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The DESY research magazine – Issue 02/15

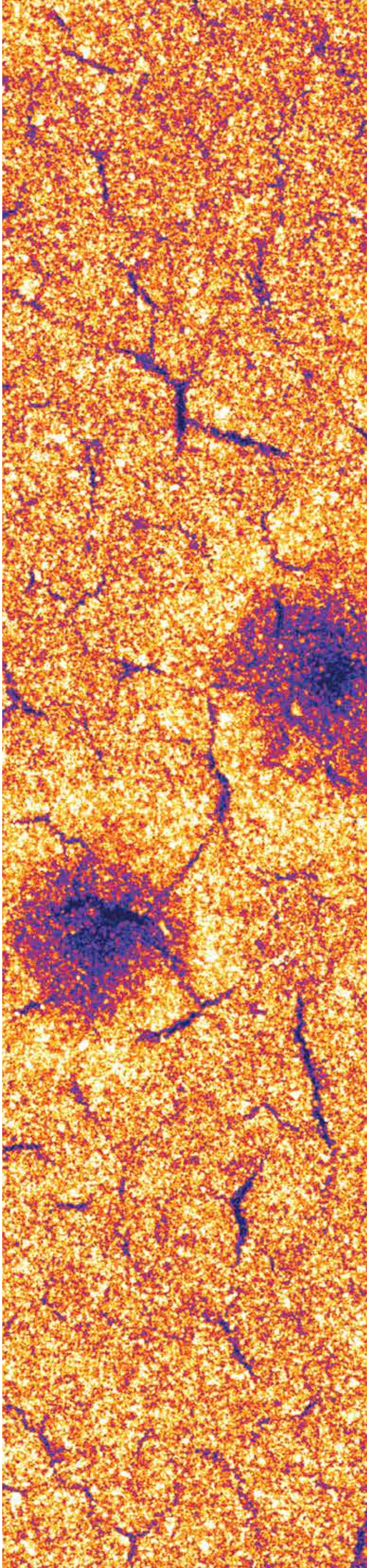
IN THE LIGHT OF RESEARCH

CHOCOLATE IN X-RAY LIGHT

SHOCKED DIAMONDS

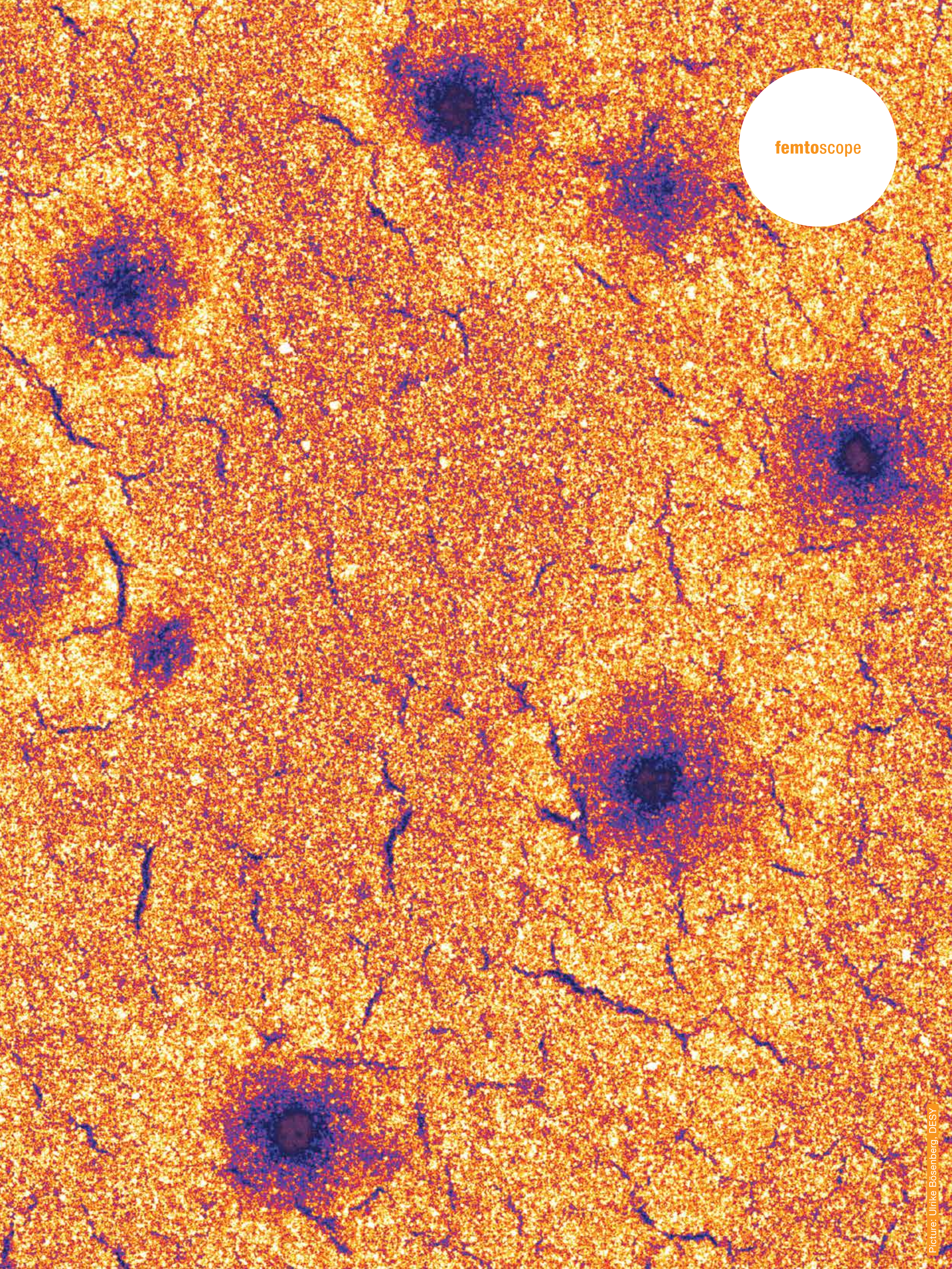
STARDUST IN THE LAB

DESY



Aging batteries

Charging lithium-ion batteries too quickly can permanently decrease their energy storage capacity. That's because the process destroys and deactivates part of the battery's structure. DESY researcher Ulrike Bösenberg and her team were the first to investigate structural changes of this kind at the X-ray source PETRA III. After only a few charging cycles, they detected unmistakable damage to the battery material's inner structure – damage that did not occur during slow charging. After 25 fast-charging cycles, the distribution of manganese in the battery's electrode showed clearly detectable gaps. The lithium–nickel–manganese oxide materials that the team investigated are promising candidates for a new generation of high-power energy storage devices.



Picture: Ulrike Bösenberg, DESY

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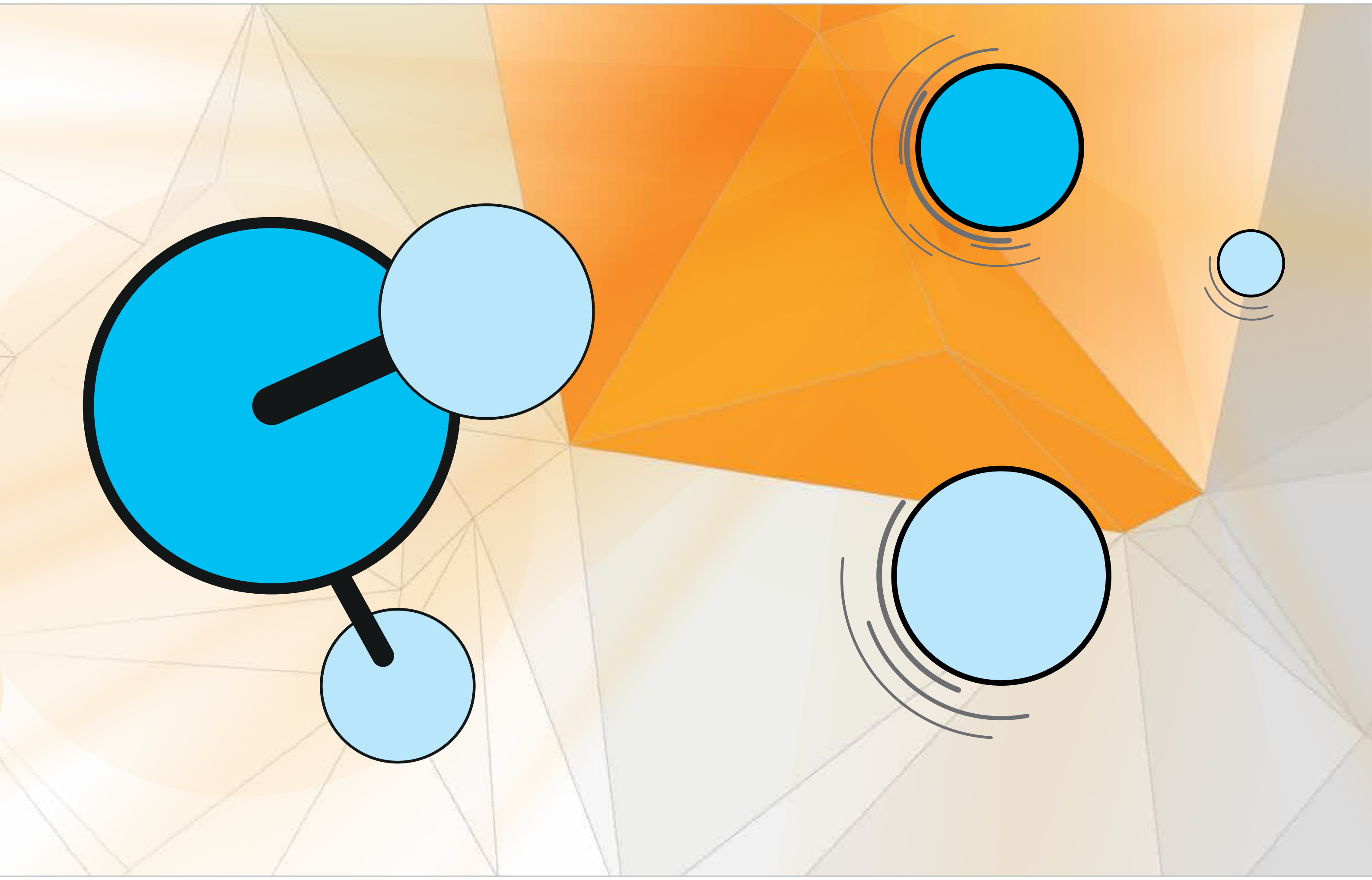
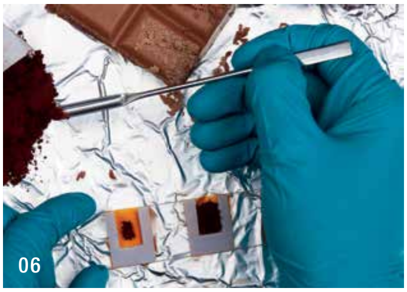


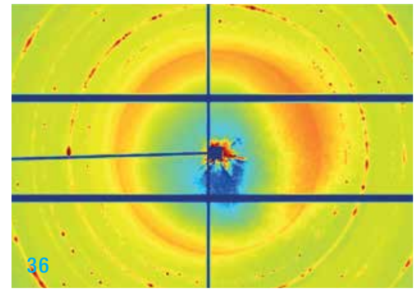
ZOOM

In the light of research

Atoms seen with X-ray vision, a universe full of gamma radiation

Light shapes our perception of the world. We experience infrared radiation as heat and ultraviolet radiation sometimes as a painful sunburn. However, our senses perceive only a tiny segment of the light spectrum. Over the centuries, scientists have learned how to use almost the entire electromagnetic spectrum. State-of-the-art supermicroscopes exploiting short-wavelength X-ray light enable researchers to investigate the infinitesimal world of atoms and molecules, the basic building blocks of matter. Astronomers are gaining new insights into the universe by using light of various wavelengths, ranging from the cosmic background radiation in the microwave band to high-energy gamma radiation.



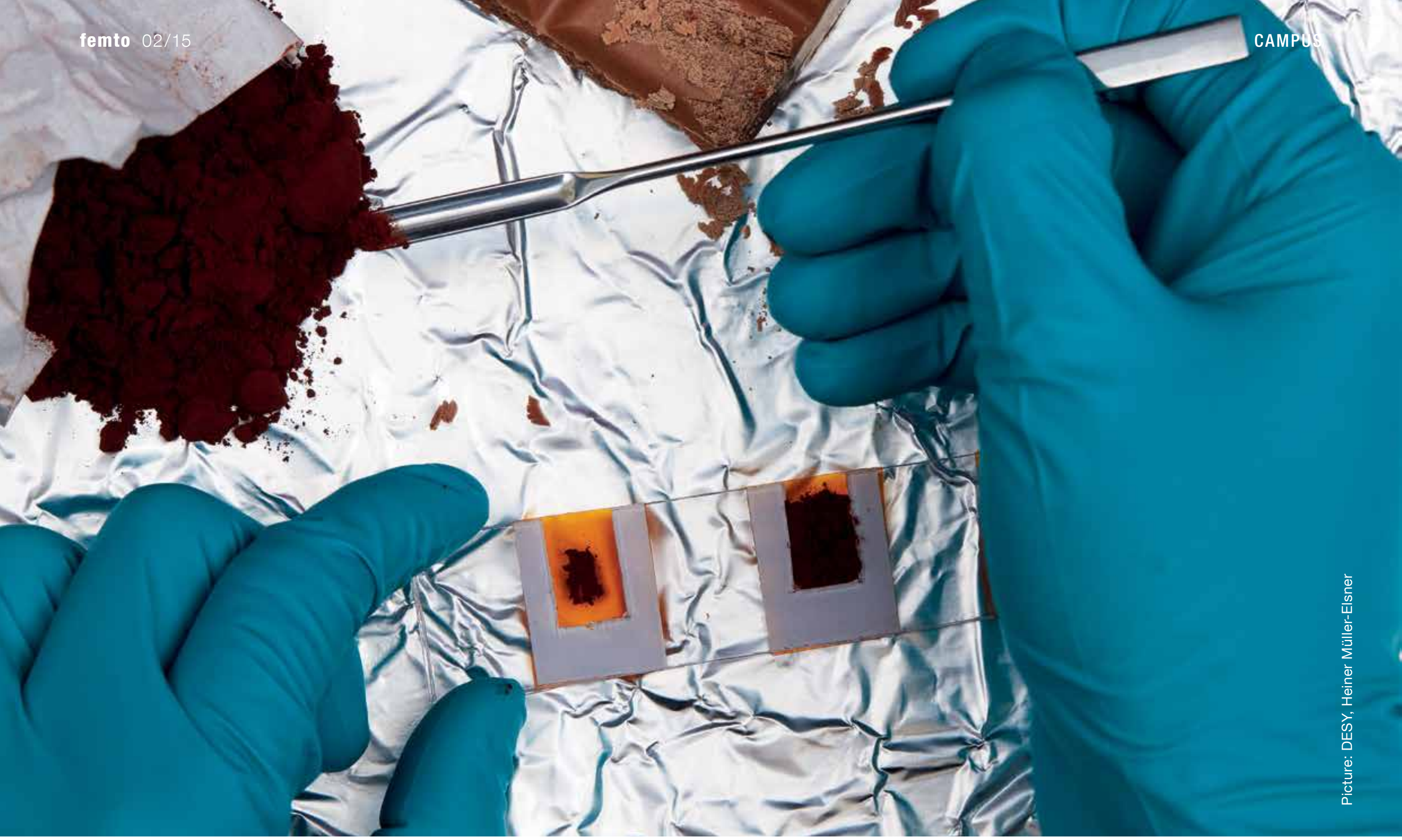


CAMPUS

ZOOM

SPECTRUM

SECTIONS



A sample carrier is filled with powdered chocolate.

Chocolate in X-ray light

Finding ways to avoid undesirable fat bloom

Chocolate should be melt-in-your-mouth, chocolatey and luscious – just waiting to be eaten! What it shouldn't have is a whitish fatty coating, which sometimes appears on chocolate and doesn't look very appetising. A team of researchers from the Hamburg University of Technology (TUHH), DESY and the Nestlé food company has been looking for the causes of this coating, which is known as fat bloom, with the help of the intense X-ray radiation generated by DESY's research light source PETRA III.

"Fat bloom is completely harmless, but it leads to millions of euros' worth of losses in the food industry, because factory rejects and products that receive customer complaints have to be scrapped," explains Svenja Reinke from the TUHH. "Nonetheless, we know relatively little about the processes that cause it."

"Fat bloom is one of the most important quality defects in the confectionery industry"

Stefan Palzer, Nestlé

Fat bloom can form when liquid fat, for example from cocoa butter, moves from the interior to the surface of the chocolate and crystallises there. "This can happen when liquid chocolate cools off erratically and unstable crystal structures are formed. In addition, a quarter of the fats in chocolate are already liquid at room temperature," she adds. Liquid fillings and components such as nougat accelerate the formation of fat bloom.

The longer chocolate is stored, the more time the fat has to migrate.

That's why white spots are often interpreted to mean the chocolate has passed its "best by" date. "Although the fat bloom does not mean the product is actually spoiled, its unattractive appearance leads to a large number of consumer complaints," explains Stefan Palzer from the company Nestlé. "That's why fat bloom is one of the most important quality defects in the confectionery industry."

The researchers at DESY's X-ray radiation source PETRA III have now been able to observe the processes causing this phenomenon "live" for the first time. They examined samples of the individual components of chocolate, for example mixtures of sugar and cocoa butter, or milk powder and cocoa butter, or cocoa and cocoa butter. The samples were ground into a fine powder in order to speed up the processes, and the bright X-ray light was shone through them. "The investigation technique shows us the fat crystals as well as the pores in the chocolate, down to a size of just a few nanometres," reports the head of the study, Stefan Heinrich from the TUHH.

In order to investigate the migration of the fat, the researchers dropped some sunflower oil on each of their samples and observed the results. "One thing we observed was a wetting process that took place within seconds. The oil penetrates into even the smallest pores very quickly, presumably through capillary forces," says Reinke. In addition, the liquid fat changes the internal structure of the chocolate. "Over a period of hours, the liquid fat dissolves additional fat crystals, and that softens the entire structure of the chocolate. That, in turn, increases the fat migration."

The precise course of these processes was not previously known. The study thus supplements earlier investigations of the crystal structure in fat bloom. "This was the first time we could directly observe in detail the dynamic mechanisms that lead to the formation of fat bloom," explains DESY researcher Stephan Roth. "The method we used – small-angle X-ray scattering – is exactly right for real-time investigations of this kind and for observing the structural changes caused by the oil. This joint study is giving us valuable information about how we can investigate structural changes in such 'everyday' multi-component systems."

The observations give the food industry concrete possible approaches to reducing fat bloom. "One of the resulting approaches might be to limit the porosity of the chocolate during the production process so that the fat migrates more slowly," Reinke says. "Another one is to limit the proportion of

"This was the first time we could directly observe in detail the dynamic mechanisms that lead to the formation of fat bloom"

Stephan Roth, DESY

liquid by storing the chocolate in an environment that is cool, but not too cold. A temperature of 18 degrees Celsius is ideal." Chocolate reacts very sensitively to changes in temperature. "A shift of just a few degrees makes a big difference," she emphasises. "At a temperature of 5 degrees Celsius, the cocoa butter is entirely solid, but above about 36 degrees Celsius it's completely liquid."

In addition, the form of the crystals in the chocolate plays an important role. "Cocoa butter crystallises into six different crystal forms," Reinke explains. "The

Picture: DESY, Heiner Müller-Elsner

Svenja Reinke from the TUHH drips oil onto the chocolate samples so that the formation of fat bloom can be followed.

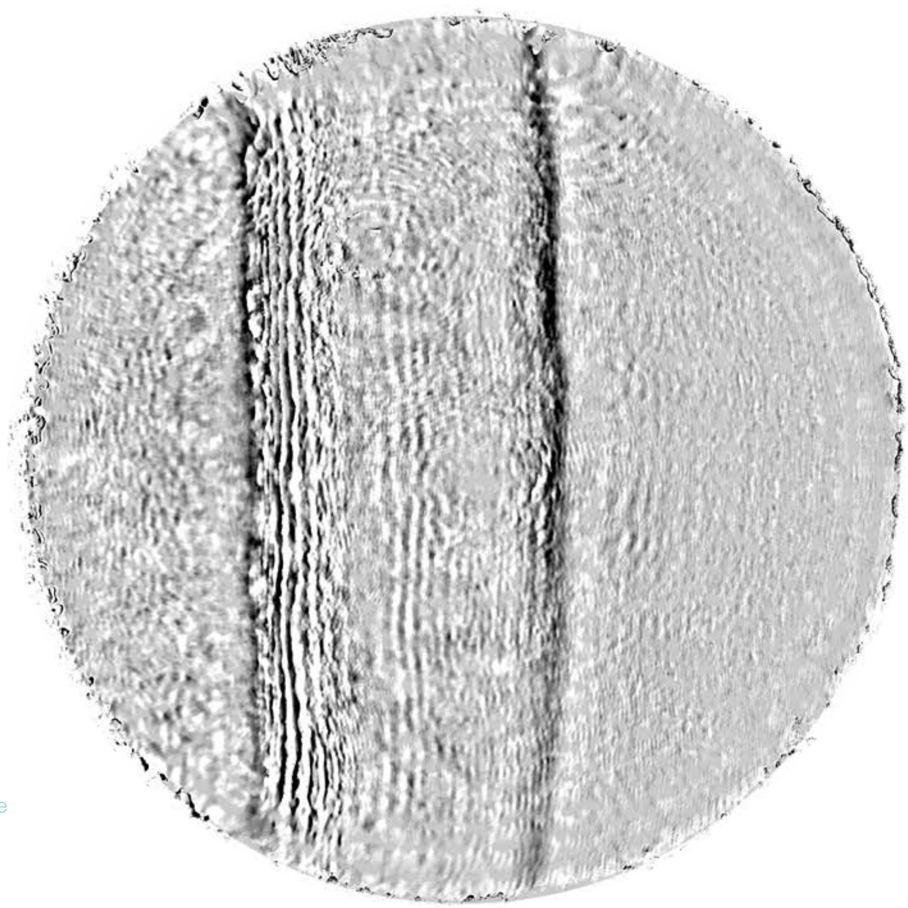
proportion of liquid depends partly on the specific crystal form of the cocoa butter." Manufacturers can also influence the formation of fat bloom by controlling the crystallisation process.

"The investigations that were conducted have enabled us, as a manufacturer of high-quality chocolate, to draw conclusions for the first time about the reasons for the migration of cocoa butter fractions in chocolate," says Palzer, a director of research at Nestlé. "The knowledge we've gained through ultramodern analytical technology in cooperation with the Hamburg University of Technology and the team from DESY forms the foundation for the development of appropriate processes for avoiding one of the most important quality defects in the food industry."

ACS Applied Materials and Interfaces, 2015; DOI: 10.1021/acsami.5b02092

Shock waves in diamonds

X-ray laser opens up new horizons in materials research



Snapshot of the shock wave (centre) in the diamond sample. The corrugated structures in the left third of the picture are created by the edge of the sample.

Researchers have used ultrashort flashes of X-ray radiation to film shock waves in diamonds. A team led by the DESY physicist Christian Schroer was able to record the rapid dynamics of the shock wave with both high spatial and high temporal precision. “With our experiment, we are venturing into new scientific terrain,” says Andreas Schropp from DESY. “This is the first time we’ve been able to use X-ray imaging to quantitatively determine the local properties and dynamics of matter under extreme conditions.” This opens up new possibilities for investigating the properties of materials.

For their pilot study, the researchers investigated their diamonds with the world’s most powerful X-ray laser, the Linac Coherent Light Source LCLS at the SLAC National Accelerator Laboratory in the USA. They began by fastening thin diamond rods, each three centimetres long and 0.3 millimetres thick, into a sample carrier. An infrared laser then triggered a shock wave by flashing a pulse lasting 0.15 billionths of a second (150 picoseconds) at the narrow side of the diamond. The flash reached a power of up to 12 trillion watts (12 terawatts) per square centimetre. The shock wave raced through the diamond at a speed of approximately 72 000 kilometres per hour.

that are as small as 500 millionths of a millimetre (500 nanometres). These details, together with the measured speed of sound, enabled

DESY scientist Andreas Schropp at the LCLS in California, where the experiments were carried out

"With our experiment, we are venturing into new scientific terrain"

Andreas Schropp, DESY

"In order to make snapshots of processes that are this fast, we need extremely short exposure times," explains Schropp, who carried out his experiments with the support of a fellowship from the Volkswagen Foundation. The LCLS delivers X-ray flashes that last only 50 millionths of a billionth of a second (50 femtoseconds) and can "freeze" the fastest movements in a static image.

However, the diamond sample is destroyed during every snapshot because of the extreme conditions of the experiment. As a result, the researchers had to repeat the experiment several times with identical samples. In each repetition, they recorded the image of the shock wave at a slightly later point in time. Finally, they assembled these still images to create a film, as in a flip book.

The researchers could use this film to determine the quantitative changes in the diamond's density caused by the shock wave. The X-ray microscope that was specially developed for this study makes it possible to image details of a sample the researchers to determine the state of the diamond under high pressures. The results showed that the powerful shock wave compressed the diamond – one of the hardest materials in the world – locally by almost ten percent.

The pilot study offers new insights into the nature of diamond. "In view of the remarkable physical properties of diamond, it continues to be important both scientifically and technologically," says Jerome Hastings from SLAC. "We have for the first time directly imaged shock waves in diamond using X-rays, and this opens up new perspectives on the dynamic behaviour of diamond under high pressure." A phenomenon that is particularly interesting for materials researchers is the complicated behaviour behind the first shock front, which could already be seen in the first snapshots.

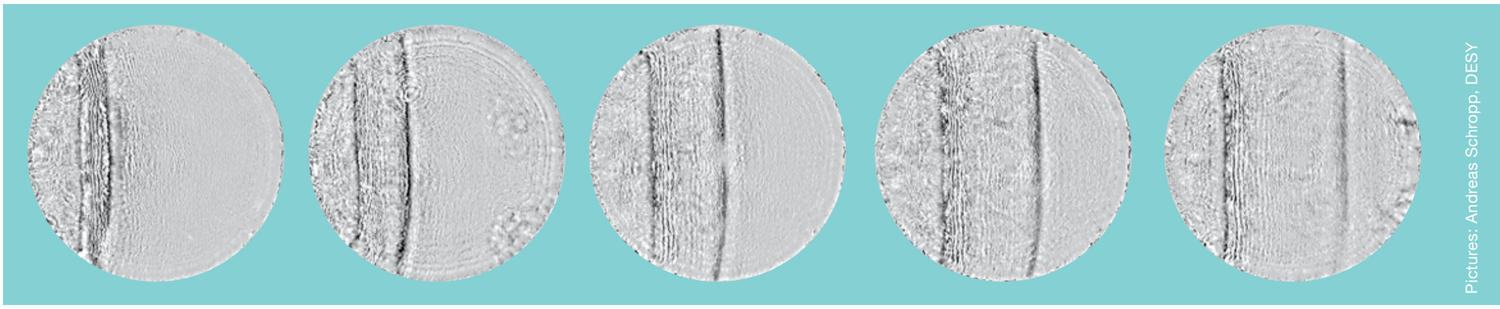
The researchers expect that the further development of X-ray lasers and the optimisation of the detector will make it possible to refine the spatial resolution even beyond 100 nanometres. Such improved experiments may also be possible at the European XFEL X-ray laser, which is currently being built from the DESY site in Hamburg to the neighbouring town of Schenefeld. Thanks to the penetrating X-ray radiation, this technique can be applied to almost any solid material, such as iron or aluminium. "This method is important for a series of applications in materials science and for the description of physical processes in the interior of planets," sums up Schroer, who headed the research team.

"This method is important for a series of applications in materials science"

Christian Schroer, DESY

Scientific Reports, 2015;
DOI: 10.1038/srep11089

The shock wave's passage through the diamond

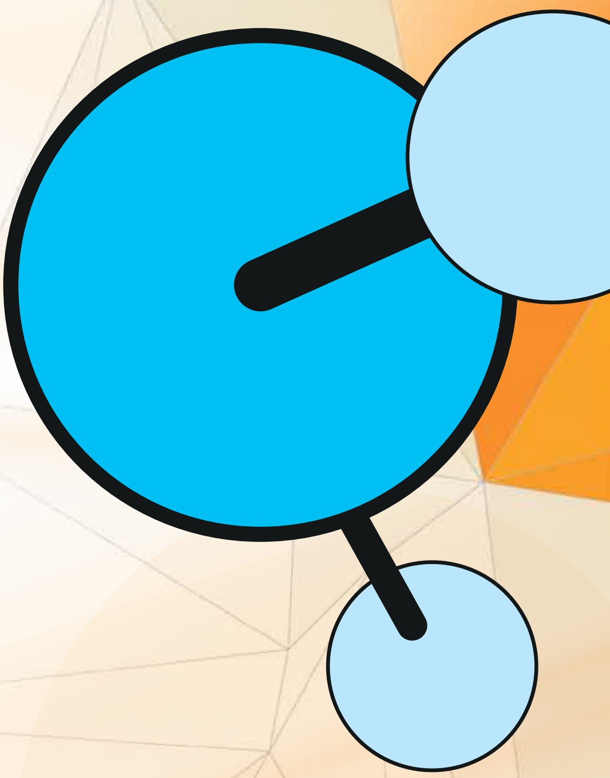


ZOOM

In the light of research

Atoms seen with X-ray vision, a universe full of gamma radiation

In our everyday perception, light is the visible part of solar radiation. Red, orange, yellow, green, blue and violet – the colours of the rainbow shape our perception of the world. We experience infrared radiation as heat and ultraviolet radiation sometimes as a painful sunburn. However, our senses perceive only a tiny segment of the electromagnetic spectrum. Over the centuries, scientists have learned how to use almost the entire electromagnetic spectrum to round out their conception of the world and make visible many of the things that are hidden to the human eye. For example, state-of-the-art supermicroscopes exploiting short-wavelength X-ray light enable researchers to investigate the infinitesimal world of atoms and molecules, the basic building blocks of matter. Astronomers are gaining new insights into the universe by using light of all the wavelengths in the electromagnetic spectrum, ranging from the cosmic background radiation in the microwave band to high-energy gamma radiation.



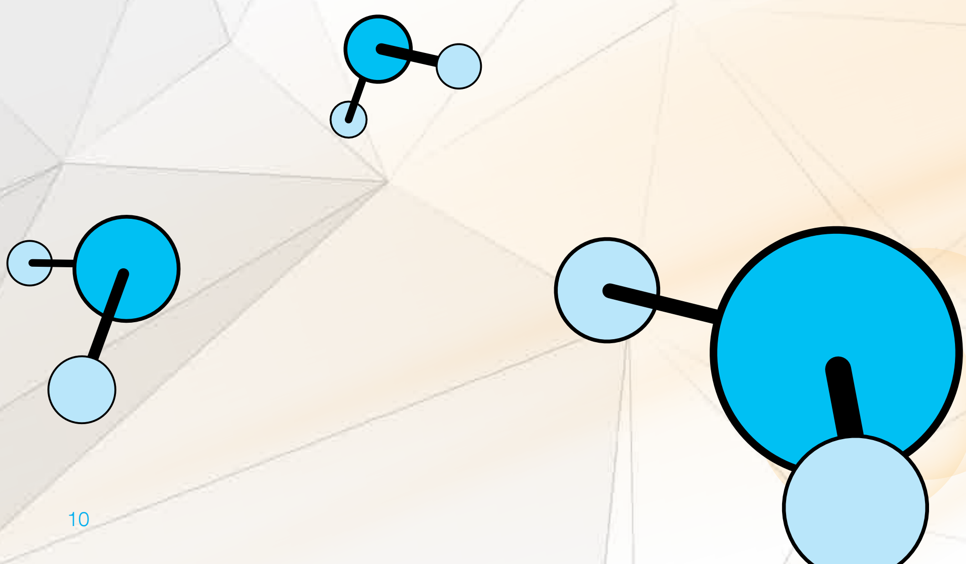
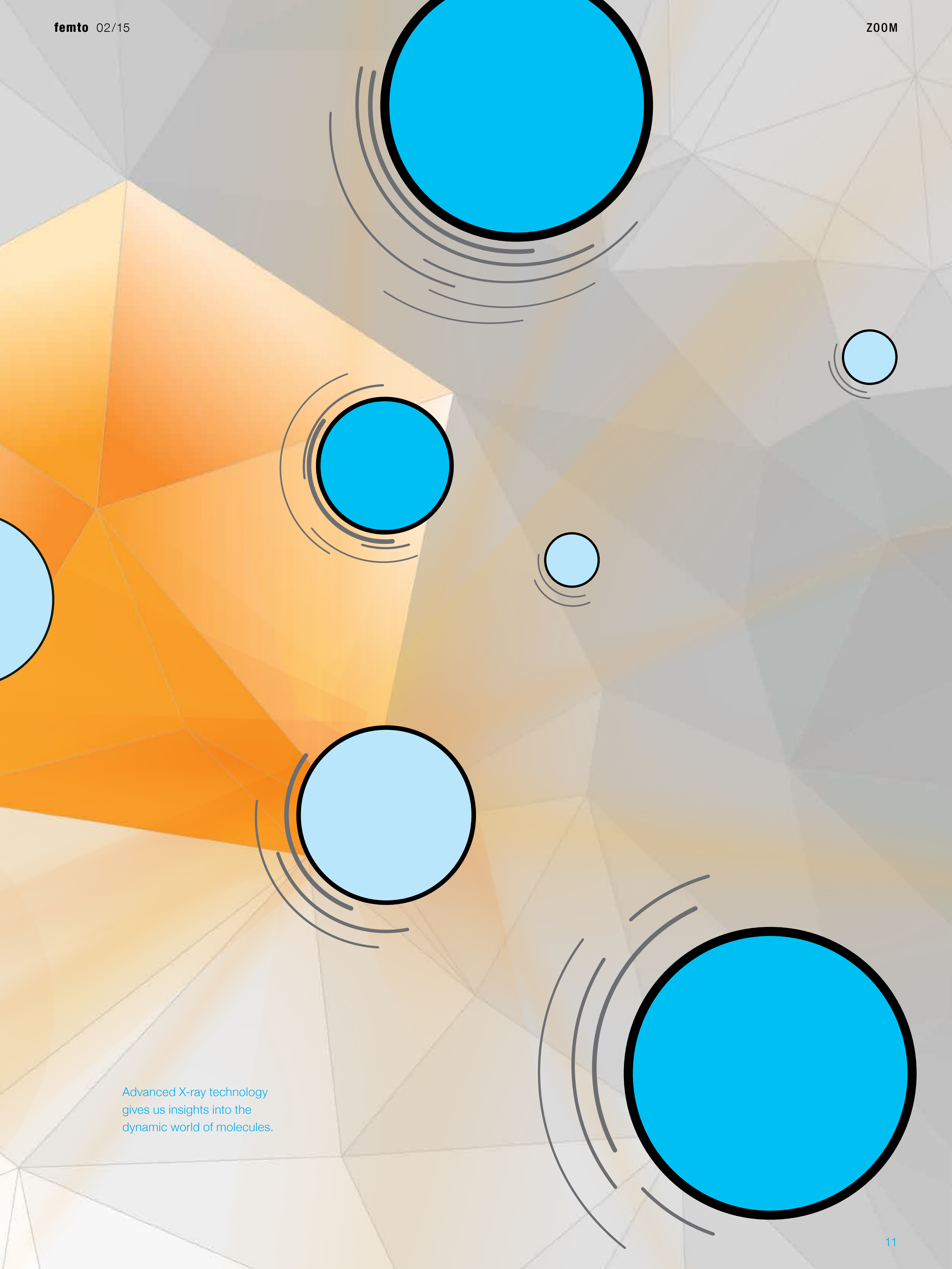


Illustration: DESY, Ian Davidson



Advanced X-ray technology gives us insights into the dynamic world of molecules.

INTERNATIONAL YEAR OF LIGHT 2015

The International Year of Light

Light has vital significance for science and culture, and it is the foundation of life. So it's no surprise that the United Nations have declared 2015 the International Year of Light. Human beings began to investigate the properties of light at an early stage of history. Down to the present day, almost every field of science has been influenced by light. Over time, we have learned to control, concentrate, divert and focus light and separate it into its distinct colours. Light is the foundation of many technologies that are the basis of today's information society. Pulses of light form the backbone of the Internet; precise optical instruments measure the world. Light technology makes a host of applications possible. Medical progress through lasers, sustainable energy use through solar cells, and energy-saving lighting thanks to light-emitting diodes (LEDs) are just a few examples.

The photosynthesis carried out by green plants is the central process for generating energy in nature. Most living things are directly or indirectly dependent on sunlight. Only in the completely dark depths of the ocean are there communities of creatures that are based exclusively on chemical sources of energy.

Shadows, sunsets, rainbows and northern lights – the variations of natural light are fascinating, and they make us curious about the scientific explanations behind these spectacles of nature. Light has also played a special role in human culture ever since ancient times. This is especially noticeable in painting, but the cultural significance of light extends much further. Light connects the natural sciences and the humanities, art and religion. It fascinates people and inspires artists and scientists in equal measure.

Wave or particle?

The mysterious double nature of light has generated discussions in the world of science for centuries. In the 17th century, for example, there were two opposing schools of thought. The astronomer Christiaan Huygens represented the concept of light waves, whereas his contemporary Isaac Newton believed that light consisted of a stream of particles. The wave nature of light was demonstrated by an experiment that today is regarded as classic. Beams of light that have the same wavelength can be superimposed and thus strengthen or extinguish one another.

"Modern sources of X-ray light enable us to gain completely new insights into the nanoworld"

Edgar Weckert, DESY

This phenomenon is known as interference and is also seen in clashing waves of water.

By contrast, in 1905 Albert Einstein explained the photoelectric effect by means of light quanta that possess particle properties. For example, if a metal is irradiated with X-ray light, electrons are knocked out of it. Einstein concluded that light cannot consist only of waves; instead, it must unite within itself the properties of waves and particles. Under certain conditions, light behaves like a stream of particles, but at the same time it propagates like a wave and oscillates like a wave.

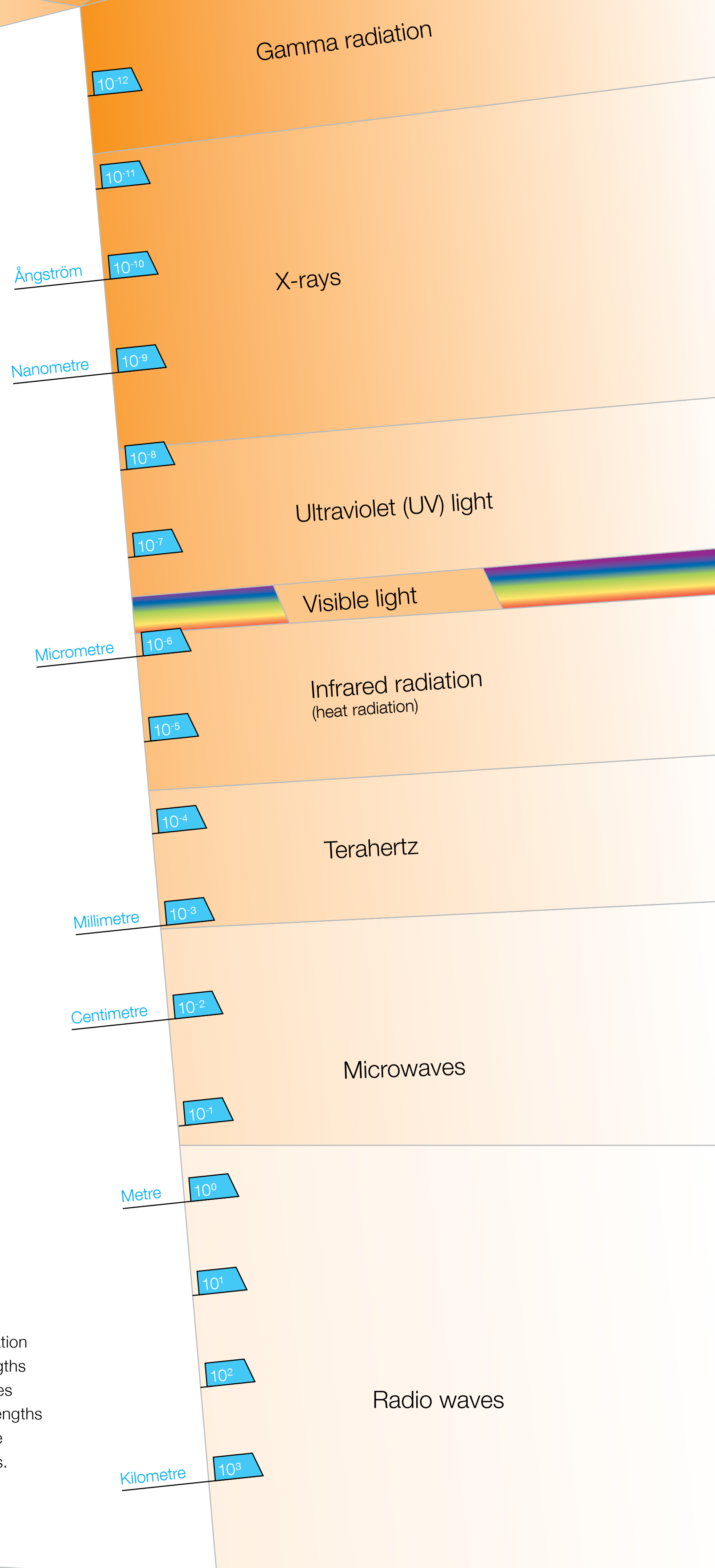
Wave or particle? Science makes use of both of these properties of light. For example,

Edgar Weckert, Director in charge of Photon Science at DESY on the basis of Einstein's photoelectric effect, the Swedish physicist Kai Siegbahn developed a method for determining the chemical composition of materials. This method, called electron spectroscopy, is used today in materials research.

By contrast, various diffraction imaging processes are based on the wave properties of light. The wavelength of X-rays is so short that they can be diffracted by individual atoms. As a result, if a crystal is irradiated with intense X-ray light, the resulting diffraction images can be used to draw conclusions about the crystal's atomic structure. And that's not all – extremely short and intense X-ray flashes can even be used to create three-dimensional images of entire biological cells.

The spectrum of light

While ultramodern supermicroscopes operating with X-ray light enable researchers to look at the tiniest components of materials, astronomers use various special instruments and light of all wavelengths to explore the largest objects in the universe. The star-studded night sky is the part of outer space that is visible to the human eye. The long-wave cosmic microwave background is the oldest light in the world. It enables us to draw conclusions about the early stages of the formation of the cosmos. The extremely high-energy gamma radiation at the other end of the electromagnetic spectrum reveals powerful explosions and gigantic particle accelerators in the universe.



Light spectrum
The spectrum of electromagnetic radiation ranges from wavelengths measured in kilometres (10^3 metres) to wavelengths of billionths of a metre (nanometres) and less.

Van Gogh and the chemistry of colours

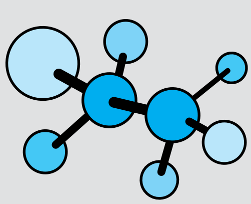
X-rays unravel the mysteries of old masters

Various riddles surround the works of Vincent Van Gogh. Among these are the pictures that may lie beneath the surface of the finished works. Indeed, art experts reckon that as many as one third of Van Gogh's paintings conceal earlier work subsequently painted over by the artist. More worryingly, art historians are concerned about how the famous yellow and orange tones in some of the works have begun to discolour and fade. With the help of X-rays, researchers have been able to analyse the chemical composition of the pigments in the various layers of a painting and thereby determine the causes of any discolouration.

Work to analyse Van Gogh paintings began at DESY in July 2008. Using intense X-ray light from the DORIS particle accelerator, an international team of researchers led by Delft University of Technology applied a technique known as X-ray fluorescence spectroscopy to reveal further layers of paint underneath the surface of Van Gogh's *Patch of Grass*, a work completed in Paris in 1887. What they discovered concealed beneath the finished work were the details of a woman's head.

> *"Once again, we see that the paintings of Van Gogh are not immune to the passage of time. Over a period of 100 years, they can actually be considered a fairly reactive cocktail of chemicals that behaves in unexpected ways"*
>
> Koen Janssens, University of Antwerp

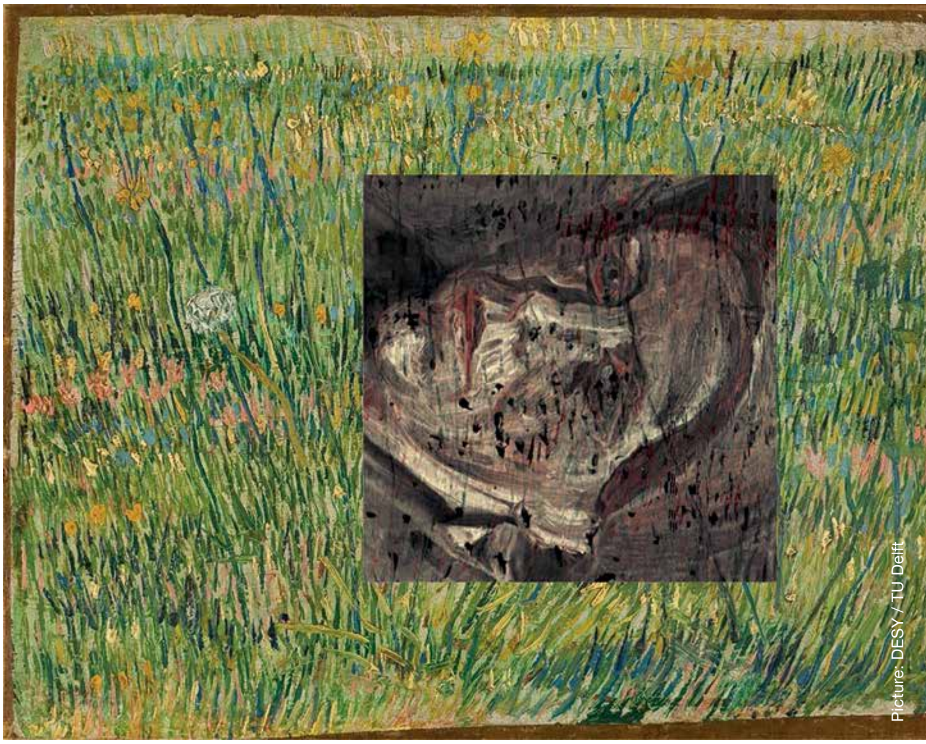
The team scanned the painting with a fine beam of intense X-rays and measured the fluorescence of each layer of paint. This produced a "chemical fingerprint" that is characteristic of the various elements present in the paint. On the basis of the distribution of mercury and antimony, which are contained in special pigments, the researchers were able to create a "colour photo" of the woman's portrait, which had been subsequently painted over by Van Gogh. This reconstruction helps art historians to better understand the development of Van Gogh's works. DESY scientists also used the same technique to determine the authenticity of a still life by Van Gogh. The discovery of a painting of two wrestlers concealed beneath an arrangement of wild flowers and roses enabled experts to



Chemical composition

Researchers use a variety of X-ray techniques to determine which chemical compounds are present in the samples under investigation.

Research revealed a woman's portrait beneath Van Gogh's painting *Patch of Grass.*



ascribe the work definitively to the Dutch painter. Part of the collection of the Kröller-Müller Museum in the Netherlands, the painting had been catalogued for a number of years as the work of an unknown artist.

Why flowers fade

In the race to preserve precious works of art against the ravages of time, experts have been analysing the chemical changes in the pigments used by Van Gogh. Researchers at DESY's X-ray radiation source PETRA III have been investigating the chemical processes that, for example, cause the bright orange-red colour of lead-based pigments to fade or the glowing cadmium yellow in the work *Flowers in a Blue Vase* to change into a dull orange-grey colour. "Once again, we see that the paintings of Van Gogh are not immune to the passage of time," says Koen Janssens from the University of Antwerp, who headed the investigation. "Over a period of 100 years, they can actually be considered a fairly reactive cocktail of chemicals that behaves in unexpected ways."

Such work is therefore of great value to conservators. "This study of the decomposition of cadmium yellow is a prime example of how collaboration between scientists and conservators can enhance our understanding of Van Gogh's paintings and help to improve their conservation," says Ella Hendriks, Head of Conservation at the Van Gogh Museum in Amsterdam.

Art forgery and London air

X-ray analysis of chemical composition can also be used to coax other works of art into divulging their deepest secrets. For example, an axe purportedly discovered at a Bronze Age site in Schleswig-Holstein in Germany proved upon closer inspection to be a clever forgery. The investigation in question was led by DESY physicist Leif Glaser. "We became suspicious after we used X-rays to analyse the chemical composition," explains Mechtild Freudenberg from Schleswig-Holstein's State Archaeological Museum in Schloss Gottorf. "The axe contained far too much iron and tin, and was quite probably not from the Bronze Age at all."

Apart from archaeological forgery, the "chemical fingerprint" produced by X-ray analysis can also reveal environmental damage. The method can show even very minor traces of pollutants. For example, particulate matter in samples of London air examined at DESY by researchers from the Paul Scherrer Institute (PSI) in Switzerland were shown to contain a number of chemical elements. "We detected both barium and antimony, which typically come from brake wear," explains researcher Suzanne Visser. In particulate matter, airborne pollutants are only detectable in trace amounts. Researchers therefore used the extremely intense X-ray light from a particle accelerator. This data was then fed into a large-scale study of London air quality.

Experimental station at DESY's X-ray radiation source PETRA III

Tough ceramics, glassy metals and viruses in 3D

X-rays reveal the atomic structure of materials and pathogens

Researchers are employing the intense X-ray light from particle accelerators in ever more sophisticated methods to study the very heart of materials, nanomaterials and pathogens. The basic principle behind these techniques was elaborated over 100 years ago by the physicist and later Nobel laureate Max von Laue and research colleagues. He discovered that X-rays are diffracted by the atoms in matter, and that the resulting diffraction patterns can be used to create a detailed reconstruction of the spatial structure of the sample under investigation. A century later, modern X-ray radiation sources such as PETRA III are being used to analyse medically relevant biomolecules made up of thousands of atoms and a host of new materials for the cars, aircraft, solar cells, catalysts and data storage media of the future.

Changes to the structure of a material also alter its properties. By understanding these changes, materials scientists hope to be able to customise new materials for specific applications. In a project to develop extremely hard and tough ceramics for industrial uses, for example, the DESY researcher Nori Nishiyama and his team investigated a material called stishovite, a rare form of silica that is only produced under extreme pressure. Stishovite is a ceramic material belonging to the group of oxides. "It is the hardest oxide known to date, even harder than ruby or sapphire," Nishiyama explains. Ceramics are generally very hard indeed, but they also tend to be brittle and break easily. This high friability is one of the reasons why stishovite is not used industrially.

"It may be possible to create ceramic composites for industrial use that can exploit the toughening mechanism of stishovite"

Nori Nishiyama, DESY

In a new development, however, Nishiyama and colleagues have been able to synthesise nanocrystals of stishovite that are not only hard but also extremely tough. To investigate the cause of this radically enhanced toughness, the researchers made use of a range of techniques including the brilliant X-ray light from PETRA III, which revealed that the exceptional toughness was due to structural changes in the nanocrystalline stishovite. If a sample is fractured, the energy from the fracturing causes the nanocrystals to change to amorphous silica, in a process similar to the melting of ice. “This transition instantaneously doubles the volume of the material, effectively pushing against the fracture and stopping it short,” explains Nishiyama. “It may be possible to create ceramic composites for industrial use that can exploit the toughening mechanism of stishovite.”

Metallic glass

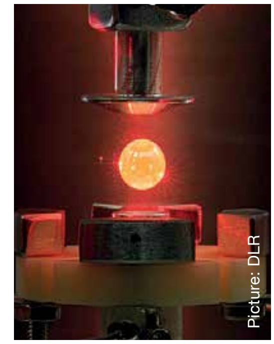
They are tough as steel, but formable like plastic: molten metals that do not crystallise when they cool, but instead harden to form a metallic glass. This gives these materials fascinating properties. As a rule, the atoms in a metal are tightly ordered in a crystal lattice. If, however, molten metal is cooled extremely rapidly, amorphous metallic glasses are formed in which the atoms are in a disordered state. Initially, it was possible to produce these ultrahard glasses only in extremely thin layers, as larger amounts of metal simply could not be cooled rapidly enough. Meanwhile, however, materials scientists have developed alloys of elements such as aluminium, titanium, copper or nickel that crystallise extremely slowly. These can be used to produce bulk metallic glasses several centimetres in thickness, which are suitable for use as production materials. Hard as steel but also extremely elastic, the materials are ideal as spring material, for example.

These metallic glasses can, in principle, be worked and processed just like normal glass or plastic. When heated to the right temperature, they become viscous and can be formed into almost any shape or blown into a metal vessel. Today, such materials are found in high-quality golf clubs, tennis racquets, luxury watches and mobile phones. Potentially, there are many more applications for this new generation of metals. Materials scientists are therefore busy investigating their properties in ever greater detail. In a project to discover what gives glassy metals their viscosity, for example, they used extremely intense and tightly focused X-ray radiation from PETRA III to determine how atoms change their position when a sample of the metal is heated and slowly becomes viscous. Such investigations help materials scientists to improve the composition and production of the alloys, the aim being to develop glassy metals with customised properties for use in industry.

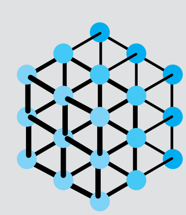
Viruses in 3D

Alongside its application in developing the materials of the future, X-ray light can also be used to conduct atomic investigations of the very building blocks of life. By examining the complex spatial structure of proteins, enzymes or hormones, researchers can determine the precise properties and functions of these biomolecules. Indeed, they are now using the latest generation of X-ray lasers to produce three-dimensional images of entire virus particles.

In order to ensure a sufficiently strong signal, however, structural biologists must first crystallise the sample under investigation. The protein crystal scatters the X-ray light in a characteristic fashion, producing a diffraction pattern from which the atomic structure can be calculated. As a rule, biomolecules consist of many thousands or even millions of atoms. The resulting diffraction patterns are correspondingly complex. To date, the structure of around 100 000 biomolecules has been determined in this way. Using the DESY light sources, researchers from the European Molecular Biology Laboratory (EMBL) have been able to decode the attack mechanism of a herpes virus and the molecular structure of a master regulator with a key role in skin cancer. They also discovered the “turbo switch” of the vital calcium pump in the cells



The structure of a hot droplet of metal is analysed as it floats in a vacuum between two electrodes.



Atomic structure

Researchers are using various methods exploiting X-ray light to analyse the spatial structure of samples with atomic resolution.

Matthias Wilmanns is head of the EMBL Hamburg outstation and founding director of the new Centre for Structural Systems Biology (CSSB).

of the human body. All of these are findings that could lead to the development of new and customised active ingredients for drug research. Pathogens such as the tuberculosis bacterium are a further object of research. "To date, we've been able to map the structure of some 50 proteins of the tuberculosis bacterium here at DESY," explains Matthias Wilmanns, who is head of the EMBL Hamburg outstation and founding director of the Centre for Structural Systems Biology (CSSB) on the DESY campus. "Some of them could be promising targets for future drugs that will attack the tuberculosis pathogen while not affecting other, useful bacteria."

Stripping proteins of lipids

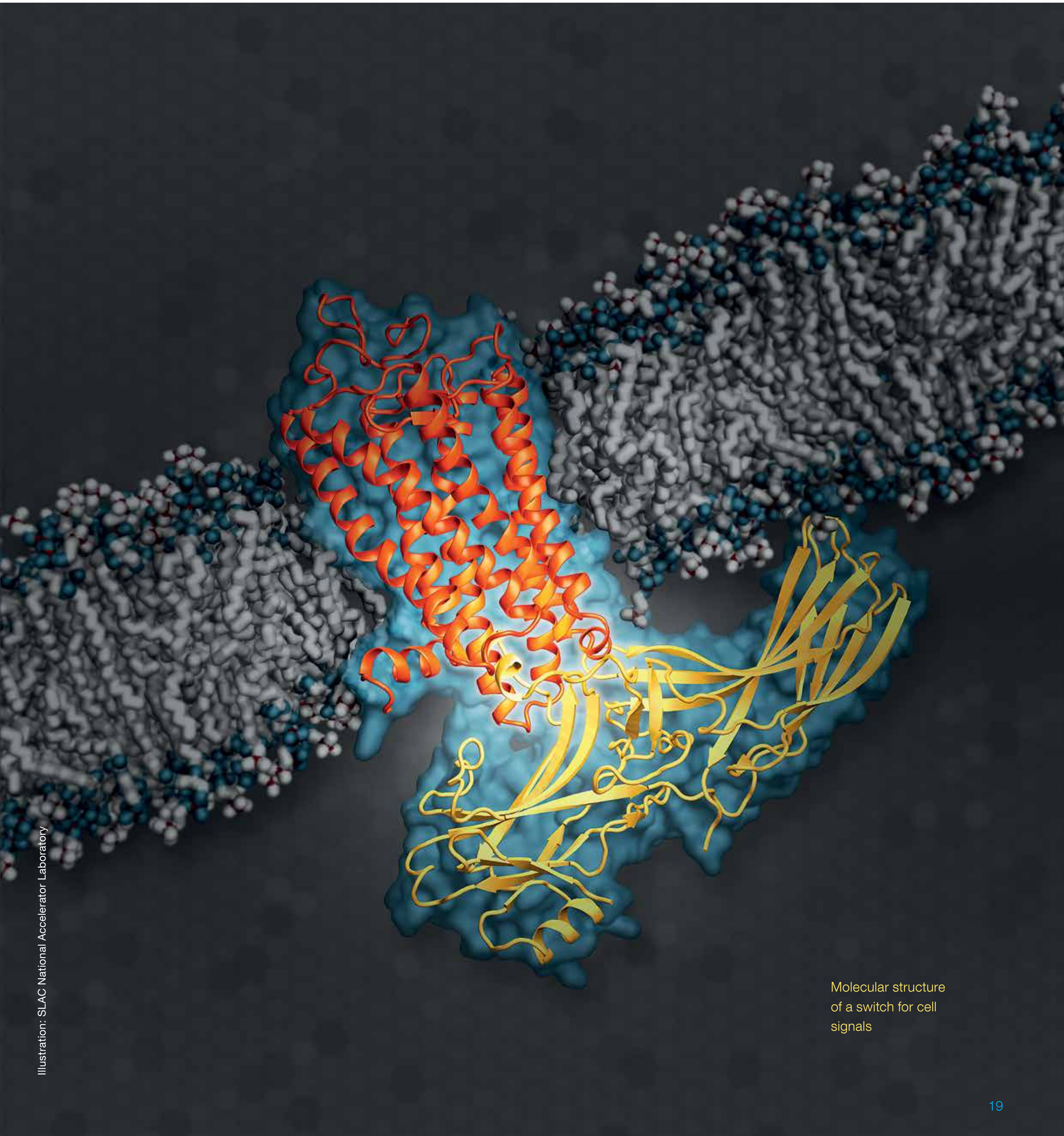
The problem with this approach is that many proteins are difficult to crystallise, since they are suited for the liquid media where biological processes take place. In fact, researchers often have to be content with producing minuscule crystals, which can only be investigated with extremely intense X-rays. Especially uncooperative in this respect are the so-called membrane proteins. These are anchored in the cell membranes of living creatures and play an important role in a host of medical contexts. Before analysis, however, they must be freed of tiny lipid molecules to which they are attached. Special detergents are used for this purpose. The drawback with this technique is that instead of the proteins being covered in fat, they are left covered in soap, which can make the crystal spongy and thereby impair the analysis. Now, however, a team working at PETRA III under the leadership of Athina Zouni from Berlin's Humboldt University has developed a process that makes it possible to study membrane proteins in a near-natural state. The researchers have been able to produce crystals that are completely free of detergent and lock the biomolecules in a configuration very similar to their natural state, offering deeper insight into exactly how they function. "Potentially, the method is suitable for a host of membrane proteins," says Zouni. This development therefore creates new opportunities for decoding this large group of medically relevant biomolecules.

"To date, we've been able to map the structure of around 50 proteins of the tuberculosis bacterium at DESY. Some of them could be promising targets for future drugs"

Matthias Wilmanns, EMBL

Off switch for cell signals

Researchers working with the world's most powerful X-ray laser, the Linac Coherent Light Source (LCLS) in California, have gained a radically new insight into the control mechanisms of biological cells. Using extremely intense X-ray laser flashes, they were able to determine the exact functioning of a crucial "off" switch for cell signals, despite being able to produce only tiny crystals of the biomolecules under investigation, measuring only a few thousands of a millimetre. "Normally, it's very difficult to investigate such small crystals, but with the brilliant X-ray light from the LCLS it was possible to produce such good diffraction images from almost 19 000 of these microcrystals that we were then able to combine the diffraction images in order to determine the biomolecule's structure," explains DESY researcher Anton Barty from the Center for Free-Electron Laser Science (CFEL), who was strongly involved in analysing the data. The work not only paves the way for the development of targeted drugs but also underlines the huge potential of X-ray lasers in the field of structural analysis. DESY and ten international partners are currently building an X-ray laser of the next generation – the European XFEL – which is scheduled to become available for research purposes in 2017.

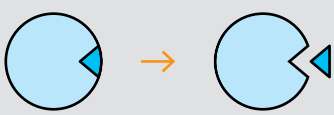


Molecular structure of a switch for cell signals

Illustration: SLAC National Accelerator Laboratory

More dynamism

Towards molecular movies



Molecular movies

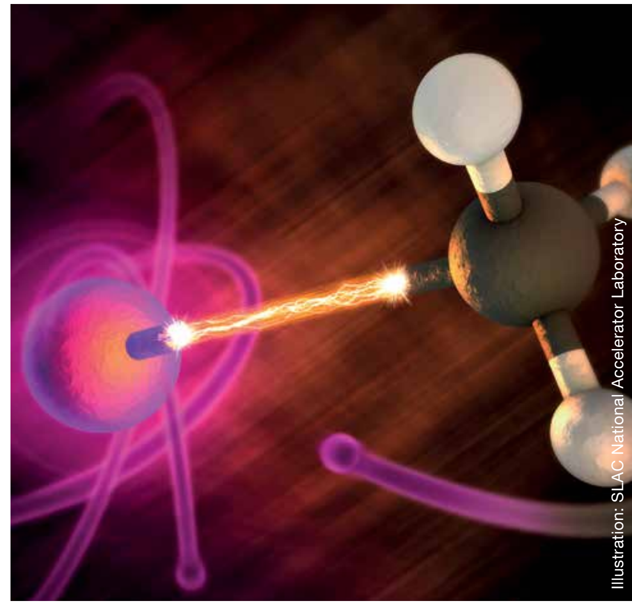
Using ultrashort, high-intensity X-ray laser flashes, researchers can follow the course of chemical reactions.

X-ray lasers are paving the way for another revolution in structural research: the still images are learning to move. The motion of atoms and molecules, chemical reactions, changes in materials, pathogens attacking human cells – all can be "filmed" as they happen, with atomic resolution. Like a flip book, these films are made up of a sequence of snapshots. X-ray lasers can deliver such images from the nanoworld at a temporal resolution in the femtosecond (quadrillionth of a second) range. "By arranging these ultrafast snapshots into a film, we can produce a slow-motion sequence of molecular dynamics," explains DESY researcher Henry Chapman from the Center for Free-Electron Laser Science (CFEL). In a groundbreaking study, Chapman and his colleagues showed that the extremely short flashes from X-ray lasers can record the dynamics of biomolecular processes in a kind of ultraslow-motion sequence. Such images will shed a whole new light on a range of biochemical processes, including those of medical relevance in the human body and those of technological interest in nature.

DESY's free-electron laser FLASH is such a high-speed camera for the nanocosmos. FLASH generates incredibly short and intense flashes of light in the femtosecond range. "This is extremely interesting because chemical reactions in nature take place on the femtosecond time scale. With FLASH, we can now effectively film these reactions," explains DESY researcher Elke Plönjes. "FLASH is the pioneering facility where all the groundbreaking work that will enable scientists to shoot films of the nanocosmos has been taking place." X-ray laser technology is paving the way for an investigation of the dynamic world of ultrafast processes on the molecular and atomic level. How can we enhance the surface of catalysts or solar cells? How can ultrathin magnetic layers be made to act as powerful data storage media? How does a virus infect a cell? And how can a pathogen be effectively stopped? With X-ray lasers, scientists can observe what really happens on the level of molecules and atoms, and they can then use this knowledge to develop new materials and new drugs.

The era of films from the nanocosmos has only just begun. For example, an international team of researchers has made the first-ever

New-generation X-ray lasers shed light on molecular dynamics.



The X-ray pulses of FLASH are generated by special arrays of magnets known as undulators.

"With FLASH, we can now effectively film chemical reactions"

Elke Plönjes, DESY

observations of the fleeting transitional states that occur at the surface of a catalyst during a chemical reaction. The team of scientists, which included researchers from the University of Hamburg and DESY, used ultrashort flashes from the LCLS X-ray laser in order to observe in detail how carbon monoxide oxidises on the hot surface of a simple ruthenium catalyst – a process very similar to the one taking place in the catalytic converter of a car. With free-electron lasers, it is possible to achieve a temporal resolution of under 100 femtoseconds, which is necessary to directly observe intermediate states in chemical reactions. Such investigations form a key part of the research effort at the Hamburg Centre for Ultrafast Imaging (CUI), a Hamburg cluster of excellence. A group headed by DESY researcher Wilfried Wurth is involved in this project as part of its activities at CUI. For Wurth, such experiments are "the first step on the road towards a 'molecular movie', which will make it possible to observe a catalyst operating under realistic conditions". In the future, it will be possible to carry out investigations of this kind – which observe not only the molecules but also the dynamic changes on the active catalyst surface – with the forthcoming European XFEL, an X-ray laser facility currently under construction in Hamburg.

Hidden worlds

Invisible light provides astronomers with new insights into the cosmos

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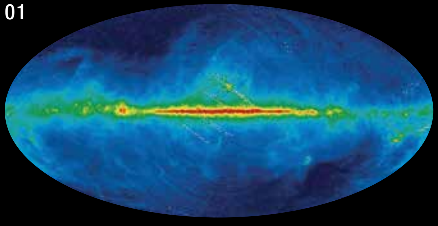

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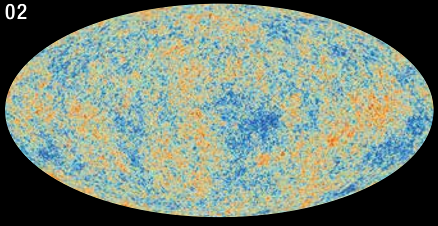

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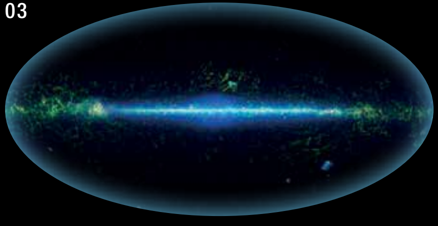

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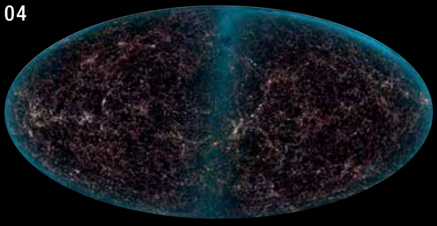

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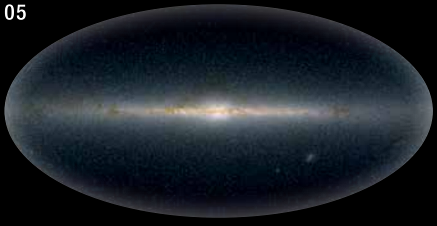

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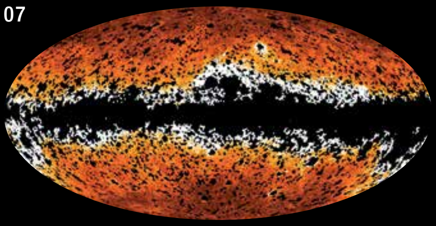

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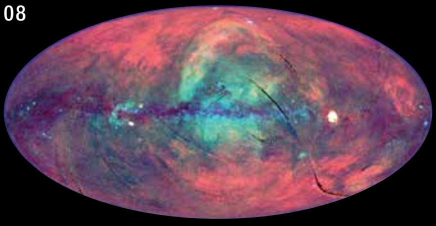

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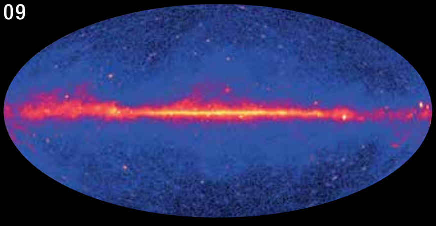


The universe emits radiation at all the wavelengths of the electromagnetic spectrum.

Whole-sky images of...
01 Radio waves
02 Big bang echo
03–05 Infrared
06 Visible light and radio waves
07 Ultraviolet
08 X-rays
09 Gamma radiation

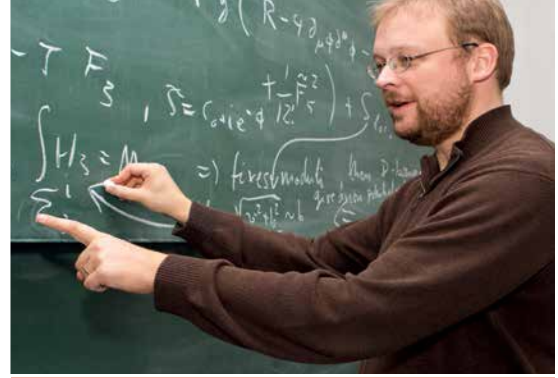
Despite being black, space is in fact full of light. The universe emits radiation at all the wavelengths of the electromagnetic spectrum. Yet the human eye can perceive but a small fraction of it. Moreover, the Earth's atmosphere shields us from large portions of this cosmic radiation. Over the years, astronomers have therefore developed various instruments to observe, from the Earth's surface or in orbit, radiation at the invisible wavelengths – for all the regions of the electromagnetic spectrum carry valuable information about the universe.

The oldest light in the universe is the cosmic microwave background, often known as the echo of the big bang. This light is the afterglow of the big bang and stems from a time when the universe first became transparent to radiation. That was around 380 000 years after the big bang, which occurred 13.82 billion years ago. Since then, the radiation from this primeval fireball has cooled to a frosty minus 270.5 degrees Celsius – a mere 2.7 degrees above absolute zero (minus 273.15 degrees Celsius).

The history of the origin of the universe reverberates in the echo of the big bang

The cosmic microwave background is omnipresent and emanates uniformly from all directions. Well, almost uniformly – for, on closer inspection, minor variations in the temperature of the radiation can be observed. These variations result from the emergence of the first spatial structures in the cosmos. The history of the origin of the universe thus reverberates in the echo of the big bang. In the manner of archaeologists, astronomers are trying to decipher this information. By investigating the cosmic microwave background, satellite missions such as COBE, WMAP and Planck have been able to determine the composition of the universe and its age.

According to these results, the universe comprises 4.9 percent normal matter – this makes up all the stars, planets, houses, people and any other objects we can see around us; 26.8 percent so-called dark matter, which is by definition invisible and reveals itself by its gravitational effect alone (physicists are still puzzling over what exactly it might consist of); and 68.3 percent dark energy, an utterly mysterious form of energy that accelerates the expansion of the universe.



DESY theorist Alexander Westphal's research focuses on cosmic inflation.

The inflation of space

In fact, the cosmic microwave background provides an opportunity to gaze even further back towards the big bang. For cosmologists such as DESY researcher Alexander Westphal, the radiation's polarisation – that is, its direction of orientation – offers hints of the so-called cosmic inflation. It is thought that, in the first few fractions of a second after the big bang, this inflation caused the universe to expand by a factor of at least one hundred septillion – that's a 1 followed by 26 zeros. Westphal is investigating how various inflation models might be embedded in string theory, one of the candidates for a completely unified description of the physical laws, including a theory of quantum gravity.

According to string theory, the basic building blocks of the universe are tiny, vibrating strings. Depending on their vibrational state, these strings appear as one or other of the elementary particles. A major obstacle to experimental verification is that these strings are so small they have not proved to be observable with any current lab method. "But one day we may be able to test the connection between string theory and inflation by measuring subtle polarisation patterns in the cosmic microwave background radiation," Westphal explains.

The cosmos revealed through the spectrum of light

The echo of the big bang consists of radio waves from the lower energy range of the electromagnetic spectrum. Using radio telescopes, astronomers investigate objects that cannot be seen in the visible region of the spectrum, looking, for example, through dust and gas to the very heart of our own galaxy, the Milky Way. Some astronomical phenomena are primarily

Picture: University of Wisconsin-Madison

Markus Ackermann investigates super-accelerators in space.

detectable in the radio range. These include fast-rotating pulsars – which, like a lighthouse, shine a beam of light out into space – and synchrotron radiation from certain galaxies.

Likewise, infrared radiation, which is located in the electromagnetic spectrum between radio waves and visible light, enables astronomers to see through cosmic dust. The infrared region, for example, lets us observe how in emerging solar systems, new planets accrete in the huge disks of dust surrounding young stars.

Our picture of the cosmos is still very much shaped by spectacular images of the visible region of the electromagnetic spectrum, as supplied by the Hubble Space Telescope and other observatories. The sun's radiation is at its most intense in the visible range, which has led to our eyes being especially sensitive to this area of the electromagnetic spectrum.

Directly adjacent to the visible spectrum is ultraviolet (UV) radiation, most of which is absorbed by the Earth's atmosphere. UV satellites orbiting outside the Earth's atmosphere enable astronomers to measure, for example, gas temperatures in the sun's atmosphere. Young, hot stars likewise emit a lot of UV radiation.

X-rays are an indication of very high-energy processes in the universe, such as extremely hot gases, several million degrees in temperature, escaping from a supernova explosion. X-rays also help to investigate black holes. No light can escape from these massive cosmic monsters. But when they swallow up matter from nearby, this heats up to such a degree that it flickers brightly in the X-ray range before disappearing into the black hole.

The part of the electromagnetic spectrum with the highest energies is gamma radiation. The gamma-ray sky reveals a cosmos quite different to that of the starry heavens twinkling peacefully above. This is where the most violent explosions are observed along with nature's gigantic particle accelerators, compared to which even the very largest of terrestrial accelerator facilities are mere toys.

High-energy particle showers

With the help of cosmic gamma rays, researchers are also investigating the origin of cosmic rays. Discovered around a century ago, cosmic rays are not electromagnetic radiation – despite the name – but rather a hail of high-energy elementary particles that continually rain down on the Earth's atmosphere. Cosmic rays consist primarily of protons – that is, electrically charged hydrogen nuclei – along with a small proportion of heavier nuclei. It is still largely a mystery just what processes are responsible for accelerating these subatomic particles to such incredibly high energies. Indeed, a single cosmic-ray proton can sometimes have as much energy as a firmly struck tennis ball. "The protons reach energies way in excess of anything that can be generated in the world's most powerful particle accelerators," explains Stefan Funk from the University of Erlangen.

> *"The protons reach energies way in excess of anything that can be generated in the world's most powerful particle accelerators"*
>
> *Stefan Funk, University of Erlangen*

Identifying the cosmic super-accelerators responsible for this feat is no easy task. The problem is that, on their journey through space, the electrically charged cosmic-ray particles are deflected by all sorts of magnetic fields and therefore reach Earth from a totally different direction than the one in which they first started out. Fortunately, researchers can also turn to cosmic gamma rays, which are equally energetic and, unlike cosmic rays, are a form of light. As such, they are not deflected and therefore reveal their point of origin. Physicists assume that both cosmic rays and cosmic gamma rays are generated by the same high-energy cosmic objects. In other words, identifying the origin of one will also reveal the source of the other. A problem is that the greater the energy of the gamma radiation, the sparser it is. Moreover, the spatial accuracy of gamma-ray telescopes is by no means as high as that of optical instruments scanning the visible region of the spectrum.

The world in gamma light

Nevertheless, researchers are getting closer and closer to identifying these cosmic super-accelerators. Observations with the Fermi gamma-ray space telescope have confirmed what scientists have long suspected, namely that large fractions of cosmic rays originate in so-called supernova remnants, i.e. the clouds of debris produced by stellar explosions. "It is the first evidence resting only on the fundamental properties of particles that supernova remnants are an important source of protons and heavier nuclei in the cosmic radiation," explains DESY scientist Markus Ackermann from the team.

Scientists now believe that there are two primary candidates as the source of cosmic radiation: stellar explosions (supernovae) and the gigantic jets of matter ejected from active black holes beyond our galaxy. With the help of a whole network of Earth-based gamma-ray observatories, researchers are striving to improve our understanding of the various celestial phenomena in the high-energy cosmos. These include gamma-ray bursts, active galaxies with monstrous black holes at their centre, supernova remnants and pulsars, the pulsating corpses of dead stars. For example, scientists working with the High Energy Stereoscopic System (H.E.S.S.), an observatory in Namibia designed to investigate cosmic gamma rays, have recently identified three exceptionally bright gamma-ray sources, each of a different type, in the Large Magellanic Cloud, a galaxy neighbouring the Milky Way. One is the pulsar wind nebula of the most powerful pulsar ever observed, another an extremely intense supernova remnant, and the other a so-called superbubble – a huge shell-like cavity spanning 270 light years and expanded by several supernovae and stars. This is the first time that a number of star-like gamma-ray sources at extremely high energies have been observed in another galaxy. What's more, the superbubble is the first identified representative of a new class of extremely energetic gamma-ray source.

Christian Stegmann heads the DESY institute in Zeuthen.

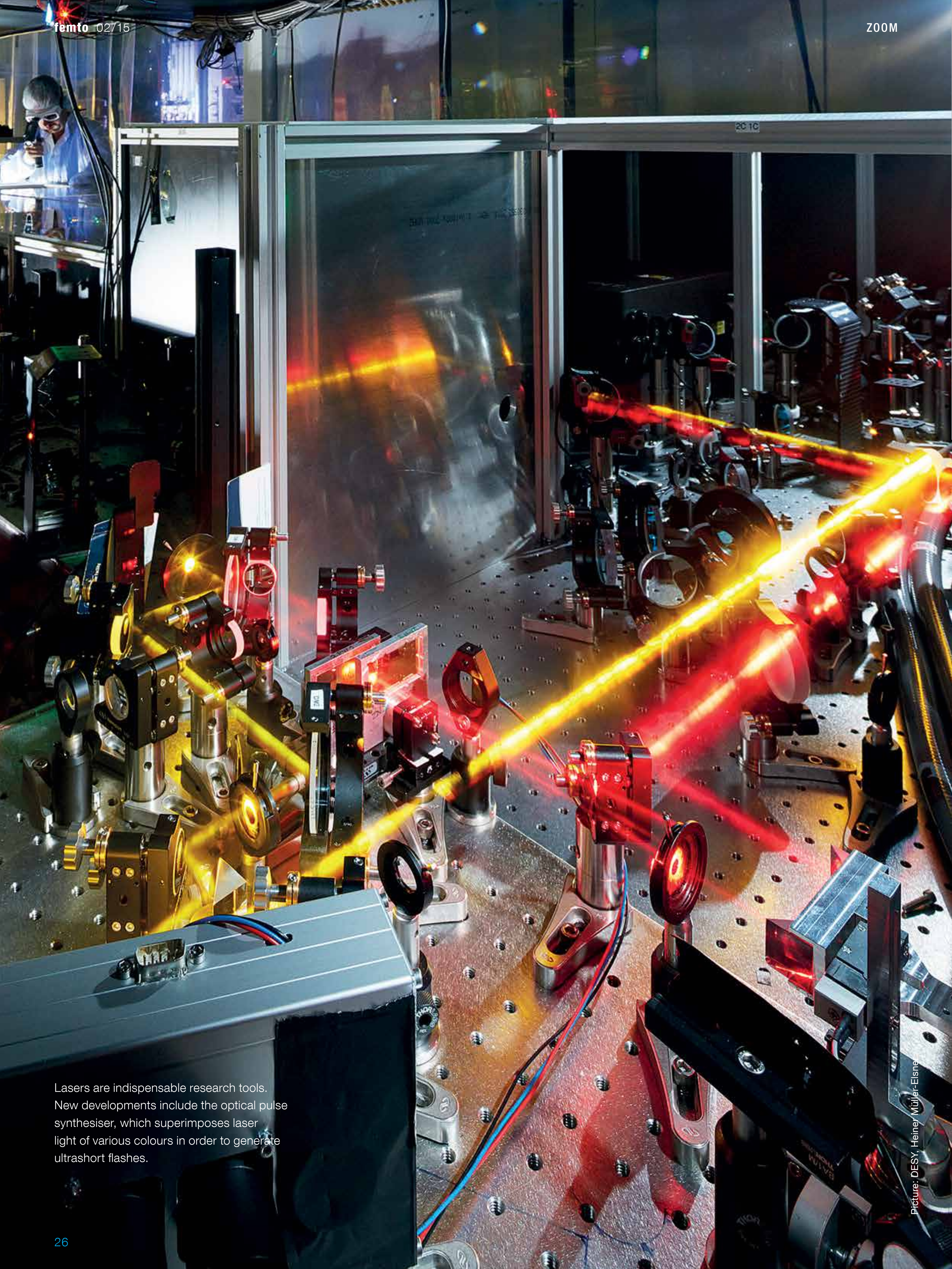
"The Cherenkov Telescope Array will be the gamma-ray observatory of the future"

Christian Stegmann, DESY

The forthcoming Cherenkov Telescope Array (CTA) will offer researchers even deeper insight into the high-energy cosmos. Over 1000 scientists from 28 countries are involved in the project, which also includes DESY as a major partner. "The universe is full of natural particle accelerators, for example in supernova explosions, binary star systems or active galactic nuclei," explains Christian Stegmann, head of the DESY institute in Zeuthen. "So far, we know only about 150 of these objects and we are only just beginning to understand the physics of these fascinating systems. The Cherenkov Telescope Array will observe thousands of these accelerators with so far unprecedented sensitivity. Hence, it will be the gamma-ray observatory of the future."

Artistic representation of an active galactic nucleus, which acts as a cosmic super-accelerator, hurling high-energy particles into space.

Illustration: ESO, M. Kornmesser



Lasers are indispensable research tools. New developments include the optical pulse synthesiser, which superimposes laser light of various colours in order to generate ultrashort flashes.

Picture: DESY, Heiner Müller-Elsner

The next revolution in laser technology

DESY researcher Franz Kärtner develops ultrafast lasers and juggles with photons and electrons on a time scale spanning quintillionths of a second

Lasers produce a special light that can even cut through steel. Laser light is used to perform extremely precise incisions during surgery, to scan our shopping at the supermarket checkout, to read the data stored on CDs and DVDs, to generate holograms on credit cards and to cut out precision components. Lasers have long been a part of everyday life. In the field of science too, the process of "light amplification by stimulated emission of radiation" – laser for short – is an indispensable tool. It is a special way of generating and focusing light. The light from a laser is intense and coherent, that is, the light waves oscillate in phase. Laser light opens up a host of scientific applications and experimental procedures. It can be generated in a range of wavelengths, from infrared to ultraviolet, via the visible spectrum. Laser light can also be generated in the X-ray waveband, although this presents special challenges. Generated in special free-electron lasers, this short-wave radiation enables researchers to observe dynamic processes right down to the level of atoms and molecules.

To observe the transport of individual electrons in photosynthesis "live" at the molecular level is one of Franz Kärtner's current research goals. Kärtner is a leading scientist at DESY and a professor at the University of Hamburg and at the Massachusetts Institute of Technology (MIT). He works on the research and development of ultrafast lasers that generate light flashes in the attosecond (quintillionth of a second) range. These ultrashort-pulse lasers enable scientists to observe the movement of electrons and to investigate key processes such as photosynthesis with a view to exploiting them, at some stage in the future, for technical purposes. Such advances will also facilitate the development of a new generation of ultrafast photon and electron sources, and of extremely precise synchronisation and analysis systems for kilometre-long facilities such as the European XFEL X-ray free-electron laser in Hamburg. "These new ultrafast lasers take us to a new order of time resolution," Kärtner explains. "They've got such huge potential that we're really talking here about the 'next revolution' in laser technology."

"These new ultrafast lasers take us to a new order of time resolution"

Franz Kärtner heads the Ultrafast Optics and X-Rays group at DESY. He is also a professor at the University of Hamburg and the Massachusetts Institute of Technology (MIT) in the USA.

Slow-motion images of the nanocosmos

To observe and to comprehend, at atomic resolution, chemical and biological processes that take only attoseconds to complete – that's the aim of a research project for which Kärtner, Petra Fromme from Arizona State University and the DESY researchers Henry Chapman and Ralph Aßmann have been awarded funding of 14 million euros from the European Research Council. Included in the project is a new research facility at DESY that will enable researchers to film ultrafast processes as if in slow motion. This requires the generation of X-ray flashes in the attosecond range. An attosecond is one quintillionth of a second – that's 18 zeros behind the point – the time in which light travels a mere 0.3 millionths of a millimetre. Using a new type of particle accelerator based on laser technology, researchers believe they can produce X-rays in very much shorter pulses than is currently feasible. Today's X-ray lasers can already generate pulses in the femtosecond (quadrillionth of second) range. An attosecond is 1000 times shorter.

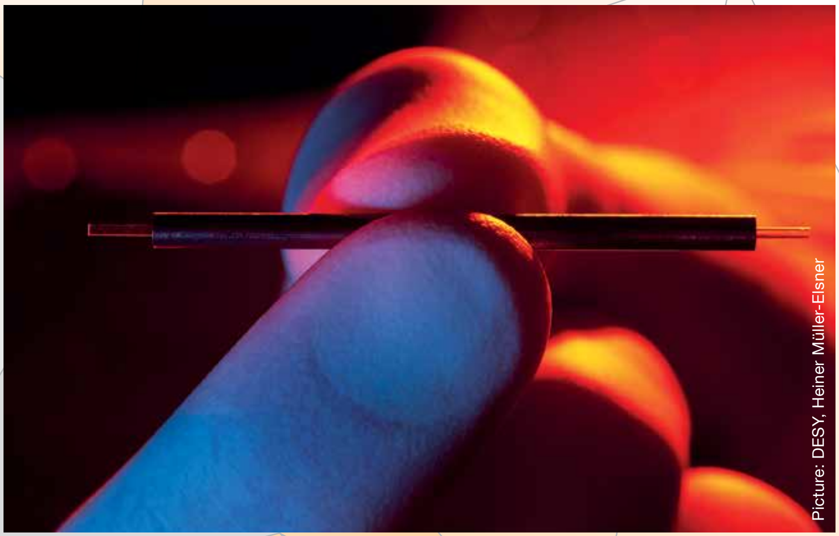
"The development of attosecond lasers will revolutionise our understanding of structure and function on the molecular and atomic level"

"For our ultrafast experiments, we're working on a totally new type of compact free-electron laser that produces bright, short-wavelength X-rays," says Kärtner. "To accelerate the electrons, we use terahertz radiation rather than radiation from the radio-frequency region, as is customary. This means that all the components are smaller by a factor of between 100 and 1000." Terahertz accelerators could thus be compact and relatively inexpensive to build. Indeed, thanks to this advance, it may one day be possible to build X-ray lasers in a laboratory format. However, terahertz radiation – which lies between infrared radiation and microwaves – is an area of the electromagnetic spectrum that remains relatively unexplored. "Only in recent years has this started to change," says Kärtner. "The powerful terahertz sources that we need are still being developed. That'll be a key technology for the years to come."

Yet accelerating the electrons is only the first step in a free-electron laser. Once they are travelling at almost the speed of light, they must be induced to emit X-ray light and this must be amplified in such a way that all the waves oscillate in phase. To achieve this, the current generation of free-electron lasers uses undulators – metre-long arrays of magnets – which force the electrons along a slalom course. Here too, Kärtner and his team are hoping to exploit light instead, using laser pulses as optical undulators. For this, however, special high-energy picosecond lasers must still be developed.

There is no doubt, however, that this pioneering work will pay off. The new lasers will enable the production of laser flashes that are a mere 100 attoseconds in length but nonetheless intense enough for imaging purposes. "The development of attosecond lasers will revolutionise our understanding of structure and function on the molecular and atomic level and help us to decipher fundamental chemical and biological processes," Kärtner predicts. "It will be possible to investigate ultrafast processes such as light absorption and electron transport in photosynthesis on a time scale of attoseconds and thereby solve one the most important problems of structural biology."

Terahertz accelerator modules fit easily in a human hand.

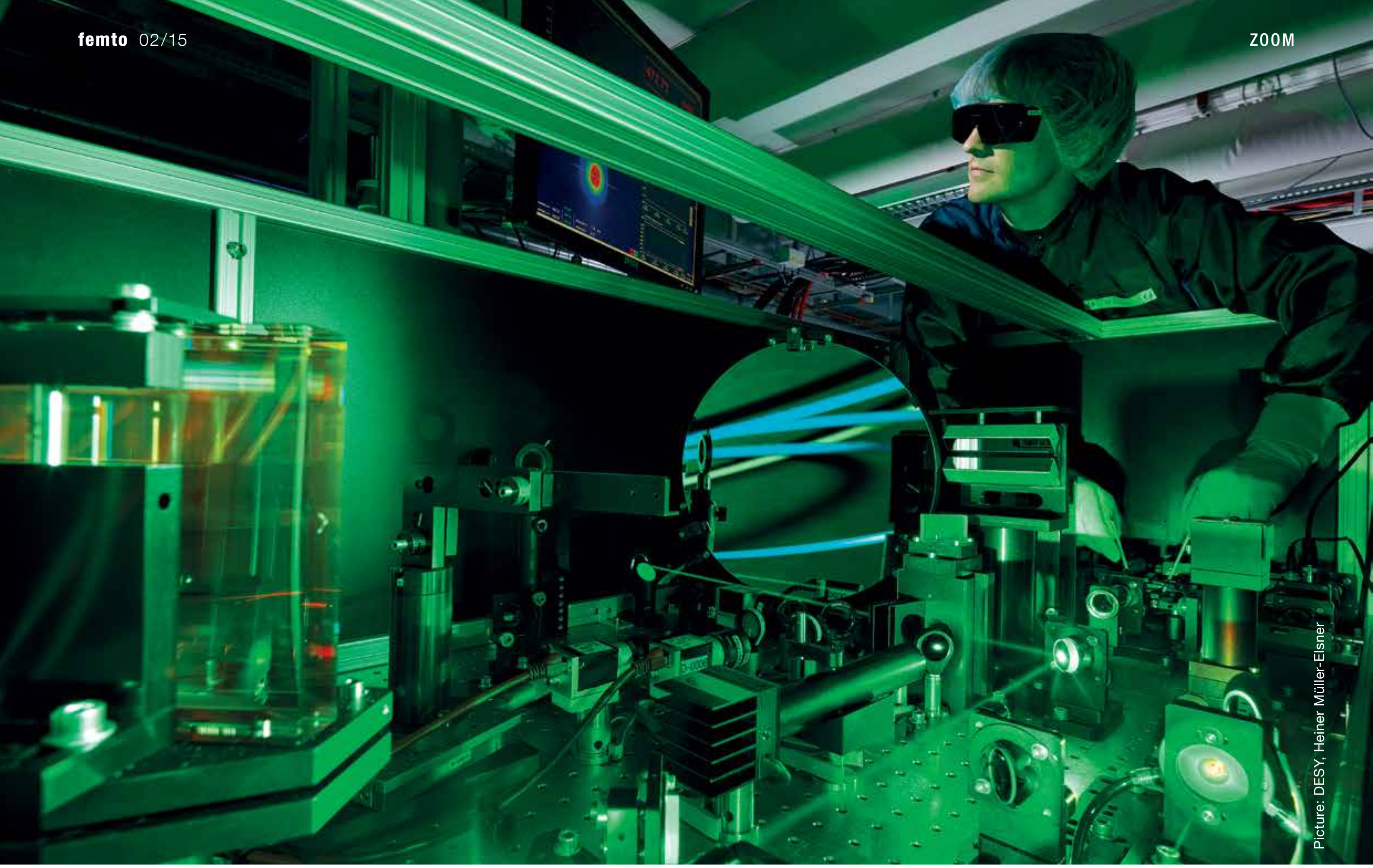


Physicists shrink particle accelerator

An interdisciplinary research team led by Franz Kärtner has built the first prototype of a small-scale particle accelerator operating with terahertz rather than radio frequency radiation. A single accelerator module is 1.5 centimetres long and one millimetre thick.

For their prototype, which was constructed in Kärtner's lab at MIT in Boston, the scientists used a special microstructured accelerator module, specifically tailored to be used with terahertz radiation. Fast electrons were fired into the miniature accelerator module using a kind of electron gun and then further accelerated by terahertz radiation fed into the module. This first prototype of a terahertz accelerator increased the energy of the particles by seven kiloelectronvolts (keV).

"This is not a particularly large acceleration, but the experiment shows that the principle does work in practice," explains Arya Fallahi from the Center for Free-Electron Laser Science (CFEL) at DESY, who carried out the theoretical calculations. "The theory indicates that we should be able to achieve an accelerating gradient of up to one gigavolt per metre." That is more than ten times what can be achieved with the best conventional accelerator modules available today. Plasma accelerators, likewise at the experimental stage, promise to produce even higher accelerating gradients. However, they will also require lasers substantially more powerful than those needed for terahertz accelerators.



Photosynthesis: fuel from light

Photosynthesis is the process by which plants and some types of bacteria produce energy-rich substances using the energy of sunlight. Researchers would like to develop a similar technical process capable of cheaply and easily converting sunlight into chemical energy. At present, they are focusing on how to use the sun's energy to split water. In nature, special metal-containing enzymes serve to catalyse this process. In artificial photosynthesis, the aim is to recreate similar catalysts so as to use sunlight to split water into oxygen and hydrogen. This hydrogen could then be stored as a source of energy. Researches hope that the development of such bioinspired catalysts will enable the large-scale, environmentally friendly and inexpensive production of hydrogen or other fuel.

"Electron transport and exchange are a fundamental part of the energy conversion process in photosynthesis," Kärtner explains. "Once we can observe and understand such ultrafast processes, we will be able to exploit them. This also applies to a whole range of catalytic reactions with huge potential for other applications."

At the same time, there is another crucial question that can only be resolved on the attosecond scale, namely what happens to a sample when it is irradiated with extremely high-intensity X-ray laser light? Although biological samples are destroyed by the intense radiation, today's X-ray lasers are fast enough to capture an image of the biomolecule under investigation before the destruction occurs. Yet what if the X-ray flash has already altered the chemistry of the sample to such an extent that it is no longer possible to observe the biochemical reaction? The answer to this question can only be found on the attosecond scale. "Ultrafast lasers can tell us how rapidly the chemistry of a sample changes after it has been hit by an X-ray flash," says Kärtner. "That's a crucial question if we want to use X-ray lasers to analyse the sequence of events in chemical reactions."

Already, researchers are looking ahead toward a further breakthrough. "Once the time resolution of X-ray lasers improves from the attosecond to the zeptosecond scale, we will be able to look right into nuclear processes," says Kärtner. A zeptosecond is one thousandth of an attosecond: i.e. 0.000 000 000 000 000 000 001 seconds. "That will certainly be possible one day. And it will provide us with revolutionary insights."

Scientists at the ANGUS laser laboratory, operated jointly by DESY and the University of Hamburg, are researching and developing laser-driven plasma accelerators.

Future technology: laser plus accelerator

Ultrafast laser systems will have a wealth of applications. "One of our key objectives right now is to develop compact free-electron lasers that use terahertz radiation to accelerate the electrons and are equipped with optical undulators.

"Once we understand such ultrafast processes, we will be able to exploit them"

These will have the potential to generate hard X-ray pulses in the attosecond range," Kärtner explains. "All in all, this combination of laser and accelerator technology will offer huge potential for research and development. At DESY, we've got some of the world's leading accelerator experts working together on a single campus with laser specialists from the University of Hamburg and other institutions. That creates unique opportunities."

Kärtner himself works along with his team at the Center for Free-Electron Laser Science (CFEL), a centre of excellence unique in Europe, which was founded jointly by DESY, the University of Hamburg and the Max Planck Society. In this interdisciplinary environment, the experts are developing new laser systems for use in accelerator technology and X-ray experiments. "Today's X-ray lasers are half accelerator and half optical laser," Kärtner explains. "The combination of accelerator technology and laser technology will enable us to build facilities of a completely new kind. There's plenty of potential for further development of X-ray lasers, in terms of both the actual technology and the fields of applications."

New types of laser are also being developed for large-scale X-ray free-electron lasers such as FLASH and the European XFEL, which is currently under construction. These futuristic facilities open up whole new insights into the dynamic world of atoms and molecules – but only if both the extremely intense, ultrashort X-ray laser pulses and all the various components of the facility are perfectly synchronised to a temporal precision in the femtosecond range. This is a task for ultrafast lasers.

"For the synchronisation of the European XFEL, we're going to be using femtosecond lasers. Much like the conductor of an orchestra, the laser ensures that the different parts of this kilometre-long facility keep in time," says Kärtner. In addition, new laser systems are being developed for the actual experiments. These will, for example, emit an ultrafast pulse of light to trigger a reaction, which will then be imaged by means of an X-ray laser flash. "If we want to image the various stages of a reaction with an X-ray laser, then the timing has to be perfect," Kärtner emphasises. "Timing, control and synchronisation all have to take place on the scale of just a few femtoseconds, and possibly even attoseconds. Only optical systems are fast enough to do that. For this purpose, we have to develop suitable ultrafast lasers from scratch." Only then can the high-intensity X-ray laser flashes provide new insight into dynamic processes in the nanocosmos.

"At DESY, some of the world's leading accelerator experts are working together with laser specialists on a single campus. That creates unique opportunities"

Underlining the commercial potential of this research field is Cycle GmbH – a new spin-off from Kärtner's Ultrafast Optics and X-Rays group. Founded in 2015, this company is supported by DESY and the Helmholtz Enterprise programme and supplies innovative products for ultrafast laser technology, including femtosecond synchronisation units intended for large-scale facilities. The company has already patented an ultrashort-pulse laser and is looking to bring it to market. "The laser supplies excellent beam quality and is robust and durable," says Kärtner. "Ultrafast laser technology has huge potential for both scientific and industrial applications."

New vision, new insight

A discussion of science and art, perception and images of the world

The human eye can perceive only the visible region of the electromagnetic spectrum. The brain processes these perceptions to generate an image of our surroundings. Science and art expand our vision of the world in equally valid ways, using different means and methods. DESY researcher Christian Schroer uses state-of-the-art X-ray sources to analyse structures whose dimensions are measured in billionths of a metre. The artist and synaesthete Anna Mandel uses her intuition to represent existing things in a new way and open up new approaches and perspectives. The worlds of colour she creates call forth emotions, whereas the scientist analyses the sources of colour as one of his fields of research. Both of them are expanding our horizon beyond what we can perceive with our senses. And both use light as a tool to throw familiar things into question and develop new ways of seeing. A discussion of light in science and art, of perception and images of the world.

femto: Christian Schroer, you are a physicist and the scientific head of PETRA III, one of the world's best X-ray sources. What exactly are you doing with this light?

Christian Schroer: I work with microscopy – in other words, I use light to examine various things. Optical microscopes work with visible light and magnify things so that they can still be seen with the naked eye. We go one step further. We use X-ray light, which has a much shorter wavelength than visible light.

femto: What's the advantage of doing that?

Christian Schroer: In microscopy, the resolution – in other words, the size of the smallest objects one can observe – is limited by the wavelength of the light you're using. In the visible region, the wavelength goes down to half a micrometre, which corresponds to one hundredth of the diameter of a human hair. The wavelength of X-ray light is ten thousand times smaller. It lies in the range of the distances between atoms. In principle, this enables us to see individual atoms.

"In principle, we are able to see individual atoms"

femto: In this case, "seeing" is a highly complex and indirect process. What do you actually "see"?

Christian Schroer: In effect, we're seeing the spatial arrangement of the atoms in matter. This, for example, is a segment of the shimmering white top layer of a beetle's wing at a scale of 1 to 10 000. *(He holds up a 3D model made of white plastic.)*

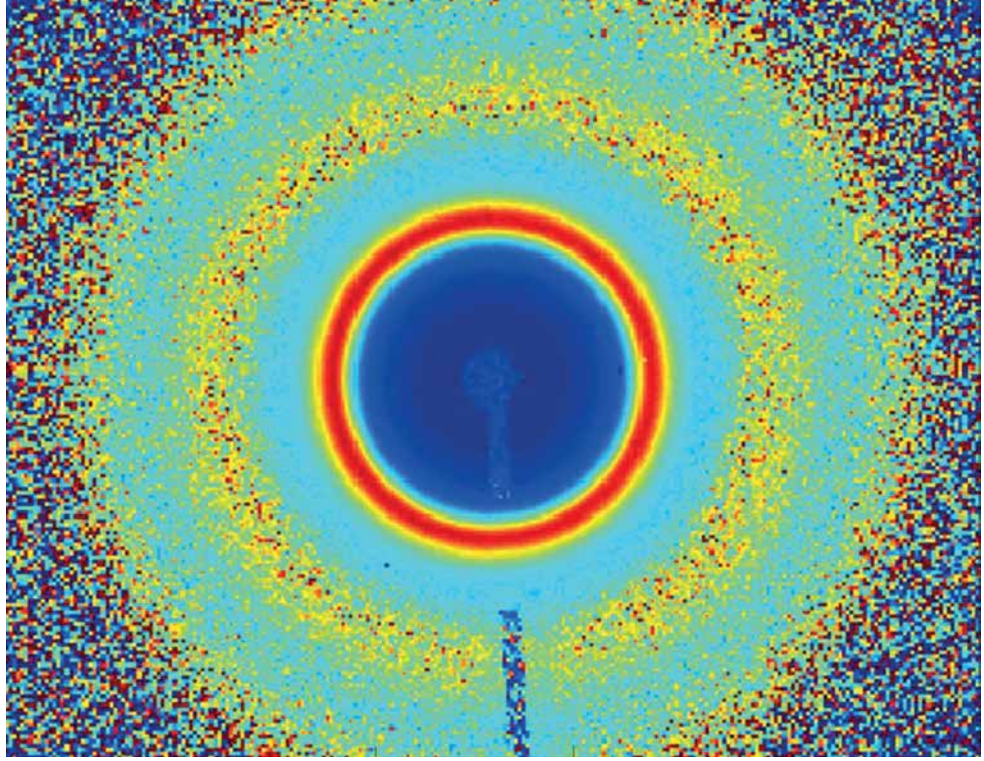
femto: It looks like an enlarged piece of a sponge, with lots of fibres and hollow spaces.

Christian Schroer: It's this labyrinthine inner structure of the wing's top layer that makes the beetle look white in the visible region of the spectrum. The structures are about 200 nanometres wide. That's about half of the wavelength of visible light. The light that radiates onto the beetle is caught up in this labyrinth and reflected by it, irrespective of the colour of the light. That's what makes the beetle look white.

femto: Because when all the colours of light are superimposed, the result looks white. So you need X-ray light to find out why the beetle's wing has a shimmering white colour.

Christian Schroer: X-ray light enables us to observe these structures precisely, whereas all you can see in visible light is an object that is reflecting white light. However, with X-ray light you don't see the object directly. You see it in translation, so to speak. The object is tiny, and it is scanned with an extremely fine X-ray beam. The short-wavelength light is scattered by the individual atoms. A computer uses hundreds of thousands of such diffraction patterns to precisely calculate the structure of the object that matches all of these images simultaneously. And the structure enables us to deduce the function – in this case, the cause of the wing's colour.

"Seeing" with X-ray light: Diffraction pattern of colloidal glass, which consists of countless silicon dioxide globules 50 nanometres in diameter, recorded at the PETRA III research light source at DESY.



Picture: Dmitry Denisov, University of Amsterdam

Christian Schroer is the scientific head of the X-ray source PETRA III at DESY and a professor at the University of Hamburg. After starting his career in theoretical physics and obtaining his doctoral degree, he specialised in X-ray nanoresearch and the development of X-ray optics. His aim is to further expand the opportunities to experiment with the brilliant X-ray light of PETRA III in order to find out more about structures and processes in the molecular world.

Anna Mandel: In art, the focus is not on the causes of colours but rather on their effects. For example, we use colours to evoke certain emotions that we then work with. Everyone knows that blue tends to calm people but red doesn't. When I paint a picture and use certain colours, I set off certain reactions in the observer.

femto: So art expands our perceptions by opening up an emotional world in addition to our visual world?

Anna Mandel: Colours can have a powerful effect. In one project, I painted a whole room in different shades of blue. Many people spoke to me about the colour blue in this room, because it had aroused something inside them. Through the experience of art, the viewer can perceive and orient himself or herself in a new way. A 14-year-old schoolgirl who had seen one of my installations came to me and thanked me for my work. She said it had given her a new kind of access to the emotional problems of a relative. I would never have had such an idea on my own.

"Through the experience of art, the viewer can perceive himself in a new way."

femto: Would you say that art can open up new perspectives for me?

Anna Mandel: Yes, that's shown very strikingly by what we call "flatware" – in other words, pictures. Forty years ago, modern artists threw representative pictures out of the window and said we don't want to see this kind of bourgeois rubbish any more. Today, we're going back to such pictures. The idea behind this movement was formulated back in the Renaissance: a picture is a window. It gives us access to a world that doesn't literally exist. A madonna is sitting in a rose garden – the wall you're looking at suddenly has an opening in it. When I work with colour, this opening for the viewer is very wide, and the space behind it is not explicitly defined. What happens after that is a very individual matter.

femto: And how do you create these spaces?

Anna Mandel: People always say that the task of the artist is to create things that don't exist. But all I can do is to take something that already exists and modify it. I have a certain intuitive idea that serves as my outline. I then use the materials and techniques I have at my disposal in order to make this idea visible to others. The situation is similar in science. This beetle's wing has existed for a long time, but we now have new technologies to investigate it for ourselves.

femto: As you work, are you pursuing a certain goal?

Anna Mandel: I don't ask myself what I plan to achieve. In non-commercial art, I have an internal image that is entirely my own, and I try to find an appropriate shape for it. If the search is successful, the result becomes meaningful for other people. You can do lots of things, but not everything is interesting.

Christian Schroer: It's the same in science. In principle, you can conduct any kind of experiment, and it can deliver absolutely correct results that are completely boring and of no interest to anyone. The trick is to devise an experiment that answers an interesting question.

"You can do lots of things, but not everything is interesting."

femto: So art and science expand our vision of the world in equally valid ways beyond what we can perceive with our senses. For example, science can analyse structures and processes that are too small, too fast or too distant for us to perceive. Art can create new emotional and rational access to things that already exist. People immediately concede that an artist needs intuition and creativity in order to do that. Does that apply to science as well?

Christian Schroer: In my experience, creativity also tends to show up in science by chance – just as it does in art. One day you might ask yourself, "Why do I actually always do things this way? Maybe this isn't the right way at all. How can I approach things differently?" In this way, you can break through the barriers. One example is the ability to focus X-rays. A few years ago, there was a dogma that said that X-rays could only be focused up to a certain point, and that you basically couldn't go beyond that point. But do I really believe that? My intuition says that it can't really be true. So I try to construct a counterexample. Today, after many discussions and developments, there are actually X-ray lenses that can focus even better. Nonetheless, no laws of physics have been disproved by that. We've simply constructed the lenses in such a way that this special law doesn't apply to them at all.

femto: So science can't function without intuition either?

Christian Schroer: Right at the beginning of a development, you might in fact have a kind of gut feeling, a vague idea or a possible inkling of a certain phenomenon. Then you begin to try things out.

femto: Can science benefit from art in processes like these?

Anna Mandel: Art can at least shake you up a bit, give you food for thought and encourage you to perceive things in new ways. Critical questioning of the status quo is an important theme in art as well. For example, a "blue thing" doesn't exist as such. There's only the light that hits something, and my sensory apparatus, which interprets this process as the sensory impression "blue". I once worked in a theatre with someone who took a picture and projected onto it a slide that slowly changed colour. The colours of the picture changed accordingly, and the entire character of the picture changed with them. This phenomenon has been known for a long time, but the projection shook the audience out of its familiar perspective. The picture doesn't exist in and of itself; it can only be perceived in the light that enables it to show itself.

femto: So we have to question our own perceptions and thus find new approaches to things we think we know well?

Anna Mandel: As a synaesthete, I'm very familiar with that idea. For me, letters and sounds also have colours. The fact that everything is connected with everything else is part of my daily experience.

femto: Synaesthesia is a congenital peculiarity of the process of perception that affects some individuals. For them, the stimulation of one sense triggers not only a "normal" perception but also additional perceptions by other senses.

Anna Mandel: Everything I hear, think and perceive is coloured. For example, once I worked together with a cellist who played Bach suites on the stage while I painted on previously prepared canvases the things I see when I hear this music. It was similar to making notations on a canvas. The viewers could follow this process as it happened. There were children in the audience, and for them it was completely normal to see the sonata suddenly transformed into a colour composition.

femto: For most adults, this is harder to understand. But actually it only illustrates the fact that our sensory perceptions are always subjective.

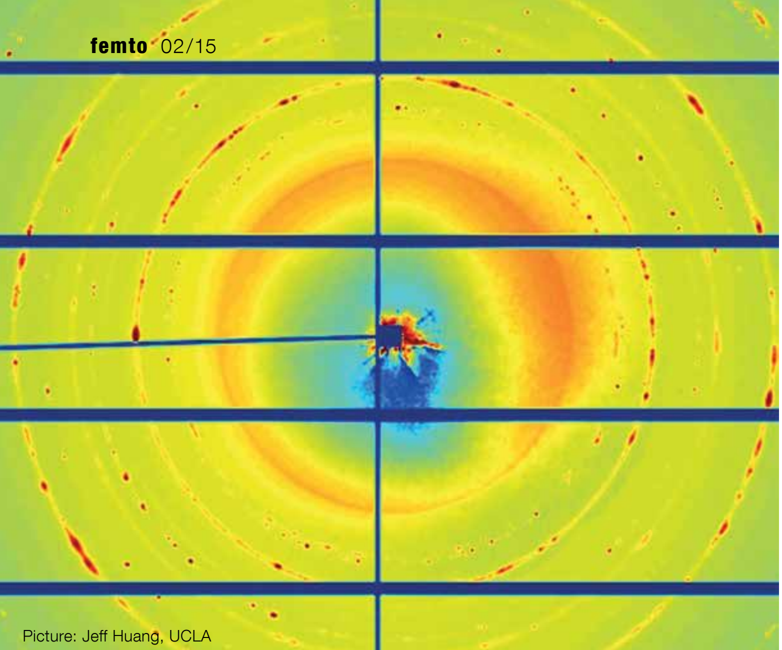
Anna Mandel: The concept in modern physics that the customary boundaries fade – as in the wave/particle discussion – is part of my daily perceptions. The boundaries between what can be heard, seen and felt are fluid. I can't imagine only hearing something, because I also see what I hear. Everything is characterised by light, both real and imaginary.

Music is coloured. *The Waterman* by Anna Mandel is a colourful painting interpreting the song of the same name by Robert Schumann. It is part of a cycle of 16 paintings corresponding to 16 songs for the concert *FarbTöne* ("ColourTones").

Picture: Jochen Quast

Anna Mandel studied philosophy and sculpting. She works as a freelance artist and illustrator in Hamburg. As a synaesthete, she knows from personal experience just how subjective our sensory impressions are. In her works, she creates new connections and new forms of access to existing things. You can see paintings by Anna Mandel in her online showroom:

http://showroom.annamandel.de



Picture: Jeff Huang, UCLA

The X-ray diffraction pattern contains detailed information about the nanostructure of the photosensitive film.

Filming a film

Researchers observe photographic exposure at the nanolevel

An international research team at DESY's bright X-ray light source PETRA III has observed the exposure of photographic paper at the level of individual nanocrystals. Their measurements show how the light-sensitive grains in the photographic emulsion are distorted, rotate and finally disintegrate. The sophisticated investigation technique they used makes it possible to investigate a broad range of chemical and physical processes in matter with millisecond precision.

Photoinduced chemical reactions play a role in numerous basic processes and technologies, ranging from energy conversion in nature to micromanufacturing with the help of photolithography. One example that can even be observed with the naked eye is the exposure of photographic films. The researchers examined the processes that take place during the exposure at the level of nanocrystallites – the light-sensitive grains in the emulsion.

The extremely bright beam of PETRA III in combination with a high-speed X-ray detector made it possible to "film" these processes with a time resolution of up to five milliseconds (thousandths of a second). "We observed, for the first time, grain rotation and lattice deformation during a photoinduced chemical reaction," explains Jianwei Miao from the University of California, Los Angeles. "We were actually surprised to see how fast some of these individual grains rotate," adds DESY researcher Michael Sprung. "Some of them spin almost once every two seconds."

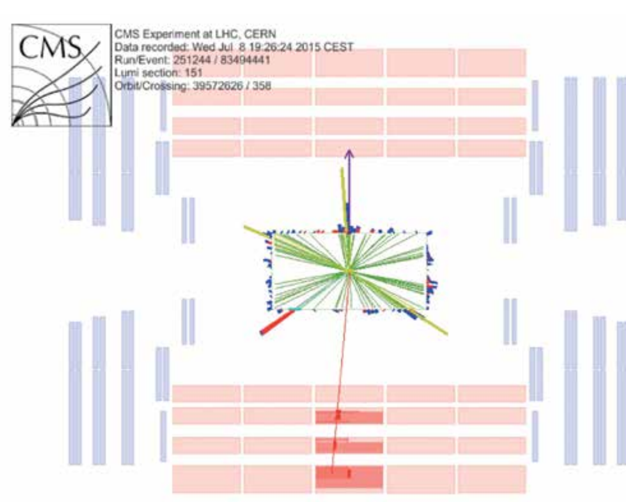
Nature Materials, 2015; DOI: 10.1038/NMAT4311

The Standard Model is still valid

Initial tests at new LHC collision energy

Shortly after the start of the second period of operation of the Large Hadron Collider (LHC) at the particle physics research centre CERN near Geneva, DESY researchers and their colleagues from the CMS and ATLAS experiments reported the results of an important initial test of the Standard Model of particle physics at the new collision energy of 13 teraelectronvolts. For this test, they used data from proton–proton collisions at beam energies never attained before. They analysed the rate of production of a known particle, the top quark, in this data to see whether it behaves differently at higher energies. Their investigation shows that, so far, the top quark behaves as predicted.

The top quark is the heaviest known elementary particle. It even weighs more than the Higgs boson, which was discovered in 2012, and for this reason it might have a special relationship with it. To understand this relationship and find out whether the top quark really behaves as theory predicts, the particle physicists at the LHC are examining it very carefully. One of these studies focuses on the rate of production of pairs of top quarks in the new energy range. "The results match our expectations very well. This is a further tremendous success for the Standard Model," says DESY researcher Alexander Grohsjean.



A candidate for top quark production in the CMS detector

A milestone for the CSSB

Topping-out ceremony for the interdisciplinary Centre for Structural Systems Biology

The topping-out ceremony for the new research building of the Centre for Structural Systems Biology (CSSB) at DESY took place on 9 September. This major milestone was celebrated by Hamburg's Senator for Science, Katharina Fegebank; Karl Eugen Huthmacher from the Federal Ministry of Education and Research; Schleswig-Holstein's Minister of Research, Kristin Alheit; DESY Director Helmut Dosch; the CSSB's founding director Matthias Wilmanns; and representatives of the nine research institutions participating in the CSSB. Starting in 2017, scientists at the CSSB will conduct research on bacterial and viral infections in a unique interdisciplinary approach. To this end, they will use the innovative light sources at DESY and cryo-electron microscopy in the future CSSB building.

"The CSSB is already an excellent research institute. The new building will only enhance the existing framework. Closer exchange between many disciplines, shorter ways and DESY particle accelerators on CSSB's doorstep; these are all things that will move infection and immunisation research forward and will contribute to the worldwide scientific reputation of the metropolitan region," said Senator Fegebank.

"The CSSB has become a magnet for innovative researchers in the field of structural and systems biology," said Alheit. "It has created the best preconditions to support the further development of interdisciplinary excellence in northern Germany, especially in the field of infection research."

Celebrating the completion of the building shell (from left): Matthias Wilmanns, Karl Eugen Huthmacher, Kristin Alheit, Helmut Dosch and Katharina Fegebank.

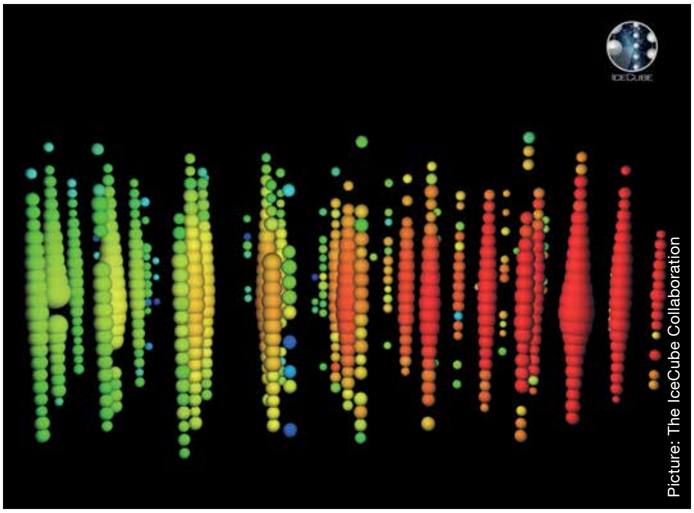
IceCube spots more cosmic neutrinos

The detector at the South Pole confirms the origin of high-energy neutrinos from outside the solar system

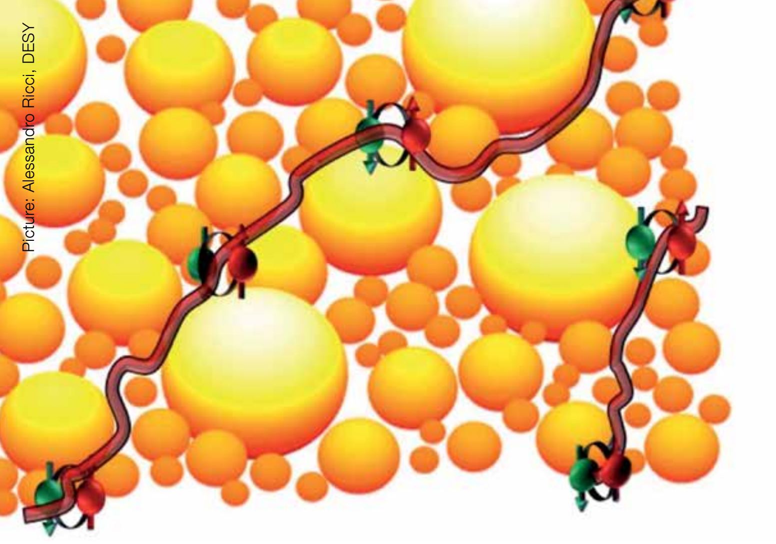
The IceCube neutrino observatory at the South Pole has registered more neutrinos from the depths of space. This confirms the cosmic origins of the highest-energy variants of these elusive elementary particles. "Thanks to the combination of several independent data sets, we can now not only say 'Hurrah, we've seen neutrinos!' We can also measure the energy spectrum of these particles with great precision and determine the relative proportions of the various types of neutrinos that come to us from outer space," explains Markus Ackermann, one of the DESY scientists who participated in the study. "This gives us information about the neutrinos' origins and the processes that create them deep within the universe," adds Lars Mohrmann, who processed the combination of data sets as part of his doctoral thesis. Neutrinos are subatomic particles that move through the universe seemingly unimpeded by matter. As a result, the tracks they leave behind point directly to their sources. Extremely high-energy neutrinos are expected to have sources that are characterised by the most extreme conditions in the universe, such as gigantic black holes or tremendous stellar explosions.

Physical Review Letters, 2015; DOI: 10.1103/PhysRevLett.115.081102
The Astrophysical Journal, 2015; http://arxiv.org/abs/1507.03991

Trail of a cosmic neutrino in the IceCube detector



Picture: The IceCube Collaboration



The superconducting electric current (red) runs through the space between the electron pools in the electronic crystal.

Electron pools

X-ray studies are improving our understanding of high-temperature superconductors

Ceramic superconductors have a surprising structure. This fact was discovered by an international research team in an experiment with high-energy X-ray radiation. Inside these high-temperature superconductors, electrons gather in pools of various sizes that occur throughout the entire material. The researchers hope this observation will help them to track down the microscopic origins of high-temperature superconductivity, which so far has not been precisely understood.

Superconductors are materials that conduct electric current without any resistance. This characteristic basically makes them interesting for a broad spectrum of applications. Certain ceramic materials do not have to be cooled as intensely as conventional superconductors. The researchers analysed one such high-temperature cuprate superconductor and discovered that, at a temperature of minus 20 degrees Celsius, the electrons start to form tiny pools. “We discovered that the size of these pools varies widely, like the chunks of a molten iceberg or the steam bubbles in a boiling pot,” explains DESY researcher Alessandro Ricci. “These results open new avenues for the design of superconducting materials, and thus could advance the search for a room-temperature superconductor.”

Nature, 2015; DOI: 10.1038/nature14987

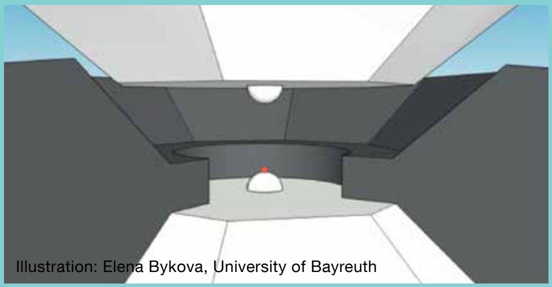
Record pressure

Squeezing osmium

Under the direction of the University of Bayreuth, an international research team including DESY scientists has generated the highest static pressure ever achieved in the lab. Using a special diamond anvil cell, the researchers investigated the behaviour of the metal osmium under pressures ranging up to 770 gigapascals (GPa) – this corresponds to 7.7 million times the atmospheric pressure on Earth and more than twice the pressure within the Earth’s core. The new recordbreaking pressure is 130 GPa higher than the previous world record, which was also set by members of this team. Surprisingly, osmium does not change its crystal structure even under such record-breaking pressure, in contrast to other materials. However, the high pressure forces the core electrons to interact with one another.

This fundamental result has important implications for our understanding of the physics and chemistry of extremely compressed matter, for the design of materials to be used under extreme conditions and for mathematical models of the interior of large planets and stars. “Our work shows that ultrahigh static pressure can force the core electrons to interact,” explains Natalia Dubrovinskaia from the University of Bayreuth. “The ability to affect the core electrons even in such incompressible metals such as osmium in static high-pressure experiments opens up exciting perspectives for the search for new states of matter.”

Nature, 2015; DOI: 10.1038/nature14681



Schematic diagram of the anvil cell: The osmium sample (red dot) is only three micrometres in diameter. It is located between two hemispheres of nanocrystalline diamond.

Natalia Dubrovinskaia and Leonid Dubrovinsky at a micromanipulator that is used to prepare the samples for investigation.

Reconstruction of the X-ray focus of the lens. At the waist, the focus is only eight nanometres wide.

Picture: Saša Bajt, DESY

An innovative X-ray lens

An innovative concept makes it possible to tightly focus X-ray radiation

A new type of X-ray lens delivers sharper and brighter images of the nanocosmos. Thanks to an innovative concept, the lens can bundle a large amount of X-ray radiation very tightly, thereby providing high spatial resolution and high intensity. The lens has a special nanostructure that is created by means of a new production process requiring atomic precision, which was developed by a team of scientists led by DESY researcher Saša Bajt.

"X-rays are used to study the nanoworld, as they are able to show much finer details than visible light and their penetrating power allows you to look inside objects," Bajt explains. The fineness of the details that can be resolved depends basically on the wavelength of the radiation used. X-ray radiation has very short wavelengths between 0.01 and 1 nanometre (millionths of a millimetre). The high penetration depth of X-ray radiation enables the three-dimensional tomography of objects such as biological cells, computer chips and nanomaterials. However, the high penetration depth also means that X-ray radiation simply passes through conventional lenses without being bent or focused.

Bajt's team has developed a new production process for so-called multilayer lenses. "The results demonstrate that our manufacturing technology can produce lenses with a high focusing power," Bajt says. "We are convinced that our method can produce even better lenses. The long-sought goal of focusing X-ray radiation to a nanometre appears to be within reach."

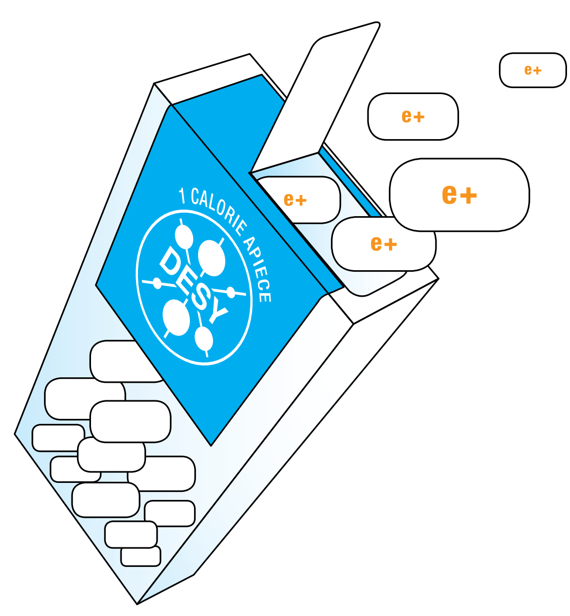
Scientific Reports, 2015; DOI: 10.1038/srep09892

femtomenal

Do positrons make you fat?

An entire kilocalorie – that's how much energy is contained in a sugar-free peppermint Tic Tac, or in the sum total of positrons that DESY's particle accelerators have generated per year so far. That corresponds to an annual amount of 46 picograms of positrons. A picogram is one trillionth of a gram – an unimaginably tiny fragment of a Tic Tac, which weighs in at half a gram.

In the past 40 years, DESY has generated positrons with a total energy of 40 kilocalories and a weight of 1.8 nanograms (billionths of a gram). This is a negligible amount in terms of calories, but it has been extremely fruitful for research. Positrons are the antiparticles of electrons, and both kinds of particles are outstanding helpers in our quest to unravel the mysteries of matter. Clearly, this is a question of class, not mass!



Highly promising anti-inflammatory agents

Researchers decode molecular structure of so-called Spiegelmers

Christian Betzel is a professor at the University of Hamburg. He specialises in infection biology.

Spiegelmers are a new group of highly promising active ingredients, which are already undergoing clinical trials as anti-inflammatory agents. Before the efficacy of a new active ingredient can be optimised, its mechanism of action must be fully understood. Researchers working at DESY's X-ray source PETRA III have succeeded in decoding, for the first time, the spatial structure of two molecules from the group of Spiegelmers. The work was accomplished by scientists from the Universities of Hamburg and Aarhus (Denmark) together with the Berlin-based biotech firm NOXXON.

Spiegelmers are based on the same building blocks as the nucleic acids RNA and DNA, which are responsible for various functions in the body, ranging from the storage and transmission of genetic information to the regulation of genes. Synthetically produced RNA or DNA molecules – so-called aptamers – are able to bind very specifically to certain proteins, thereby blocking their functioning. Yet they are well tolerated by the body, as they are made up of natural building blocks. Aptamers are therefore widely viewed as promising drug candidates. An aptamer for the treatment of age-related macular degeneration (AMD), an eye condition that can lead to blindness, has been approved since 2006.

As a rule, RNA and DNA molecules are rapidly degraded by enzymes within the body, a restriction that severely constrains their use as pharmaceutical drugs. However, most biomolecules come in two mirror-image variants, an L-form and a D-form. In the body, RNA always occurs in the D-form, proteins only in the L-form. Synthetically produced L-ribonucleic acid aptamers are not degraded in the body. These mirror-image variants are called Spiegelmers. "The advantage is that Spiegelmers are not targeted by the body's enzymes," explains Christian Betzel from the University of Hamburg. "Spiegelmers are identified and optimised in the lab by means of a sophisticated evolutionary procedure. However, exact structural data on Spiegelmers have not been available until now," says Dominik Oberthür from the Center for Free-Electron Laser Science (CFEL). If, however, the precise three-dimensional structure of a Spiegelmer along with its binding site at the target protein were known, its mechanism of action could be decoded and its structure further fine-tuned, if necessary.

> *"The advantage is that Spiegelmers are not targeted by the body's enzymes"*
>
> *Christian Betzel, University of Hamburg*

To this end, Betzel and his team have been using the bright X-ray light from PETRA III to analyse the Spiegelmer NOX-E36 from NOXXON. This blocks the protein CCL2, which is involved in many inflammatory processes in the body. "If you target an inflammatory protein with a Spiegelmer, you have a good chance of toning down the inflammation in the body," explains Betzel. NOX-E36 has already been successfully tested in a so-called Phase IIA clinical trial with patients.

To analyse the structure of this new active ingredient, the scientists first grew crystals of the Spiegelmer and the target protein CCL2 to which it is bound. "Growing the crystals was quite a challenge," says Betzel. Most biomolecules are notoriously hard to crystallise, because this runs counter to their natural function.

When a crystal is illuminated with X-rays, the result is a characteristic diffraction pattern, which can then be used to calculate the structure of the biomolecule under investigation – in this case, the Spiegelmer, bound to its target protein. Using the same process, a group led by Laure Yatime from the University of Aarhus analysed the structure of another Spiegelmer: NOX-D20, bound to the protein C5a, which is likewise involved in numerous inflammatory processes.

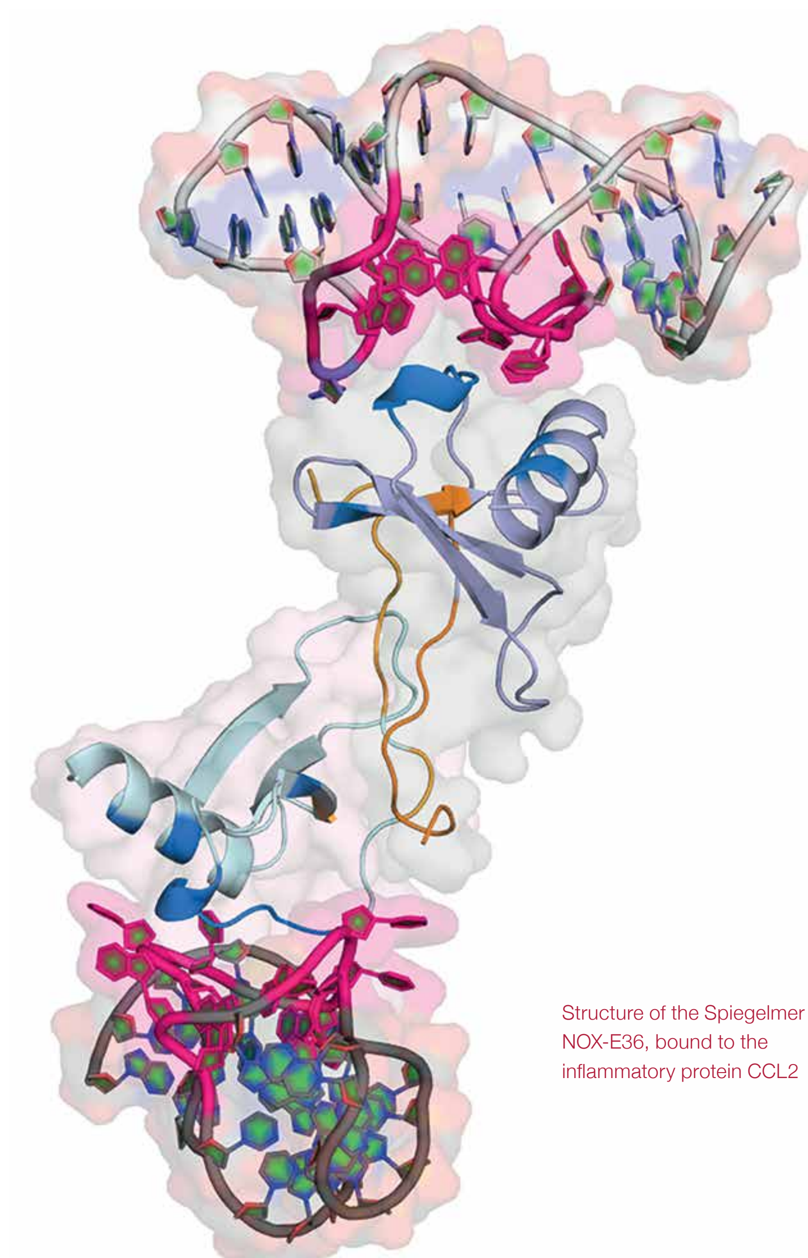
The analyses revealed the three-dimensional structure of the two Spiegelmers with a spatial resolution of 0.2 nanometres, or 0.2 millionths of a millimetre, which is on the scale of individual atoms. "I'm delighted that we have finally

"The structural data deepen our understanding of the two molecules' mode of action"

Sven Klussmann, NOXXON

obtained high-resolution visualisations of the remarkable structure of two Spiegelmer drug candidates," says Sven Klussmann, founder and Chief Scientific Officer of NOXXON. "The structural data not only give us a first insight into the unusual interaction between a mirror-image oligonucleotide and a natural protein, but also deepen our understanding of the two molecules' mode of action."

Nature Communications, 2015; DOI: 10.1038/ncomms7923
Nature Communications, 2015; DOI: 10.1038/ncomms7481



Picture: Dominik Oberthür, CFEL

Structure of the Spiegelmer NOX-E36, bound to the inflammatory protein CCL2


01

Stardust in the lab

DESY physicist Saša Bajt is examining samples of cosmic matter

Normally, DESY physicist Saša Bajt is responsible for developing new X-ray optics systems and devising ingenious ways of placing biological samples in the beam from X-ray lasers. However, she also devotes some of her time to cultivating a passion for space – in her capacity as an expert in the analysis of cosmic dust. At present, she is part of a team investigating tiny fragments of the asteroid Itokawa, which were brought back to Earth by the Japanese space mission Hayabusa. In the past, Bajt has also been involved in the analysis of the first-ever cometary and interstellar dust samples returned to Earth.

femto: How is stardust collected?

Saša Bajt: Interstellar dust is, by definition, dust created outside of our solar system, probably by the explosion of a dying star in a supernova. There's not much of it around in our solar system. Back in 1999, the US space agency, NASA, launched the Stardust space probe. Its primary mission was to fly through the tail of the comet Wild 2 and collect cometary dust. On its journey to the comet, it also held out a collector filled with so-called aerogel – an extremely lightweight silica-based material, also known as frozen smoke – into free space for almost 200 days in the hope of capturing interstellar dust.

femto: Was the mission successful?

Bajt: Yes, it was. The collector looked a bit like a tennis racquet filled on both sides with aerogel. This substance brakes and captures the particles. On the probe's journey to the comet, one side of the collector was held out to capture interstellar dust. When it flew through the comet's tail, the collector was turned around, and the other side captured cometary dust. In the course of the mission, a lot of particles of comet dust were captured, some so large they are visible to the naked eye. On the side collecting interstellar dust, however, it was a different story. To date, after years of investigation, we've only been able to identify seven particles that may be of interstellar origin. If so, this would be the first time that interstellar material has been gathered in space and brought back to Earth for analysis.

femto: How big are these particles of stardust?

Bajt: This was the first mission since the Apollo space programme to collect samples and return them to Earth. Apollo brought back a lot of material from the moon – we're talking here about hundreds of kilos. Stardust, on the other hand, was a relatively inexpensive mission, so we knew from the very start that only an extremely small amount of material would be returned to Earth. Whereas the probe collected over 1000 particles of comet dust, the final number of interstellar dust particles is not yet known. Comet dust particles normally measure somewhere between several thousandths of a millimetre and several hundredths of a millimetre in diameter, whereas a particle of interstellar dust measures only a fraction of a micrometre.

femto: How do you handle something so tiny and fragile?

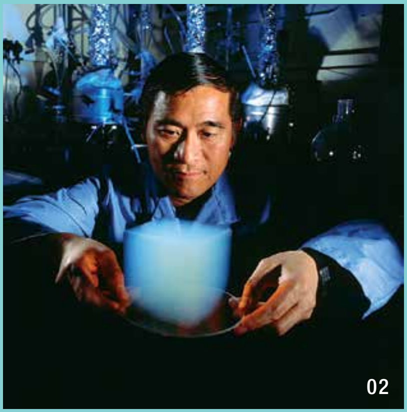
Bajt: That's a good question. It was only after the mission was under way that people began to think seriously about the best way to handle, identify and analyse the particles captured in the aerogel. No one was certain, for example, whether the aerogel would remain transparent after being in space, and whether it would be possible to see the particles and their tracks. At the Space Sciences Laboratory of the University of California, Berkeley, Andrew Westphal and his team developed a process to cut out tiny pieces of aerogel containing particles and their tracks. These so-called picokeystones are held with a tiny fork. Handling the aerogel is very tricky. You almost have to hold your breath while moving a sample. Later, NASA set up a special lab in Houston, where this process was used to produce samples that were then sent for analysis to various laboratories.

femto: What did this analysis show?

Bajt: I used a microscopy process based on synchrotron radiation in the infrared range to analyse the samples, which is a great way of detecting any organic molecules. Our basic assumption was that the particles of comet dust are made up of amorphous silicates wrapped in ice and organic materials. But although the particles were rich in oxygen and nitrogen, they only contained relatively simple organic molecules. To our surprise, lots of the particles contained crystalline material with a highly diverse mix of minerals, some of which could have only arisen at high temperatures. This discovery has actually changed our picture of the origins of comets and our solar system.

femto: In what way?

Bajt: The standard theory says that the solar nebula slowly agglomerated to form planets and that, from the remaining material at the icy fringes of the solar system, comets arose. But now it seems that our solar system was much more turbulent and that everything was much more mixed up in the early stages. Even material that we thought was frozen and untouched



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must at some stage have been subject to processes in which high temperatures were involved and these minerals could form. However, we can't be sure whether what we have observed of this comet is also true of other comets, or whether this comet is simply out of the ordinary. It's difficult to draw general conclusions when you've only got material from one single comet.

femto: And what about the particles that may be of interstellar origin?

Bajt: After preliminary investigations of the comet dust particles had been completed, part of the team decided to continue examination of the particles of interstellar dust. There was no special funding for this part of the project, and researchers did most of the work on a voluntary, *pro bono* basis. But the first problem was to find out whether we actually had any interstellar dust. And even that seemed an almost impossible task, until Andrew had the brilliant idea of calling on the general public to help.

femto: Like a citizen science project?

Bajt: Yes, that's right, it became a citizen science project. Millions of microscope images of the aerogel matrix were posted on the Internet site Stardust@home, along with instructions as to what we were looking for. The reaction was amazing! More than 30 000 volunteers combed through the images and marked areas where

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Pictures: NASA / JPL-Caltech

01 Artistic representation of Stardust on its flight through the comet's tail
02 NASA researcher Peter Tsou with a block of aerogel
03 Particle track in the aerogel
04 The Stardust capsule after its return to Earth

there might be particle tracks. It would have taken us an absurd amount of time to do the work ourselves. When we published our first findings, all 30 000 citizen science participants were named as co-authors. In fact, the project is still up and running. Anyone who would like to help us look for more of the tiny tracks left by interstellar dust particles is very welcome to join us!

Scientists check all the images marked by volunteers, and any promising-looking tracks in the aerogel are removed and analysed. This way, we've so far been able to identify three possible candidates of interstellar dust. In addition, a team led by Rhonda Stroud from the Naval Research Lab is looking for tracks left by particles striking the aluminium frame of the collector. Whenever they discover a potential

Saša Bajt is the leader of the Multilayer X-ray Optics group at DESY, which develops new optics for advanced X-ray sources. She also leads the development of new methods for placing protein nanocrystals and other biological samples in X-ray laser and synchrotron radiation beams. Bajt received her PhD from Heidelberg University and the Max Planck Institute for Nuclear Physics. She then went on to work at the University of Chicago and the Lawrence Livermore National Laboratory, before joining DESY. She also has had a long interest in studying extraterrestrial materials.

candidate, they analyse the residues on the bottom of the tiny crater for their chemical and isotopic composition.

femto: Did the potential candidates of interstellar dust also contain organic substances?

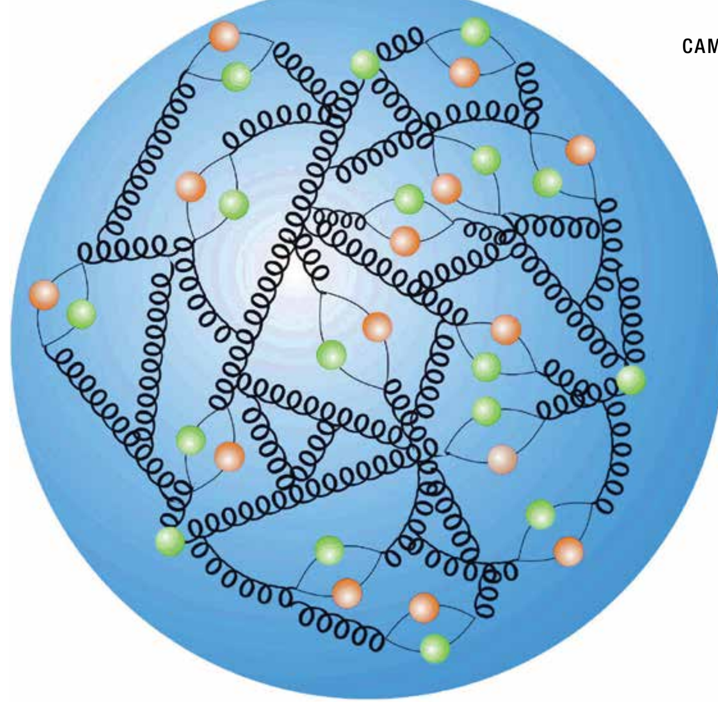
Bajt: We tried to test for organic substances in the particle tracks, but the aerogel itself contained organic impurities. In other words, even if there were organic molecules from interstellar dust in the aerogel, we wouldn't be able to distinguish these from impurities. On the other hand, other analyses turned up a bunch of surprising findings. The particles have very different structure and chemical composition. They are in fact loose agglomerates of even smaller particles, which doesn't fit in with the simple model predictions. With two of the four potential candidates of interstellar dust in the aluminium frame, an analysis of oxygen isotopes was also conducted. This revealed a close approximation to the composition of oxygen isotopes in the solar system. Naturally, this doesn't exclude the possibility that they are of interstellar origin.

femto: So, are these seven particles from interstellar space?

Bajt: We don't have 100 percent proof that they are from interstellar space, but we know for definite that they are of extraterrestrial origin. We now need to conduct further tests. The plan is to examine two of the three candidates found in the aerogel tracks for the relative abundance of oxygen isotopes. Unfortunately, the third particle vaporised upon impact, so there's nothing left to analyse there. Generally speaking, the amount of material available is so small that we really need to make further improvements to our analytical procedures.

femto: What's next on the agenda?

Bajt: I've just started investigating a new type of extraterrestrial sample. These consist of larger particles with a diameter of between 50 and 100 micrometres, which the Japanese space probe Hayabusa brought back from the asteroid Itokawa. The team on this project has been put together by Henner Busemann from the ETH Zurich and is much smaller and completely European. Here, too, I'm using my microscopy process with synchrotron radiation in the infrared range. The work is being carried out at BESSY II in Berlin. Most of the particles that we have looked at consist of silicate minerals with small metallic inclusions. But it's going to take a while before we have any tangible results.



A proton not only consists of three quarks (green), which are held together by gluons (black springs), but also contains a seething mass of gluons and short-lived pairs of quarks and antiquarks (orange).

The sharpest picture of the proton

HERA researchers publish comprehensive analysis of their combined data

HERA is the largest particle accelerator ever built in Germany. In an underground ring-shaped tunnel some six kilometres in length, electrons and protons (hydrogen nuclei) were accelerated to almost the speed of light and then made to collide with one another at enormous energy. Although the experimental programme was completed in 2007, it is only now that analysis of the huge data sets has reached a tentative end. In a joint presentation, the two HERA teams from the H1 and ZEUS detectors have provided a comprehensive evaluation of their measurement data. The result is the most precise picture ever of the proton, the central building block of the atomic nucleus.

It was back in the late 1970s that DESY physicists forged a bold plan to build an accelerator that would fire electrons and protons at one another. This was a first for particle physics. Until then, the only colliding-beam facilities in operation were ring-shaped accelerators for head-on collisions between electrons and electrons or protons and protons. “A mixed operation with collisions between electron and proton beams was completely uncharted territory,” explains Reinhard Brinkmann, Director of the Accelerator Division at DESY. “For example, it was quite unclear how the two beams would affect each other in areas where they run in close proximity.”

The second obstacle was proton acceleration. This required powerful magnetic forces to keep the protons circulating on a circular path. The sole way to generate these forces was with superconducting magnets, which only function at temperatures approaching absolute zero. This presented a major technical challenge. “The design and construction of HERA involved practically the whole of DESY,” says Brinkmann.

After six years’ construction, the facility was completed in 1991, just about on schedule. It then took a while, however, for physicists to learn how to control the interplay between the electron and proton rings. Progress was slow at first, but gradually the experts were able to steadily increase the number of particles in both rings. As a result, the collision rate increased, along with the output of experimental data. The original target for the facility was met in 1997, and

“Uncharted territory”. Reinhard Brinkmann, Director of the Accelerator Division at DESY, looks back at the construction of HERA.

"Surprisingly complex": Joachim Mnich, Director in charge of Particle Physics and Astro-particle Physics at DESY, comments on the HERA results.

The HERA particle accelerator consists of a proton ring (above) and an electron ring (below).

then, following modifications in 2000 and 2001, significantly surpassed.

A sea of gluons

Most of these collisions were measured by two huge detectors, H1 and ZEUS, each the size of a large building. Over 15 years, they registered more than two billion particle collisions, thereby helping to put together a new picture of the proton. "Before HERA, we had a relatively simple picture of the proton, consisting of three quarks plus a number of gluons holding these quarks together," explains Joachim Mnich, Director in charge of Particle Physics and Astroparticle Physics at DESY. "HERA showed that the proton is, in fact, surprisingly complex." Closer inspection revealed further quarks that fleetingly appear before vanishing again – in a sea of equally ephemeral gluons.

HERA was also able to provide impressive proof of two key elements of the Standard Model, the currently accepted theory of particle physics. Firstly, the theory of quantum chromodynamics (QCD) was tested and verified. Among other things, QCD describes how quarks are held together in the proton, with gluons as "adhesive" particles. "A major result here was the measurement of the QCD coupling constant," Mnich explains. "This fundamental natural constant determines the strength of the interactions between quarks, and HERA provided one of the most precise experimental values for it." Secondly, the HERA experiments showed that two other fundamental forces of nature, the electromagnetic and weak interactions, do in fact seem to combine into a single force at high collision energies. "Here too, HERA delivered textbook results," says Mnich.

HERA and the Higgs particle

The results from HERA are also relevant for the current experiments at the world's largest accelerator, the LHC in Geneva. This has protons collide at record energy levels. To understand what happens in such collisions, it is vital to have as precise a picture as possible of the inner workings of the proton. "Without the HERA data, it would be all but impossible to understand the LHC data in detail and to be able, for example, to filter out the signals from the Higgs particle from the tangled mass of data," Mnich explains.

The hope that HERA would detect totally new particles, such as the hypothetical leptoquark, remained unfulfilled. There was no little excitement in 1997 when the detectors supplied data that were seemingly inexplicable in terms of the Standard Model. "But further measurements showed that these were just statistical outliers," says Mnich. The physics revolution had failed to materialise.

Yet the work looks to be far from coming to an end. "Lots of experts from around the world are still interested in analysing the data from HERA," says Mnich. "They believe there is even more information to be got out of them." To this end, the DESY computing centre will hold the data in a suitable form for at least ten years, so that physicists from around the world can use them for further analysis.

For accelerator physicists such as Reinhard Brinkmann, HERA was also a source of important knowledge: "The expertise we acquired in superconductivity was extremely important for the further development of superconducting accelerator structures." Current facilities such as FLASH and the European XFEL X-ray laser are now based on this technology. "Today, we're world leaders in this field," says Brinkmann. "I'm not sure we would have achieved that without the experience gained with HERA."

Although the accelerator was mothballed in 2007, and the detectors have now been dismantled, parts of the ring may well be resurrected for an experiment by the name of ALPS. The plan is to use 20 HERA magnets in one of the straight tunnel segments in order to search for hypothetical particles known as axions. "This experiment would be a thousand times more sensitive than all previous attempts," explains Mnich. In fact, CERN in Geneva is even considering the idea of building a successor to HERA, significantly larger than the Hamburg original. Under the project name LHeC, experts are working on plans to connect up the existing, 27-kilometre LHC ring to an electron accelerator. This would enable a much more precise investigation into the inner structure of the proton – and perhaps even the detection of the elusive leptoquark.

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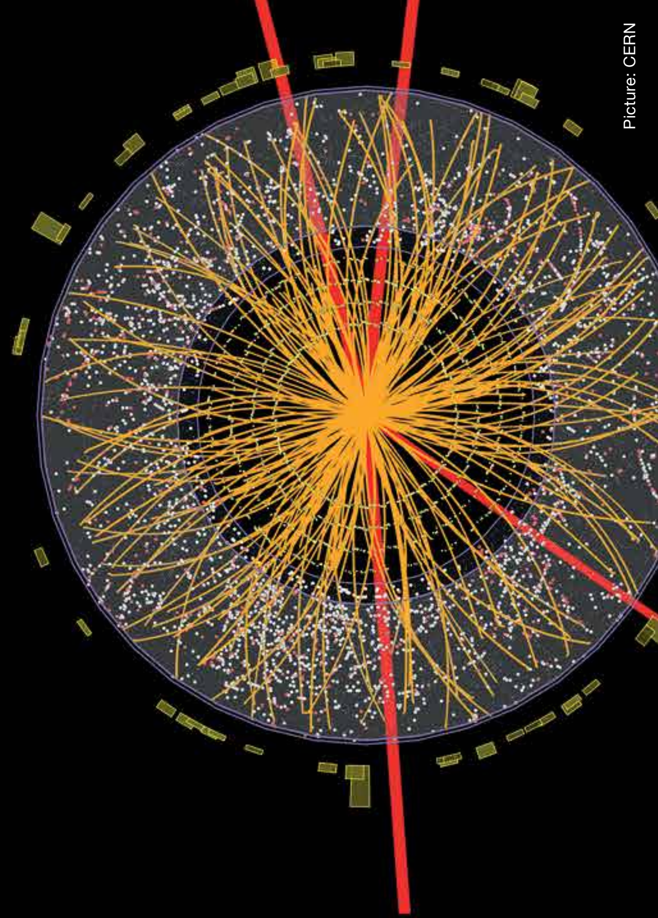


Picture: CERN

What's a barn doing in particle physics?

Collision tracks in the ATLAS detector at the LHC

The story of an unusual unit of measurement

For DESY particle physicist Thomas Schörner-Sadenius, the unit of measurement known as the "barn" is almost as common as the gram. He is used to dealing with orders of magnitude on the femto scale – femto is one thousandth of a millionth of a millionth – with the same dexterity that others add 250 grams of flour to a cake recipe.

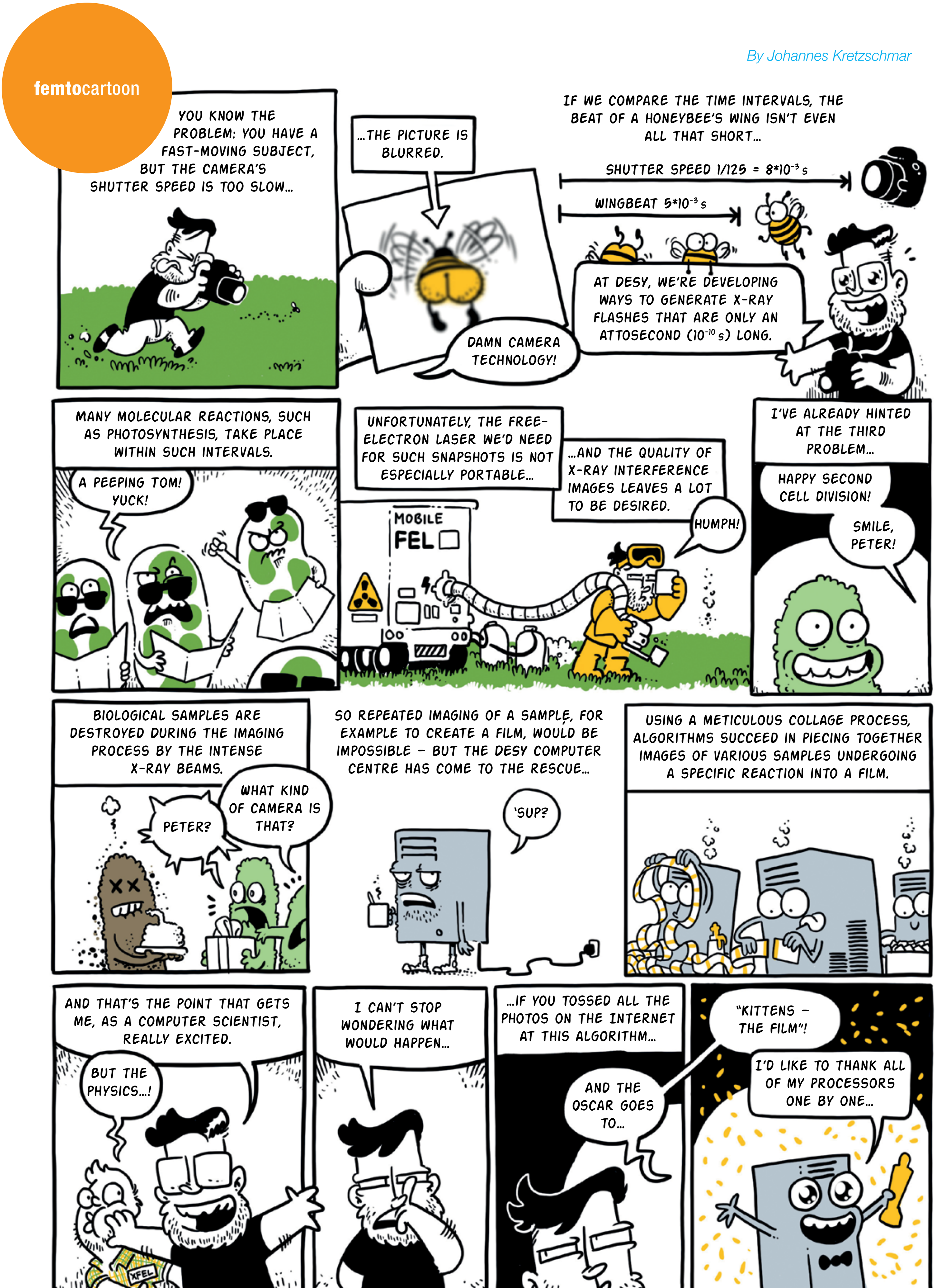
For all non-physicists, a barn would not, at first sight, seem to have much in common with the world of science. So just what is its role in physics? "The barn is a unit of measurement for what we call the cross section," explains Schörner-Sadenius. "The cross section is a crucial parameter in particle physics, for example when we're colliding protons at almost the speed of light in the hope of discovering signs of new and exciting physics in the products of these reactions."

A proton has a radius of only one femtometre, that is, 0.000 000 000 000 001 metres. The chance of a collision between two such minuscule particles is relatively small – even if billions of particles are fired at one another simultaneously, rather than just individual protons. The essential parameter here is the cross section. "In simple terms, the cross section is a measure of the effective area that a target offers to a projectile; in this case, one proton to another," says Schörner-Sadenius. "If this area is large, then the likelihood of a collision is also high."

But why is it measured in terms of a barn? How did scientists come to name a physical unit for a complex collision event involving extremely small particles after an agricultural building? The term dates from the 1940s, when two physicists working on the Manhattan Project to develop the atomic bomb were looking for a concept to describe the unexpectedly high reaction rate of neutrons with uranium atoms. "Compared to other particles, the uranium atom had such an enormous effective area that the two of them thought, it's 'as big as a barn'!" explains Schörner-Sadenius. The name stuck, and since then the barn has been the unit of measurement for cross sections. A wartime need to avoid any reference to investigations into nuclear structure meant that the term and its definition remained top secret until 1948.

Particle physicists such as Schörner-Sadenius can only dream of working at a scale of one barn, the cross section of a uranium nucleus when bombarded with neutrons: "In particle physics, the cross sections for interesting processes such as the production of Higgs particles at the LHC lie more in the femtobarn region, that is, one quadrillionth of a barn. We particle physicists really do live in a femtoworld!"

By Johannes Kretzschmar



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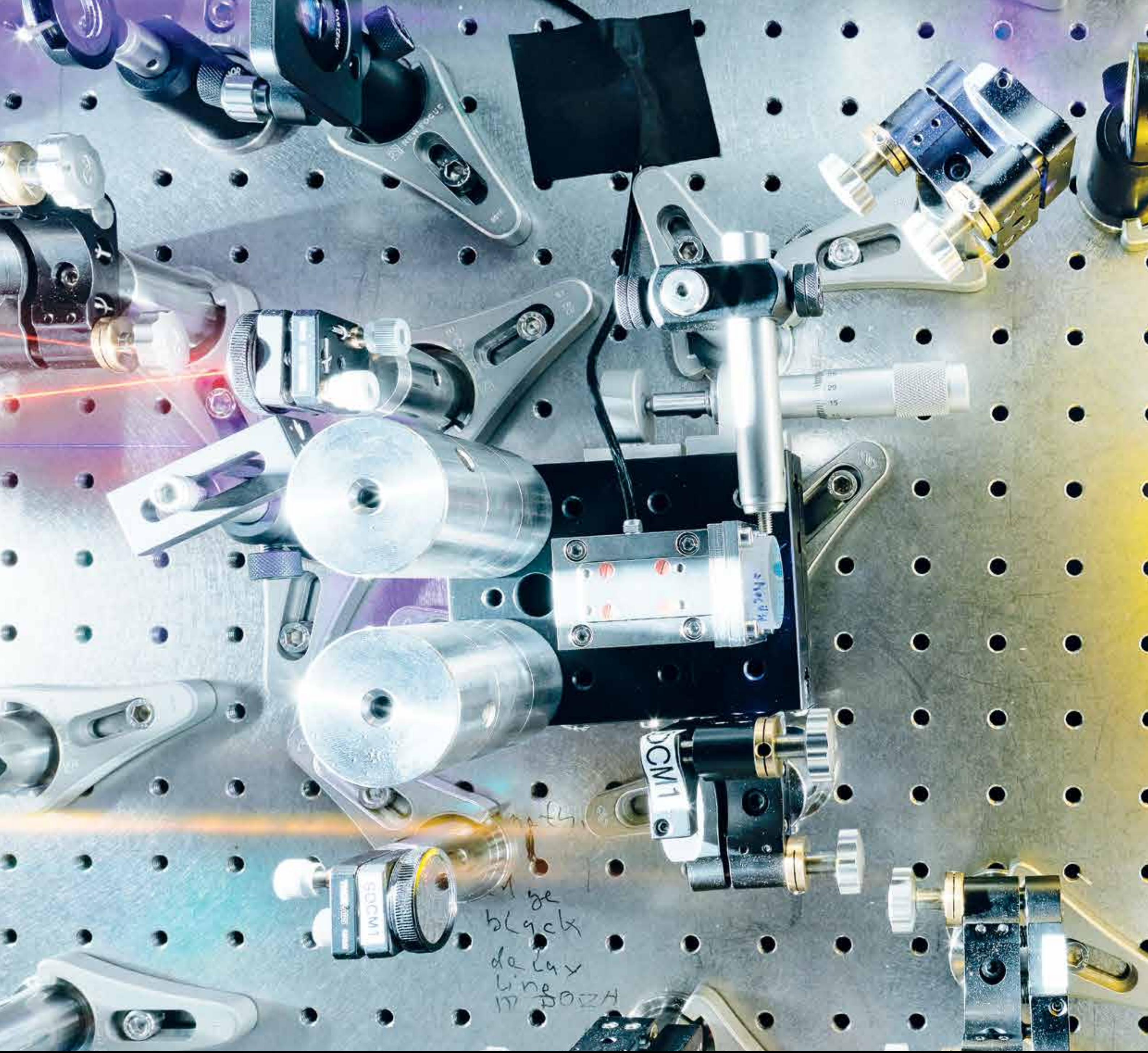
Lasers generate a special kind of light that makes a wide variety of scientific applications and research methods possible. This innovative optical pulse synthesiser superimposes laser light of various colours, thus generating ultrashort flashes of light. The experts at DESY work with a wide range of laser systems, from tabletop devices to X-ray lasers that are kilometres long.



The DESY research centre

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

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