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The DESY research magazine – Issue 01/19

The perfect wave

Physicists are devising the next generation of particle accelerators

Black hole
Active galaxy hurls
high-energy neutrinos
into space

Strange mirror world
Corkscrew lasers
produce mirror
molecules

Quick start for X-ray laser
First experiments
reveal structure
of antibiotics killer

Picture: Ashley Jones

Astroparticle Immersive Synthesizer³ – AIS³ [aiskju:b]

Science meets art: The conceptual artist Tim Otto Roth was inspired to build his light and sound installation [aiskju:b] by the neutrino observatory IceCube, which spies for high-energy cosmic particles in the perpetual ice of Antarctica. DESY, the largest European partner involved in IceCube, supported Tim Otto Roth in the realisation of the installation "Astroparticle Immersive Synthesizer³ – AIS³ [aiskju:b]", which was on view for several weeks in the cultural church St. Elisabeth in Berlin. [aiskju:b] enables visitors to immerse themselves in the events taking place at the South Pole by experiencing neutrino collisions in IceCube virtually in real time. "This project allows an audience that does not have close connections with science to experience the fascination of science. The unconventional approach to a current research topic offers a sensory experience that augments our classical communication of research," explains Christian Spiering, former head of the IceCube group at DESY and founder of the Global Neutrino Network.

Although billions of neutrinos zoom through us every second, they are extremely difficult to detect because these light elementary particles hardly ever interact. In order to capture a few of the extremely rare interactions, the scientists at IceCube have frozen 5160 light sensors into the ice in long strings, distributed throughout one cubic kilometre of the Antarctic ice shield. The sensors register the tiny flashes of light that are created during the neutrinos' rare reactions. These flashes can be used to determine the direction in which the neutrinos were travelling as well as their energy.

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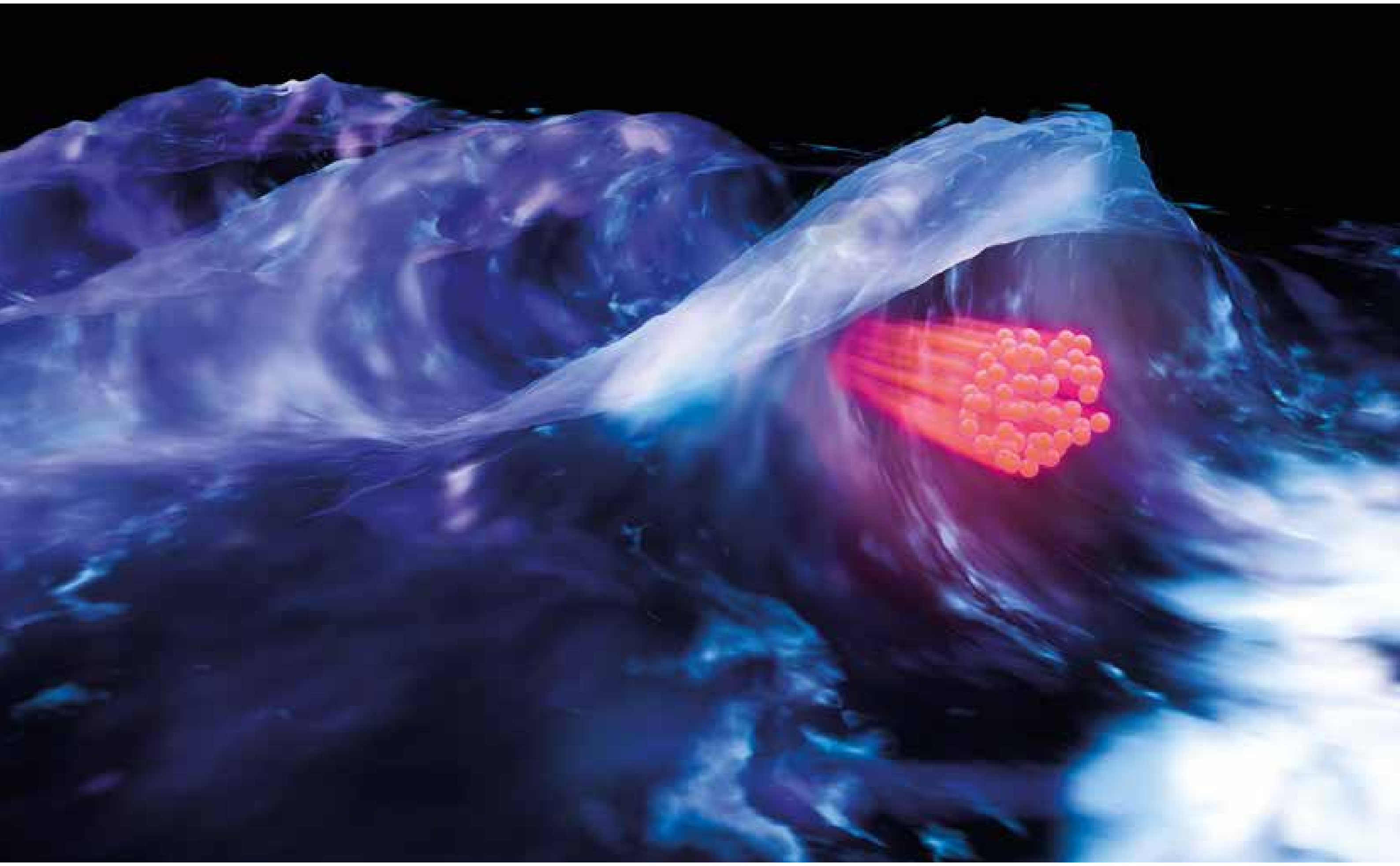
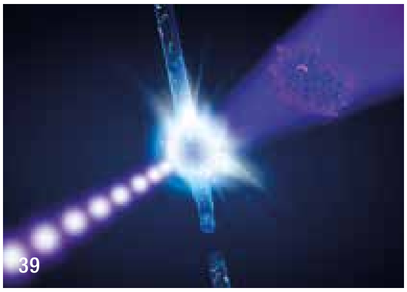


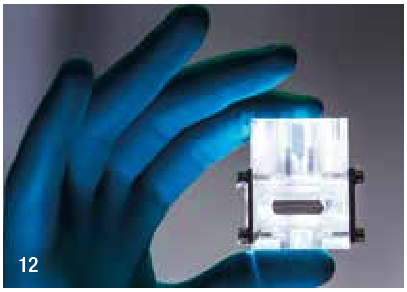
ZOOM

The perfect wave

Physicists are devising the next generation of particle accelerators

Particle accelerators have an extremely wide range of applications, for example in materials processing and cancer therapy. They are also an important tool for research. However, with the technology used so far, these facilities must be very large, some of them measuring several kilometres. That's why physicists around the world are trying to make them much smaller – and thus cheaper. Some of the researchers are using ultrapowerful lasers, others short-wave terahertz radiation, and some are even developing an accelerator that fits on a microchip.





CAMPUS

ZOOM

SPECTRUM

SECTIONS

Artist's representation of an active galactic nucleus. The supermassive black hole at the centre of the accretion disc sends a highly collimated high-energy particle beam into space perpendicular to the disc.

Cosmic particle accelerator:

News from a **black hole**

Researchers trace single neutrino back to galaxy billions of light-years away

Using an astronomical dragnet, researchers have for the first time located a source of extremely high-energy neutrinos from outer space – ghostly elementary particles that travel through space for billions of light-years, effortlessly penetrating stars, planets and entire galaxies as they go. The collaborative observation campaign was triggered by a single particle that was registered by the neutrino telescope IceCube at the South Pole on 22 September 2017. Telescopes on Earth and in space succeeded in tracing the origin of this exotic elementary particle back to a galaxy in the constellation Orion that is approximately four billion light-years away. Within this galaxy, a gigantic black hole acts as a natural particle accelerator. This successful astronomical search by scientists from a total of eighteen participating observatories is a key step toward drawing up a new picture of the universe. ››

The IceCube observation station at the South Pole

A short blue flash briefly lights up the eternal darkness in the depths of the Antarctic ice. This faint shower of light is the trail of a very rare occurrence that scientists have taken great pains to record: An extremely light elementary particle from space, a neutrino, smashed into a water molecule hundreds of metres below the surface of the ice. Actually, neutrinos are not so very rare in themselves. Approximately 60 billion of these particles pass through every square centimetre – that's about the size of a thumbnail – every second without leaving a trace. What's rare is for one of these countless neutrinos to interact with an atom, thus making itself detectable. In order to observe these rare events, researchers have melted the world's biggest particle detector kilometre-deep into the Antarctic ice: Within a cubic kilometre of ice, IceCube searches for the traces of these rare neutrino collisions. This one, which the neutrino telescope recorded on 22 September 2017, was a real stroke of luck.

"Initially it was just an alarm, like many others before it," says Marek Kowalski, who is the head of neutrino astronomy at DESY and also a researcher at the Humboldt University in Berlin. After observing the collision, the IceCube team sent out an astronomical telegram, or A-Tel. This is how observatories all over the world share information. The alarm signal went out to dozens of other astronomical observatories around the world, which then started trying to trace the source of the neutrino by looking in the direction it came from.

After one week, a message came from Fermi, the gamma radiation telescope stationed in space. It had detected a flare – a surge of high-energy gamma radiation – near the calculated source of the neutrino. The MAGIC telescope system on La Palma in the Canary Islands also sent an A-Tel reporting gamma radiation coming from the same direction as the neutrino. The astronomers' excitement was growing. "We see a neutrino like this one about once a month and we also see a flare about once a month, but a combination of the two occurs only once every 5000 to 10 000 years," says Kowalski.

A gigantic black hole

After the A-Tel from MAGIC was sent out at the end of September 2017, the astronomical dragnet began. Other observatories followed up these leads and discovered various kinds of radiation, ranging from radio waves to X-rays, at the same celestial position. For the first time ever, astronomers had found the source of a high-energy cosmic neutrino at a location far beyond our home galaxy. "We saw an active galaxy – a huge galaxy with a gigantic black hole at its centre," Kowalski reports. The black hole is swallowing large amounts of matter. However, part of this matter is being catapulted back into space in the shape of tightly collimated beams of matter, called jets, instead of falling into the black hole. Astrophysicists assume that these jets are powerful natural particle accelerators. If the jet of an active galaxy is pointing directly toward Earth, astrophysicists call the active galaxy a blazar.

In the meantime, the experts have become practically certain that the neutrino and the radiation that was measured by the other telescopes originated within the same source: the

Pictures: The IceCube Collaboration (2); The chestnut creative (portrait)

> *“The probability of this being only a random coincidence is about 1 in 1000”*
>
> **Anna Franckowiak, DESY**

blazar TXS0506+056, nicknamed “Texas Source” and located four billion light-years from Earth in the constellation Orion.

In order to exclude the possibility that the concurrence of the neutrino and the gamma ray observations was only accidental, a worldwide team of scientists made a detailed statistical analysis. “We calculated that the probability of this being only a random coincidence was about 1 in 1000,” explains the leader of this analysis, Anna Franckowiak from DESY. That sounds small, but it wasn’t yet small enough to counter the professional scepticism of physicists.

This scepticism was removed by a second analysis. The IceCube researchers sifted through their data from past years in a search for possible earlier readings of neutrinos coming from the direction of the blazar that had now been identified. And their search was successful. They found a marked temporary excess of neutrinos – consisting of more than a dozen of these ghostly particles – coming from the direction of TXS0506+056 between September 2014 and March 2015. The researchers estimate that the probability that this excess is only a statistical outlier is only 1 in 5000.

Together with the single event of September 2017, the IceCube data now provide the best experimental evidence to date that active galaxies are sources of high-energy cosmic neutrinos and thus also belong to the accelerators of cosmic rays. For the astronomers, this has been a key step toward solving the century-old mystery of the origin of these high-energy subatomic particles from outer space.

Artist’s representation: IceCube light sensors (photomultipiers) within the Antarctic ice

Picture: The IceCube Collaboration

Pictures: Wikimedia Commons (2)

femtopolis

Victor Franz Hess returning from a balloon flight in 1912

Cosmic rays

Solar radiation, which warms our Earth and tans our skin, is not the only thing that reaches us from space. **Cosmic rays**, which were discovered by the Austrian physicist Victor Franz Hess in 1912 as he was floating in a hydrogen balloon at an altitude of 5300 metres above sea level, also originate from space. Hess proved the existence of pervasive cosmic rays by means of his instruments for measuring ionisation. Many years later, scientists realised that these cosmic “rays” are actually a torrent of high-energy, electrically charged atomic nuclei and other particles from space. But the name stuck, and cosmic rays turned out to be extremely useful for the early era of particle physics.

When these particles from outer space enter the Earth’s atmosphere, they generate cascades of secondary particles that are known as **air showers**. These high-energy cascades of particles were the initial objects of investigation of astroparticle physics, before sophisticated measuring methods and observatories made additional “messenger particles” from space accessible to researchers. In addition to our Sun, stellar explosions in the Milky Way and active galactic nuclei outside the Milky Way are all considered possible sources of cosmic rays. However, the origin of cosmic rays – and in particular, the origin of the highest-energy particles – has still not been conclusively determined.

Oddly enough, genuine cosmic radiation is (electromagnetic) gamma radiation, which is not considered a type of cosmic (particle) ray. Instead, it is called “cosmic gamma radiation”.

An intergalactic journey

An interactive website shows the path of the neutrino from the active galaxy to the Antarctic ice. Users can trace it back to the black hole that provides the energy for the cosmic particle accelerator:

https://multimessenger.desy.de

Particle accelerator
The active galaxy shoots a beam of matter into space in which particles are strongly accelerated.

Intergalactic journey
Electrically charged particles are deflected by magnetic fields as they travel through space.

Orbit
Satellites such as Fermi can directly detect gamma radiation emitted by the active galaxy.

Reaching Earth
Special telescopes observe the particle showers generated by cosmic gamma quanta in the atmosphere.

South Pole
Deep in the Antarctic ice, IceCube keeps watch for high-energy neutrinos from the active galaxy.

"We can learn a lot about the **universe** at one go"

The identification of the active galaxy as a source of high-energy neutrinos is not only a breakthrough in the search for cosmic particle accelerators. The success is also a crucial step for the young discipline of multimessenger astronomy, explains Marek Kowalski, the head of neutrino astronomy at DESY.

femto: The observation confirms the long-held hypothesis that active galactic nuclei are natural particle accelerators. Why have these results triggered such euphoria among astrophysicists?

Kowalski: We've known about the existence of cosmic rays for more than 100 years. The physicist Victor Hess discovered them in 1912. There have been many hypotheses about their origin, but now we've been able to locate a specific extragalactic source of these high-energy particles for the very first time. This is a gigantic success and a crucial step for multimessenger astronomy, or MMA for short.

femto: What is multimessenger astronomy?

Kowalski: MMA is the investigation of the universe with the help of various messengers such as electromagnetic radiation, gravitational waves and neutrinos. They can provide us with information about the nature of cosmic phenomena and processes. Each type of messenger gives us a different kind of information. Only after we've linked all of this information together do we have a complete picture. That way, we can learn a lot about the universe at one go.

femto: Why are the cosmic neutrinos so important for MMA?

Kowalski: The special thing about neutrinos is that they very rarely interact with other particles. That's a huge problem for us researchers. We need gigantic detectors to find them. At the same time, this fact increases the value of neutrinos. Because they interact so rarely, they might be coming from regions that are completely non-transparent for visible light or other photons – regions such as the interior of stellar explosions. Thus, we now basically have the ultimate X-ray vision.

femto: Are you planning to use neutrinos to X-ray the universe?

Kowalski: Metaphorically speaking, yes. We can use X-rays to study the human body. But if we want to study a star, X-rays are not a suitable method. Neutrinos, however, make it possible. We can use them to look at the interior of stars and thus view a region of the universe that we can't see by means of electromagnetic radiation.

femto: How do neutrinos make that possible?

Kowalski: For the same reason I mentioned before: because they interact so rarely. Neutrinos are not absorbed during their journey to us from their source. By contrast, light is absorbed – especially gamma radiation, which is the electromagnetic radiation with the highest energies. Gamma radiation from our own galaxy can reach us, but gamma radiation from other galaxies can no longer reach us at the energies at which we observe cosmic neutrinos. This doesn't mean that there's no gamma

Pictures: DESY, Science Communication Lab (sequence); DESY (portrait)

radiation in other galaxies. It is emitted, but it is then absorbed by the universe itself.

femto: What do researchers want to study with the help of MMA?

Kowalski: We would like to understand how particles are accelerated to the highest energies. We know that cosmic rays attain extremely high energies – ten million times higher than the ones we can generate in the biggest particle accelerator on Earth, the Large Hadron Collider (LHC) at the European particle physics centre CERN near Geneva. This is a phenomenon whose mechanism we basically don't understand. With the help of neutrinos, we can identify the cosmic accelerators. That's because, unlike the electrically charged particles of cosmic rays, neutrinos are not deflected by magnetic fields on their journey through space. As a result, they can be traced back directly to their place of origin. And as soon as we have identified the accelerators, the next step will be to understand the acceleration mechanism. Here too, neutrinos are helping us, because for the reasons I mentioned before, they give us information that we can't get from electromagnetic radiation.

femto: What other open questions do you want to answer in the future?

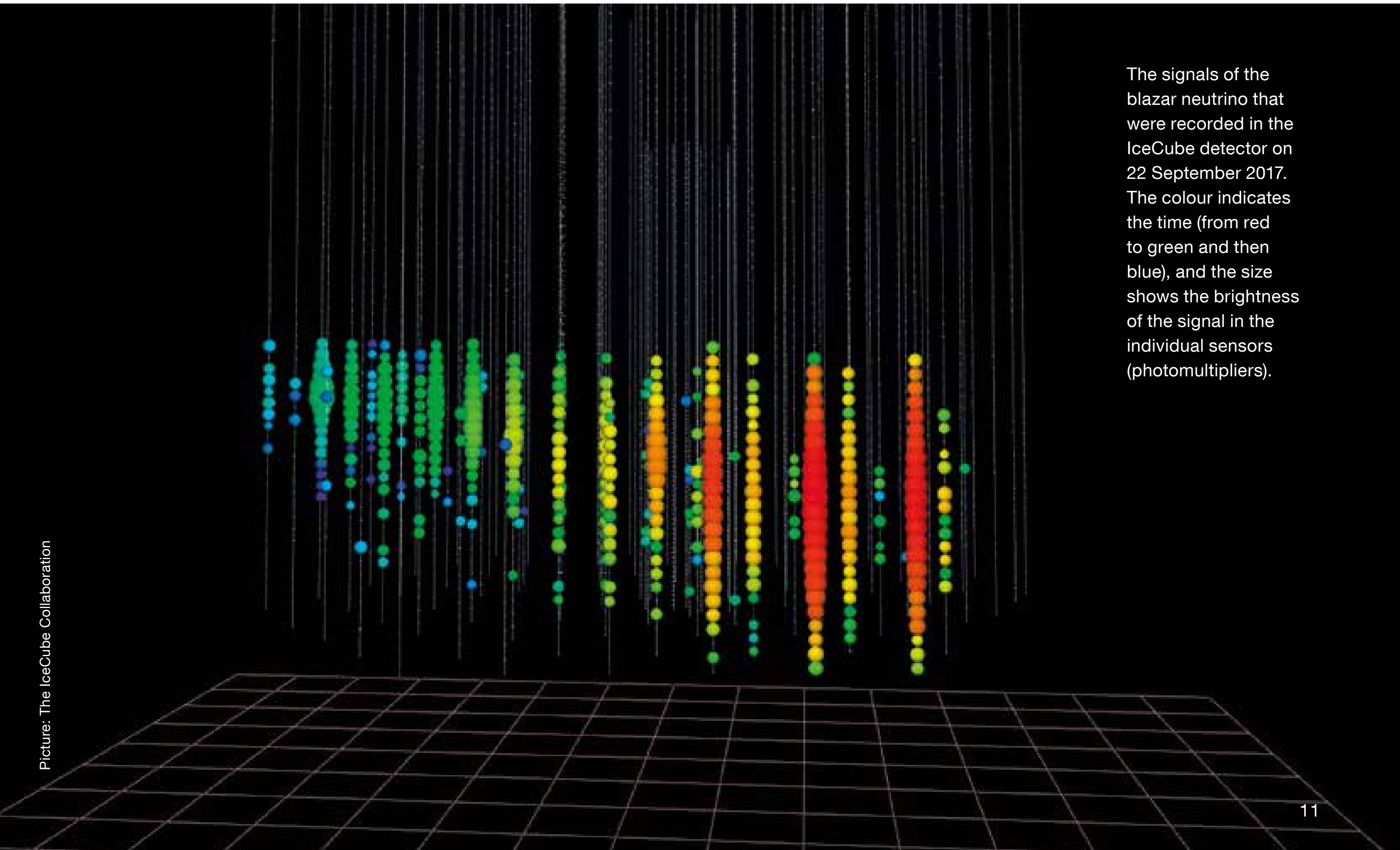
Kowalski: For one thing, we want to understand how a star explodes. In a stellar explosion, or supernova, a huge amount of kinetic energy is released. We want to understand the dynamics of such explosions.

femto: Are the current results a long-sought-after breakthrough?

Kowalski: Yes, after the discovery of extragalactic cosmic neutrinos in 2013, that is the next big breakthrough. And we hope it won't be the last one. We still can't say with absolute certainty that we've made a discovery. But that's what it feels like, because everything fits together. I hope that we'll soon receive confirmation of these results. However, we also want to find additional source classes and track down completely different phenomena. We definitely regard this as the beginning of something new and very important.

"We're opening a new window onto the high-energy universe"

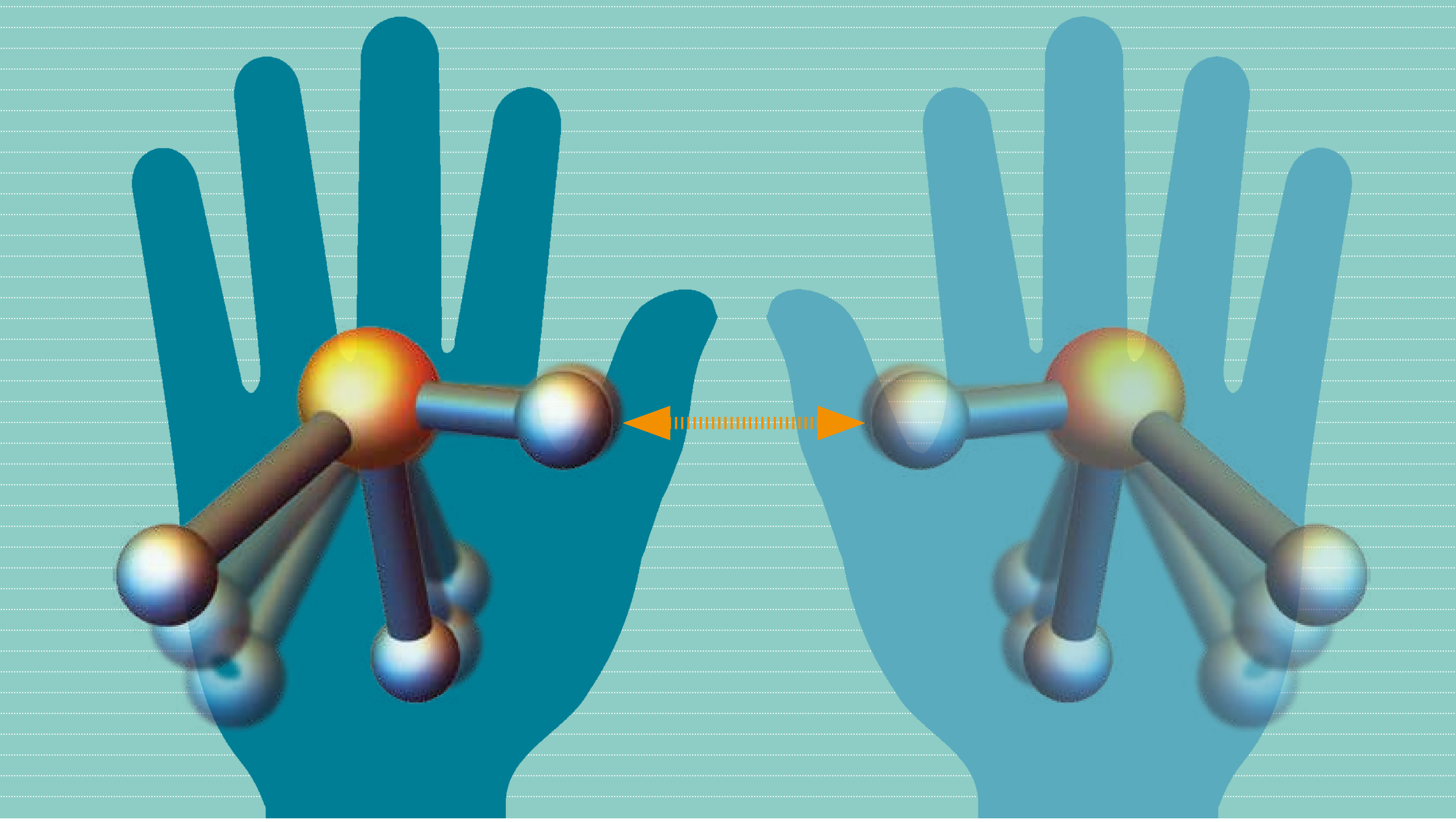
Marek Kowalski, DESY



The signals of the blazar neutrino that were recorded in the IceCube detector on 22 September 2017. The colour indicates the time (from red to green and then blue), and the size shows the brightness of the signal in the individual sensors (photomultipliers).

Picture: The IceCube Collaboration

The **strange** world of mirror molecules



The term chiral is used to describe molecules which, like the right and left hands, exist in two mirror-image forms. The term chirality (handedness) is derived from the ancient Greek word stem χειρ~ (cheir~) for „hand~“.

Exploring the mystery of molecular handedness in nature, scientists have proposed a new experimental scheme to create custom-made mirror molecules for analysis. The technique can make ordinary molecules spin so fast that they lose their normal symmetry and shape and instead form mirrored versions of each other. A research team from DESY, Universität Hamburg and University College London around group leader Jochen Küpper developed the innovative method. The further exploration of handedness, or chirality, does not only enhance insight into the workings of nature, but could also pave the way for new materials and methods.

Many molecules in nature exist in two versions that are mirror images of each other. “For unknown reasons, life as we know it on Earth almost exclusively prefers left-handed proteins, while the genome is organised as the famous right-handed double helix,” explains Andrey Yachmenev, who led this theoretical work in Küpper’s group at the Center for Free-Electron Laser Science (CFEL). “For more than a century, researchers have been unravelling the secrets of this handedness in nature, which does not only affect the living world: Mirror versions of certain molecules alter chemical reactions and change the behaviour of materials.” For instance, the right-handed version of caravone gives caraway its distinctive taste, while the left-handed version is a key factor for the taste of spearmint.

Rotating molecules

Handedness only occurs naturally in some types of molecules. “However, it can be artificially

Pictures: DESY, Andrey Yachmenev

induced in so-called symmetric-top molecules," says co-author Alec Owens from the Center for Ultrafast Imaging (CUI). "If these molecules are stirred fast enough, they lose their symmetry and form two mirror forms, depending on their sense of rotation. So far, very little is known about this phenomenon of rotationally-induced chirality, because hardly any schemes for its generation exist that can be followed experimentally."

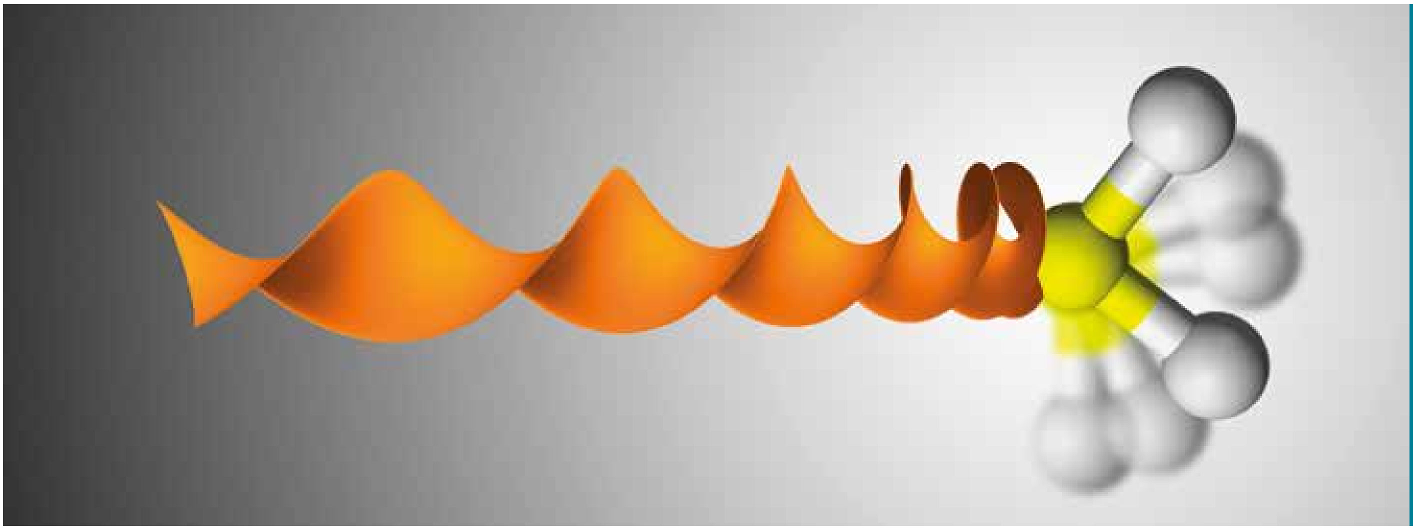
Küpper's team has now computationally devised a way to achieve this rotationally-induced chirality with realistic parameters in the lab. It uses corkscrew-shaped laser pulses known as optical centrifuges. For the example of phosphine, the team's quantum-mechanical calculations show that, at rotation rates of trillions of times per second, the phosphorus–hydrogen bond that the molecule rotates about becomes shorter than the other two of these bonds, and depending on the sense of rotation, two chiral forms of phosphine emerge. "Using a strong static electric field, the left-handed or right-handed version of the spinning phosphine can be selected," explains Yachmenev.

This scheme promises a completely new path through the looking-glass into the mirror world, as it would in principle also work with other, heavier molecules. In fact, these would actually require weaker laser pulses and electric fields. For the first stages of the investigation, the researchers chose phosphine because heavier molecules were initially too complex for exact quantum-mechanical calculations. As phosphine is highly toxic, however, such heavier and also slower molecules would probably be preferred for experiments.

The proposed method could deliver custom-made mirror molecules. The investigation of their interactions with the environment, for instance with polarised light, should help to further penetrate the mysteries of handedness in nature and explore possible applications, expects Küpper, who is also a professor of physics and chemistry at Universität Hamburg: "Facilitating a deeper understanding of the phenomenon of handedness this way could also contribute to the development of chirality-based tailor-made molecules and materials, novel states of matter and the potential utilisation of rotationally-induced chirality in novel metamaterials or optical devices."

Physical Review Letters, 2018;
DOI: 10.1103/PhysRevLett.121.193201

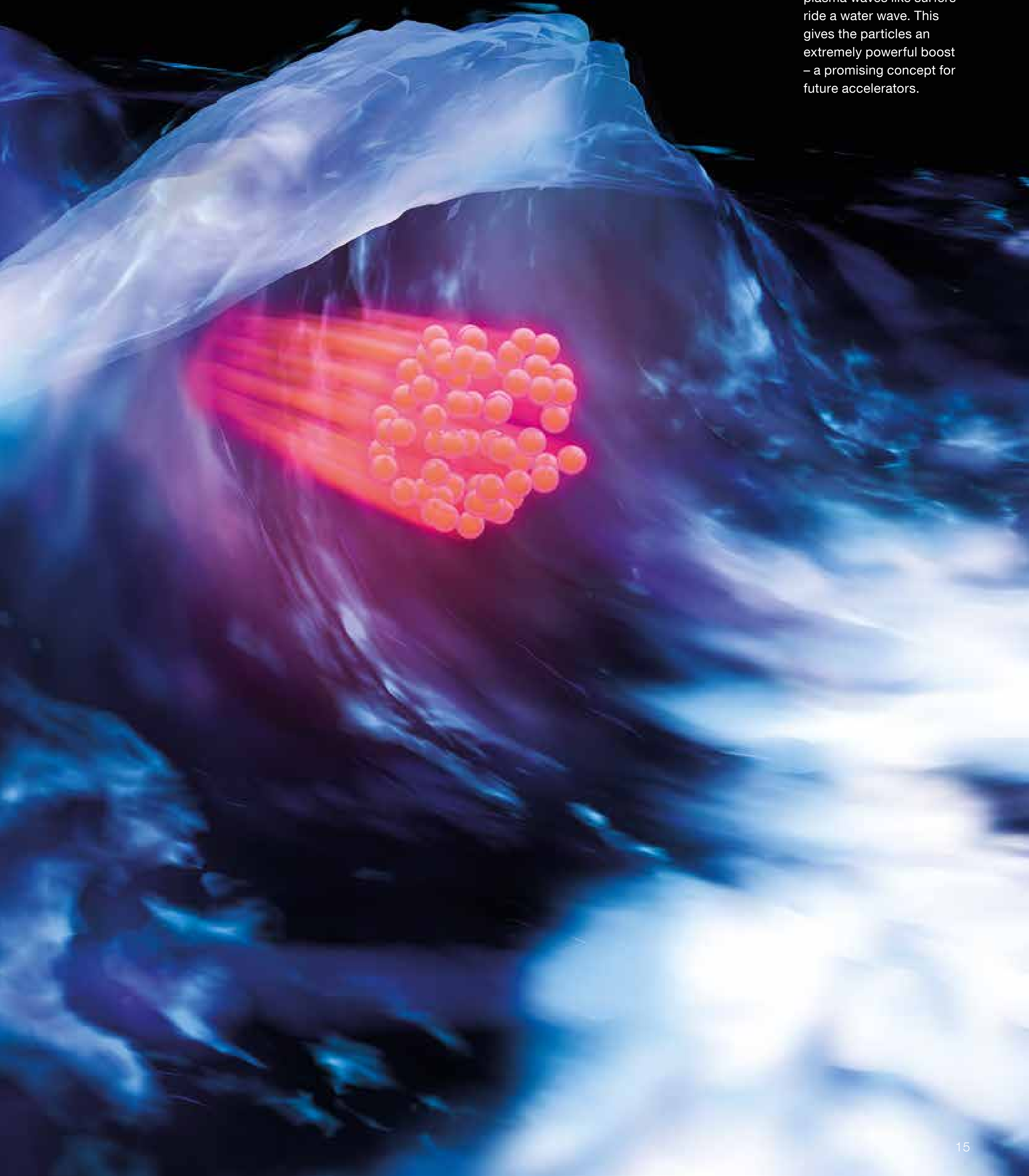
> *"For unknown reasons, life as we know it on Earth almost exclusively prefers left-handed proteins"*
>
> **Andrey Yachmenev, CFEL**



ZOOM

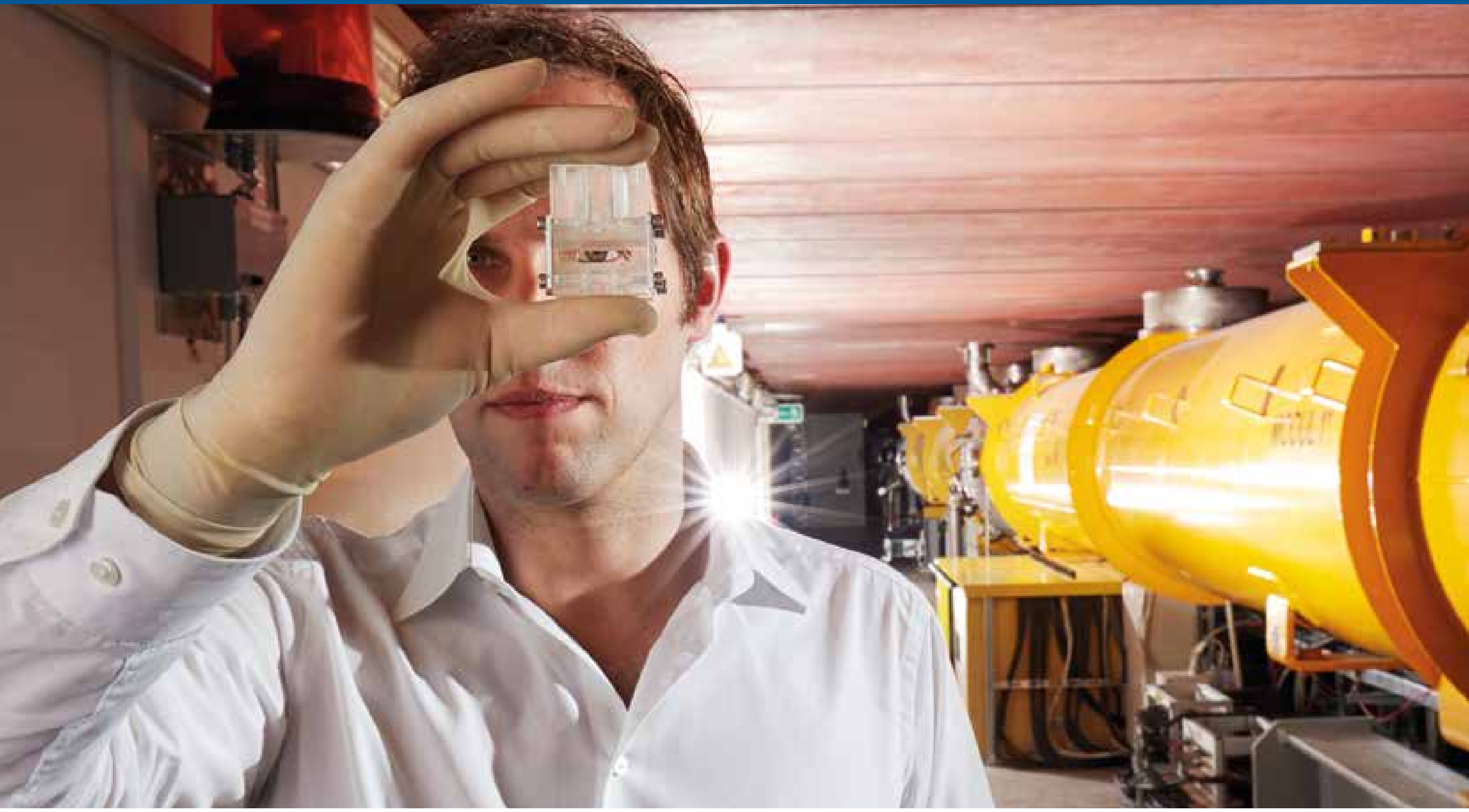
The perfect wave

Particle accelerators have an extremely wide range of applications, for example in materials processing and cancer therapy. They are also an important tool for research. Giants such as the Large Hadron Collider (LHC) near Geneva search for new elementary particles, while facilities such as the European XFEL X-ray laser in Hamburg analyse material samples down to atomic detail. However, with the technology used so far, these facilities must be very large, some of them measuring several kilometres. That's why physicists around the world are trying to make them much smaller – and thus cheaper. Some of the researchers are using ultrapowerful lasers that generate plasma waves, others short-wave terahertz radiation, and some are even developing an accelerator that fits on a microchip.



Subatomic surfers: Electrons (red) can ride plasma waves like surfers ride a water wave. This gives the particles an extremely powerful boost – a promising concept for future accelerators.

Jens Osterhoff uses bunches of electrons from DESY's linear accelerator FLASH (right) to generate plasma waves in miniature accelerator cells.



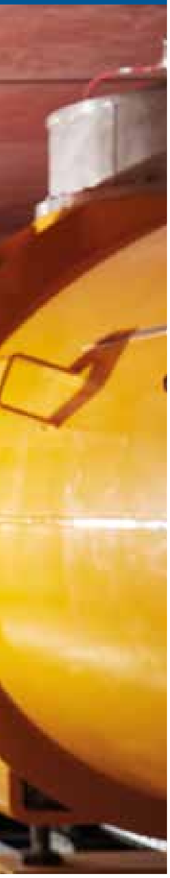
A big boost *from a small accelerator*

Physicists are devising methods for smaller accelerators

Andreas Maier has just entered a kind of bunker on the DESY campus in Hamburg. From the outside, it looks like a dreary concrete block, but within it's full of high tech: stainless-steel pipes, a control room full of flat-screen monitors and an ultramodern laser. Maier, a physicist and group leader at Universität Hamburg, pulls on his lab coat, overshoes and a hood. He's dressing up for absolute cleanliness. "Any speck of dust on the optical elements could cause damage," he says, pointing to his high-power laser ANGUS, (A Next-Generation Ultrafast laSer), which is unofficially named after the guitarist Angus Young from the hard rock band AC/DC. The laser fills one of the bunker rooms, consists of several red boxes and generates flashes of light that last for considerably less than one billionth of a second. "Its average power is only about 25 watts, roughly as much as a light bulb," explains Maier. "But in the moments when ANGUS fires, we reach enormous beam powers of around 200 terawatts."

The superlaser in the research bunker is a central element of a new technology –

Picture: DESY, Heiner Müller-Elsner



> *“Our target here at DESY is 50 gigavolts per metre – 500 times today’s peak value”*

Ralph Aßmann, DESY

plasma acceleration. In a conventional particle accelerator such as the LHC at the European particle physics centre CERN near Geneva, powerful radio waves are fed into specially shaped metal tubes known as cavities. The particles to be accelerated can then ride on the radio waves like surfers on a wave. The problem is that feeding too much radio waves into the cavities increases the risk of electrical discharges – small flashes of lightning that would damage the cavity walls. “That’s why the maximum voltage that today’s facilities can use to accelerate particles is limited to around 50 to 100 megavolts per metre,” says Ralph Aßmann, leading DESY scientist for accelerator research. The consequence is that in order to accelerate particles to the highest energies, it is necessary to use many cavities placed one after another, which makes accelerators long – sometimes even kilometres long.

Acceleration by plasma wave

Plasma acceleration, in contrast, could be used to achieve much greater voltages. “Our target here at DESY is 50 gigavolts per metre – 500 times today’s peak value,” says Aßmann. If the venture succeeds, accelerators could get a lot smaller – in future, a hundred-metre-long facility such as DESY’s FLASH accelerator could fit in a normal laboratory basement.

The principle of laser plasma acceleration is that ultrapowerful, extremely short laser flashes are fired into a plasma – a type of gas, of hydrogen for example, that is completely ionised. That means the negatively charged electrons are separated from the positively charged remainders of the atoms – the ions. “The electrons are much lighter than the ions, and thus extremely mobile,” explains Aßmann. “The heavy ions, in contrast, like to stay where they are.” If a powerful laser pulse is now fired into the plasma, it pushes the light electrons outward and produces a wake, like a ship.

The result is that the negative charges collect on the outside, the positive charges remain inside, and an enormous voltage arises in a tiny space within an incredibly short time. The electrons immediately rush back to the centre and beyond – a high-frequency oscillation with an enormous field strength sets in. “This field can tremendously accelerate some of the plasma electrons that are located within the wave,” says Aßmann. “Alternatively, you can fire an electron pulse into the plasma cell immediately after the laser flash – that too will be strongly accelerated by the wave.”

The initial ideas for this laser plasma acceleration go back to the late 1970s. The first implementation, however, was not even conceivable until the mid-1980s, when the Canadian Donna Strickland and the Frenchman Gérard Mourou developed a method of building high-power, short-pulse lasers – an achievement that won them both the Nobel Prize in Physics in 2018. It actually took until 2006 before US researchers were first able to bring electrons to a noteworthy energy of one gigaelectronvolt (GeV) using laser plasma acceleration. Since then, the record has risen to 8 GeV over an acceleration section just 20 centimetres long – thanks to the rapid progress of laser technology.

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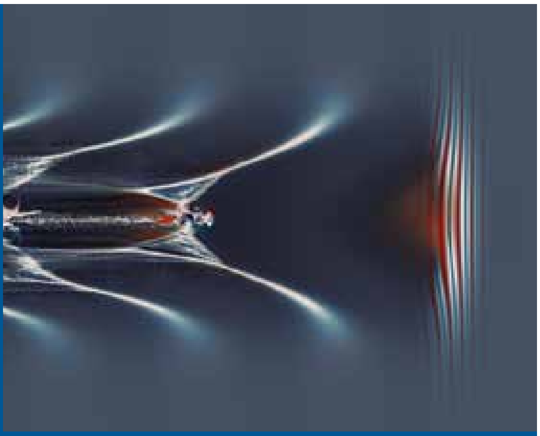
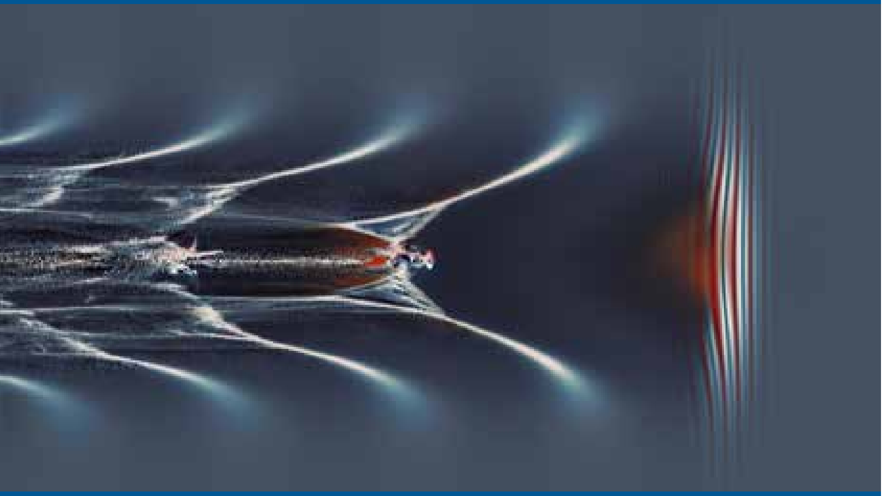
Superconducting cavities made of the metal niobium accelerate the electrons in facilities such as FLASH and the European XFEL X-ray laser.

Pictures: DESY, Gesine Born (top), Heiner Müller-Elsner (bottom)

Miniarure accelerator: LUX uses a 200 terawatt laser that fires ultra-short flashes into a thin gas-filled capillary (right). The laser achieves five flashes per second and generates strong plasma waves (simulation calculation below).





> *“The laser pulse sweeps the electrons to the side like a snowplough”*
>
> **Andreas Maier, Universität Hamburg**

What that looks like in the lab can be seen in Andreas Maier’s bunker. The physicist points to the plasma cell – a small sapphire crystal in which a tiny channel measuring just 300 micrometres has been milled. It is filled with hydrogen gas. “We aim our high-intensity laser pulses at this channel,” explains Maier. “That turns the hydrogen in the cell into a plasma, and then the laser pulse sweeps the electrons to the side like a snowplough.” The resulting plasma wave causes electrons to chase after the laser pulse and, to use a visual image, to surf on its wake. This trick enables particles to be brought up to speed in a very small space.

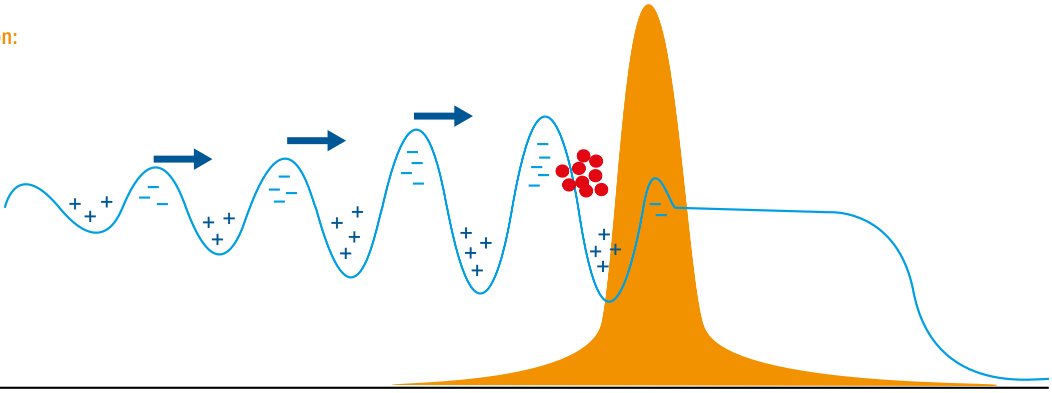
Turning metres into millimetres

“In 2016, we succeeded in accelerating electrons to an energy of 400 MeV over a distance of just four millimetres,” says Maier. “A conventional accelerator would have to be dozens of metres long to accomplish this.” Recently, the physicists even managed to achieve a kind of continuous operation and let their plasma accelerator run for a full 24 hours – a milestone for the joint project of DESY and Universität Hamburg. Furthermore, they succeeded in sending the electrons coming out of the plasma accelerator through an undulator – an arrangement of magnets that forces the electrons to follow a slalom course and so makes them emit intense X-ray radiation.

Such compact X-ray sources could be one of the main applications of the new technology – for example, for materials inspection in industry. “They could also be used for the X-ray inspection of shipping containers,” says Ralph Aßmann. “At present, this is done using conventional accelerators, at the port of Hamburg, for example.” The current systems are stationary, so the trucks have to drive with their loads under a kind of bridge. If the inspection systems were based on plasma accelerators, they could be designed to be much smaller, and perhaps even portable –

››

The principle of laser plasma acceleration:
A powerful laser pulse (orange) ploughs through a gas, for example hydrogen. It strips the hydrogen molecules of their electrons, which are swept to one side as if by a snowplough. The electrons (red) gather in the wake of the flash and are then accelerated by the positively charged plasma wave – just like a wakeboarder riding the wake of a ship.



Pictures: Universität Hamburg, Niels Delbos (top), Sören Jalas (middle); Thomas Schuster (portrait)

Promising *new possibilities*

Reinhard Brinkmann, DESY

DESY's long-time accelerator director Reinhard Brinkmann expects innovative accelerator technologies to open up interesting new applications in research and medicine. But they won't replace the established facilities in the near future.

femto: How do today's accelerators at DESY work?

Reinhard Brinkmann: Today, we are working with radio frequency cavities. These use electromagnetic waves with high field strengths that accelerate electrically charged particles. For many years, this has been the fundamental principle behind all accelerators.

femto: How mature is the technology, and where are its limits?

Reinhard Brinkmann: Because we've been continuing to develop it for many decades, the technology can nowadays be considered very mature. However, the maximum field strengths that can be fed into these cavities are limited. The accelerating field collapses above a certain threshold. This limit is currently around 100 million volts per metre. Another important parameter is the time for which the accelerating field can be maintained. This can be dramatically improved with the help of a technology that we at DESY played a decisive role in developing – we made the cavities superconducting. This eliminated unwanted heat losses in the cavities. However, at a certain field strength the superconductivity breaks down, so that this method also has its limits regarding the maximum achievable accelerating field.

femto: How could we achieve even higher accelerating voltages?

Reinhard Brinkmann: At the moment, plasma accelerators are considered the most promising way forward. They contain an ionised gas that is excited for example by a laser pulse in such a way that the plasma can accelerate charged particles. As there are no wall losses here, there is no limit in principle to the accelerating voltages that can be achieved. The disadvantage is that the segments over which the acceleration takes place are extremely short – typically less than one centimetre. It would be necessary to join a large number of these structures together in order to reach a high total voltage. And there's another problem: So far, it's only been possible to accelerate far fewer particles than with conventional facilities. But there are other interesting approaches that use terahertz waves to accelerate particles – and the "accelerator on a chip" that uses a laser to directly bring the particles up to speed.

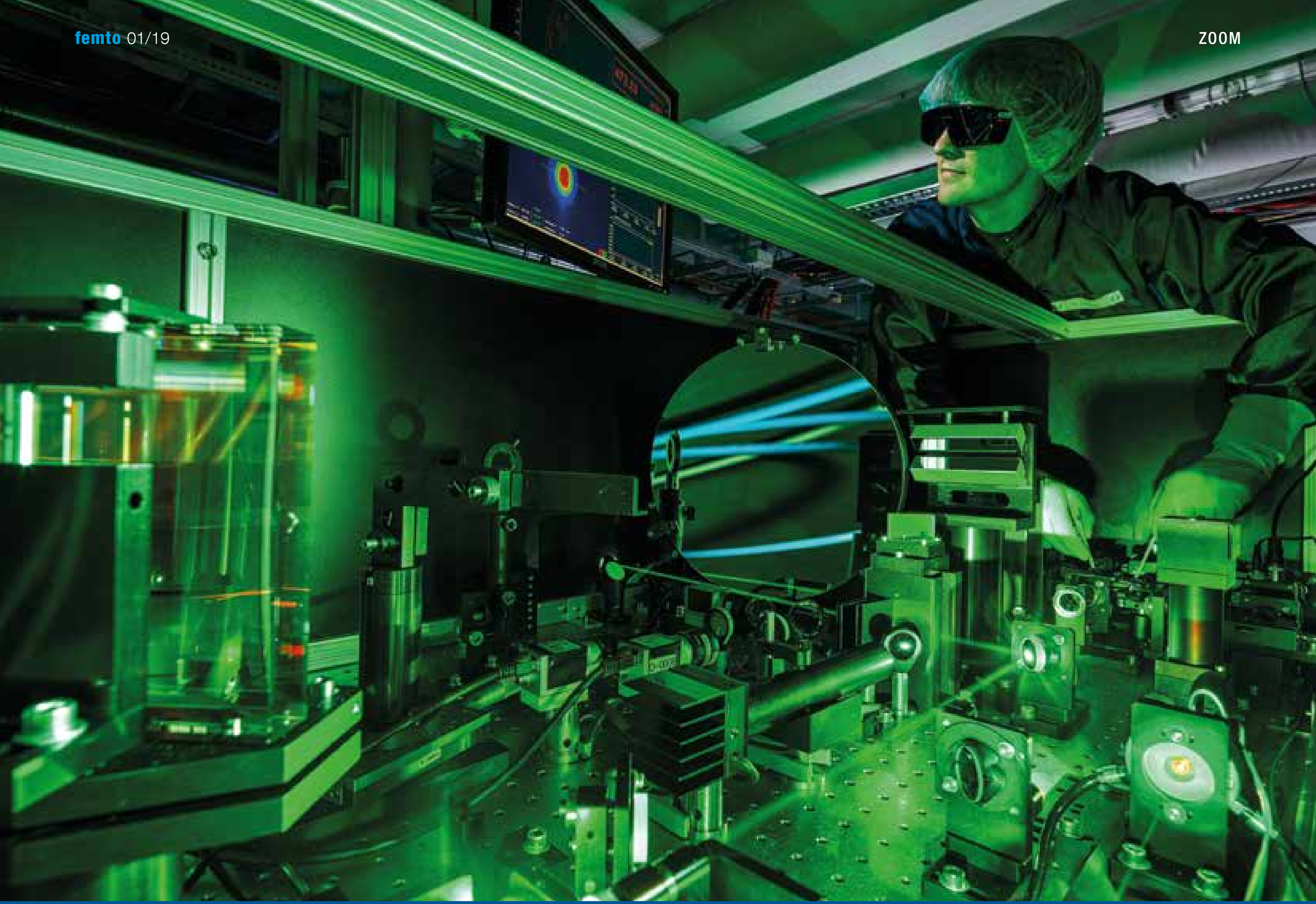
femto: What would be the applications for these kinds of new accelerator technologies?

Reinhard Brinkmann: I don't think that existing accelerators such as the superconducting European XFEL here in Hamburg will be replaced by these new technologies – at least not within the next 20 years. But I believe that we will be able to build extremely compact accelerators that generate high-quality beams. These could be used, for example, to create economical X-ray sources that could serve as research tools in universities or for radiation therapy in hospitals. I am also particularly interested in ideas on how new technologies can be combined with established concepts in order to achieve specific beam properties. Our research programmes here at DESY are also aiming in these directions.

femto: And a super accelerator for particle physics? Could a plasma accelerator conceivably provide the basis for this?

Reinhard Brinkmann: There are certainly experts who are thinking about what a facility of this kind could look like. But this is still up in the air. That's because building it would require a large number of plasma accelerators connected in series and synchronised with one another, which is a massive challenge in itself. Even after that has been accomplished, it would be a major problem to reach a high beam intensity – that is, to accelerate a sufficient number of particles. Accelerators for particle physics have to deliver a high beam intensity for the experiments, otherwise they would not generate enough particle collisions and so would produce insufficient measurement data. Whether or not this can be achieved with a plasma accelerator is a big question, in my opinion.

Picture: DESY, Gesine Born



The 200 terawatt special laser ANGUS generates ultrashort flashes. The laser pulses last for just 30 quadrillionths of a second (30 femtoseconds). They are 0.01 millimetres long and 0.035 millimetres high, so they resemble small disks. ANGUS delivers five of these pulses per second.

the scanner could go to the container, instead of the current situation where the freight has to go to the scanner. This type of mobile and simultaneously powerful X-ray source would also be ideal for inspecting road bridges – a very pressing topic.

A further potential area of application is medicine. Equipment based on plasma accelerators could not only replace conventional X-ray sources but also open up new diagnostic possibilities – such as X-ray fluorescence. The underlying idea is that antibodies are attached to tiny nanoparticles of gold using biochemical methods. “A patient would be injected with a solution containing these nanoparticles,” explains Florian Grüner, professor of physics at Universität Hamburg. “The particles travel through the body, and the antibodies attach themselves to any tumours that might be present.” Scanning the corresponding region of the patient’s body with a hair-thin beam of X-rays will cause the gold particles to fluoresce and emit characteristic X-ray signals that are recorded by a special detector. It is hoped that, in this way, smallest tumours that can’t be found using today’s methods could eventually be tracked down.

“Breast cancer tumours are frequently not recognised until they are larger than a centimetre,” says Grüner. “Our method could potentially discover millimetre-sized tumours, thus strongly increasing the chance of successful therapy.” A further area of application for the method could be in the development of drugs. Here, the nanoparticles would be attached to new potential active ingredients, and the X-ray fluorescence would be used to track how the medication is distributed in the body and whether it reaches the desired target area. The hope is that this would enable ineffective active ingredient candidates to be separated from promising ones at an earlier stage than is currently the case.

Although the idea of X-ray fluorescence is more than 30 years old, it hasn’t yet been possible

Picture: DESY, Heiner Müller-Elsner

to apply it to human beings. The reason is that the X-rays are scattered in the interior of the body. This gives rise to an interfering background, which makes the actual signals difficult to read out. “My team has gone into this subject in depth, and we are the first group worldwide to have shown experimentally how this problem can be solved,” says Grüner. It’s done by using a computer algorithm to determine from the spatial distribution of the measured X-ray spectra exactly which areas produce signals containing an especially low amount of interfering background.

Medical applications

The team accomplished the first demonstration experiments at an established accelerator, DESY’s kilometre-sized X-ray radiation source PETRA III. For later use in a hospital, Grüner and his team intend to use a plasma accelerator. Such an accelerator would be compact enough and should be able to deliver the hair-thin X-ray beams required for the new technique. There is still a need for further research in this area, however. “The electron beams from a plasma accelerator are still not as tightly collimated as is needed,” says Grüner. And the prototypes are not yet stable enough in operation and can’t manage enough “shots”: Today’s lasers that are used to drive the plasma acceleration only deliver a few flashes per second. What’s wanted are many thousands, otherwise the imaging process would take far too long in clinical use.

“The quality of the beams is constantly increasing, and we are close to building useable plasma accelerators today,” says Ralph Aßmann. “But they can’t yet reach the beam quality of conventional accelerators – among other things, the electrons from the prototypes have a very wide range of energies.” In order to solve the problems and further develop the technology, Aßmann and his team are currently creating a new research infrastructure – the multipurpose facility SINBAD (Short Innovative Bunches and Accelerators at DESY). “Here, we will be able to systematically develop and test different approaches for future accelerator technology,” says Aßmann.

SINBAD will be built in a quite historical location – in the hall of DORIS, the first storage ring to be constructed at DESY. It was completed in 1974, and has now been decommissioned and dismantled. SINBAD project leader Ulrich Dorda goes into one of the four tunnel segments which together make up a ring tunnel in the shape of a racetrack. These days, the mostly empty tunnel is filling up again, as one of the first core components of SINBAD is almost complete here, behind the metre-thick concrete walls. Dorda points to a construction of stainless-steel tubes and vacuum pipes that leads through a succession of cylindrical, blue-painted magnets. “This is our ARES accelerator,” explains the physicist. “It produces ultrashort, sharply defined and very stable electron bunches.” These bunches will later be used to test the new technology in depth by further accelerating them as effectively as possible by laser.

To this end, a new high-power laser laboratory will be set up in the centre of the hall, financed as part of the ATHENA project – a joint project of six research centres of the Helmholtz Association. In addition to DESY, the participants are GSI Helmholtzzentrum für Schwerionenforschung, Karlsruhe Institute of Technology KIT, Helmholtz-Zentrum Berlin HZB, Forschungszentrum Jülich FZJ and Helmholtz-Zentrum Dresden-Rossendorf HZDR. Dorda points to a still empty part of the tunnel. “This is where the plasma cell will stand,” he says. “The ANGUS laser – which is currently set up at another location – will fire laser flashes into the plasma and create a kind of bubble. We will then

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> *“Our method could potentially discover millimetre-sized tumours, thus strongly increasing the chance of successful therapy”*

Florian Grüner, Universität Hamburg

Picture: DESY, Heiner Müller-Elsner

New accelerator technologies

A dedicated facility for the development of new accelerator technologies is being set up in international collaboration at DESY. It is called SINBAD (Short Innovative Bunches and Accelerators at DESY). The ARES experiment (Accelerator Research Experiment at SINBAD) is currently under construction. It will be used to try out acceleration physics and technologies and to test future accelerator concepts. The objective is to develop practical particle accelerators that thanks to their short particle pulses and their compact size will achieve economic advantages and open up new areas of application in science, medicine and society.

fire the electron beam from the ARES accelerator into this bubble with the right timing.”

New accelerator concepts

Other tunnel segments of SINBAD are already planned as well. One of them will host Andreas Maier’s laser plasma experiment, which is still set up in the cramped research bunker. Another will accommodate the experimental particle accelerator AXSIS, which is headed by DESY researcher Franz Kärtner and is intended to make substantially smaller accelerator components possible through the use of terahertz radiation with much shorter wavelengths.

“One important objective of SINBAD is to show that a plasma accelerator can be used to drive a free-electron laser,” emphasises Ralph Aßmann. “That’s the Holy Grail that researchers in our field are seeking.” Free-electron lasers (FELs) are the brightest X-ray sources in the world. Their principle is that an accelerator fires sharply collimated bunches of electrons at close to the speed of light through an undulator, so that the particles emit high-intensity X-ray flashes. Accomplishing this with present-day technology requires long facilities – the accelerator of the European XFEL X-ray laser in Hamburg is 1.7 kilometres long. If conventional accelerators were to be replaced by plasma variants, much more compact and thus less costly FELs would be conceivable.

The European project EuPRAXIA, which is coordinated by DESY, is aiming in this direction. Forty institutes from twelve countries are participating, including various European countries and Japan, Israel, Russia, China and the USA. “We want to find out how to build a plasma accelerator that can boost electrons to an energy of 5 GeV and generate X-ray radiation using an undulator,” explains Aßmann. “Various pilot users will then try out the technology.” One of the challenges is to develop a laser that delivers 100 flashes per second, each with a power of one petawatt. A design study is scheduled for completion in autumn 2019. The European plasma FEL could go into operation around the year 2025 – possibly in Hamburg, hopes Aßmann.

But there is another variant of plasma acceleration. Instead of powerful laser flashes, it is driven by high-intensity particle bunches. “We focus electron bunches travelling at almost the speed of light on a focal point, rather like the way a lens focuses light,” explains DESY physicist Jens Osterhoff, head of the FLASHForward project. “Then we send the particle bunches into a plasma cell.” This cell consists of a channel just 1.5 millimetres wide and three centimetres long that is filled with argon or helium. As in a fluorescent light tube, a high-voltage discharge ionises the atoms of the gas, and so ignites a plasma.

As the particle bunch shoots into the cell, it pushes the electrons in the plasma aside. Behind it, in its wake, so to speak, there are no more electrons, just positively charged ions. This creates a strong alternating electrical field – a plasma wave. “If you now send a second electron bunch along behind the first, it can surf on this wave and accelerate enormously,” says Osterhoff. The concept is thus based on two bunches of

Picture: DESY, Heiner Müller-Elsner

electrons, one closely following the other: First comes the driver beam, which deposits energy in the plasma. It is followed by the beam to be accelerated, which taps the plasma and gains energy from it.

Faster with FLASHForward

In 2018, Osterhoff and his team succeeded in demonstrating an important step of beam-driven plasma acceleration for the first time in Europe. They sent the fast electron bunches from the DESY accelerator FLASH into a plasma cell and achieved an acceleration field strength of 12 gigavolts per metre – 500 times that of conventional facilities.

This approach has two advantages over the laser-driven method: “The particles can be accelerated over longer stretches, making it easier to achieve higher energies,” says Osterhoff. “And because you can accelerate considerably more electrons per second, you can achieve high beam intensities, which is important for particle physics, for example.” Using particle beams, continuous power outputs in the megawatt range are feasible. Lasers, in contrast, currently achieve a little over 100 watts – no more than a bright light bulb.

But the method needs a conventional accelerator to drive it. Facilities as compact as those of the laser-driven technique are thus difficult to conceive. Viewed in this way, the two concepts seem to be complementary. Facilities that need to fit in the laboratory basement can be based on the laser-driven scheme. The particle-driven approach appears to be superior for accelerators that need to deliver high energies and beam intensities.

And what could a future accelerator for particle physics look like? “A 500-metre-long conventional accelerator supplies electron bunches with high power and an energy of around 1 GeV,” says Osterhoff. “A plasma cell then gives the electrons an additional energy of 10 GeV.” If you could connect 50 of these cells one behind the other, you would achieve a total energy of 500 GeV. Using today’s technology, that would require an accelerator 15 kilometres long. Using the plasma technology, it would in principle be possible in a kilometre.

But before we can seriously consider this vision, the experts will have to lay various foundations. “In the next step, we have to show that we can maintain the beam quality and accelerate the particles really efficiently,” says Jens Osterhoff. “We want to demonstrate that most of the energy from a driver beam can

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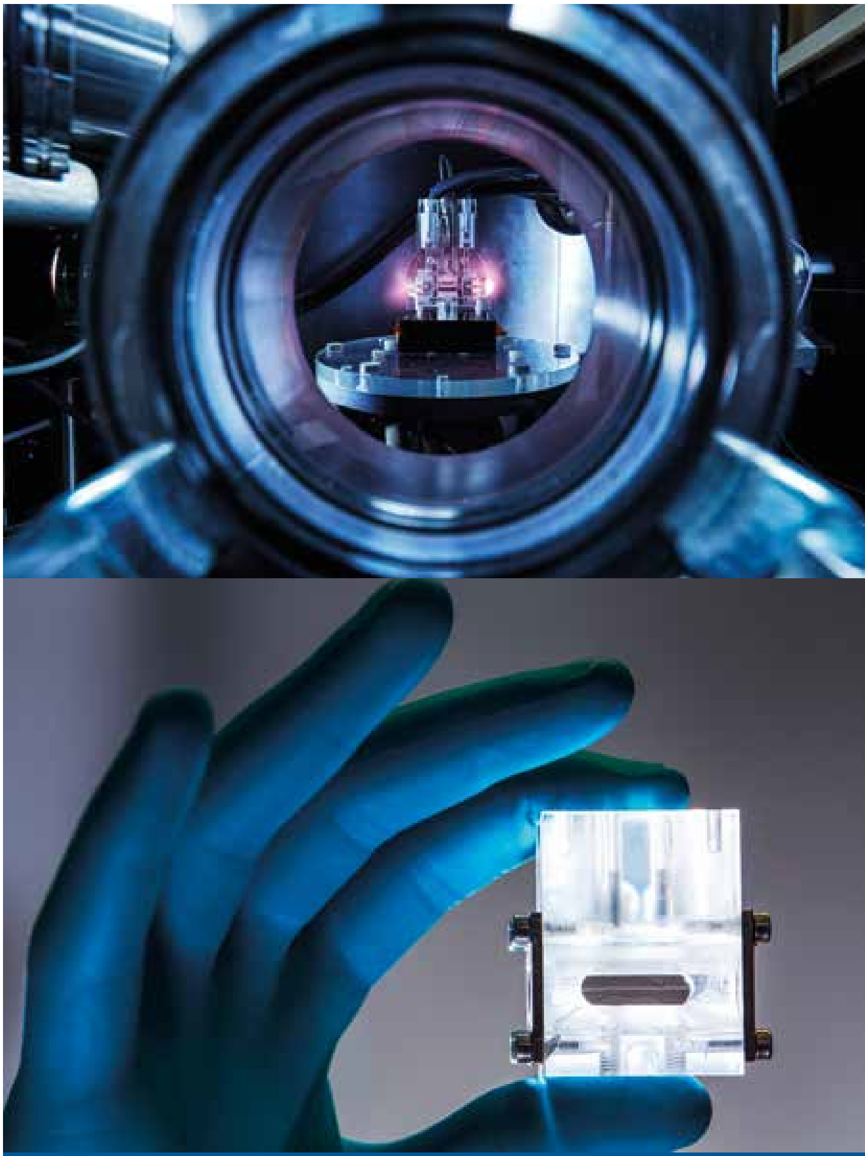
“In the next step, we have to show that we can maintain the beam quality and accelerate the particles really efficiently”

Jens Osterhoff, DESY



The plasma cell of FLASHforward consists of two sapphire blocks, in each of which a semi-circular groove has been milled with a laser. The two blocks are put together to form a circular cavity that is several centimetres long. This hollow space is then filled with hydrogen, from which the plasma is generated.

Picture: DESY, Heiner Müller-Elsner

> *“With PITZ, we have been able to prove for the first time in electron beams that this self-modulation really happens”*
>
> **Frank Stephan, DESY**

be transferred to the plasma wave and can subsequently be passed on to the beam being accelerated. That would be a milestone.” Another question is: How well can multiple plasma cells be cascaded, i.e. placed one after the other? US researchers have already been able to demonstrate this, at least to some extent, for laser plasma acceleration. The demonstration for the particle-driven variant is still outstanding.

Support for the development of particle-driven plasma acceleration is being provided from DESY’s Zeuthen location, which is situated close to Berlin. The location is home to PITZ, the Photo Injector Test facility in Zeuthen. “On the one hand, we use this test stand to optimise components for existing DESY accelerators such as FLASH and the European XFEL,” says PITZ group leader Frank Stephan. “On the other, we carry out fundamental experiments for the future concept of plasma acceleration.”

Made-to-measure electron bunches

Thanks to a sophisticated laser system, the electron bunches from PITZ can be precisely tailored. “We have fired a specially shaped electron bunch as driver pulse into a plasma cell,” says Stephan. “It was a small pulse, directly followed by a linearly increasing larger pulse.” The result was that this tailor-made driver pulse lost little energy while generating a high plasma wave – similar to how a ship will glide easily through the water yet at the same time leave a high wake behind it – and so accelerated a subsequent test pulse extremely effectively. In principle, this could be used to considerably shorten the length of the preaccelerator of a future plasma facility.

Another PITZ experiment is relevant to a further variant of particle-driven plasma acceleration in which protons – i.e. hydrogen nuclei – are used as driver beams. The problem is that “the proton bunches that are produced by a conventional preaccelerator have a length of ten centimetres – much too long to generate

Picture: ZAB GmbH, Till Budde

The PITZ facility can generate made-to-measure electron bunches.

In the AWAKE experiment at the European particle physics centre CERN near Geneva, researchers have demonstrated plasma acceleration with proton beams for the first time.

Picture: CERN

high accelerating fields in a plasma cell," says Frank Stephan. "So they have to be split up into smaller bunches, which can be done using a process known as self-modulation."

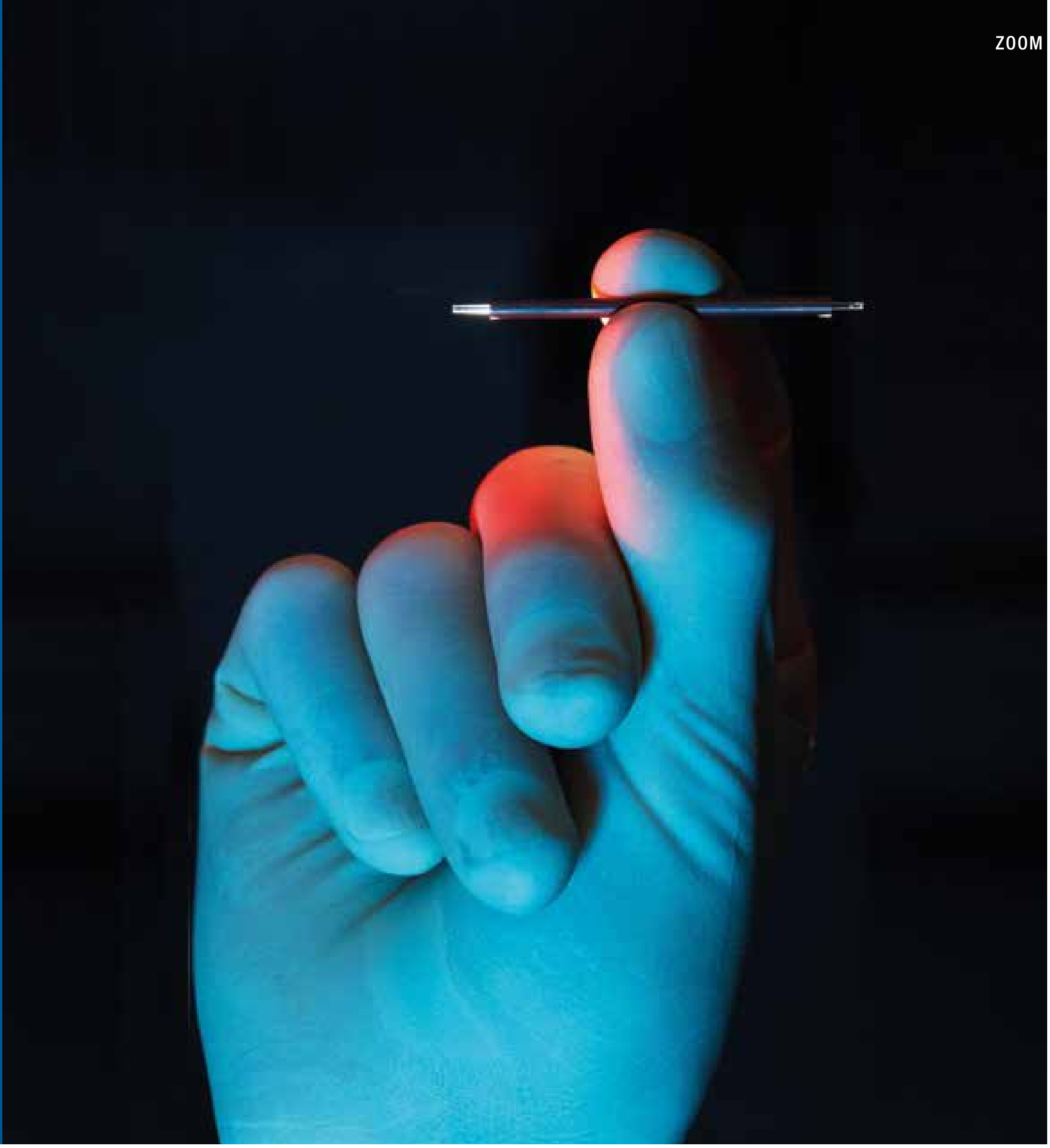
The principle is as follows: The long particle bunch passes through a plasma, so that a plasma wave forms on the bunch's leading edge. The resulting electromagnetic fields then reorganise the particles into multiple short bunches. "Computer simulations have indeed suggested that this should work," says Stephan. "But with PITZ, we have now been able to prove for the first time in electron beams that this self-modulation really happens." In concrete terms, the researchers observed a long electron bunch splitting into three smaller bunches. The measurements are relevant to a worldwide unique experiment: In May 2018, a research team at the AWAKE experiment at CERN succeeded in accelerating electrons using a beam of protons.

This approach has a big advantage: "Protons are considerably heavier than electrons and can thus be accelerated to much higher energies," says Matthew Wing, professor of physics at University College London and a guest scientist at DESY. "As a result, they can penetrate a plasma to a much greater depth." The consequence is that it would be possible to build very long plasma cells that could accelerate the electrons to enormous energies in a single stage. The plasma cell in the pioneering experiment in May was about ten metres long and accelerated the electrons, which had been injected into the cell with an energy of 20 MeV, to one hundred times that value – to 2 GeV.

"The biggest challenge was to tune three different beams to one another," explains Wing, "a laser beam that generates the plasma, the proton driver beam and the beam of electrons to be accelerated." The large SPS accelerator – a ring with a diameter of seven kilometres that is otherwise used as a preaccelerator for the LHC – served as the source of the fast protons. In the coming years, the experts will attempt to optimise their processes in the hope that by 2025 they will be able to show that the principle is suitable for use as a powerful electron accelerator.

"A facility of this type would be especially interesting for particle physics," says Wing. It could be an accelerator designed to look for the ominous dark matter – or a successor to the LHC in which high-energy protons would collide with fast electrons generated by a plasma accelerator. What seems clear is that such a proton-driven facility would not be particularly small. The reason is that "ultimately, you still need high-energy protons," says Matthew Wing. "Generating these will probably still require extremely large preaccelerators in the future."

> *"The quality of the beams is constantly increasing, and we are close to building useable plasma accelerators today"*
>
> **Ralph Aßmann, DESY**



Terahertz accelerator modules fit easily between two fingers.

The terahertz trick

Short wavelength promises accelerators hundreds of times smaller

Franz Kärtner holds up an unremarkable copper tube. It has the same diameter as a ballpoint pen refill, but it's much shorter. "Here you see one of the core components of our terahertz accelerator," explains Kärtner, who is a physicist at the Centre for Free-Electron Laser Science (CFEL), a joint institution of DESY, Universität Hamburg and the Max Planck Society. Kärtner's objective is to build an accelerator that is significantly shorter than today's facilities, but can accelerate electrons to the same energies.

In conventional accelerators, the particles are brought up to speed using radio waves. These have wavelengths in the ten-centimetre region. "Our concept makes use of considerably shorter wavelengths," explains Kärtner, who is a leading scientist at DESY. "Instead of ten centimetres we take one millimetre, that is one hundredth the size." This terahertz radiation can be used to accelerate particles more efficiently. The idea is that much more energy can be transferred to the particles over the same distance.

But generating sufficiently powerful terahertz radiation is not straightforward. In Kärtner's laboratory, this is done on a massive, vibration-damped table. Mounted on the table is a laser that fires intense flashes of light onto

Picture: DESY, Heiner Müller-Elsner

a small crystal. This causes the crystal lattice to emit terahertz waves. A parabolic reflector captures these waves and focuses them on a small copper tube – the actual accelerator. Inside it is another, even smaller tube made of quartz. Within it, the injected terahertz waves give a substantial boost to a bunch of electrons that the researchers guide through the tube.

In 2015, the experts at CFEL first succeeded in operating their prototype. At that time, they achieved an accelerating voltage of five megavolts per metre – just about one fifth of the acceleration gradient delivered by the accelerating cavities of the European XFEL X-ray laser. But the feasibility had been proven. By now, the group can generate much more powerful terahertz waves with their equipment and achieves accelerating voltages of up to 70 megavolts per metre – three times that of the European XFEL cavities.

> *“Our concept makes use of considerably shorter wavelengths”*

Franz Kärtner, DESY

Electrons at almost the speed of light

At the moment, Franz Kärtner and his team are building a larger experiment named AXSIS at DESY, which is financed by a Synergy Grant from the European Research Council (ERC). “We want to realise the first X-ray source based on terahertz technology here,” explains the physicist.

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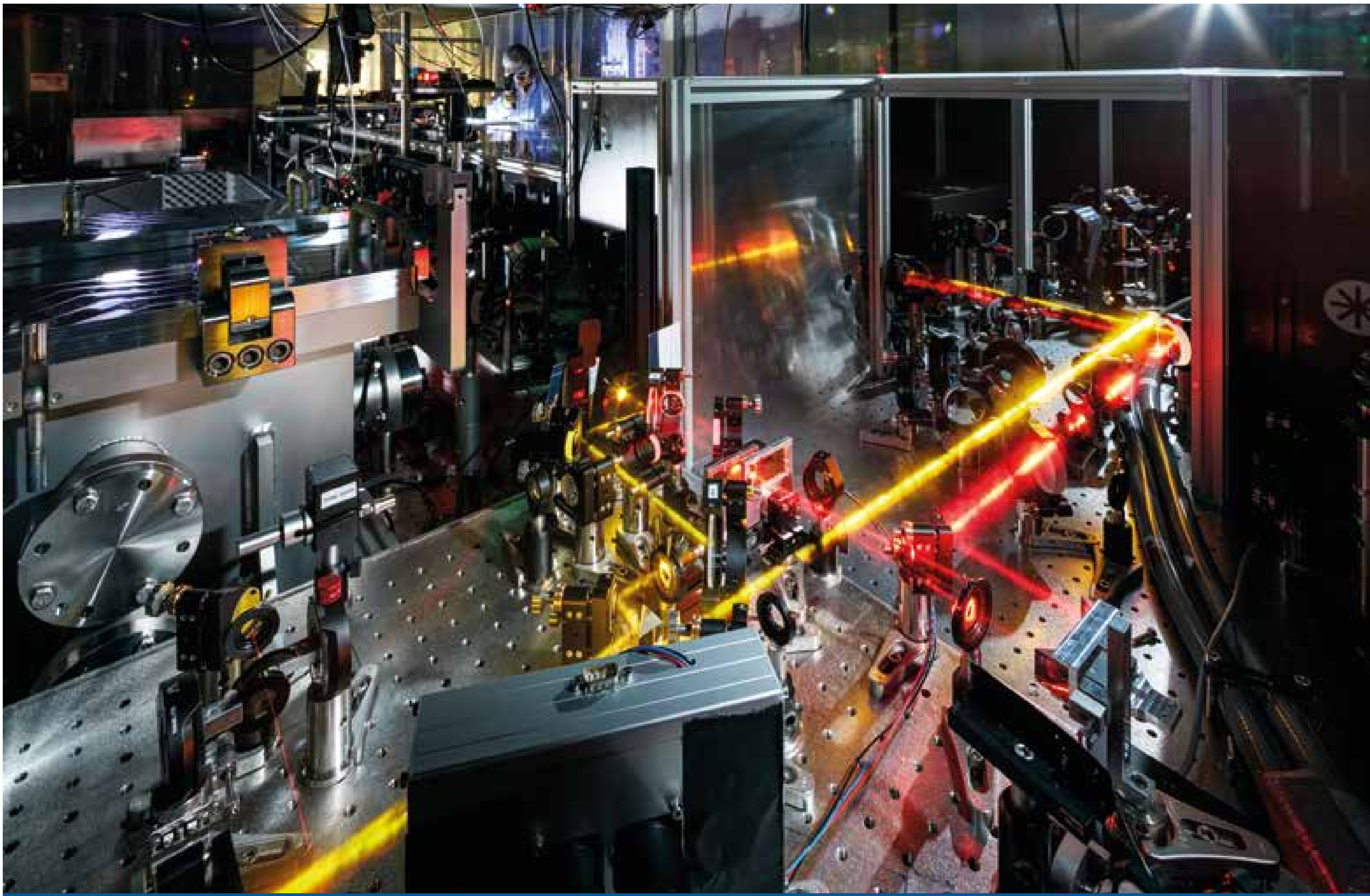


Lasers of various wavelengths play a central role in new accelerator technologies. They can for example be used to generate terahertz waves, which are difficult to produce.

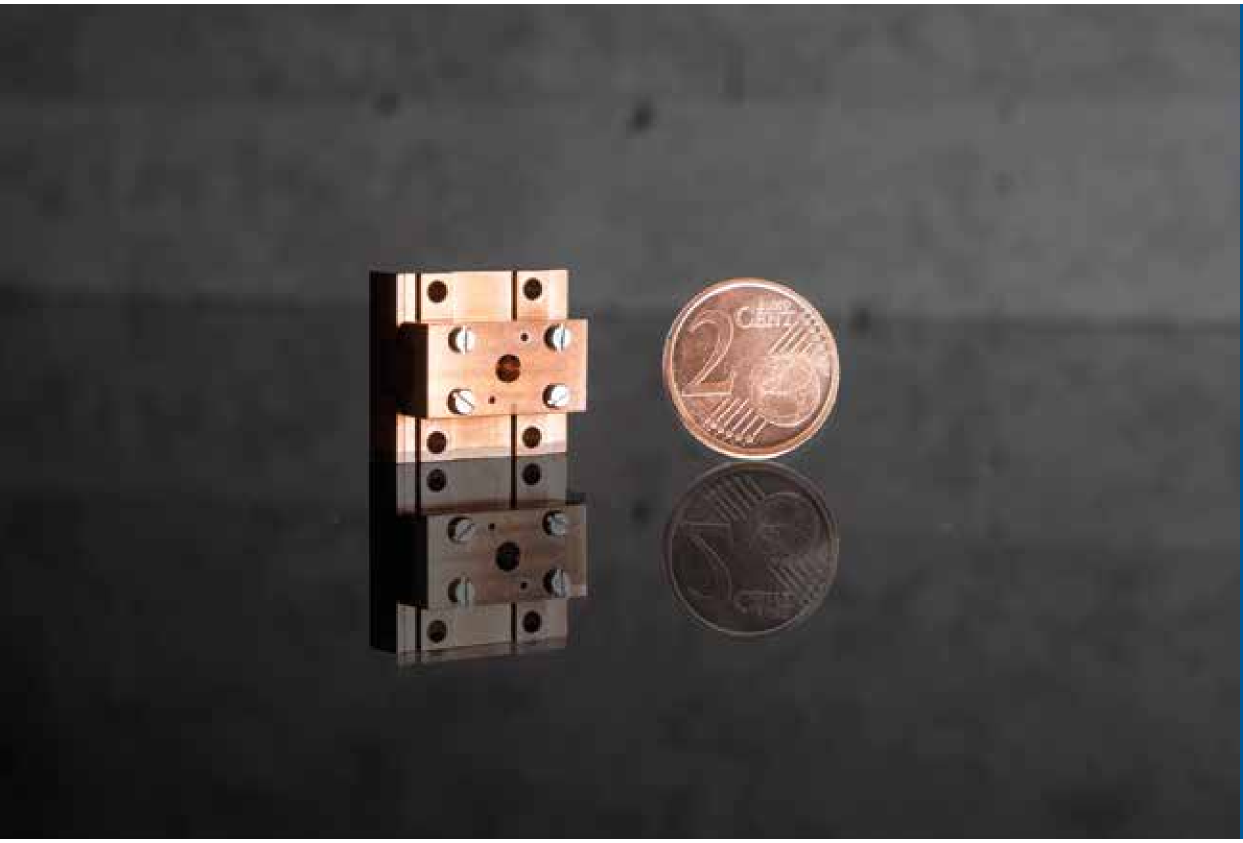
Picture: DESY, Heiner Müller-Elsner, Gesine Born (portrait)

> *“In principle, it would be possible to shrink a 100-metre-long accelerator down to one metre”*
>
> **Franz Kärtner, DESY**

The plan is to bring the particles to an energy of almost a million electronvolts (MeV) using a terahertz-based electron gun. This means the electrons are travelling at close to the speed of light, which makes it easier to inject them into the main accelerator, the small copper tube. Driven by 1000 ultrapowerful flashes of light per second, the device should accelerate the particles to 20 times their initial energy – to 20 MeV. The researchers then want to direct this high-speed bunch of electrons towards an “optical undulator” – a laser beam that will cause the electrons to sway from side to side in a controlled fashion and so force them to emit intensive X-ray radiation.

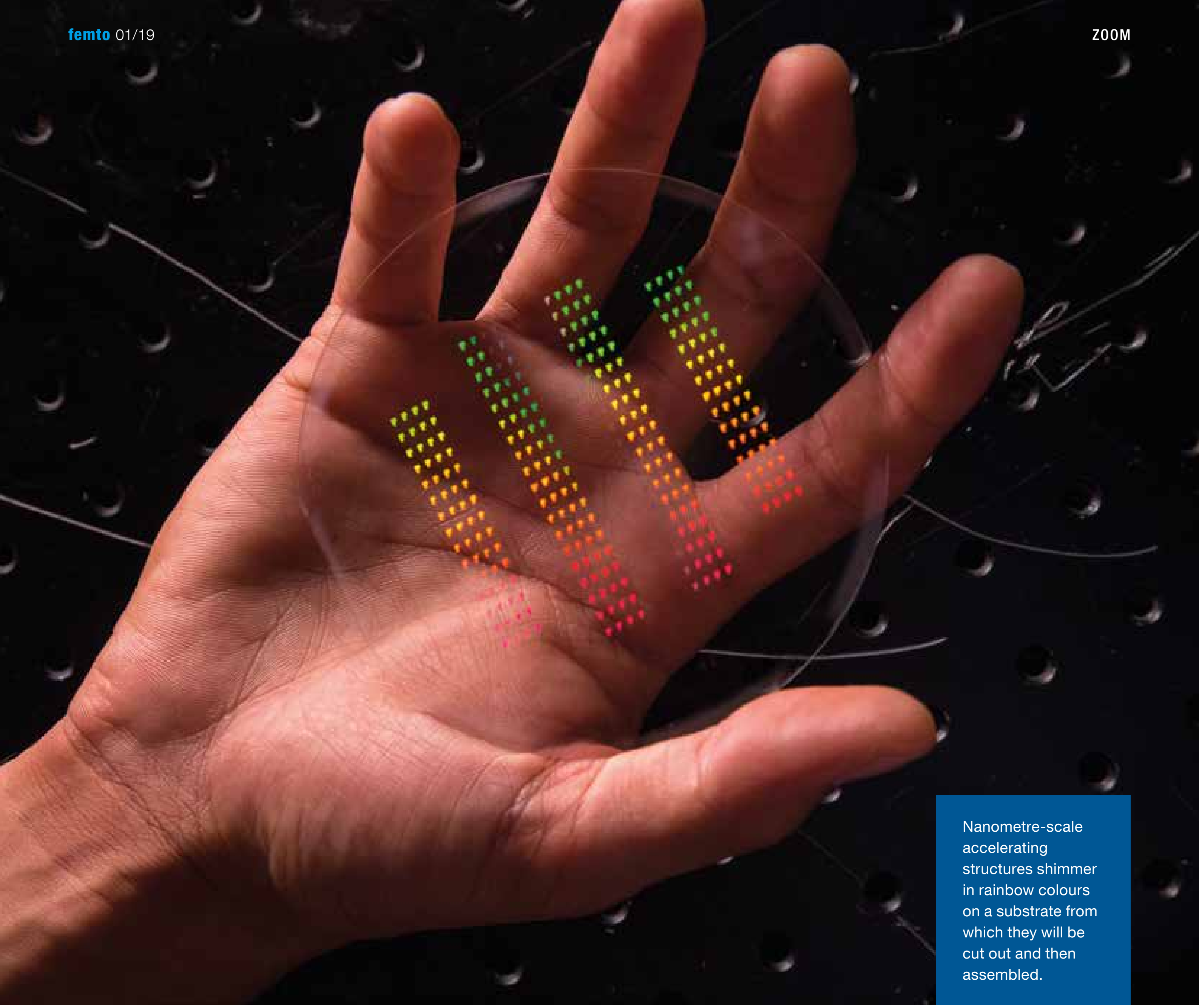
But the laser appears to be just one way to generate terahertz waves for future accelerators. This could also be done using gyrotrons – devices in which fast electrons race along helical paths through a magnetic field and emit high-frequency radiation as they do so. The usual application for this type of gyrotron is as a kind of microwave heater for nuclear fusion experiments such as the International Test Reactor (ITER) in Cadarache in the south of France. In the coming years, Kärtner and his colleagues intend to find out whether gyrotrons are also suitable for use as drivers for their accelerator. “It’s possible that terahertz waves can be produced much more efficiently with a gyrotron than with a laser,” says Kärtner. “In principle, we should be able to achieve accelerating voltages of 300 megavolts per metre. Then it would be possible to shrink a 100-metre-long accelerator down to one metre.”

That would open the door to ultracompact X-ray lasers firing a rapid succession of high-precision X-ray flashes, with which it would be possible to study proteins essential for life, for example. A terahertz accelerator would also be of interest as a diagnostic tool for medical applications. As an alternative to the good old X-ray tube, it could provide images with extremely high resolution while lowering the radiation load on the patients at the same time.



Multi-talent: The Segmented Terahertz Electron Accelerator and Manipulator (STEAM) developed by the group of Franz Kärtner is a kind of Swiss Army knife for electron beams. STEAM is powered by terahertz radiation and can accelerate, compress, focus and analyse electron bunches. The experimental device is about the size of a two-cent coin. The active structure in its interior is just a few millimetres in size.

Picture: DESY, Gesine Born



Nanometre-scale accelerating structures shimmer in rainbow colours on a substrate from which they will be cut out and then assembled.

Picture: SLAC National Accelerator Laboratory

The accelerator on a **chip**

Researchers are working on a mini particle gun on a microchip

When specialists seek to shrink particle accelerators, it's usually a question of fitting a facility the size of a sports hall into a laboratory basement. The vision behind ACHIP sounds significantly more ambitious, however. The international team of researchers is working on an accelerator that fits on a microchip. The possible applications sound spectacular. They range from ultracompact X-ray lasers to microrobots that patrol the body and destroy tumours.

Bob Byer picks up a small plastic box. It contains a centimetre-sized piece of quartz glass with multiple stripes that are hardly visible to the naked eye. They are just half a micrometre wide. "We illuminate this chip with ultrashort laser flashes and inject electrons at the same time," says Byer, who is a professor of physics at Stanford University. "The result is that the electrons are accelerated enormously."

The idea behind the accelerator on a chip originated in the 1960s. "But then, there were no lasers that could be used to actually

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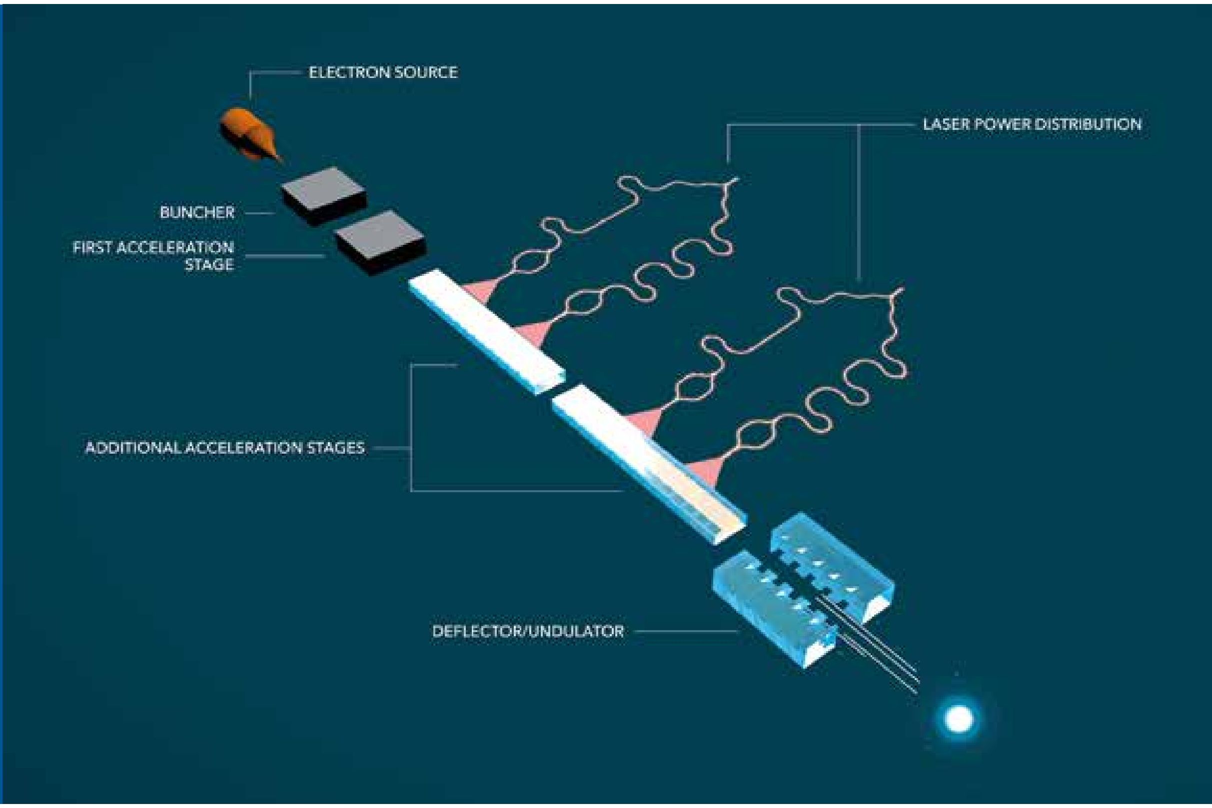
implement the principle," says Byer. It wasn't until the start of this decade that the research community started to realise the dream with the help of advanced laser technology. In 2013, simultaneously with a German research group, Byer's team accelerated electrons using a quartz glass chip for the first time.

As in a conventional accelerator, which uses radio waves, the electrons in an accelerator on a chip ride on an electromagnetic wave. But here, they ride on light waves generated by a powerful laser. This light has wavelengths around 100 000 times shorter than that of the radio waves in a conventional facility. The accelerating segments are tiny. Instead of metre-long metal tubes, they are made of materials similar to glass with tiny structures – extremely fine channels created by means of the lithographic techniques that are also used by chip manufacturers for the mass production of microprocessors.

Three miniature silicon accelerator modules on a transparent base

> *"The light pulses from powerful femtosecond lasers can be used to generate extremely high field strengths"*
>
> **Peter Hommelhoff, University of Erlangen-Nuremberg**

"The light pulses from powerful femtosecond lasers can be used to generate extremely high field strengths in these channels," explains Peter Hommelhoff, professor of physics at the University of Erlangen-Nuremberg. In 2013, simultaneously with the researchers from Stanford, his team succeeded in building a first prototype of an accelerator on a chip. Today, five years later, electrons can be accelerated to energies of around 850 megaelectronvolts (MeV) using chips with accelerating voltages of close to one gigavolt per metre – around 20 times more than in the best conventional accelerators, which would need to be a few dozens of metres long to achieve the same particle energy. However, they



A pocket-sized X-ray laser could be set up like this: A miniature electron source (above left) generates electrons that are first assembled into bunches in the buncher before being preaccelerated. The electron bunches are brought to the required energy in the laser-driven accelerating elements and then forced to follow a slalom course through an undulator, so that they emit bright flashes of X-ray laser radiation.

also reach a much higher intensity – i.e. they can accelerate significantly more particles at once.

Small, smaller, ACHIP

In order to further develop the technology, Byer and Hommelhoff have established ACHIP – a research programme with a duration of five years. Their objective is to develop an accelerator on a chip that can be used to generate X-rays. ACHIP is financed by the foundation set up by Gordon Moore, the founder of Intel. One of the project's aims is to accommodate the core components in as compact a space as possible. "The chip, a light distribution system and an electron preaccelerator should fit in two or three shoe boxes," says Hommelhoff. "Ideally, the system would only be connected to the outside world by a high-voltage cable and a glass fibre for the light pulses."

In the long term, the researchers also plan to fit the lasers on a chip – together with other components belonging to an accelerator. These include elements that monitor the respective position of the electron beam, focus the beam and guide it through the channels. "The first tests to show that this works on a chip have already been done," says Hommelhoff. "It's important that not too many electrons are lost during the process – otherwise such an accelerator wouldn't be especially useful."

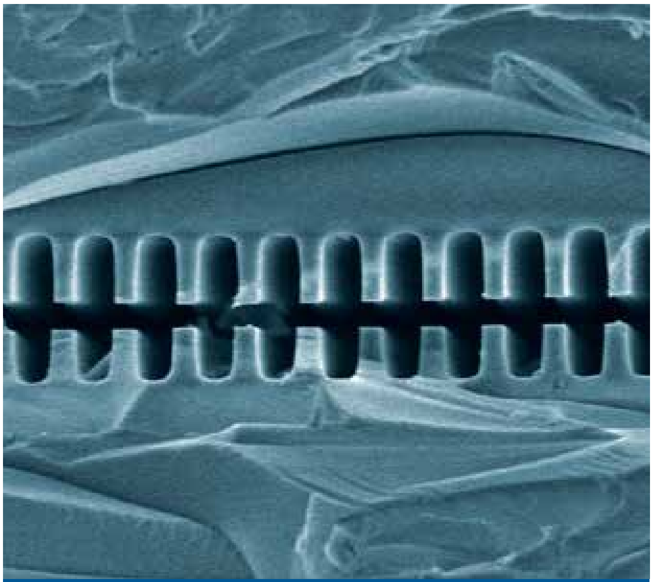
Another challenge for the experts is to design the number and course of the fine channels on the chip so that the acceleration process is as efficient as possible. Recently, they have been getting help from computer simulations that use an algorithm to search for the optimal structures. "These structures sometimes look like artworks when viewed under the microscope," says Bob Byer. "They're highly complex aesthetic patterns." The resulting chip structures will soon also be tested at DESY, where the new facility SINBAD (Short Innovative Bunches and Accelerators at DESY) is being set up to enable detailed testing of new accelerator concepts.

And what could the new technology be used for one day? "We already have a few ideas," says Byer. "My dream is that it will be possible to build an extremely compact X-ray laser for scientific use on the basis of an accelerator on a chip." Ideally, it would fit in every university laboratory and enable detailed studies of proteins and high-tech materials at a reasonable cost. Compact electron microscopes would also be conceivable. Today, these are person-sized pieces of equipment – in future, they could fit in a pocket.

> *"My dream is that it will be possible to build an extremely compact X-ray laser for scientific use on the basis of an accelerator on a chip"*
>
> **Bob Byer, Stanford University**

Medical specialists would also be interested. They envision a tiny electron accelerator built into a catheter. It would be able to irradiate tumours directly and at very close range, sparing the surrounding tissue and possibly offering an alternative to today's radiotherapy. It's even conceivable that in the distant future small autonomous robots could patrol the body and use a microaccelerator to eliminate a tumour in the very earliest stages.

There's one remaining hurdle to overcome: "We still have to convince the experts that the electron beams from our chips are sufficiently intense," says Peter Hommelhoff. The reason for this is that the channels in the chips are so small that they can only accelerate a few electrons at once. But the researchers already have an approach to solving this problem. In principle, it is possible to stack hundreds or even thousands of accelerators on a chip and connect them in parallel, thus multiplying the number of electrons accelerated by a factor of a thousand.



Examples of nanostructures being studied for the miniature accelerator

Pictures: SLAC National Accelerator Laboratory

Future data storage technology

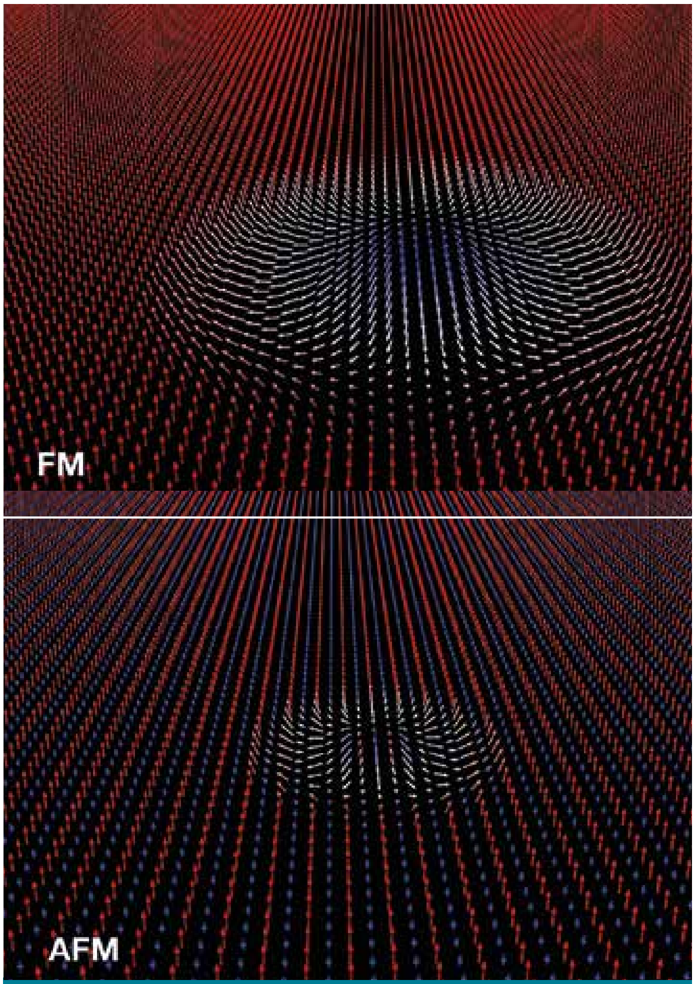
Novel concepts of magnetic data storage aim at sending especially small magnetic bits back and forth in a chip structure, storing them densely packed and reading them out later. So far the magnetic stray field has prevented the generation of particularly tiny bits, however. Researchers at the Max Born Institute (MBI), the Massachusetts Institute of Technology (MIT) and DESY have now succeeded in putting an “invisibility cloak” on the magnetic structures and observing how small and fast such cloaked bits can get.

To this end, different atomic elements with opposite rotation of the electrons and thus opposite magnetic moment were combined in one material. In this way, the magnetic stray field can be reduced or even completely cancelled – the individual atoms in the nanostructure still carry a magnetic moment, but together they appear cloaked.

In spite of this cloaking, the scientists were able to image the tiny structures. For this purpose, they made use of the method of X-ray holography, which allowed them to selectively make only the magnetic moments of a single type of atom visible. At DESY’s high-brilliance X-ray light source PETRA III, they thus succeeded in imaging the structures despite their invisibility cloak.

If the strength of the invisibility cloak is adjusted just right, the resulting magnetic nanostructures can at once be made very small and be made to move quickly – an interesting prospect for novel data storage technologies based on magnetic nanostructures.

Nature Nanotechnology, 2018;
DOI: 10.1038/s41565-018-0255-3



Skyrmions consist of a specific arrangement of the magnetic moments of neighbouring atoms. In the anti-ferromagnetic (AFM) order, the neighbouring magnetic moments are almost opposite – the stray field is reduced, the skyrmion wears a kind of invisibility cloak and can become particularly small.

Picture: MIT, L. Caretta/M. Huang

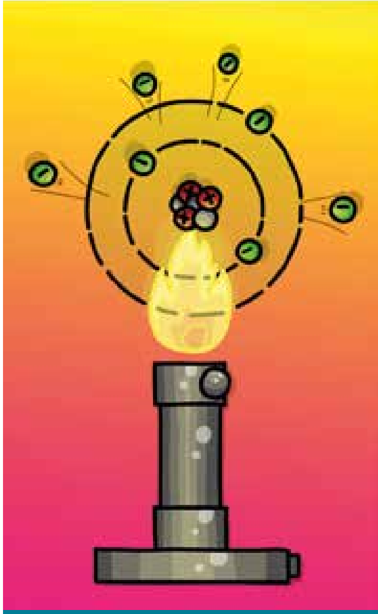
"Quantum boiling" for atoms

In a way of "quantum boiling" with intense X-ray flashes, scientists have stripped xenon atoms of most of their electrons. With these experiments, an international team around Sang-Kil Son and Robin Santra from the Center for Free-Electron Laser Science (CFEL) at DESY has revealed the impact of Albert Einstein's theory of special relativity on the quantum structure of atoms.

"Understanding atomic structure is fundamentally important," explains Son. "Quantum mechanics tells us how electrons are placed in different atomic shells." The atomic shell structure forms the basis for Mendeleev's periodic table and determines the chemical properties of the elements. "Electrons in the outermost atomic shells typically move already at about one percent of the speed of light," adds Santra. "The electrons in inner atomic shells, however, move even faster, particularly in heavier atoms. Then, quantum mechanics must be complemented by the theory of special relativity to accurately describe the atomic structure."

Strong X-ray light can "evaporate" electrons from atoms in a process that is similar to the boiling of water. This quantum boiling has only been made possible by modern accelerator-driven facilities called free-electron lasers, however, which deliver the strongest X-ray flashes in the world. These facilities generate conditions corresponding to temperatures of several hundred million degrees Celsius. Quantum boiling then lays bare the inner shells of the atom and makes relativistic effects visible in a new way.

Nature Communications, 2018;
DOI: 10.1038/s41467-018-06745-6



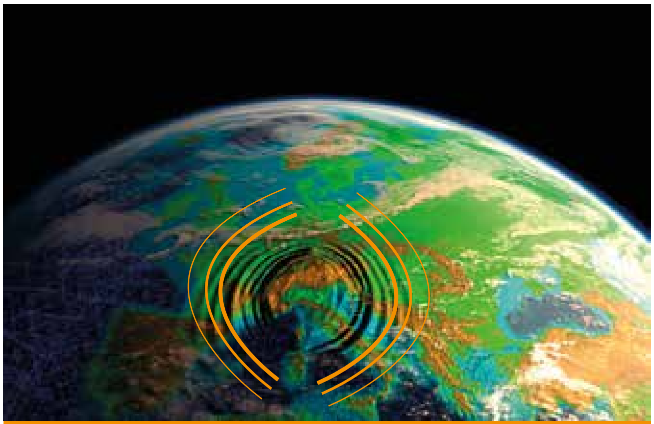
Quantum boiling evaporates electrons from the atom much like conventional boiling evaporates water molecules.

Earthquake in the laboratory

Researchers at DESY have used a new experimental approach to simulate the way in which seismic waves propagate within a sample, while closely observing the changes taking place inside the material itself. In their study, the scientists led by Hauke Marquardt from the University of Oxford and Bayerisches Geoinstitut (BGI) at the University of Bayreuth were able to show how a process occurring in the mineral ferropericlase above a certain pressure influences the speed with which such waves propagate. The finding could help to map the composition of the interior of the Earth more accurately.

The new experimental method allows scientists to simulate seismic waves in the laboratory under different conditions of pressure and to measure their effects on samples with a high temporal resolution. "We simulate the seismic waves by cyclically compressing and relaxing the sample in a controlled manner, at frequencies that are typical of seismic waves. At the same time, we can use X-rays to measure very accurately how the volume of the material under investigation changes during this time," says Hanns-Peter Liermann, who leads the beamline at DESY's X-ray source PETRA III where the new experimental set-up was developed and the measurements were carried out.

Geophysical Research Letters, 2018;
DOI: 10.1029/2018GL077982



Simulation of the propagation of seismic waves

Pictures: Sherin Santra (quantum boiling); M. Meschede (simulation)

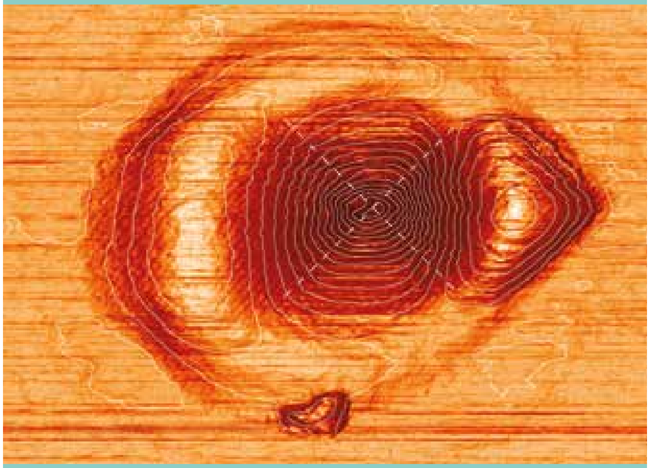
Kick-off for Hamburg graduate school for data science

A new graduate school for data science will be established in Hamburg. The “Data Science in Hamburg – Helmholtz Graduate School for the Structure of Matter”, or DASHH for short, will offer young scientists an interdisciplinary and application-oriented education in the processing and analysis of large volumes of data when studying the structure of matter. The Helmholtz Association has decided to fund the joint initiative of DESY, Universität Hamburg, the Hamburg University of Technology and five other northern German research institutions with almost six million euros over the next six years.

“Data Science is a key technology for current and future natural sciences. Together with the universities, we would like to establish computer science geared towards the natural sciences on the Bahrenfeld campus and offer very good research opportunities to PhD students in the field of big data,” says Helmut Dosch, the chairman of the DESY Board of Directors.

Key fields of application lie in structural biology, materials sciences, physics using ultrafast X-ray pulses and particle physics. The DASHH graduate school will offer highly talented young researchers from all over the world the opportunity to do their doctorate. In the research groups, they will be working on the challenges posed by large volumes of highly complex scientific data.

DESY’s research facilities produce huge amounts of data. Their intelligent and efficient use is the subject of the new graduate school.



Nanoholes in semiconductors

A German–French research team has identified surprising properties of nanoholes in semiconductor materials produced by a promising technique: In their experiments, hot aluminium droplets etched remarkably smooth holes into an aluminium gallium arsenide substrate. The method is suitable, among other things, for the production of so-called quantum dots, which can be used, for example, for light sources with a very sharply defined colour or for storage cells in quantum computers.

The team from the Center for Hybrid Nanostructures (CHyN) at Universität Hamburg, the DESY NanoLab and the European Synchrotron Radiation Source (ESRF) in France investigated a typical semiconductor material made of gallium arsenide, the second most important material in the semiconductor industry after silicon.

For their etching experiments, the researchers coated the semiconductor material with aluminium, which forms droplets on the surface. At temperatures of nearly 700 degrees Celsius, the aluminium droplets etched holes into the semiconductor material. X-ray examinations at the ESRF revealed the smooth, regular shape of the holes. Investigations at CHyN and at the DESY Nanolab showed that the holes are each about 100 nanometres wide and 60 nanometres deep. One nanometre is one millionth of a millimetre. By being filled with a new material, such holes could serve as templates for quantum dots with tailor-made properties. In future analyses, the researchers hope to find out how the shape of the nanoholes can be understood and controlled.

Physical Review Materials, 2018;
DOI: 10.1103/PhysRevMaterials.2.106001

Pictures: DESY, Heiner Müller-Elsner (data science); CHyN/Universität Hamburg (nanoholes)

Unexpected form of scaffolding protein

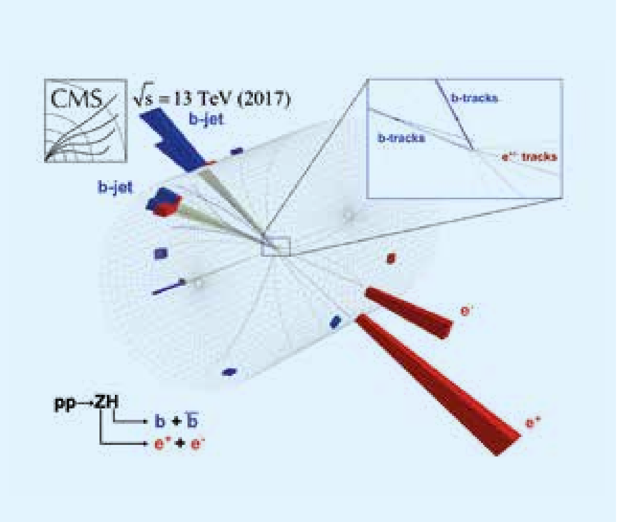
Artistic representation of the L-shape of the scaffolding protein PDZK1

A structural biology investigation at DESY's X-ray light source PETRA III has revealed a surprising shape of an important scaffolding protein for biological cells.

The scaffolding protein PDZK1 comprises four so-called PDZ domains, three linkers and a C-terminal tail. While bioinformatics tools had suggested that PDZK1's PDZ domains and linkers would behave like beads on a string moving around in a highly flexible manner, the X-ray experiments showed that PDZK1 has a relatively firmly defined L-shaped conformation with only moderate flexibility. The experiment was carried out by a team led by Christian Löw from the Centre for Structural Systems Biology (CSSB) and Dmitri Svergun from the Hamburg branch of the European Molecular Biology Laboratory (EMBL). For the future, Löw and his group plan to examine PDZK1 in complex with binding partners using electron cryo-microscopy. "Only by integrating a range of techniques and collaborating with colleagues will we be able to fully understand complex proteins like PDZK1," says Löw, who heads groups at both CSSB and EMBL. The teamwork of Löw and Svergun's groups has not only led to an initial structural model for PDZK1, it also shows the importance of using an integrated research approach for solving complex questions in structural biology.

Structure, 2018; DOI: 10.1016/j.str.2018.07.016

Decay of the Higgs particle



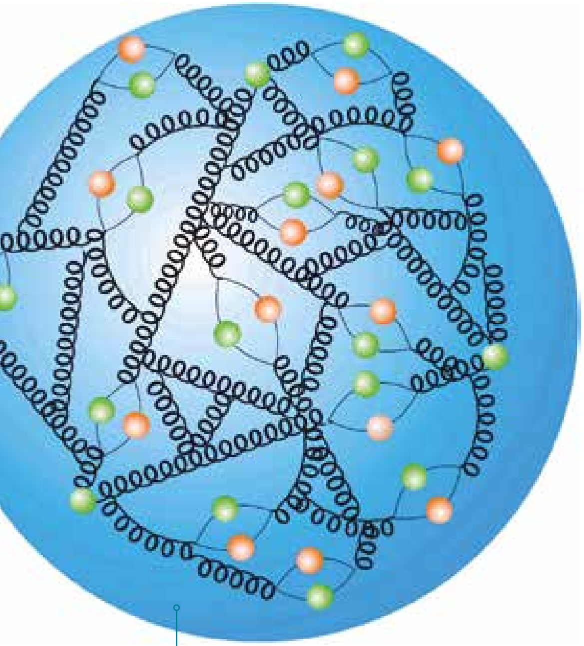
Collision in the particle detector CMS, in which a Higgs particle decays into two bottom quarks (blue)

Scientists from the two major particle physics experiments ATLAS and CMS at the European particle physics centre CERN have observed for the first time the Higgs boson decaying into two bottom quarks. According to theory, far more than half of all Higgs particles decay into these two quarks, but it is extremely difficult to filter out these processes from the many other things that happen when particles collide in the Large Hadron Collider (LHC) at CERN, the world's biggest particle accelerator. The result is another confirmation of the Standard Model of particle physics – the theory that describes all particles and forces – and a further proof that the Higgs particle does indeed give mass to all elementary particles. DESY researchers played key roles in the search.

Quarks are the fundamental constituents of all atomic nuclei. They come in six different kinds. The matter we know consists of up and down quarks, but there are also strange, charm, bottom and top quarks, which can for example be produced in particle accelerators. The discovery of the Higgs boson at the LHC in 2012 marked the final missing piece of the Standard Model. By studying the properties of the particle, which is named after the British theorist Peter Higgs, physicists hope to better understand how it gives mass to other elementary particles.

Pictures: EMBL, Manon Boschard (scaffolding protein); CERN/CMS Collaboration

Heavy quarks



The HERA experiments showed that the proton is a very dynamic entity made up of quarks, antiquarks and gluons.

The research teams of the large H1 and ZEUS detectors at DESY's former HERA particle accelerator have combined their measurements on heavy quark production. They analysed all HERA particle collisions in which charm and beauty quarks were produced – a culmination of over 20 years of work.

From 1992 to 2007, the 6.3-kilometre underground storage ring HERA (Hadron Electron Ring Accelerator) at DESY collided electrons and protons accelerated close to the speed of light in order to resolve and study the structure of the proton. HERA revealed a very complicated picture of the proton: a sizzling soup where gluons can produce more gluons and split into pairs of quarks and antiquarks, all of them interacting again very quickly.

The detailed analysis of heavy quark production allows precision tests of the theory of the strong force, quantum chromodynamics (QCD), and insights into the structure of matter. "The HERA experiments have collected a very valuable set of lepton–proton collisions and continue to produce high-level publications even 10 years after the end of data taking," says Joachim Mnich, director in charge of particle physics at DESY. "The publication is also a substantial proof that our efforts to preserve the HERA data for later analysis pay off."

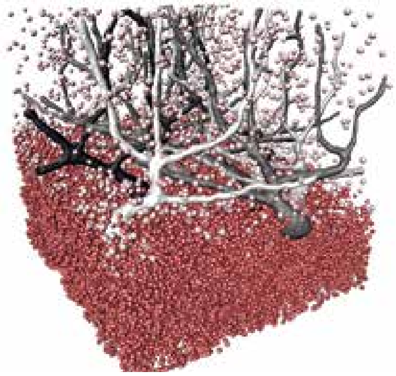
The European Physics Journal, 2018; DOI: 10.1140/epjc/s10052-018-5848-3

Google Maps for the cerebellum

A team of researchers from Göttingen has successfully applied a special variant of X-ray imaging to brain tissue. By combining high-resolution measurements at DESY's X-ray light source PETRA III and data from a laboratory X-ray source, Tim Salditt's group from the Institute of X-ray Physics at the Georg August University of Göttingen was able to visualise about 1.8 million nerve cells in the cerebellar cortex using phase contrast tomography.

The human cerebellum contains about 80 percent of all nerve cells in 10 percent of the brain volume – one cubic millimetre can therefore hold more than one million nerve cells. These cells process signals that mainly control learned and unconscious movement sequences. However, their exact positions and neighbourhood relationships are largely unknown. "Tomography in the so-called phase contrast mode and subsequent automated image processing enable the cells to be located and displayed in their exact position," explains Mareike Töpperwien from the Institute of X-ray Physics at the University of Göttingen, lead author of the publication.

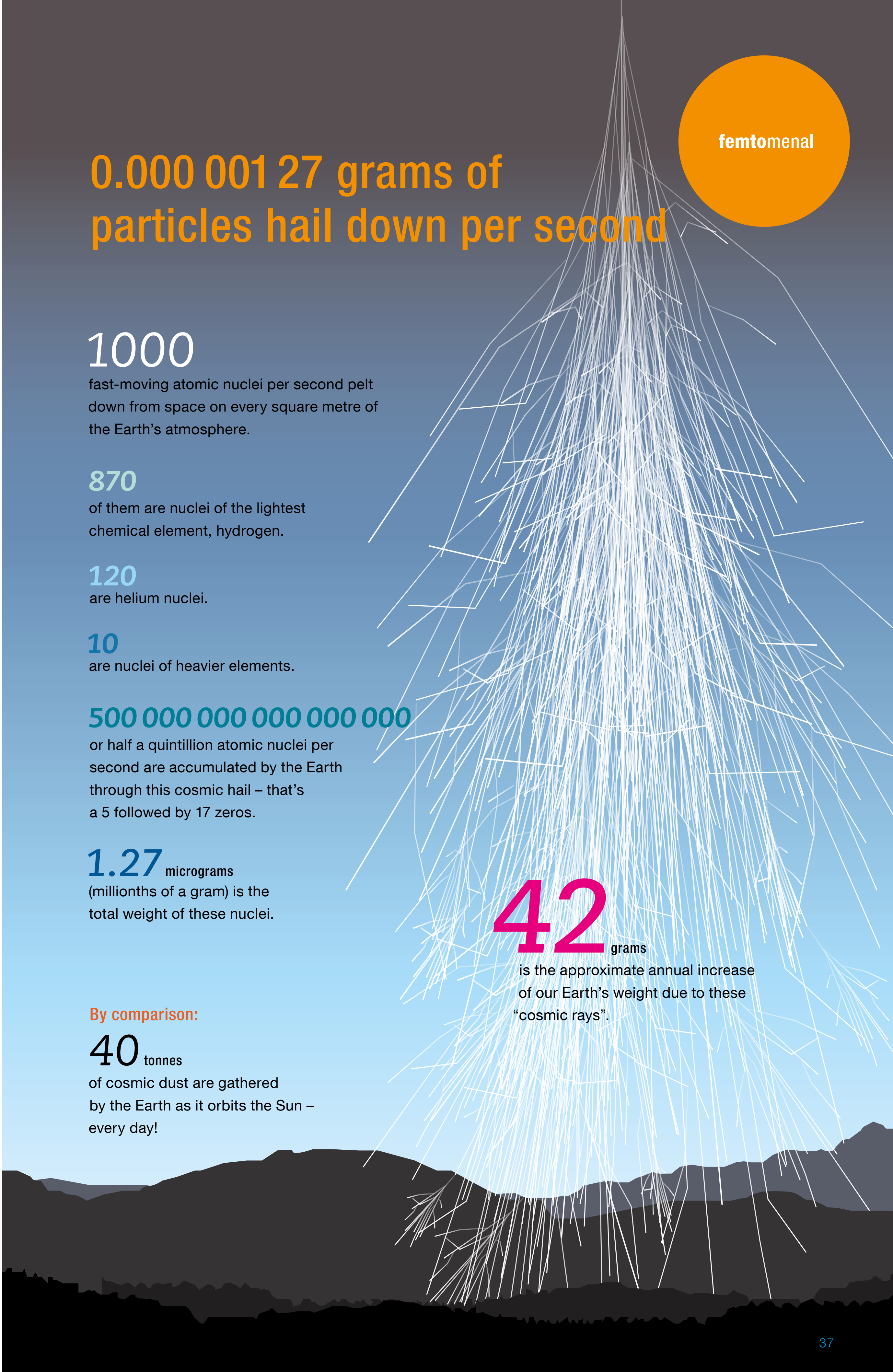
The combination of images of different magnifications enabled the Göttingen team to map the cerebellum over many orders of magnitude. "In the future, we want to be able to zoom even further into interesting brain regions, almost like on Google Maps," says Salditt.



Result of the phase contrast tomography study at DESY's X-ray source PETRA III

PNAS, 2018; DOI: 10.1073/pnas.1801678115

Pictures: DESY; University of Göttingen, Töpperwien et al. (bottom)



femtomenal

0.000 001 27 grams of particles hail down per second

1000

fast-moving atomic nuclei per second pelt down from space on every square metre of the Earth’s atmosphere.

870

of them are nuclei of the lightest chemical element, hydrogen.

120

are helium nuclei.

10

are nuclei of heavier elements.

500 000 000 000 000 000

or half a quintillion atomic nuclei per second are accumulated by the Earth through this cosmic hail – that’s a 5 followed by 17 zeros.

1.27 micrograms

(millionths of a gram) is the total weight of these nuclei.

42 grams

is the approximate annual increase of our Earth’s weight due to these “cosmic rays”.

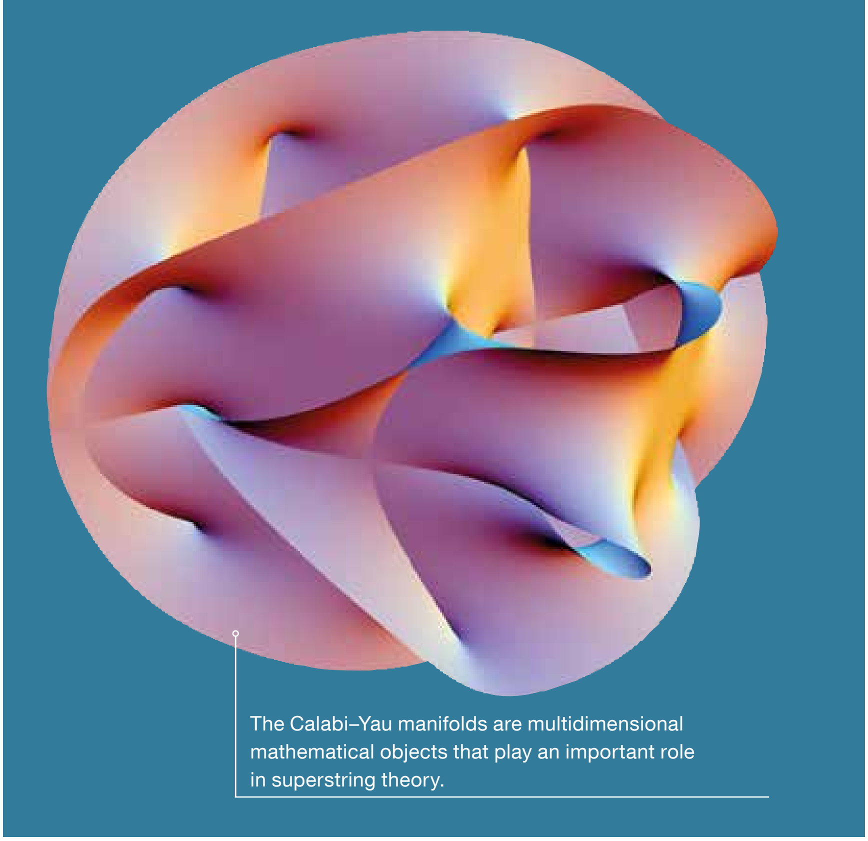
By comparison:

40 tonnes

of cosmic dust are gathered by the Earth as it orbits the Sun – every day!

Cosmic knots

Hamburg Prize for Theoretical Physics awarded to Hirosi Ooguri



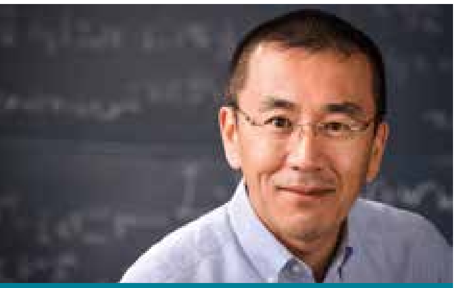
The Calabi–Yau manifolds are multidimensional mathematical objects that play an important role in superstring theory.

The smallest building blocks of the world are tiny oscillating strings in nine spatial dimensions – that's the fundamental assumption behind string theory. Hirosi Ooguri, a professor at the California Institute of Technology (Caltech) in the USA and the University of Tokyo in Japan, is one of the leading theoreticians in this field. He has now been awarded the Hamburg Prize for Theoretical Physics 2018 for his outstanding contributions to the mathematical treatment of these strings. Among other things, Ooguri will use the prize money for a research visit to the Wolfgang Pauli Centre for Theoretical Physics of DESY and Universität Hamburg.

According to the theory, the strings are wound up in six spatial dimensions, so that only the three dimensions that we are familiar with remain. The six-dimensional knots form "Calabi–Yau manifolds" in the process. Their mathematical properties are also useful in other areas of physics, for example in the description of the quark–gluon plasma that filled the universe shortly after the big bang. The main motivation for the work on string theory, however, is the search for an all-encompassing "Theory of Everything". This theory should describe all of the properties of the elementary particles as well as gravity, which has to date resisted incorporation into the Standard Model of particle physics.

"We are very much looking forward to discussing our research with Hirosi Ooguri in person. We hope that this will lead to inspirations on both sides for our work in string theory and quantum field theory," says Volker Schomerus, chairman of the prize jury and a leading scientist at DESY.

"Networking and personal discussions are extremely important, especially in such an abstract subject as theoretical physics," explains Eva Ackermann, project manager at the Joachim Herz Stiftung, which awards the prize together with the Hamburg Centre for Ultrafast Imaging (CUI) and the Wolfgang Pauli Centre. "In practice, it's often the joint coffee break, a bus journey or the meal in the canteen rather than exchanging e-mails or videoconferencing that make it easier to consider what initially seem to be absurd ideas. That's why we attach great importance to research stays of the prize winner in Hamburg."

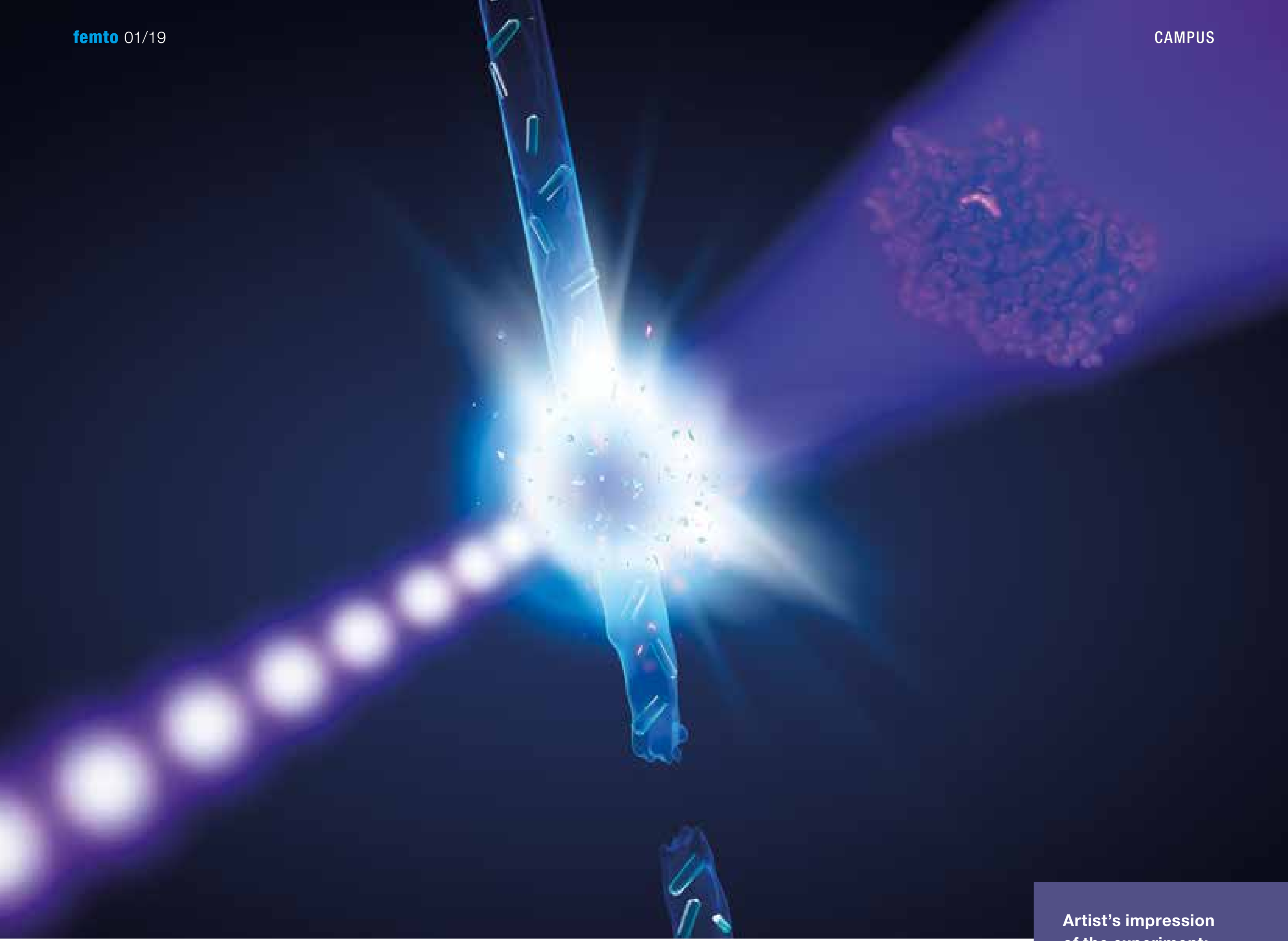


Hirosi Ooguri is director and Fred Kavli professor at Caltech and a professor at the University of Tokyo.

137 036 € IN PRIZE MONEY

The Joachim Herz Stiftung – a Hamburg-based non-profit foundation – is active in the areas of the natural sciences, economics and personal development. The Hamburg Prize for Theoretical Physics was established in 2010 and is endowed with 137 036 euros. The prize money's amount is a homage to Wolfgang Pauli's doctoral supervisor, Arnold Sommerfeld, who in 1916 introduced the fine structure constant α in order to explain the fine structure of the spectral lines of the hydrogen atom. The prize money amounts to 1000 €/α.

Pictures: Andrew J. Hanson, Wikimedia Commons, CC-BY-SA-4.0; Caltech, Bill Youngblood (portrait)



Artist's impression of the experiment: When the ultrabright X-ray flashes (violet) hit the enzyme crystals in the water jet (blue), the recorded diffraction data allow the spatial structure of the enzyme (right) to be reconstructed.

Picture: DESY, Lucid Berlin

Quick start for **Europe's X-ray laser**

First experiments at the European XFEL reveal unknown structure of antibiotics killer

An international collaboration has announced the results of the first scientific experiments at Europe's new X-ray laser European XFEL. The pioneering work not only demonstrates that the new research facility can speed up experiments by more than an order of magnitude, it also reveals a previously unknown structure of an enzyme that plays a major role in antibiotic resistance. "Being at a totally new class of facility, we had to master many challenges that nobody had tackled before," says DESY scientist Anton Barty from the Center for Free-Electron Laser Science (CFEL), who led the team of about 125 researchers.

The 3.4-kilometre-long European XFEL is designed to deliver X-ray flashes every 220 nanoseconds, that is every 0.000 000 220 seconds. The flashes can for example be used to illuminate biomolecules in order to determine their three-dimensional shape. The spatial structure of proteins and enzymes can reveal much about how exactly these molecules work. For such studies, tiny crystals are first grown from many identical biomolecules, which are then exposed to the X-ray flashes. Each crystal generates a characteristic diffraction pattern, which is recorded by a detector. If enough such patterns are recorded from all sides of a crystal, its inner structure – and thus also that of its building blocks, the biomolecules – can be calculated with atomic resolution.

Biomolecules in 3D

However, every crystal can only be X-rayed once since it is vaporised by the intense

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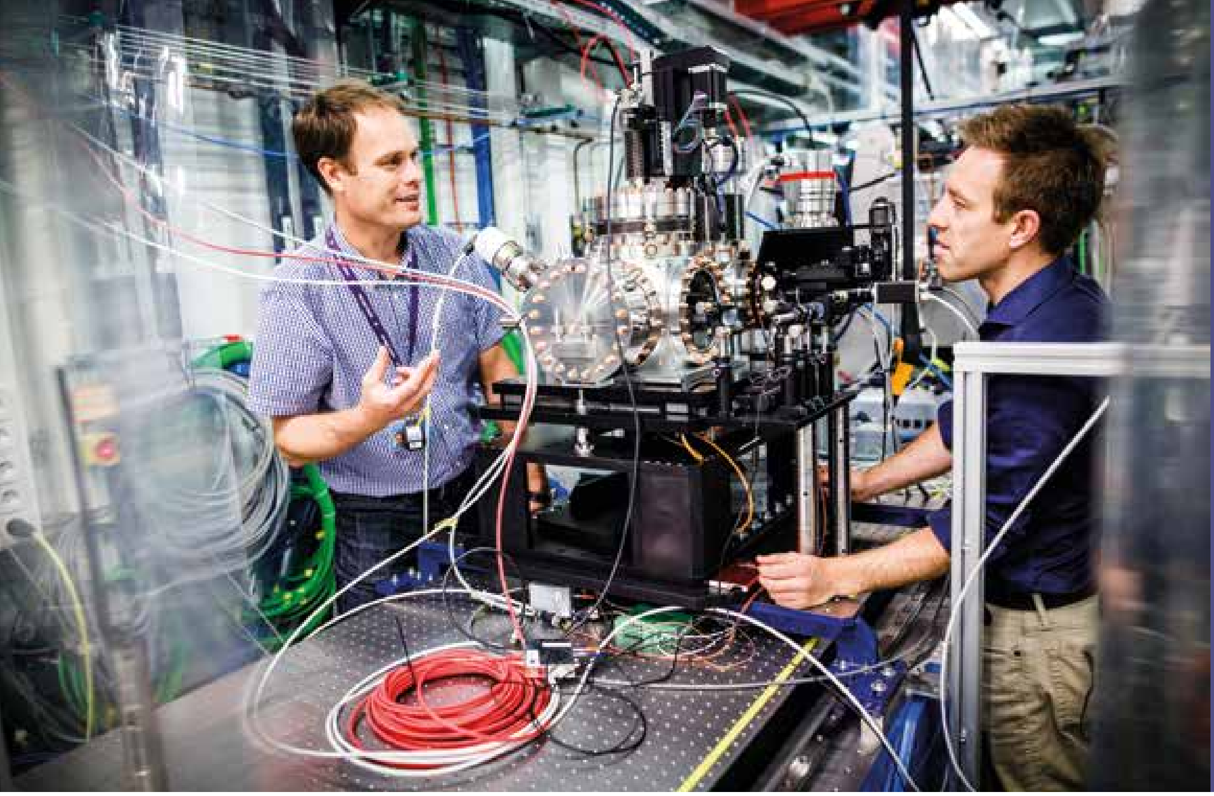


Principal investigator Anton Barty (left) from DESY and European XFEL scientist Richard Bean at the SPB/SFX instrument

flash of the X-ray laser (after it has produced a diffraction pattern). So, to determine the full three-dimensional structure of the biomolecule, a new crystal has to be delivered into the beam in time for the next flash, by spraying it across the path of the laser in a water jet. With its extremely fast pulse rate, the European XFEL can greatly accelerate such studies – however, nobody has tried to X-ray samples with atomic resolution at this fast rate before. The fastest pulse rate so far of any such X-ray laser has been 120 flashes per second, that is one flash every 0.008 seconds (or 8 000 000 nanoseconds).

> *“Such movies would give us crucial insights that could one day help us to design better inhibitors, reducing antibiotic resistance”*
>
> **Christian Betzel, Universität Hamburg**

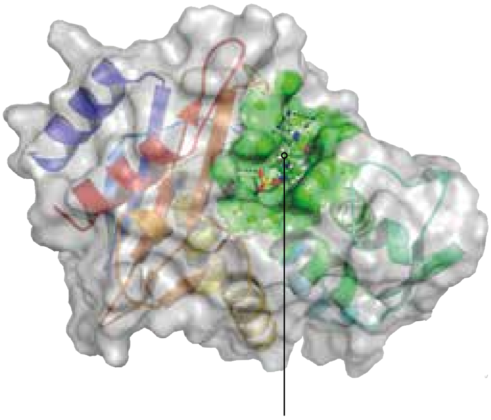
To probe biomolecules at full speed, not only the crystals must be replenished fast enough – the water jet is also vaporised by the X-rays and has to recover in time. “We revved up the speed of the water jet carrying the samples to 100 metres per second, that’s about as fast as the speed record in formula 1,” explains Max Wiedorn from CFEL. A specially designed nozzle made sure the high-speed jet would be stable and meet the requirements. To record the X-ray diffraction patterns at this fast rate, an international consortium led by DESY scientist Heinz Graafsma had spent years designing and building one of the world’s fastest X-ray cameras, tailor-made for the European XFEL.

Understanding antibiotic resistance

As one of their samples, the team chose a bacterial enzyme that plays an important role in antibiotic resistance. The molecule designated CTX-M-14-β-lactamase was isolated from the bacterium *Klebsiella pneumoniae*, whose multidrug-resistant strains are a grave concern in hospitals worldwide. Two years ago, a “pandrug-resistant” strain was even identified in the USA, which, according to the Centers for Disease Control and Prevention (CDC), was resistant to all 26 commonly available antibiotics.

The enzyme CTX-M-14-β-lactamase is present in all strains of the bacterium. It works like a molecular pair of scissors cutting lactam rings of penicillin-derived antibiotics open, thereby rendering them useless. To avoid this, antibiotics are often administered together with a compound called avibactam that blocks the molecular scissors of the enzyme. Unfortunately, mutations can change the form of the scissors. “Some hospital strains of *Klebsiella pneumoniae* are already able to cleave even specifically developed third-generation antibiotics,” explains Christian Betzel, co-author of the study and also a professor at Universität Hamburg. “If we understand how this happens, it might help to design antibiotics that avoid this problem.”

Picture: DESY, Lars Berg



The reconstructed three-dimensional structure of the enzyme CTX-M-14-β-lactamase with the inhibitor avibactam bound to its active centre (green)

The measurements show that it is possible to obtain high-quality structural information at the European XFEL. The researchers see this as the first step towards recording serial snapshots of biochemical reactions between enzymes and their substrates at different stages. The X-ray laser can thus be used as a kind of film camera to create movies of the molecular dynamics of enzyme and inhibitor by assembling such serial snapshots. “Such movies would give us crucial insights into the biochemical process, which could one day help us to design better inhibitors, reducing antibiotic resistance,” says Betzel.

Nature Communications, 2018;
DOI: 10.1038/s41467-018-06156-7

Pictures: Universität Hamburg, Markus Perbandt; DESY (bottom)

The fastest X-ray serial images in the world

The European XFEL X-ray laser stands out thanks to its extremely fast pulse sequence: The laser can generate up to 27 000 flashes per second. For scientists to be able to use this super stroboscope effectively, the detectors have to record data at the same rate. The detector employed in the first experiments was therefore custom-designed for use at the SPB/SFX instrument by an international consortium led by DESY. The special camera called **AGIPD** can take images at intervals of only 220 billionths of a second (220 nanoseconds) – that’s the world’s fastest X-ray serial images currently available.

“Unlike in a conventional digital camera, each pixel of the detector has 352 memory cells, so that **352 images** can be temporarily stored and then read out in one go,” says DESY researcher Heinz Graafsma, who coordinated the development and production of the detector. AGIPD accomplishes this ten times per second. The challenge is not only to capture the fast image sequence, however, but also to process it. Even at a resolution of one megapixel, which is moderate compared to a photo camera, the high-speed detector generates a data stream of around eight gigabytes per second – that’s almost two full DVDs every second.

But the special camera must be capable of doing much more. For analysing biomolecules, the researchers usually direct the bright X-ray radiation at tiny crystals of the molecules under investigation. The crystals scatter the X-rays, and the information about the structure of the molecule is encoded in the complex scattering pattern. “These X-ray scattering images are not only produced at the European XFEL in extremely fast sequence, they also have a very large brightness range,” says Graafsma. However, every detail is important in order to be able to decode the often very complicated protein structures.

While fine details of the scattering pattern may only be indicated by single particles of light (photons), there are also very bright reflections comprising many thousands of photons. “In the new detector, each pixel dynamically adjusts its sensitivity depending on the number of incoming photons. This makes it possible to capture areas with both single photons and several thousand photons in the same image,” explains Graafsma. Accordingly, AGIPD stands for “Adaptive Gain Integrating Pixel Detector”.

The Adaptive Gain Integrating Pixel Detector (AGIPD), tailor-made for the European XFEL, can record the world’s fastest X-ray serial images.

femtofinale

Trump cards in the light source quartet

The X-ray light sources operated by DESY and its partners provide bespoke light for research.

A1 X-ray laser European XFEL

Size	3400 metres, world's largest X-ray laser
Speed	of the accelerated electrons: 99.999 999 95 percent of the speed of light
Brightness	10^{14} photons per pulse
Users	Approximately 1000 scientists from all over the world per year
Operation since	2017

The 3.4-kilometer-long European XFEL produces extremely intense, ultrashort X-ray laser flashes that may be used by guest scientists from around the world. The X-ray flashes, which are generated by a particle accelerator in an underground tunnel system, enable scientists to map the atomic details of viruses, film chemical reactions and study processes such as those occurring deep inside planets.

A2 X-ray light source PETRA III

Size	2304-metre-long ring tunnel with 3 experimental halls
Speed	of the accelerated electrons: 99.999 999 6 percent of the speed of light
Brightness	10^{11} photons per pulse
Users	Approximately 2400 scientists from all over the world per year
Operation since	2009

DESY operates one of the world's brightest storage-ring-based X-ray radiation sources: PETRA III offers scientists outstanding opportunities for experiments with X-rays of exceptionally high brilliance. This particularly benefits researchers investigating very small samples or requiring tightly collimated and very short-wave X-rays for their experiments – ranging from medical research to nanotechnology.

A3 Free-electron laser FLASH

Size	315-metre-long X-ray laser with 2 experimental halls
Speed	of the accelerated electrons: 99.999 986 percent of the speed of light
Brightness	10^{13} photons per pulse
Users	Approximately 200 scientists from all over the world per year
Operation since	2005

Since 2005, FLASH, the world's first free-electron laser in the X-ray range, has been generating a very special light at DESY in Hamburg: extremely intense, ultrashort pulsed X-ray laser flashes. Researchers from around the world use them to observe the motion of atoms and molecules. FLASH is the pioneering facility at which important foundations for movies of the nanocosmos were worked out.

A4 Central star Sun

Size	Diameter 1.4 million kilometres
Speed	of the photons on their way from the ultra-dense solar core to the solar surface: ø 0.22 m/s or 0.000 000 000 074 percent of the speed of light
Brightness	10^{45} photons per second
Users	7 635 250 000 humans, countless animals and plants all over the world
Operation since	around 4.5 billion years ago

The Sun is a huge nuclear reactor. Inside it, energy is produced through the fusion of hydrogen to helium at temperatures of around 15 million degrees. Its surface is still at temperatures of around 5700 degrees Celsius. From the Sun's surface, the photosphere, light and energy flow into space, providing the basis for the diverse life on Earth.

Pictures: DESY; NASA (Sun)

Imprint

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Editorial board address
Notkestraße 85, 22607 Hamburg, Germany
Tel. +49 40 8998-3613, fax +49 40 8998-4307
e-mail: femto@desy.de
Internet: www.desy.de/femto
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Editorial board
Ute Wilhelmsen,
Till Mundzeck (responsible under press law)

Contributors to this issue
Frank Grotelüschen, Jens Kube

Design and production
Ulrike Darwisch

Translation
TransForm, Cologne
Ilka Flegel, Kapellendorf

Printing and image processing
EHS, Hamburg

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The **cover picture** was taken by photographer Philip Thurston (www.thurstonphoto.com) off the southwest coast of Western Australia, a rough and isolated coastal region that is constantly hit by large waves and strong winds from the Indian Ocean. When the tides are right and the autumn trade winds are blowing, four to six metre high swells come in from the open sea and suddenly run onto the shallow reef. “This produces extremely powerful breaking waves, which can be incredibly photogenic, especially in early or late sunlight,” reports Thurston. “I’ve documented breaking waves my whole life. No two are ever the same, which makes them a constantly changing subject and creates an almost addictive passion.” Waves also play a decisive role in accelerator physics: Plasma waves, for example, can give electrons a huge boost.

Cover picture: Philip Thurston (www.thurstonphoto.com)

The DESY research centre

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