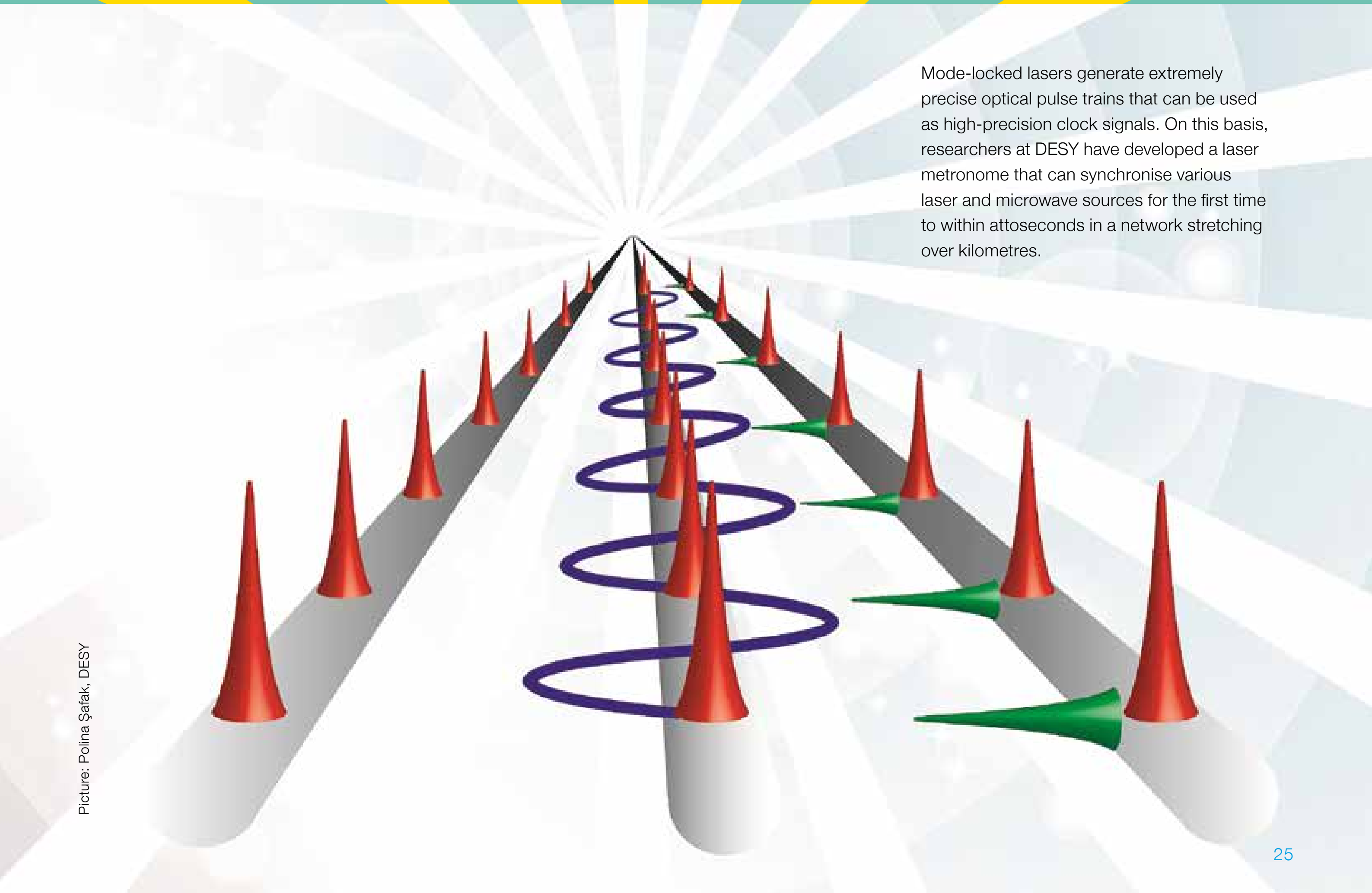
Under controlled laboratory conditions, it is now even possible to synchronise optical laser systems with one another to a precision of below one femtosecond. Using a high-precision laser metronome in a 4.7-kilometre test network for laser and microwave signals, a team around leading DESY scientist Franz Kärtner has achieved synchronisation to within 950 attoseconds, which remained stable over several hours.

"Future advances will bring this value down even further," says Kärtner. "And that could make it possible to carry out experiments at the European XFEL that are synchronised to within a few femtoseconds or even less."

Kärtner is currently working with DESY scientists Henry Chapman and Ralph Aßmann and with Petra Fromme from the Arizona State University in the USA on an extremely promising X-ray technique. Entitled "Frontiers in Attosecond X-ray Science: Imaging and Spectroscopy" (AXSIS), the EU-funded project aims to develop a method for high-resolution, super slow-motion imaging of atomic processes – chemical and biological – on a time scale of quintillionths of a second. To this end, the researchers are using new methods for accelerating electrons using terahertz radiation.

Terahertz technology is still at the experimental stage, but the prospects are highly promising. Since terahertz radiation has much shorter wavelengths than the radio frequencies used in large accelerator facilities, many of the components used in such facilities could be downsized by potentially a factor of 100. These new laser systems will generate X-ray pulses that are a mere 100 attoseconds in length but still sufficiently intense for a host of experiments. “Attosecond technology will revolutionise our understanding of structure and function on the molecular and atomic level, and help us decipher fundamental processes in biology and chemistry,” Kärtner predicts.

The X-ray pulses from the European XFEL are already a mere 100 femtoseconds in length. There are plans, however, to reduce these even further to enable experiments with an even higher temporal resolution. “Under ten femtoseconds is a real prospect for the foreseeable future,” asserts Kärtner. “And I will be very surprised if we don’t have an X-ray laser producing attosecond pulses within the next ten years.”



Mode-locked lasers generate extremely precise optical pulse trains that can be used as high-precision clock signals. On this basis, researchers at DESY have developed a laser metronome that can synchronise various laser and microwave sources for the first time to within attoseconds in a network stretching over kilometres.

Picture: Polina Şafak, DESY

THE ENERGY RESEARCH OF THE **FUTURE**

Simone Techert, who heads the Chemical Structural Dynamics group at DESY, uses ultrashort pulses of light and X-ray radiation for purposes including energy research.

femto: You've succeeded in recording a kind of "molecular movie" using X-ray flashes. How did you manage to do that?

Techert: After receiving my doctorate, I went to work at the European Synchrotron Radiation Facility (ESRF) in Grenoble, which at that time had just been put into operation and was the world's most powerful source of X-ray radiation. In the group at ESRF, we hooked up a femtosecond laser to the synchrotron. The ultrashort light pulses from this laser triggered a chemical reaction, and with the X-ray beam of the ESRF we were able to observe the progress of the reaction. Owing to the high temporal resolution, this was the first film clip showing a chemical reaction investigated by means of high-energy X-ray radiation.

femto: What kind of reaction was it?

Techert: We were investigating organic molecules that are similar to the photoreaction centre in cells or can be derived from them. This centre plays an important role in photosynthesis, the process by which plants, algae or bacteria transform sunlight into chemical energy. We were able to watch how the structure of the molecules changed after the process had been triggered by the laser pulse.

femto: For a few years now, we've had a new generation of X-ray sources, the free-electron lasers. They can generate significantly shorter X-ray flashes than ring accelerators such as the ESRF. How are you benefiting from that?

Techert: In the experiments conducted at the ESRF, we were able to study the reactions with a resolution of up to 50 picoseconds. However, this was still too slow to allow us to observe the very first steps that take place when investigating any forms of light-induced processes or chemical reactions: How are the electrons inside the molecule excited, and where do they move? Free-electron lasers enable measurements on the femtosecond time scale. This allows us to observe the very first moments of chemical reactions or of artificial systems that simulate the photoreaction centre. In this respect, we're looking forward to obtaining particular insights from the European XFEL, the world's most powerful X-ray laser. With it, measurements that require one week at other facilities can be performed in one hour.

femto: What can we do with these findings beyond acquiring a fundamental knowledge of the processes involved?

Techert: Some of the materials we examine are suitable for use in solar cells. The challenge here is the following: During natural photosynthesis, only a few percent of the light at most is transformed into energy. This is too little for solar cells, where we'd like to have an efficiency of 20 percent or even more. On the basis of our "molecular movies", we've already been able to develop molecules that have an efficiency of approximately ten percent. We've thus demonstrated that a free-electron laser can be used to carry out energy research.

femto: During the time when you had your first scientific successes, you also had your first child. How did you manage to reconcile this with your career?

Techert: I was very lucky. At that time, I was working at the Max Planck Institute for Biophysical Chemistry in Göttingen. When I had my first son, the Max Planck Institute regarded this as one more reason to set up its first in-house day-care centre. To a certain extent, that became a model for other institutions. Today, this is making it easier for young mothers – and fathers as well – to harmonise their family and career responsibilities.

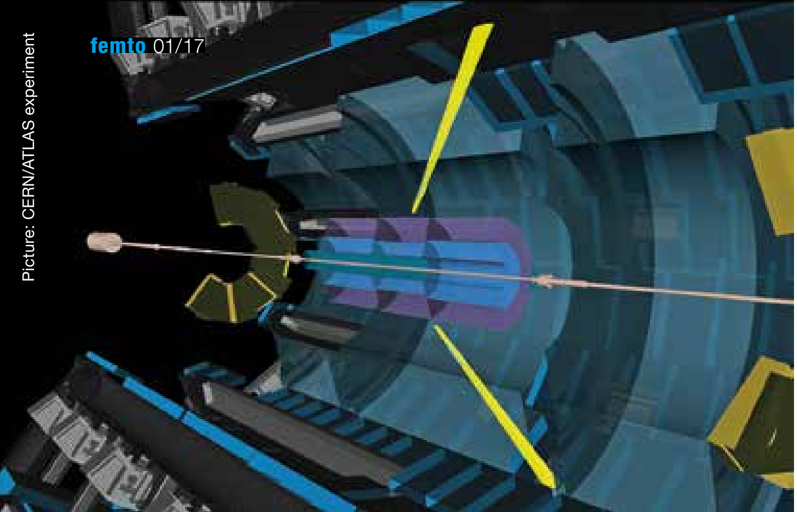
femto: All the same, is it still more difficult for women than for men to move into leading positions in the field of research?

Techert: When looking at my younger women colleagues, I do indeed observe that they need to make a bigger effort in order to receive the same degree of recognition. This is still an issue in the German research community. Nonetheless, much has been done in recent years. At DESY, in particular, there's been a lot of progress. I'm enthusiastic to see how many women occupy positions as leading scientists here today. That's really setting the pace.

femto: What still needs to be done in order to improve the situation?

Techert: For example, there are still not enough day-care opportunities or other childcare programmes. But the main problem is that today's science organisation makes family planning difficult. After receiving your doctorate, you have to hop from one temporary contract to the next. In countries such as France and the USA, the situation is better, as they provide more support for women in the field of science. There, young mothers can stay at one stage of their careers for a number of years and still move upward later on. Germany should adopt that system as a model.

Simone Techert is leading scientist of the Chemical Structural Dynamics group at DESY. She is also a professor at the University of Göttingen and head of a research group at the Max Planck Institute for Biophysical Chemistry in Göttingen.



Picture: CERN/ATLAS experiment

As the result of light-by-light scattering, two low-energy photons are observed in the ATLAS detector.

Light-by-light scattering

Scientists from the ATLAS collaboration at the Large Hadron Collider (LHC) at the CERN research centre near Geneva have found evidence for light-by-light scattering, in which two photons interact and change their trajectory. This is the first time that the phenomenon could be observed in a particle accelerator. The researchers studied the scattering in collisions of lead ions at the LHC.

"According to classical electrodynamics, beams of light pass each other without being scattered. But if we take quantum physics into account, light can be scattered by light, even though this phenomenon seems very improbable," explains Mateusz Dyndal from DESY. So far, the process had been investigated only indirectly.

Lead ions that are accelerated to nearly the speed of light produce a very strong electromagnetic field. When two such ions collide in the LHC, two photons can scatter off one another while the ions themselves stay intact. In the data taken in 2015 at the LHC, physicists at the ATLAS experiment found evidence for the phenomenon. Because the scientists observed only a few events attributed to light-by-light scattering, the statistical accuracy of their results is still limited. In four billion analysed events, only 13 candidates for such diphoton events were observed.

Molecules change shape when wet

In two studies, researchers from the Max Planck Institute for the Structure and Dynamics of Matter (MPSD) at the Center for Free-Electron Laser Science (CFEL) and from the Hamburg Centre for Ultrafast Imaging (CUI) have shown that water promotes the structural reshaping of flexible molecules. The scientists used high-resolution rotational spectroscopy to investigate the structural effects that water induces in crown ethers and biphenyl molecules.

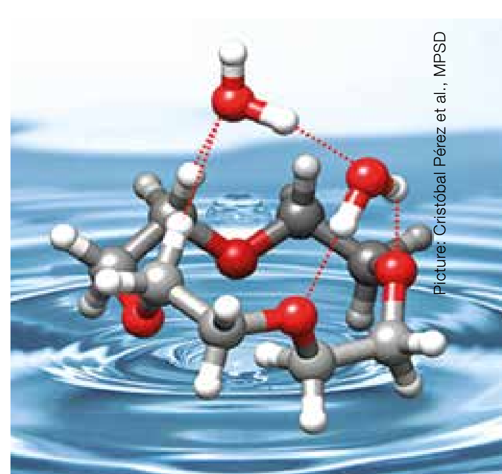
Crown ethers are cyclic molecules in a motif that resembles a crown. They are key systems in catalysis, separation and encapsulation processes. The researchers discovered that when binding to water, the crown ethers' preferred shape changes. "The unexpected structural changes induced by the hydration of the crown ethers reveals new roads for host–guest interactions to take place," says Cristóbal Pérez, scientist at MPSD.

Biphenyl-based systems are employed in drug design. They have a core consisting of two benzene (C_6H_6) rings connected by an axis. The scientists showed that when hydrated, the biphenyl system uses two water molecules to form what the authors call a "water wire". The water wire links the two rings of the biphenyl motif and consequently locks the position of the two rings with respect to each other. "The observed phenomenon provides us with new clues to how water may mediate the interactions between a molecule and its potential receptor," says Sérgio Domingos, researcher at MPSD.

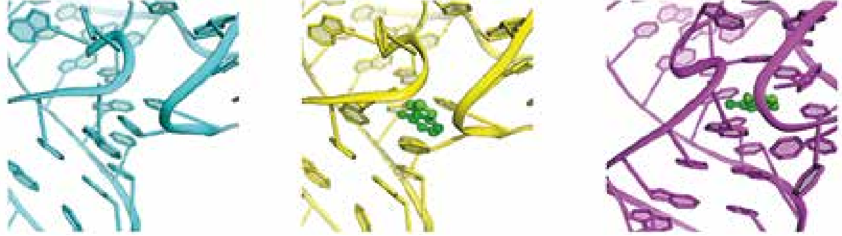
The Journal of Physical Chemistry Letters, 2016; DOI: 10.1021/acs.jpclett.6b01939

The Journal of Chemical Physics, 2016; DOI: 10.1063/1.4966584

The crowm ether's preferred structure changes when water molecules bind to it (dashed lines).



Picture: Cristóbal Pérez et al., MPSD



From left to right: the riboswitch "button" before, during and after coupling of the ligand (green)

Picture: Yun-Xing Wang & Jason Stagno, National Cancer Institute

Genetic switch in action

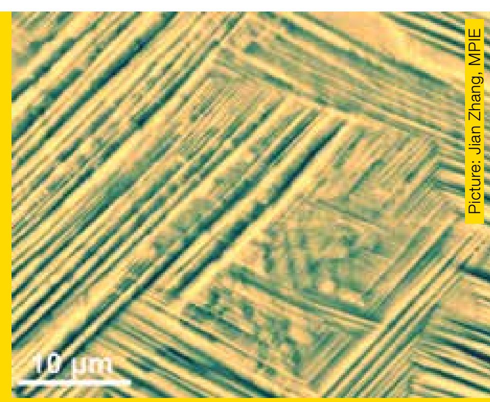
Using a powerful X-ray laser, an international team of scientists has watched a genetic switch at work for the first time. The study led by Yun-Xing Wang from the National Cancer Institute in the USA reveals the ultrafast dynamics of a riboswitch, a gene regulator that can switch individual genes on and off.

"It's the proof that the structural changes occurring in biochemical reactions or interactions between molecules can be recorded in real time with the help of powerful X-ray lasers," says DESY scientist Henry Chapman from the Center for Free-Electron Laser Science (CFEL).

The researchers studied a riboswitch from the bacterium *Vibrio vulnificus*, a close relative of the cholera germ. It can cause infections that are especially hard to treat and often fatal. To see how the switch is activated, the scientists crystallised its "button", the part where the signal molecule that activates the switch binds. In this way, the researchers discovered an intermediate state of the riboswitch that had never been seen before and that likely only exists for milliseconds in a living organism. Targeting the genetic switches in bacteria might offer a powerful weapon in the fight against diseases.

Nature, 2016; DOI: 10.1038/nature20599

New crystal structure in "gum metal"



Scanning electron microscopy image showing the different phases in the investigated "gum-type" titanium alloy

Picture: Jian Zhang, MPIE

Scientists from the Max-Planck-Institut für Eisenforschung (MPIE) in Düsseldorf, Germany, have observed a new phase transformation in a titanium alloy at DESY. The scientists used DESY's X-ray source PETRA III to examine the inner structure of a special alloy consisting of the (transition) metals titanium, niobium, tantalum and zirconium.

This titanium alloy displays some unusual mechanical properties, which have earned it the name "gum metal". "On being deformed, it does not become harder or brittle, the way metals usually do, but instead it bends, almost like honey. In scientific terms, it has a very low elastic stiffness and very high ductility," explains Dierk Raabe, director at MPIE. This makes the alloy extremely attractive for various industrial applications. In the aerospace industry, for example, it can be used as a kind of crash absorber.

It is not yet quite clear why this alloy can be deformed to such a high degree. Titanium alloys normally occur in two different phases, called alpha and beta phase. The researchers at MPIE have now discovered a new structure, the omega phase, which occurs during the transition between these two phases. The scientists are hoping that the newly discovered structure will help them to better understand the properties of this material and develop new, improved varieties of titanium alloys.

Nature Communications, 2017;
DOI: 10.1038/ncomms14210

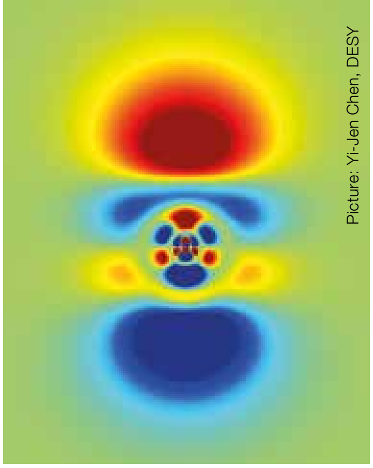
Dynamics of electron clouds

A US–German research team has elucidated the ultrafast dynamics of electron clouds in xenon atoms. Using ultrafast attosecond technology, the scientists were able to measure the reaction of the electrons to the strong electric field of an intense laser pulse in real time.

Atoms consist of a positively charged nucleus surrounded by negatively charged electrons. In the quantum physics view, the electrons form a fuzzy cloud. The physicists sent bright flashes of an infrared laser into a chamber filled with xenon atoms and recorded the reaction of the xenon electrons with an extremely fast ultraviolet camera.

The experiment yielded surprising results. The scientists had expected to observe an ionisation of the xenon atoms, i.e. that electrons would absorb the energy of the incoming light and thereby get kicked out of the atoms. "The quantum mechanical analysis showed that only a part of the so-called wave packet with which the electrons are described in quantum mechanics is actually ionised," says DESY scientist Robin Santra. "Another part is distorted by the oscillating electric field of the laser and always snaps back to its ground state when the oscillating field passes through zero. Just think of a spring that is periodically stretched and relaxed again."

Nature Physics, 2017; DOI: 10.1038/NPHYS4027



Picture: Yi-Jen Chen, DESY

Snapshot of the electron cloud of a xenon atom, deformed by the instantaneous electric field of a strong laser pulse

X-rays reveal weaving of golden coat

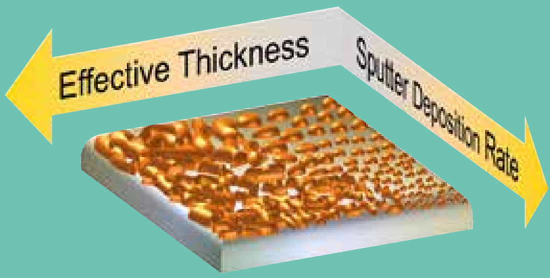
Applying nanoscale metal coatings to thin polymer films is of interest for various promising industrial applications. At DESY, scientists have now studied in real time how the structure of a fine gold coating produced by an industrially important technique known as sputter deposition can be modified.

For their study, the scientists deposited a nanolayer of gold atoms on a polymer substrate made of polystyrene and observed how different rates of sputtering affect the growth of the structures. "Sputtering gold onto a polymer is rather like a shower of gold atoms raining onto a sheet of plastic. Different structures form on the sheet, depending on whether it 'rains' harder or more gently, even when the amount of material deposited remains the same," says Matthias Schwartzkopf from DESY.

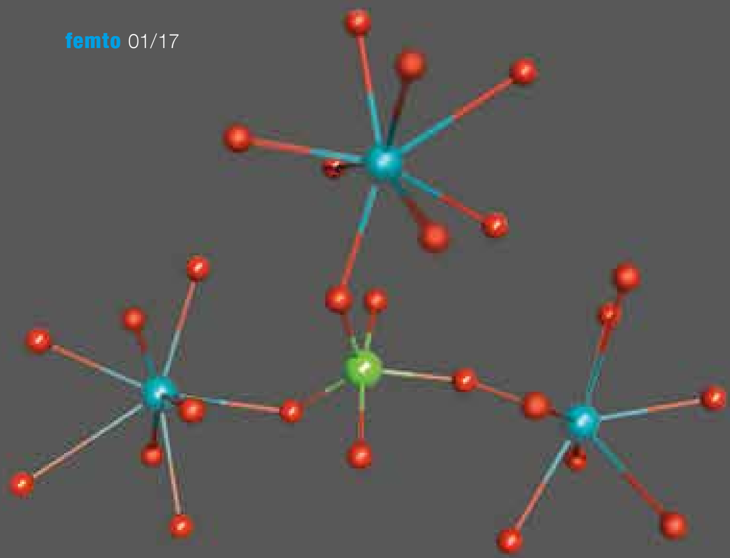
At higher deposition rates, long branching structures made of smaller clusters are formed, whereas at lower rates larger blobs emerge. This means that metal coatings created at high deposition rates are smoother and more compact. These observations allow the researchers to deduce what sputter deposition rates are best suited for specific applications. For example, if the material is to be used as a catalyst, its structure ought to consist of many small gold clusters, and this can be achieved using a high sputter rate.

ACS Applied Materials & Interfaces, 2017; DOI: 10.1021/acsami.6b15172

The structure of a gold coating depends on the sputtering speed.



Picture: Matthias Schwartzkopf, DESY



Picture: Elena Bykova, University of Bayreuth

Fragment of the crystal structure of titanium orthophosphate-V: The central phosphorus atom is shown in green, titanium atoms are blue, oxygen atoms are red.

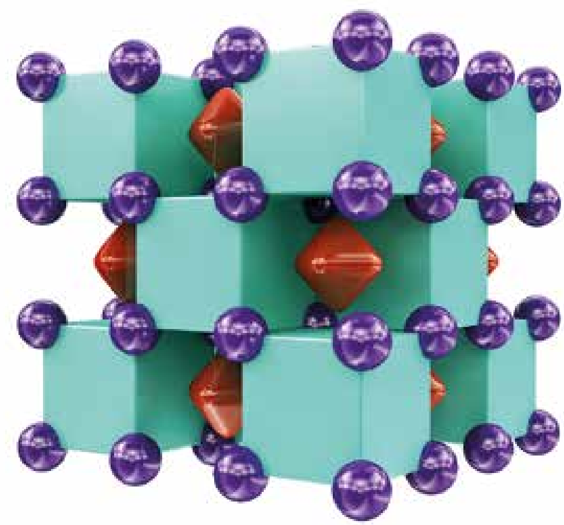
New form of phosphorus compound

Scientists have discovered a new and very unusual form of phosphorus compound. In high-pressure experiments at DESY and at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, an international research team found evidence for a special configuration where a central phosphorus atom is bound to five surrounding oxygen atoms (PO_5). Such a configuration is very rare, and it is the first time that PO_5 groups were found in an inorganic phosphate compound.

The scientists studied titanium orthophosphate at pressures of up to 56 gigapascals (GPa), which is more than 500 000 times the average pressure at sea level. Using the intense X-ray beams produced by DESY's synchrotron radiation source PETRA III, the researchers were able to distinguish and characterise four phase transitions that appeared during the compression to over half a million atmospheres. "In the last phase discovered at the highest achievable pressure, a central phosphorus atom was bound to – or coordinated by – five surrounding oxygen atoms," explains Maxim Bykov from the University of Bayreuth in Germany. Pentacoordinated (5-coordinated) phosphorus is expected to be especially chemically active and thus may play a significant role in the synthesis of novel organic or metal–organic compounds.

Angewandte Chemie, 2016; DOI: 10.1002/ange.201608530

femtomenal



Picture: Artem R. Oganov/Skoltech

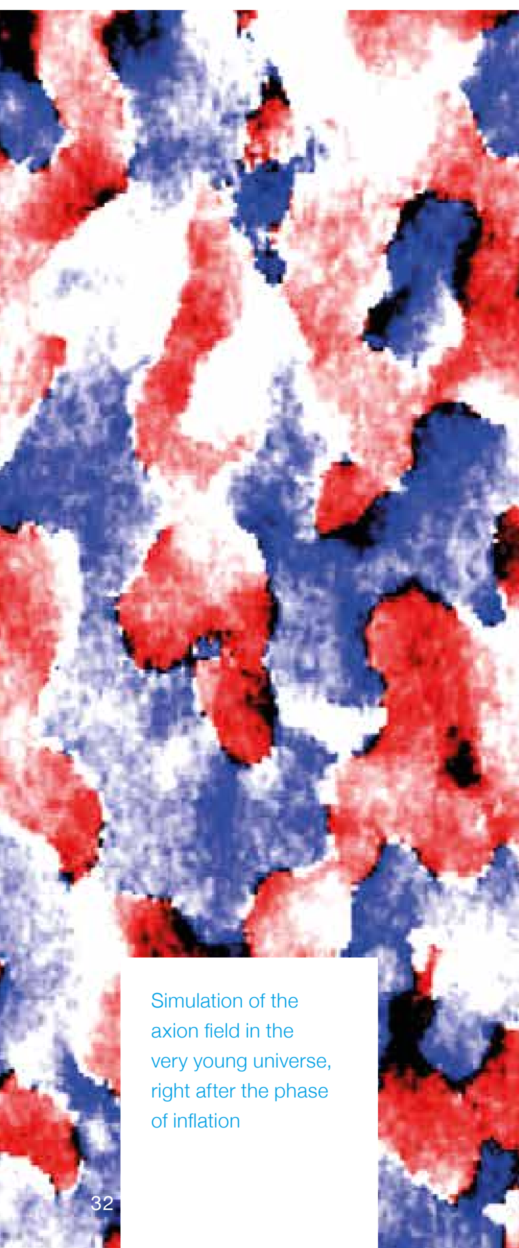
113 GIGA-PASCALS

– that's the extremely high pressure required to prompt helium to form a compound with another element, sodium. This corresponds to about 1.1 million times Earth's atmospheric pressure and shows how much you have to oppress chemically inert noble gases such as helium to induce them to a reaction. Under normal conditions, helium does not form any compounds with other elements.

All the more extraordinary is the sodium–helium crystal that researchers produced and analysed among others at a special measuring station for high-pressure experiments at DESY's X-ray source PETRA III. The results could further our understanding of the chemistry occurring inside giant gas planets and possibly even inside stars, in which high pressure reigns and helium plays a major role.

Solving five big questions in particle physics in a SMASH

Extension of the standard model provides complete description of the history of the universe



Simulation of the axion field in the very young universe, right after the phase of inflation

Particle physicists around the world are seeking for theories that could provide a more complete picture of our universe than the current standard model of particle physics. For although the standard model has always been impressively confirmed by experiments, its current version explains only about 15 percent of the matter found in the universe. It describes and categorises all the known fundamental particles and interactions, but it does so only for the type of matter we are familiar with. In contrast, astrophysical observations suggest that a mysterious kind of dark matter is more than five times as common. An international team of physicists has now come up with an extension to the standard model that could not only explain dark matter, but at the same time solve five major problems in particle physics at one stroke.

Astrophysical measurements indicate that there must be more to the universe than the familiar matter of which stars, planets, plants and humans are made. The most prominent example is that some galaxies rotate so fast that they should actually fly apart. An unknown and invisible mass must hold these galaxies together with its additional gravitational pull. This enigmatic dark matter makes itself felt only through its gravitational effects, it emits no light and absorbs none. What it consists of remains a complete mystery. According to measurements, it is over five times more common than the familiar matter, making it the second-largest component of the universe after the equally mysterious dark energy, which appears to make the universe expand ever faster. In addition, there are many other observations that have physicists puzzling. Researchers around the world are therefore on the lookout for physics beyond the standard model that could explain theses phenomena.

Picture: SMASH

An answer to the open questions in particle physics?

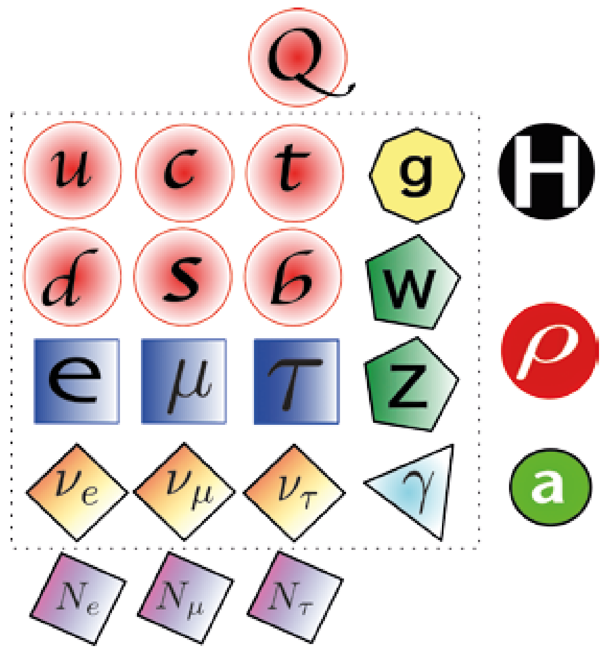
A new model is now attempting to solve five major problems in particle physics at once with a relatively small extension of the standard model. Guillermo Ballesteros from the University of Paris-Saclay and his colleagues presented their SMASH (Standard Model Axion Seesaw Higgs portal inflation) model in the journal *Physical Review Letters*. SMASH is intended to answer the following fundamental questions:

1. What is dark matter made of, which, according to high-precision measurements by the European satellite "Planck", must account for almost 85 percent of the entire mass of the universe, but which has so far remained hidden from the researchers' eyes?

2. Shortly after the formation of the universe, its size increased by a factor of at least a hundred million billion billion (10^{26}) in just fractions of a second. Why did the universe expand so rapidly in this phase of cosmic inflation?

3. The formation of the universe should have created as much antimatter as matter. The antimatter seems to have disappeared, however. How could this imbalance arise?

4. According to the standard model, the ghostly neutrinos should have no mass – contrary to experimental observations. Where does the mass of the neutrinos come from?



Picture: Guillermo Ballesteros, University of Paris-Saclay

The standard model of particle physics comprises all the known building blocks of matter and the forces that hold them together. The matter particles are six quarks (in red) and six leptons (in blue and orange). The force particles are the gluon for the strong interaction (yellow), the *W*- and *Z*-boson for the weak interaction (green) and the photon (light blue) for the electromagnetic interaction. The Higgs particle (black) is responsible for the mass of the particles. SMASH adds six new particles to this kit: three neutrinos (purple), a quark (*Q*, red), the axion (light green) and the rho (dark red).

5. In the strong interaction, one of the four fundamental forces of nature, a much too small violation of the so-called time reversal symmetry has so far been observed. That is, processes are running forwards almost in the same way as backwards. Actually, from various theoretical considerations, this should not be the case. What is conserving time reversal symmetry?

To solve all these puzzles, SMASH requires only six new particles. This is relatively little, especially when compared to models of supersymmetry, which include a multitude of new particles. "SMASH was actually developed from the bottom up," explains DESY scientist Andreas Ringwald. "We started off with the standard model and only added as few new concepts as were necessary in order to answer the unresolved issues." To do this, the scientists combined various existing theoretical approaches and came up with a simple, uniform model. Each new particle fulfils a certain function to resolve the open issues.

> *"We started off with the standard model and only added as few new concepts as were necessary to answer the unresolved issues"*
>
> *Andreas Ringwald, DESY*

Three new neutrinos are required to explain the mass of the neutrinos. As heavy particles, they form sort of a counterpart to the known light neutrinos. The corresponding mechanism is appropriately named "seesaw mechanism". At the same time, the decay of the heavy neutrinos at a certain moment in the history of the universe causes ›› the predominance of matter over antimatter. Regarding the other three problems, a new field that pervades the whole universe plays a crucial role. This field assumes very large values in the early universe, and the related large field energy leads to cosmic inflation. At the same time, the field contains a lightweight particle, the axion, which solves two further problems: On the one hand, it forms dark matter, and on the other hand, in conjunction with an additional quark, it explains time reversal symmetry.

A consistent description of cosmic history

To make the total of six new particles complete, the three neutrinos, the axion and the new quark are complemented by a heavy particle called ρ (rho), which is also included in the new field. Central to SMASH is also a new global symmetry that was broken very early on during the cooling of the universe, whereby the newly posited particles gained their mass. This mechanism resembles the Higgs mechanism by which the standard-model particles get their mass. "Overall, the resulting description of the history of the universe is complete and consistent, from the period of inflation to the present day," emphasises Ringwald. "And unlike many older models, the individual important values can be calculated to a high level of precision, for example the time at which the universe starts heating up again after inflation."

This leads to a further strength of the theory: The model can be tested experimentally in a relatively straightforward manner. In contrast, one big problem of the many proposed extensions of the standard model is that they are often very complicated to check. There are many different theoretical concepts that all offer explanations for various phenomena and extend the standard model in a meaningful way, but that could so far neither be confirmed nor refuted. With SMASH, various predictions could potentially be tested in experiments relatively soon, perhaps even in the next ten years.

"The good thing about SMASH is that the theory is falsifiable. For example, it contains very precise predictions of certain features of the cosmic microwave background," explains Ringwald. The cosmic microwave background fills the entire cosmos. It emerged when the universe became transparent almost 400 000 years after the big bang. "Future experiments that measure this radiation with even greater precision could therefore soon rule out SMASH – or else confirm its predictions," says Ringwald.

A further critical test of the model is the search for axions. In order to detect these postulated particles, it is very helpful to know which mass to look for.

"The resulting description of the history of the universe is complete and consistent, from inflation to the present day"

Andreas Ringwald, DESY

Otherwise the search could take a very long time, because one would have to scan far too large a range. The expected mass of a particle essentially determines the physicists' search strategy. The fact that SMASH can provide an accurate prediction of the axion mass is owing to an elaborate supercomputer calculation published in the journal *Nature* by a team led by Zoltán Fodor of the University of Wuppertal, Eötvös University in Budapest and Forschungszentrum Jülich.

DESY scientist Andreas Ringwald is working in theoretical physics.

Searching for the mass of the axion

It's not only the SMASH researchers who are keen to obtain precise values for the mass of this so far hypothetical particle. Axions are posited in many theories as an explanation of dark matter. This is because dark matter can either consist of comparatively few, but very heavy particles, or of a large number of light ones. The direct searches for heavy dark matter candidates using large detectors in underground laboratories and the indirect searches for them using large particle accelerators are still ongoing, but have not turned up any dark matter particles so far. A range of physical considerations make the extremely light axions very promising candidates. The search for them has hitherto been hampered by the fact that calculating their mass is very complicated.

Using the Jülich supercomputer JUQUEEN (BlueGene/Q), the researchers around Fodor have now calculated an extension of quantum chromodynamics (QCD), the quantum theory of the strong interaction. Much like SMASH, this extension provides a solution to the problem of time reversal symmetry. ››

Light shining through a wall

ALPS II is searching for axion-like particles

At DESY, new extensions to the standard model are not only being conceived in theory, but also tested in experiments. The ALPS (Any Light Particle Search) experiment is looking for so-called axion-like particles, which are extremely light and interact only very weakly with other particles, more faintly even than the ghostly neutrinos do. Their existence could account for two unexplained cosmic phenomena: "On the one hand, astrophysical observations show that extremely energetic photons, i.e. particles of light, propagate much further in the universe than should actually be possible. And on the other hand, stars seem to radiate energy in a previously unknown form," reports Axel Lindner, spokesperson of the ALPS experiment.

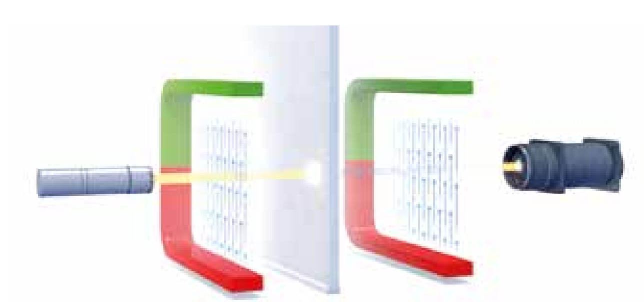
Because these hypothetical particles interact so weakly, however, it is very difficult to detect them. ALPS therefore exploits a specific property predicted for the particles. In rare cases, photons in a strong magnetic field could transform into the axion-like particles and vice versa. This leads to an experiment that is basically simple, but complicated to put into practice: Between two long rows of magnets, light from a strong laser is shone onto a light-tight wall. "If the theory is correct, individual light particles in the magnetic field are transformed into axion-like particles, pass through the wall and then change back into photons again behind the wall," explains Lindner. At the end of the setup, a highly sensitive detector is waiting to record the photons.

The experiment uses so-called dipole magnets from the large HERA accelerator, which was in operation at DESY until 2007. From 2007 to 2010, ALPS I already ran with this setup. ALPS II will now significantly increase the sensitivity of the search. The laser is stronger, many more magnets are lined up, and the detector is even more sensitive. In addition, ALPS II uses a technology that has also played an important role in the discovery of gravitational waves: optical resonators that increase the likelihood that photons and axion-like particles are transformed into each other before and after the wall.

The development of the individual components of ALPS II is almost completed. The experiment is to be built over the next two years, and data taking could begin at the end of 2019 at the earliest. "If everything goes well, ALPS II will be more sensitive than any other experiment in this area," says Lindner. "Then we can scan the mass range from zero mass to about 100 microelectronvolts and also take a look at the parameter range suggested by astrophysics." Apart from DESY, the Albert Einstein Institute in Hannover, the Universities of Hamburg and Mainz in Germany and the University of Florida in Gainesville, USA, are also involved in the experiment.

Aaron Spector, postdoc at the University of Hamburg, working on the ALPS optics

Picture: Marian Dürbeck, ALPS



Picture: DESY/ALPS

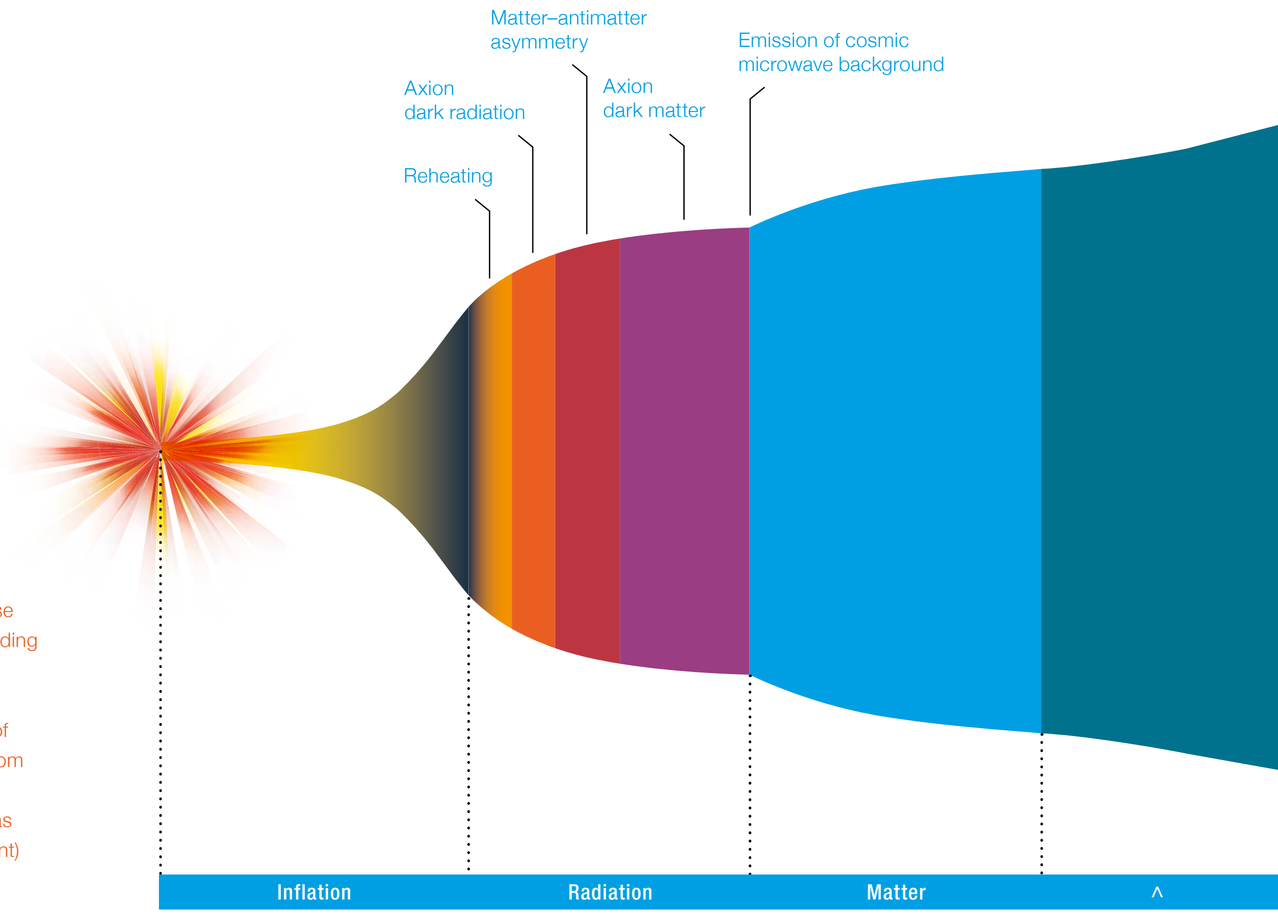
The principle of the ALPS experiment: A light beam is directed between magnets onto a wall. In the magnetic field, individual photons should be converted into axion-like particles and thus pass through the wall. Behind the wall, they should be converted back into photons in a further magnetic field, before being recorded by a detector.

"There are so-called topological quantum fluctuations in quantum chromodynamics that ought to result in an observable violation of time reversal symmetry," explains Ringwald, who was also involved in this study. The proposed extension compensates for these violations of time reversal symmetry by the quantum fluctuations, but at the same time predicts the existence of a very weakly interacting particle, the axion.

The results show, among other things, that if axions do make up the bulk of dark matter, they should have a mass of 50 to 1500 micro-electronvolts, expressed in the customary units of particle physics, and thus be up to ten billion times lighter than electrons. This would require every cubic centimetre of the universe to contain on average ten million such ultra-lightweight particles. Dark matter is not spread out evenly in the universe, however, but forms clumps and branches in a weblike network. Because of this, our local region of the Milky Way should contain about one trillion axions per cubic centimetre. Within the framework of SMASH, an even smaller mass range is obtained for the axions, as specific variables that influence the value of the mass are determined more precisely in the model. According to SMASH, the axion mass should be between 50 and 200 microelectronvolts.

These predictions provide physicists with a concrete range in which their search for axions is likely to be most promising. "The results we are presenting will probably lead to a race to discover these particles," says Fodor. Their discovery would not only solve the problem of dark matter in the universe, but at the same time answer the question why the strong interaction is so surprisingly symmetrical with respect to time reversal. In addition, it would be a first step towards the confirmation of the SMASH model. Thus, it could soon become clear whether SMASH is just one theory among many, or a great advance on our way to a complete understanding of our universe.

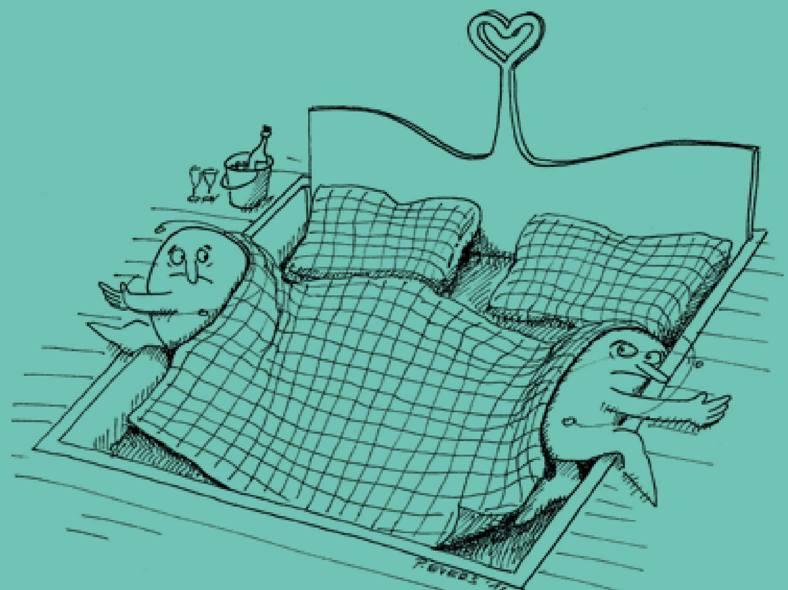
> *"The results we are presenting will probably lead to a race to discover these particles"*
>
> *Zoltán Fodor, University of Wuppertal*



The history of the universe since the big bang according to SMASH, denoting the different phases and the dominant energy forms of the various epochs (bottom line, the letter lambda represents dark energy as the cosmological constant)

Partnership at a distance

Deep-frozen helium molecules enable precise test of quantum mechanical tunnel effect at DESY's X-ray laser FLASH



Helium atoms are loners. Only when you cool them to very low temperatures do they form extremely weakly bonded molecules. Yet even in this state, they are able to maintain an extremely large separation from each other thanks to quantum tunnelling. With the help of DESY's X-ray laser FLASH, nuclear physicists from the Goethe University in Frankfurt am Main, Germany, have been able to confirm that the atoms spend more than 75 percent of their time so far apart from each other that their bond can only be explained by means of quantum tunnelling.

The binding energy of a helium molecule is approximately one billionth of the binding energy of everyday molecules such as oxygen or nitrogen. On top of this, the molecule is so huge that small viruses or soot particles could actually pass between the atoms. Physicists explain this in terms of quantum tunnelling. They visualise the bond in a classical molecule as a potential well, in which atoms cannot get further apart from each other than by going to opposite "walls" of the well. However, quantum theory also allows atoms to tunnel into these walls. "It is as if each of them were to dig a shaft without an exit," explains Reinhard Dörner, a professor at the Institute of Nuclear Physics at the Goethe University.

Dörner's group produced these helium molecules in an experiment and studied them using the COLTRIMS reaction microscope developed at the Goethe University. They determined the strength of the bond in COLTRIMS measurements at FLASH with hitherto unparalleled precision and measured the distance between the two atoms forming the molecule. "In a sense, the helium molecule is a touchstone for quantum theory, because the binding energy predicted by theory is extremely sensitive to how carefully all the different physical and quantum mechanical effects have been taken into account," says Dörner.

Even the theory of relativity, which is otherwise used primarily for astronomical calculations, needs to be included. "The smallest error in the calculations can lead to large deviations in the results or they may even predict that the helium molecule cannot exist at all," notes Dörner. The high-precision measurements carried out by his group will serve as a reference for future experiments.

The findings form part of the research for which the group was awarded the 2016 Helmholtz Prize in Metrology, which is presented by the independent Helmholtz Fund.

PNAS, 2016; DOI: 10.1073/pnas.1610688113

Spectacles for X-ray lasers

Tailor-made corrective glasses permit unparalleled focusing of X-ray beam

DESY scientist Andreas Schropp researches X-ray optics.

An international team of scientists has tailored special X-ray glasses to concentrate the beam of an X-ray laser stronger than ever before. The individually produced corrective lens, which was developed by a team around DESY scientist Christian Schroer, eliminates the inevitable defects of the previously used X-ray optics stack almost completely and focuses three quarters of the X-ray beam to a spot of 250 nanometres (millionths of a millimetre) diameter, thereby closely approaching the theoretical limit. The strongly focused X-ray beam can improve the quality of certain measurements and even open up entirely new research avenues.

"Since the wavelength of X-rays is very much smaller than that of visible light, manufacturing X-ray optics calls for a far higher degree of precision"

Andreas Schropp, DESY

Although X-rays obey the same optical laws as visible light, they are difficult to focus or deflect: "Only a few materials are available for making suitable X-ray lenses and mirrors," explains Andreas Schropp from DESY. "Also, since the wavelength of X-rays is very much smaller than that of visible light, manufacturing such X-ray optics calls for a far higher degree of precision than is required in the realm of optical wavelengths – even the slightest defect in the shape of the lens can have a detrimental effect."

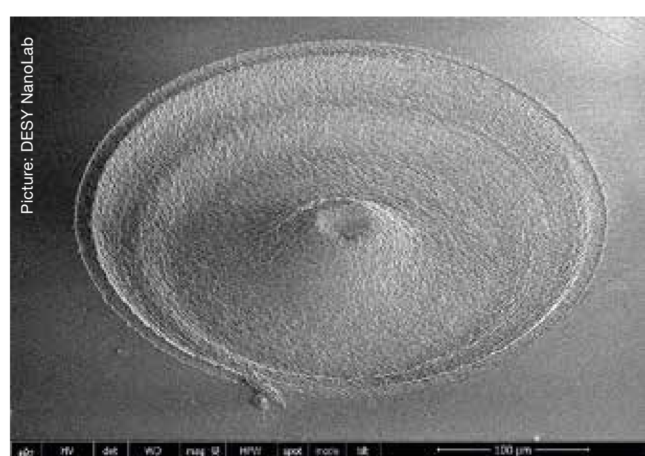
The production of suitable lenses and mirrors has already reached a very high level of precision, but the standard lenses, made of the element beryllium, are usually slightly too strongly curved near the centre, as Schropp notes. "Beryllium lenses are compression-moulded using precision dies. Shape errors on the order of a few hundred nanometres are practically inevitable in the process." This results in more light scattered out of the focus than unavoidable due to the laws of physics. What's more, this light is distributed quite evenly over a rather large area.

Such defects are irrelevant in many applications. "However, if you want to heat up small samples using the X-ray laser, you want the radiation to be focused on an area as small as possible," says Schropp. "The same is true in certain imaging techniques, where you want to obtain an image of tiny samples with as much details as possible."

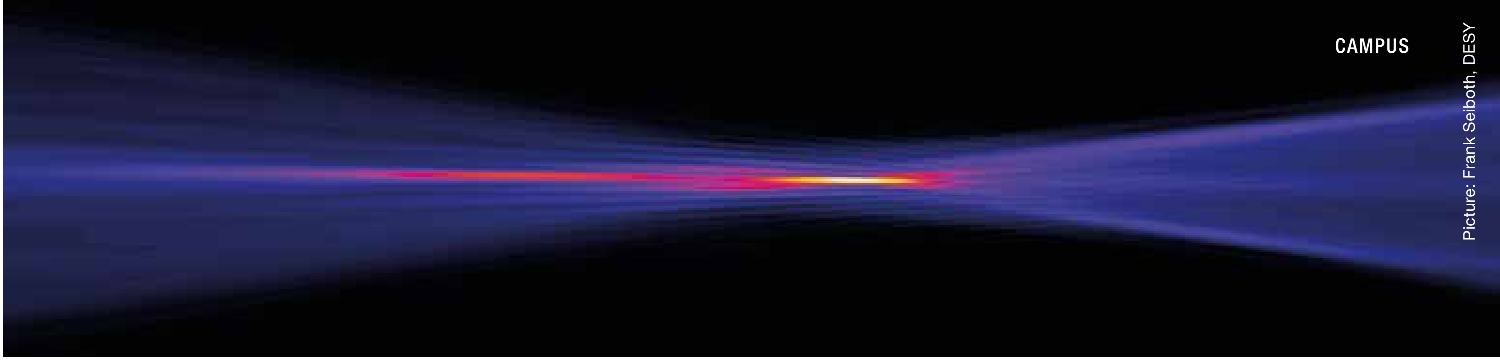
Concentrating X-rays in a tiny space

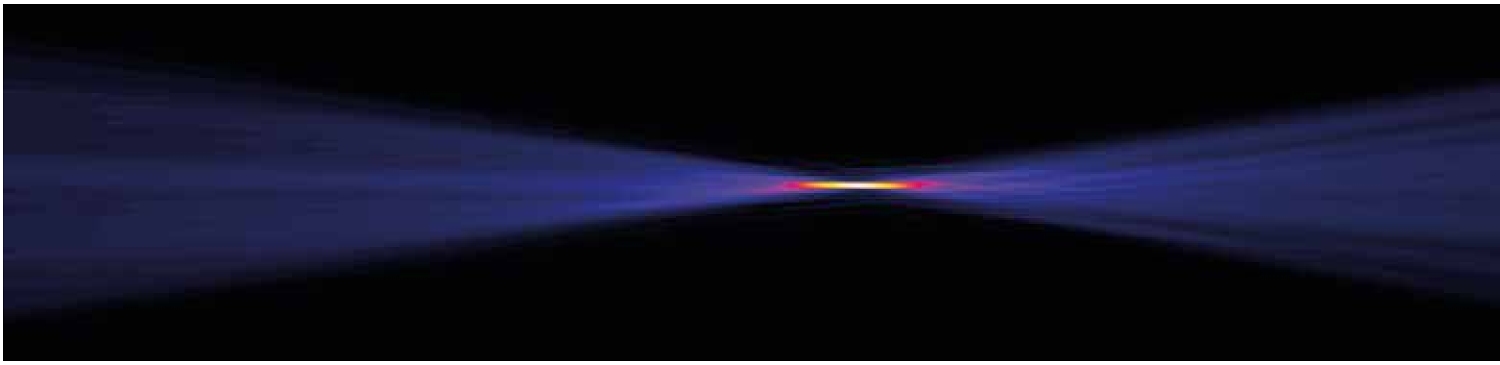
In order to optimise the focusing, the scientists first meticulously measured the defects in their portable beryllium X-ray lens stack. They then used these data to machine a customised corrective lens out of quartz glass by means of a precision laser at the University of Jena in Germany. The effect of these glasses was then tested using the LCLS X-ray laser at the SLAC research centre in the USA.

"Without the corrective glasses, our lens focused about 75 percent of the X-ray light onto an area with a diameter of about 1600 nanometres. That is about ten times as large as theoretically achievable," reports principal author Frank Seiboth from the Technical University of Dresden in Germany, who now works at DESY.



The X-ray spectacles under an electron microscope





Picture: Frank Seiboth, DESY

Profile of the focused X-ray beam, without (top) and with (bottom) the corrective lens

“When the glasses were used, 75 percent of the X-rays could be focused onto an area of about 250 nanometres in diameter, bringing it close to the theoretical optimum.” With the corrective lens, about three times as much X-ray light was concentrated in the central part of the focus than without it. In contrast, the full width at half maximum (FWHM) of the focused X-ray beam – the scientific measure of focus sharpness, describing the limit at which the brightness inside the X-ray beam drops to half its maximum value – did not change much and remained at about 150 nanometres, with and without the corrective lens.

The team studied the same combination of mobile standard optics and tailor-made glasses at DESY’s synchrotron X-ray source PETRA III and at the Diamond Light Source in the UK. In both cases, the corrective lens led to a comparable improvement to that seen at the X-ray laser. “In principle, our method allows an individual corrective lens to be made for every X-ray optics,” explains lead scientist Schroer, who is also a professor of physics at the University of Hamburg.

“These so-called phase plates can not only benefit existing X-ray sources, but could in particular become a key component of next-generation X-ray lasers and synchrotron light sources,” emphasises Schroer. “Focusing X-rays to the theoretical limits is not only a prerequisite for a substantial improvement in a range of different experimental techniques; it can also pave the way for completely new methods of investigation. Examples include the non-linear scattering of particles of light by particles of matter, or creating particles of matter from the interaction of two particles of light. For these methods, the X-rays need to be concentrated in a tiny space, which means efficient focusing is essential.”

“In principle, our method allows an individual corrective lens to be made for every X-ray optics”

Christian Schroer, DESY

Nature Communications, 2017; DOI: 10.1038/ncomms14623

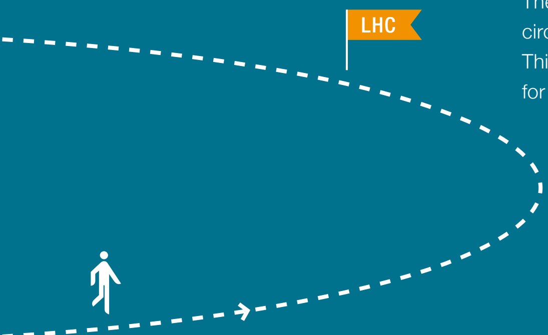
femtofinale

More pixels for new physics

With a height of 15 metres, the ***CMS detector*** is as high as a ***multi-storey house***. It weighs 14 000 tonnes, which makes it the heaviest detector ever built at a particle accelerator.

01 LARGE HADRON COLLIDER LHC

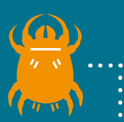
The Large Hadron Collider (LHC) at the CERN research centre near Geneva is the world's largest particle accelerator. Scientists investigate the fundamental building blocks and processes in the universe by making protons – building blocks of atomic nuclei – collide inside the LHC at highest energies.



The LHC accelerator ring has a circumference of ***27 kilometres***. This corresponds to ***a day's march*** for a human.

02 CMS DETECTOR

The CMS detector is one of the four large detectors with which scientists are searching for new particles and phenomena generated in the collisions inside the LHC.



The individual ***pixels*** have a surface of 0.1 times 0.15 square millimetres, which is about the size of a ***dust mite***.

04 PIXELS

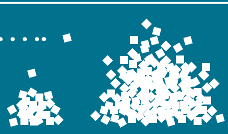
Each module accommodates 66 650 pixels, distributed over 16 chips. Each pixel can measure one signal. A cable relays the signals measured in one module.

03 PIXEL DETECTOR

During the latest shutdown period of the LHC, the innermost part of CMS – the pixel detector – was replaced. It surrounds the beam pipe at a distance of only a few centimetres and measures the tracks on which charged particles fly away from the collision point.

The new pixel detector is made up of 1856 individual modules on which the measuring units (pixels) are located. Each ***module*** is about as large as a ***visit card***.

05 UPGRADE



Boasting 124 million pixels instead of the previous 66 millions, the upgraded pixel detector can collect twice as much data as before. In addition, it processes the data faster. DESY and the University of Hamburg were strongly involved in the upgrade.

AND WHAT FOR?

in the course of its operating time, the LHC achieves ever higher collision rates (luminosity), which is why the pixel detector must process more and more data at the same time. It has been upgraded in order to meet these higher rates. In addition, the particle tracks can now be reconstructed more precisely.

More pixels to unravel the mysteries of the big bang and the universe.

Imprint

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