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The DESY research magazine – Anniversary issue

English edition

60

DESY.

1959 ······ 2019


PETRA III

Dear Readers,

The research centre DESY is looking back at 60 years of successful and eventful research.

With its two sites, in Hamburg-Bahrenfeld and Zeuthen, DESY is today recognised as one of the leading centres for research into the properties of matter, and a reliable partner and safe haven for scientists from all over the world.

Over the past six decades, DESY has won highest recognition around the world with its visionary ideas, its high-tech accelerator facilities and its scientific achievements. With its seminal mission to decipher the structure of matter, it has made history in the scientific world.

In our strategy “DESY 2030”, we have laid down the cornerstones upon which we will continue to consolidate and expand our leading role in the world in the coming decades. This includes continuing to develop our two sites to become pioneering scientific ecosystems in which top-class research, sustainable building concepts, innovation and technology transfer, science communication and the training of young scientists combine to form an intelligent overall concept.

From the start, DESY has viewed itself as an international anchor for researchers in need of scientific and political support. DESY also believes that, in a world that is becoming increasingly complicated, it has more than ever the responsibility to build scientific bridges to countries where science needs DESY’s support.

This anniversary issue invites you to explore the world of DESY. We hope you enjoy the read!

Helmut Dosch
Chairman of the DESY Board of Directors

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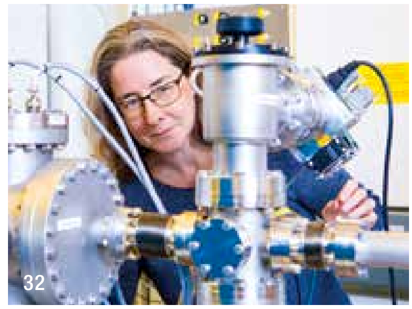
Campus of the future

When DESY was founded 60 years ago, the goal was clear: The new research centre was to explore the basic building blocks that make up our world and the forces acting between them. The tools needed for the task were quite sizeable: accelerators able to push tiny particles to close to the speed of light before making them collide with each other. The hopes placed in the new research centre were fulfilled, and over the decades, DESY's accelerators have made numerous important discoveries.

But particle accelerators are capable of more: They can also be used to produce the most brilliant X-rays in the world, providing insights into the structure of matter that cannot be achieved by any other means. Today, DESY is not only the national German laboratory for particle physics; it has also evolved into a leading international centre for research using X-rays. Meanwhile, scientists at DESY are already working on entirely new designs for compact particle accelerators for future applications. Moreover, researchers at DESY's Zeuthen site are studying the gigantic natural particle accelerators found in space in order to better understand how our universe has evolved.



SECTIONS


Picture: DESY

• 1959

DESY, Deutsches Elektronen-SYnchrotron
18.12.1959: Foundation of the research centre DESY
1964: The DESY synchrotron goes into operation

The founding of DESY

Built on an old parade ground

What basic building blocks is matter made of? In the 1950s, this became one of the central questions in physics. To answer it, accelerators were built, the main tools of particle physics. Germany too had plans for such a facility: a type of circular accelerator known as a synchrotron, with a circumference of 300 metres, which would take electrons to record-breaking energies. It was to go by the name of Deutsches Elektronen-Synchrotron (German electron synchrotron), or DESY for short.

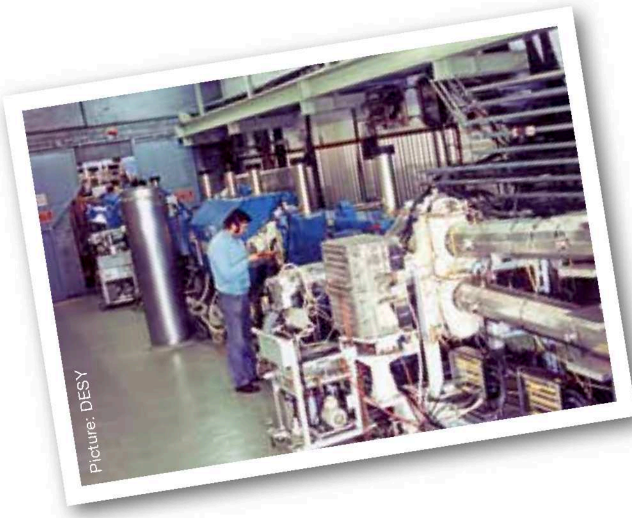
Construction work began in the Hamburg district of Bahrenfeld in 1958, on a former parade ground. When the founding charter was signed at Hamburg's town hall on 18 December 1959, the first building in Bahrenfeld had already been completed. On 25 February 1964, the physicists fired electrons around the synchrotron, the "original accelerator" at DESY, for the first time. Before long, the first interesting results began to emerge. For example, the physicists at DESY succeeded in creating an antiproton – the antiparticle of a hydrogen nucleus – with the help of high-energy radiation. A world first! They were also able to take a very detailed look inside protons, establishing that these did not in fact have a solid nucleus. These experiments continued until 1978, but even then the synchrotron was far from having outlived its usefulness. To this day – after repeated modifications – it still serves as a pre-accelerator and test facility.

The storage ring DORIS

Electrons in continuous duty

1974

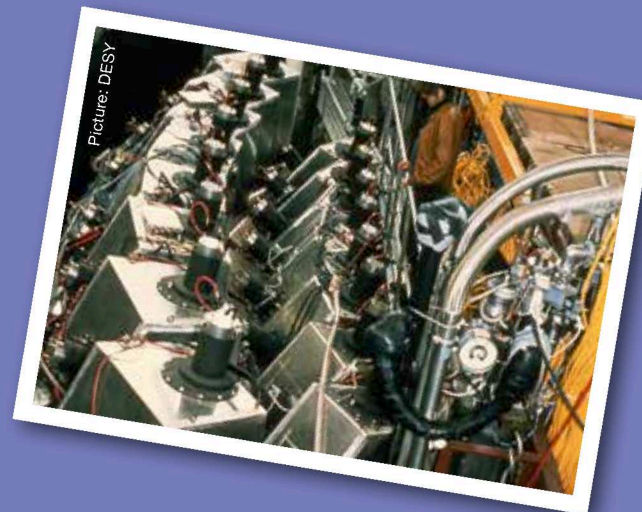
DORIS, DOuble RIng Storage
1974: DORIS goes into operation



DESY's second big facility was a type of accelerator that was still fairly new at the time – a storage ring. In contrast to a synchrotron, the high-speed particles are not fired at a target, but instead collide with each other head-on. This enables higher collision energies to be achieved.

The trouble was that this fledgling technology had scarcely been tested yet. It was by no means certain whether it would yield anything of interest. Nevertheless, the people in charge of DESY took the chance – and their gamble paid off. The double-ring storage facility DORIS was completed in 1974. It had a circumference of 288 metres and was shaped like a sports stadium, with two curved sections joined together by two straight stretches.

DORIS helped to study the quarks, which had just been discovered at the time – marking the dawn of a new era in physics. Today, quarks are thought to be the fundamental particles out of which all atomic nuclei are ultimately composed, ranking them among the basic building blocks of all matter. After repeated modifications, under the name of DORIS III, the ring served up until 2012 as a source of brilliant X-rays, which were used to investigate a wide variety of substances in great detail.



1978

PETRA, Positron-Electron Tandem Ring Accelerator
1978: PETRA goes into operation

PETRA, the accelerator that set records

Collisions at full tilt

In 1978, the DESY physicists set an impressive new record: They started up the world's largest storage ring at the time, named PETRA. With a circumference of 2.3 kilometres, it only just fitted inside the DESY grounds. PETRA was used to fire electrons at their own antiparticles, called positrons. The size of the ring meant that it could produce five times higher collision energies than previous accelerators. The engineers managed to complete it in just three years – one year ahead of schedule.

The most important discovery at PETRA occurred in 1979, when physicists managed to identify the gluon, the adhesive particle that mediates the force between quarks, figuratively holding them together. With this finding, DESY established its position among the cutting-edge research facilities once and for all, and from this day forward, it has been one of the most prominent centres for particle physics. In 1986, PETRA was modified to become the pre-accelerator for the even larger HERA ring. Today, the ring is enjoying its third incarnation as PETRA III, the brightest X-ray source of its kind anywhere in the world.

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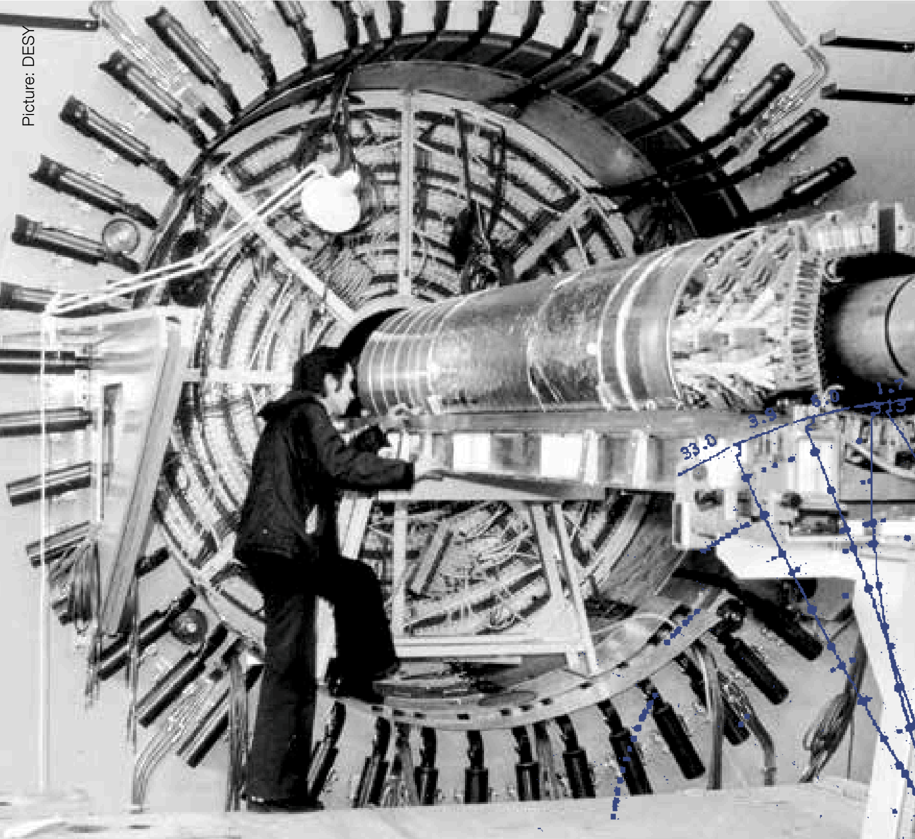


Picture: DESY

The TASSO detector went into operation in 1978 in PETRA's south-east experimental hall.

Superglue for atoms

The gluon was discovered 40 years ago at the PETRA accelerator

Determining the innermost force that glues the world together – the discovery of the gluon in 1979 explained why everything that exists doesn't simply fly apart. The gluon was named for its "adhesive" property, and the powerful particle certainly lives up to its name: The gluon holds together quarks to form protons and neutrons, which in turn form atomic nuclei, surrounding themselves with an envelope of electrons and thereby forming the basis of our world, made up of atoms. Without this subatomic superglue, houses, trees and we ourselves would fall apart – or more to the point, would never have formed in the first place.

The gluon was discovered 40 years ago at the PETRA storage ring – one of the most momentous discoveries in particle physics ever to be made at DESY. In particle physics, however, a "discovery" is an extremely tortuous process. Particles never reveal themselves directly; they merely leave behind traces in the large detectors set up at the particle accelerators.

On 18 June 1979, Bjørn Wiik, who was at the time a member of the TASSO collaboration and would later go on to become director of DESY, presented the first image of tracks recorded by the TASSO detector and displaying the characteristic signature of a gluon, at the "Neutrino 79" particle physics conference in Bergen, Norway. The picture showed three particle beams, so-called jets, which had been produced by two quarks and the hitherto elusive gluon. Shortly afterwards, all four experiments at the PETRA accelerator were able to reproduce these characteristic three-jet images in their detectors. In 1995, the TASSO scientists Paul Söding, Bjørn Wiik, Günther Wolf and Sau Lan Wu were awarded the High Energy and Particle Physics Prize by the European Physical Society for the discovery.

Scientists came up with an entire system of rules to describe the strong force transmitted by gluons, known as quantum chromodynamics (QCD) – in a sense, a theory of stickiness. To this day, it is an important basis for understanding particle physics.

The X-ray laboratory HASYLAB

Particle accelerators as light sources

1978

HASYLAB, HAmburg SYnchrotron radiation LABoratory
1978: HASYLAB is established

Picture: Peter Ginter, Lohmar

Hamburg quickly became a Mecca for particle physicists. Before long, however, DESY added another string to its bow – putting synchrotron radiation to use. Indeed, accelerators are not only useful tools in the hunt for particles; they are also exceptional sources of radiation. The experts at DESY realised this early on, and in 1966, they had built a small measuring bunker alongside the synchrotron to explore the potential of this radiation. They found that the X-rays produced by the accelerator were substantially brighter than those emitted by an X-ray tube. Materials could therefore be analysed far more precisely – metals, synthetic materials and also biological samples.

Eventually, the interest among scientists became so strong that, in 1978, a large laboratory was set up, dedicated specifically to this type of research: the Hamburg Synchrotron Radiation Laboratory HASYLAB. It soon became one of the top sites for doing research using X-rays. Thousands of scientists benefited from the possibilities it offered – physicists, chemists and materials scientists as well as biologists, medical scientists and geologists.

Picture: David Parker

HERA, the giant

DESY's largest storage ring

1990

HERA, Hadron-Electron Ring Accelerator
1990: HERA goes into operation

The biggest accelerator ever built by DESY went into operation at the end of 1990. With a circumference of 6.3 kilometres, HERA was too large to fit inside the DESY grounds. So the experts had to dig an underground, circular tunnel running beneath the nearby Volkspark, the harness racecourse and an industrial estate. One of HERA's distinguishing features was that it was the only accelerator in the world in which electrons were made to collide with hydrogen nuclei (protons). This made HERA an extremely powerful microscope for protons.

To keep the hydrogen nuclei travelling along their circular orbit, the scientists resorted to superconducting magnets, which had to be cooled to minus 269 degrees Celsius using liquid helium. A striking feature of the project was that foreign investments accounted for more than 20 percent of the funding for the accelerator and detectors – amounting to almost 300 million Deutschmarks.

HERA continued to run and produce data extremely reliably until it was eventually shut down in 2007. Among other things, physicists discovered that the proton is in fact far more complex than previously assumed, being made up of a host of even smaller components: the quarks and gluons.

DESY in Zeuthen

A second site in Eastern Germany

1991

DESY expands to Zeuthen

Since 1991, DESY has had a second site in Zeuthen, just outside Berlin. A nuclear physics laboratory was set up there in 1939 by the Reichspostministerium. After the Second World War, the East German authorities wanted it to explore the possibilities of nuclear energy, naming it "Institute X". Later, it became the "Institute for High-Energy Physics", where East German particle physicists managed to conduct internationally recognised top-class research despite the constraints that existed at the time.

After the Berlin Wall came down, independent experts recommended that the institute should be preserved. It became a part of DESY at the end of 1991 and developed its own fields of research. The Centre for Parallel Computing was established as a highly recognised computing centre for theoretical particle physics. The PITZ accelerator serves as a test bench for high-precision electron sources, such as those required for X-ray lasers. And Zeuthen's astrophysicists are participating in IceCube. This spectacular experiment at the South Pole has measured high-energy cosmic neutrinos for the first time and thereby opened up a new window onto the cosmos. Today, DESY's Zeuthen site is evolving into a national hub for astroparticle physics.

The free-electron laser FLASH

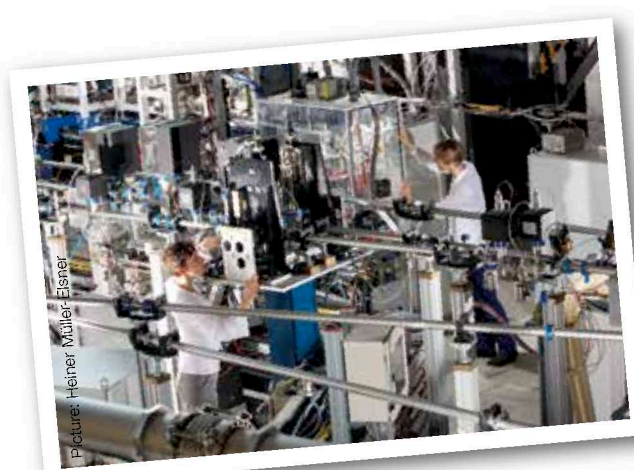
Flashes from the Hamburg superlaser

2005

FLASH, Free-Electron LASer in Hamburg
2005: Research operation begins

In the early 1990s, DESY decided to advance the development of a new technology: superconducting accelerator tubes that are able to bring particles to speed very efficiently, but have to be cooled to minus 271 degrees Celsius using liquid helium. The first research facility to be fitted with this so-called TESLA technology was FLASH – a novel type of laser with unique properties.

The free-electron laser FLASH is 260 metres long and can accelerate electrons to almost the speed of light. Carefully arranged magnets, called undulators, then cause the electrons to follow a slalom course. Each time the high-speed particles are forced to change direction, they emit a flash of X-rays, which are superimposed onto each other and oscillate in unison. This technique enables FLASH to produce incredibly intense, ultrashort pulses of radiation. Since 2005, scientists from all over the world have been using these pulses to examine tiniest nanoparticles or melting processes on surfaces. In view of the tremendous interest in FLASH, the facility has been expanded and a second tunnel has been added, including an experimental hall for six further measuring stations.




Picture: DESY

The brilliant ring PETRA III

One of the world's best storage ring X-ray sources

2009

PETRA III, the third stage of the Positron-Electron Tandem Ring Accelerator
2009: PETRA III goes into operation

At one time, it was the most powerful electron accelerator for particle physics anywhere in the world. Now, the storage ring serves as a brilliant source of X-rays, by the name of PETRA III. The specialists at DESY had to go to considerable lengths to modify it. In order to introduce a number of special magnets (undulators), they had to completely redesign one eighth of the accelerator ring. And the vibration-free floor of the new experimental hall, which is almost 300 metres long, is made of the longest concrete slab ever to be cast in a single piece.

Since 2010, the now upgraded PETRA III has been providing particularly powerful and focused X-rays for a wide range of experiments, aimed at deciphering matter at the level of atoms and molecules. Biologists, for example, are able to study protein molecules, the building blocks of life, in great detail. And materials scientists are testing and developing materials for a host of different applications.


Picture: Heiner Müller-Elsner

The X-ray laser European XFEL

A research facility of superlatives

2017

European XFEL, European X-Ray Free-Electron Laser
2017: The European XFEL goes into operation

A research facility of superlatives went into operation in the Hamburg metropolitan region in 2017: The European XFEL produces ultrashort laser flashes in the X-ray range – 27 000 times a second, and a billion times brighter than those generated by the best conventional X-ray sources. The worldwide unique facility opens up completely new research avenues for natural scientists and industrial users. As the primary shareholder, DESY is closely involved in the operation of the facility.

The European XFEL, which is more than three kilometres long, is installed in underground tunnels, extending from the DESY site in Hamburg to the neighbouring town of Schenefeld, in Schleswig-Holstein, where the research campus and a large experimental hall are located. The billion-euro project is an international venture, for which the company European XFEL GmbH was specifically set up.

The X-ray laser flashes can be used to reveal the atomic details of viruses and cells, take three-dimensional pictures of the nanocosm, film chemical reactions and study processes like those occurring inside planets.

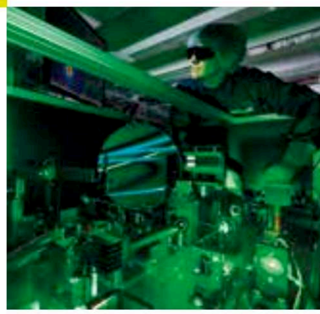
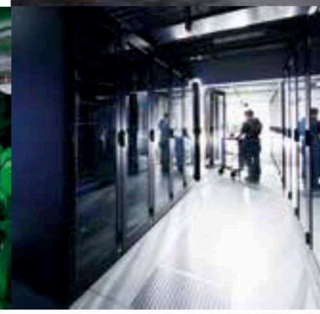
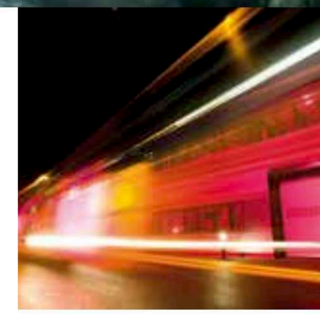
Campus of the future

DESY brings together an international community of scientists, top-class particle accelerators and research institutes of world renown

When DESY was founded on 18 December 1959, the goal was clear. The new research centre, established on a former parade ground in Hamburg-Bahrenfeld, was to explore the basic building blocks that make up our world and the forces acting between them. The tools needed for the task were quite sizeable: accelerators able to push tiny particles to close to the speed of light before making them collide with each other. The hopes placed in the new research centre were fulfilled, and over the decades, DESY's accelerators have contributed important discoveries towards advances in particle physics: DORIS shed light on the question why the universe contains more matter than antimatter. PETRA tracked down the gluons – adhesive particles that ultimately hold together atomic nuclei. And HERA, the largest particle accelerator ever built in Germany, provided key details about the internal structure of the proton, one of the building blocks of atomic nuclei.

Over time, the range of research carried out at DESY has expanded. In the 1980s, it became increasingly clear that accelerators could be used not only to make new discoveries in particle physics, but also to produce extremely powerful and narrowly focused X-rays, which open up



a window on the atomic structure of matter. Over the years, more and more researchers from many different scientific disciplines have come to Hamburg to conduct detailed analyses of their samples.

In medical research, DESY's X-ray sources provide unique insights into pathogens and the way in which drugs work. Energy and materials sciences also benefit from the insights gained into processes and materials on an atomic level.

Light sources with international appeal

Today, the DESY campus in Hamburg has become a leading centre for photon science – research conducted using the high-intensity radiation produced by its accelerators. The storage ring PETRA III and the free-electron laser FLASH are in strong demand as X-ray sources and attract thousands of scientists from all over the world to Hamburg every year. In addition, together with European partners, DESY has launched the X-ray laser European XFEL. This facility is about three kilometres long, beginning on the DESY campus and ending in a large hall in Schenefeld, a neighbouring town in Schleswig-Holstein, where an international community of scientists has been using the world's most powerful X-ray flashes for novel experiments since 2017.

Unravelling the mysteries of the universe

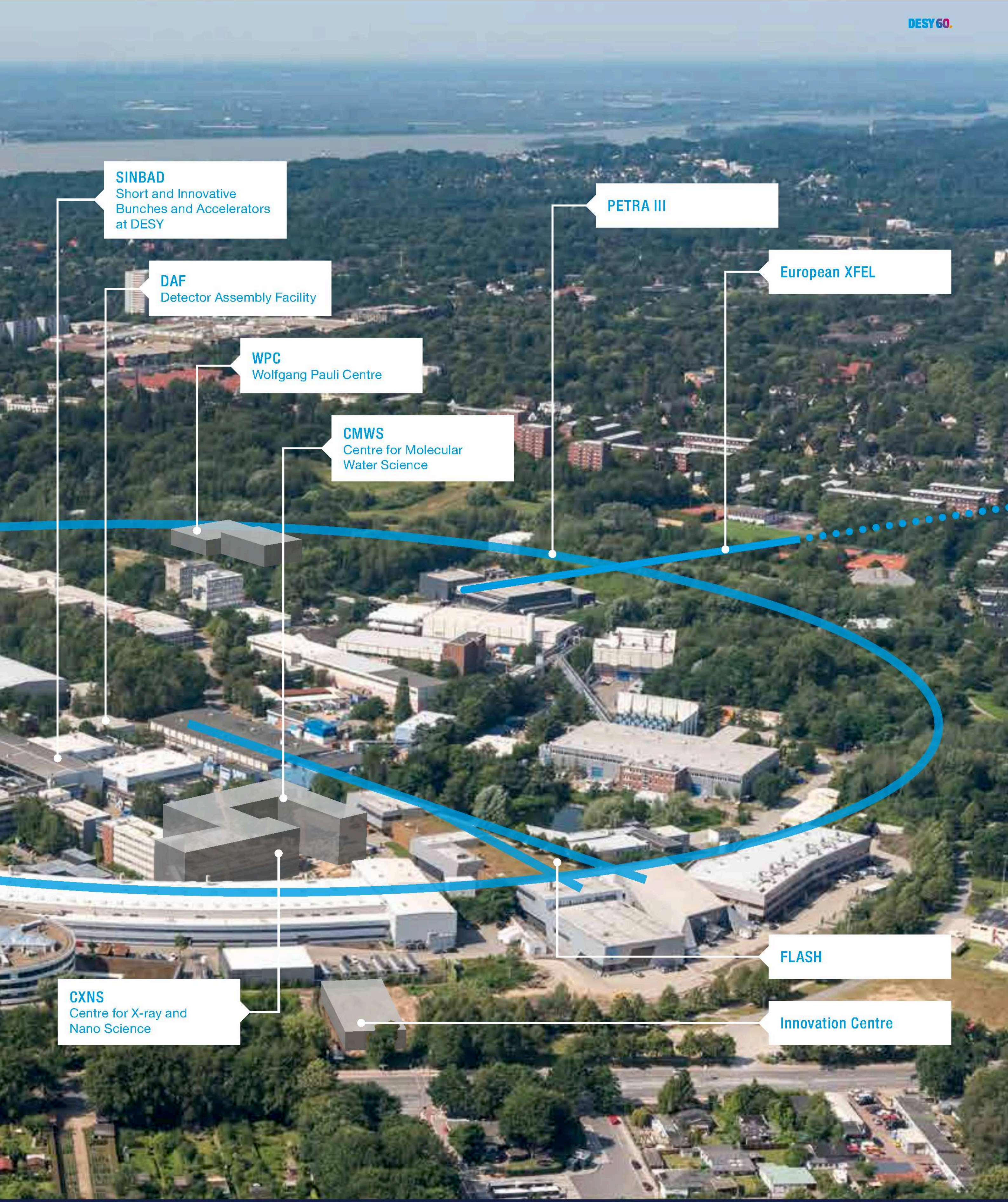
Particle physics continues to play an important role. Research groups at DESY are instrumentally involved in experiments conducted at the world's largest accelerator, the Large Hadron Collider (LHC) at the European centre for particle physics CERN near Geneva. Teams of theoreticians are coming up with new models for a deeper understanding of the microcosm, while others groups are using sophisticated experiments to track down the mysterious dark matter. DESY is expanding its second site, in Zeuthen outside Berlin, to become a national centre for astroparticle physics and makes substantial contributions to two large-scale international projects: the IceCube neutrino detector in the Antarctic ice and the future gamma-ray observatory CTA (Cherenkov Telescope Array).

Starting point for collaborations

This increasing diversity is also reflected by the continued development of the Bahrenfeld site. Numerous collaborative ventures and institutions have settled there over the years, and DESY has become the nucleus of an internationally renowned research campus. And it doesn't stop there: DESY's "Strategy 2030" is a master plan describing key areas of future interest. Accelerator development will remain an important cornerstone: Novel technologies for compact and versatile facilities are to be perfected until they are ready for application, while PETRA IV is to become a cutting-edge 3D X-ray microscope for studying the nanocosm.

In the long run, DESY is to become the centrepiece of a ground-breaking project called the Science City Bahrenfeld. The plan involves moving further university departments as well as numerous research facilities and technology companies to Hamburg's western suburbs and creating an entire, innovative science district.

Picture: Reimo Schaaf, DESY



The DESY campus in the west of Hamburg

The DESY accelerators are the nucleus for a variety of interdisciplinary institutes and collaborative ventures between DESY and its campus partners.


Picture: Gesine Born

The research pioneer

Henry Chapman thinks in new ways about many different fields

Henry Chapman leans back in his office chair, looking deeply contented. “Over the past few days, we have been doing experiments at the European XFEL, the European X-ray laser here in Hamburg,” explains the Australian scientist. “We’ve been studying individual DNA molecules, and we’re really pleased with the measurements.” Experiments like these are part of the vision of Chapman’s research centre, the Center for Free-Electron Laser Science (CFEL), to explore the scientific opportunities offered by a new generation of large-scale facilities. Free-electron lasers (FEL) produce by far the shortest and most powerful X-ray flashes in the world – affording new insights into events happening in the nanocosm.

Having taken a degree in physics in his home country, Chapman began his career in the USA. There, he came up with some early ideas as to what an X-ray FEL might be used for – experiments that were still very much a vision of the future back then. In 2008, he was invited to move to Hamburg to help set up a new research centre: CFEL, a cooperative venture between DESY, Universität Hamburg and the Max Planck Society. “The concept is geared to the collaboration between different scientific disciplines,” says Chapman, who is also a leading scientist at DESY and a professor of physics at Universität Hamburg. “That is what convinced me.”

> “You won’t find this kind of setting anywhere else in the world”
>
> **Henry Chapman, DESY**

Another reason was that a few years earlier, a pioneering new facility had gone into operation in Hamburg: the free-electron laser FLASH, which is based on a superconducting accelerator, almost 100 metres long, and produces X-ray pulses with laser properties. Soon afterwards, Chapman’s team succeeded in carrying out a landmark measurement using FLASH. One problem posed by FELs is that the laser pulses are so strong that, in certain experiments, they can literally pulverise the sample under investigation. “Theoretically, it should be possible to collect the measurement data before the sample is destroyed,” says

Chapman. “But it wasn’t until FLASH came along that we had the opportunity of actually demonstrating this.” Today, the method is routinely used all over the world.

> “We want to understand matter by observing its fundamental processes on the atomic scale”
>
> **Henry Chapman, DESY**

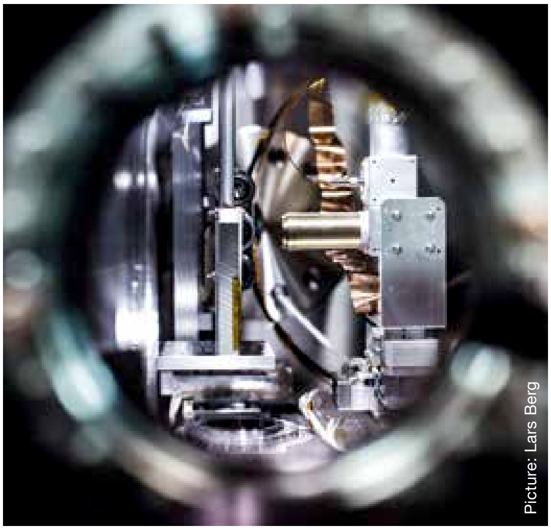
Later, working with international partners, Chapman and biologists from the universities of Hamburg, Lübeck and Tübingen used a Californian FEL to determine the precise structure of an enzyme of the pathogen that causes sleeping sickness – another spectacular achievement. This enzyme could not be analysed using conventional X-ray techniques because the crystals formed were too small. Only the flashes emitted by the X-ray laser were ultimately intense enough to extract the necessary information from crystals of the enzyme, which were just micrometres across. The achievement, which the US journal “Science” pronounced to be one of the ten most important discoveries of 2012, provided the basis for developing new drugs against the disease.

Recently, Chapman has been particularly fascinated by the European XFEL – this European X-ray free-electron laser has been operating in the Hamburg metropolitan region for two years now. “It’s a fantastic machine, which produces far more pulses per second than any other similar facility,” he says enthusiastically. “It does come with certain challenges, though. The detectors, for example, need to be able to collect huge amounts of data in a very short time.”

To deal with these challenges, the physicist initiated the SFX consortium – an international group of users that develops new techniques for examining tiny crystals made of biomolecules. Chapman himself is equally active in Hamburg’s new cluster of excellence “CUI: Advanced Imaging of Matter”. “Our aims are ambitious,” he stresses. “We want to understand matter by observing its fundamental processes on the atomic scale.” A range of different topics are on the agenda: from the analysis of new types of superconductors through to the study of nanoparticles that could one day be used in electronics and medicine.

Chapman is a natural when it comes to networking, getting involved in countless projects and cooperating with innumerable partners. “Sometimes you just happen to run into people in the CFEL building and strike up a conversation,” he explains. “The conversations keep leading to new ideas, as do our workshops and seminars.” His plans for the future certainly sound very concrete: He wants to continue to develop new instruments and methods for the European XFEL and turn an old dream into a reality – by carrying out high-precision measurements on individual molecules using ultrastrong X-ray pulses. “An ambitious goal, but the campus in Bahrenfeld offers the right environment,” says an enthusiastic Chapman. “You won’t find this kind of setting anywhere else in the world.”

View inside the experimental chamber: This is where ultrabright X-ray laser flashes from the European XFEL take images of biomolecules.



Picture: Lars Berg

In the undulators, which weigh several tonnes, strong magnets produce the coveted X-rays.

Picture: Dirk Nölle

A brilliant ring

PETRA III provides X-ray insights for medicine and materials science – and it has far from exhausted its potential for innovation

In 2009, PETRA III went into operation: one of the most brilliant storage-ring-based sources of X-rays in the world. The principle behind it is to send electrons racing around a ring, over two kilometres long, at close to the speed of light. Along the way, they pass special magnets known as undulators, which force them to emit extremely intense X-rays. This radiation travels through vacuum tubes to three experimental halls, where scientists can use a total of more than 20 measuring stations to perform a wide range of experiments – such as detailed studies of protein molecules, nanoparticles and high-tech materials.

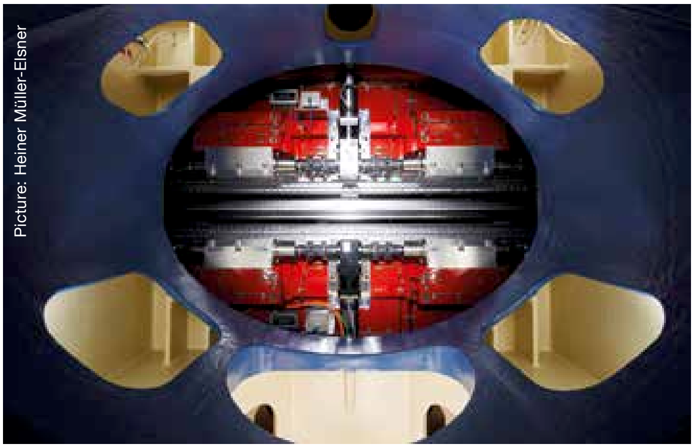
PETRA III is in strong demand – every year, some 2500 users from around world come to Hamburg to carry out their experiments here. Now, DESY is planning the next step: In a few years, the ring will be upgraded with new components and made substantially more powerful – turning PETRA III into PETRA IV. "This will open up fantastic new opportunities," says DESY physicist Christian Schroer. "PETRA IV will allow a targeted microscopic view of the samples."

> "Our users fully support the PETRA IV project and really want these fantastic new possibilities."
>
> Christian Schroer, DESY

The basis for the upgrade is a new storage ring technology, which allows the cross section of the individual electron bunches in the ring to be reduced one hundredfold. This would also focus the X-rays created by the electron bunches inside the undulators into a much narrower beam – which in turn has the advantage that much smaller areas of a sample can be illuminated, enabling it to be studied in much greater detail.

Christian Schroer is the scientific head of PETRA III.

Picture: Gesine Born



The large PETRA III undulator consists of 1170 magnets for producing X-rays and weighs 18 tonnes.

To achieve this, PETRA will have to be fitted with new electromagnets. Their task is to keep the fast-moving electrons travelling on their circular orbit. “PETRA III uses comparatively few and strong deflecting magnets,” explains Schroer. “This has the disadvantage that electrons with different energies diverge from each other, and the electron bunches spread out as a result.” Consequently, the X-ray beam emitted by the particles also diverges considerably.

“PETRA IV will open up new opportunities that we are not even aware of today”

Christian Schroer, DESY

In PETRA IV, the current deflecting magnets will be replaced by significantly more, but weaker ones. “This makes the deflection much gentler, so the electrons remain closer together within their bunches,” explains Schroer. The new setup will be augmented by sophisticated magnetic lenses to focus the electron beam efficiently. In order to exploit the full potential, the experts will also have to refine the X-ray optical systems at the measuring stations. The aim is to focus the X-rays, at maximum intensity, onto a single point no larger than a nanometre (millionth of a millimetre) across – dozens of times smaller than possible today. A further experimental hall is to be built to house all the planned measuring stations.

Christian Schroer is confident that, “In terms of science, PETRA IV will open up new opportunities that we are not even aware of today.” At the moment, the samples studied are mostly ordered systems, especially crystals. Experts will be able to use the much finer beam of PETRA IV to examine considerably more complex samples. “We could scan a sample of the order of millimetres right down to its atomic structures,” says Schroer. “We refer to this as the ultimate 3D microscope.” One could even monitor the sequence of events during a chemical reaction in greater detail than ever. For example, how do the reactants reach the reaction site during a catalytic reaction? How exactly do they react with each other, and how are the resulting molecules transported away?

The conceptual design for PETRA IV has already been completed; by the end of 2021, the experts intend to have finished the detailed construction plans – providing a solid foundation on which to reach a policy decision. The hope is that refitting can begin in 2025, and two years later, PETRA IV could light up for the first time. Its competitors certainly haven’t been idle. The Swedish X-ray source MAX IV and the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, have already upgraded to the new technology, while Japan and the USA are pursuing similar plans. “The conversion makes a great deal of sense if PETRA is to remain internationally competitive,” Christian Schroer points out. “At any rate, one thing is clear: Our users fully support the PETRA IV project and really want the fantastic new possibilities it would offer.”

Edgar Weckert
Director in charge of Photon Science

“The high-intensity X-rays from DESY’s particle accelerators can be used to decipher the atomic structure of materials and biological structures. Today, our campus combines outstanding scientific expertise with the wide range of possible applications of the free-electron lasers FLASH and European XFEL and the storage ring X-ray source PETRA III. Together with our partners, we will continue to expand and consolidate our role as the world’s leading centre for studying the structure, dynamics and function of matter using X-rays.”

Forge for new materials

How X-rays and artificial intelligence are helping the development of new implants

The Institute of Materials Research at the Helmholtz Centre Geesthacht (HZG) is working on a medical innovation – screws, pins or plates made of magnesium alloys that can be implanted into the body, for example to hold fractured bones in place. What distinguishes them from conventional implants made of stainless steel or titanium is that the magnesium degrades in the body over time. In the future, this could dispense with the need for strenuous follow-up surgery – at the moment, screws and pins often have to be removed again after the bone has healed.

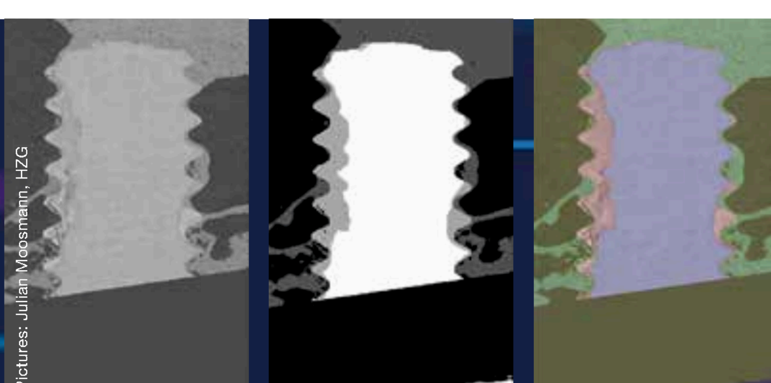
One of the challenges is that if the magnesium alloy breaks down too quickly, the bone will not be stabilised for long enough. So the experts are systematically searching for alloys that offer a good compromise between stability and degradability. An important analytical tool in this search is microtomography using the high-intensity X-rays from the PETRA III storage ring, where the HZG maintains an outstation for materials research.

The technique is similar to that used by CT scanners in hospitals – it produces 3D X-ray images of the inside of the body. "However, the X-rays from PETRA III are far more intense than in the kind of device used in hospitals," explains HZG scientist Felix Beckmann. "This makes our image resolution higher by a factor of 1000." During imaging, the sample is rotated inside the beam, so as to take pictures from all sides. Each individual picture looks like a normal X-ray image. A software program then assembles the many individual pictures to produce a 3D representation. In the case of the biodegradable magnesium implants, this allows the disintegration of the alloy to be tracked in detail.

Felix Beckmann is the head of the beamline P05 operated by the Helmholtz Centre Geesthacht at DESY's X-ray source PETRA III.

> "The X-rays from PETRA III are far more intense than in the kind of device used in hospitals. This makes our resolution higher by a factor of 1000."
>
> Felix Beckmann, HZG

In concrete terms, a German–Swedish research collaboration supported by the Röntgen Ångström Cluster examined hundreds of implants in order to characterise the interface between the implant and the bone in as much detail as possible and to test different alloys. Afterwards, the bones were imaged using micro-tomography to answer important questions: Did the new bone tissue form quickly enough, or did the magnesium dissolve too soon?



In the original the X-ray tomograph (far left), artificial intelligence is used to identify the magnesium screw (centre, white), bone (right, greenish areas) and the corrosion of the screw (right, pink).

There is one problem in analysing the images, however. "You need to be able to distinguish the bone, the corrosion layer and the rest of the implant from each other in the pictures," explains Beckmann's colleague Julian Moosmann. "But all three of them have similar grey levels with sometimes seamless transitions, so that they are often difficult to identify with the human eye and cannot be distinguished by standard image processing techniques."

To solve this problem, the HZG experts went to Philipp Heuser at DESY's computer centre for assistance. He developed a program that automatically segments the images, i.e. separates the different areas from each other. The software is based on machine learning, in which a neural network is trained using known sets of data and then gradually learns to distinguish the three regions – the bone, the corroded alloy and the remaining intact implant.

"In the meantime, the software is actually able to improve on the data that was segmented by hand and that we used to train the network," Moosmann is pleased to report. "This means we can now extract the various components from the image data, including the relatively complex structures that make up the corrosion layer." A small but important step on the way to the long-term research goal: a bone screw that simply disappears once it has served its purpose.

Gateway to the nanoworld

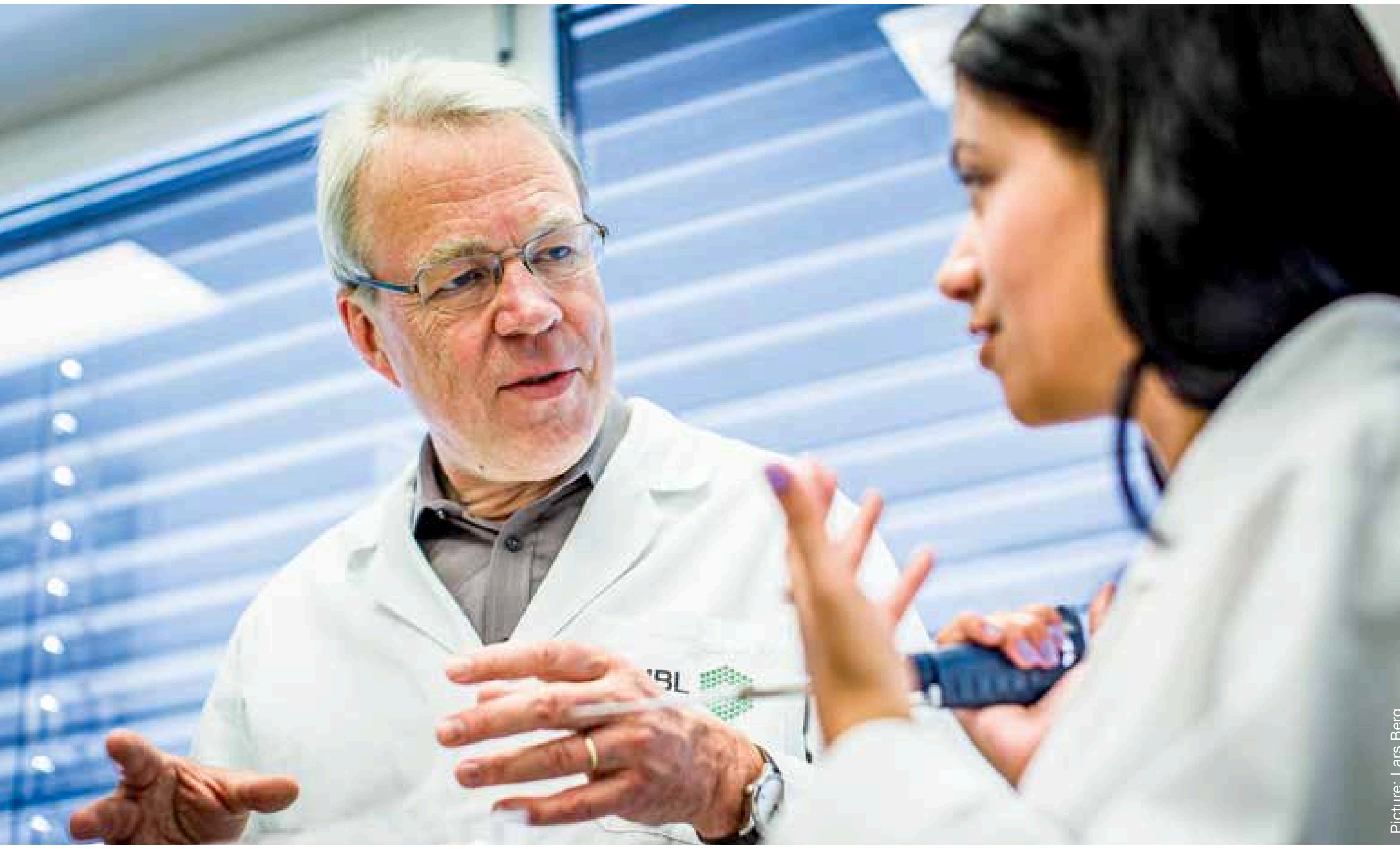
A new centre for X-ray and nanoscience brings together expertise and high-tech to study materials and catalytic processes

The PETRA III storage ring attracts scientists from a wide range of different disciplines. Among those who can benefit from its high-intensity, focused X-ray beams are experts in nanotechnology: The X-ray flashes can be used to elucidate many of the fascinating properties of nanoparticles and nanostructures down to the finest detail. In the future, DESY will further strengthen this area of research. As of 2021, experts will be able to manufacture, prepare and analyse their nanosamples at the new Centre for X-Ray and Nano Science (CXNS), before illuminating them with the X-ray beam from PETRA III.

"The CXNS will harbour several groups working in similar fields," explains DESY physicist Andreas Stierle. These include teams from Kiel University and the Helmholtz Centre Geesthacht, as well as the DESY NanoLab. "Users of PETRA III will be able to book the CXNS in order to manufacture and prepare their samples," says Stierle. "This is a unique service not available at any other X-ray source." The scientific instruments available include a range of high-tech microscopes as well as an ion beam system that allows micrometre-sized snippets to be cut from a sample, which can then be examined using PETRA III to obtain 3D X-ray images.

Among other things, the samples studied include nanoparticles made of noble metals, such as platinum and palladium. These are used in the catalytic converters of cars and in fuel cells, where they increase the rate of the chemical reactions taking place there, e.g. the conversion of toxic carbon monoxide to carbon dioxide or of hydrogen into electricity. The precise shape of the nanoparticles plays an important role in such applications – some shapes display a higher catalytic activity than others. "Although we know that these catalysts work," explains Stierle, "in many cases we do not yet know precisely which atoms are doing most of the work during the chemical reaction." At PETRA III, the experts can analyse these processes under real-life conditions. As of 2021, the CXNS will be assisting them in doing so.

Andreas Stierle is in charge of the DESY NanoLab.



Picture: Lars Berg

Paver of paths

Matthias Wilmanns is moving research into infectious diseases forward on the campus

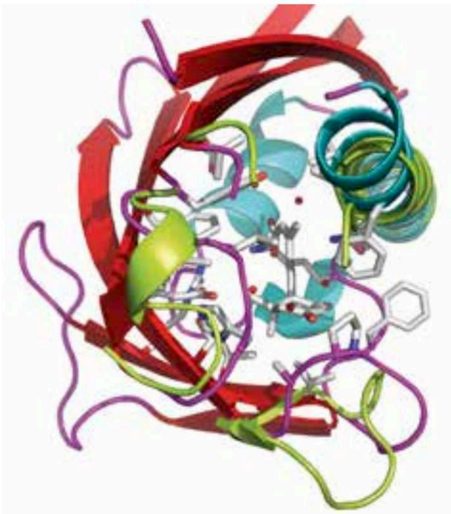
With his fingers, Saravanan Panneerselvam picks up an object resembling a household pin. “This is a sample holder for a protein crystal that is only a few dozen micrometres across,” explains the scientist. “Growing protein crystals like that can be very difficult, and sometimes it takes years.” Then he points to a robot arm, which gently grasps the sample holder together with the crystal and places it accurately inside a piece of equipment. Later, a narrow beam of high-intensity X-rays will be focused on it – the beam from the PETRA III storage ring. The X-rays are diffracted by the crystal, and detectors record the diffraction patterns. Experts can then use these patterns to work out the detailed structure of the protein, which in turn allows them to determine how it works – an important basis for systematically developing new drugs.

“Ten different partner institutions work under the same roof at the CSSB, leading to collaborations that would never have come about before”

Matthias Wilmanns, EMBL

Panneerselvam is standing at the beamline P13, operated by the European Molecular Biology Laboratory (EMBL) in Hamburg. The analyses are conducted like on a production line: Every two to three minutes, the robot places a new crystal inside the device, and the detectors are able to take twelve high-resolution images per second. “All this is remotely controlled,” explains Panneerselvam. “Scientists using our instrument can operate it from their own institutes.”

When Matthias Wilmanns started in his current position as the head of EMBL Hamburg on the DESY campus in 1997, such possibilities were little more than a dream. “I was a young scientist at the time, Pictures: EMBL



"I have been able to participate in some fantastic developments here, and I really feel very privileged"

Matthias Wilmanns, EMBL

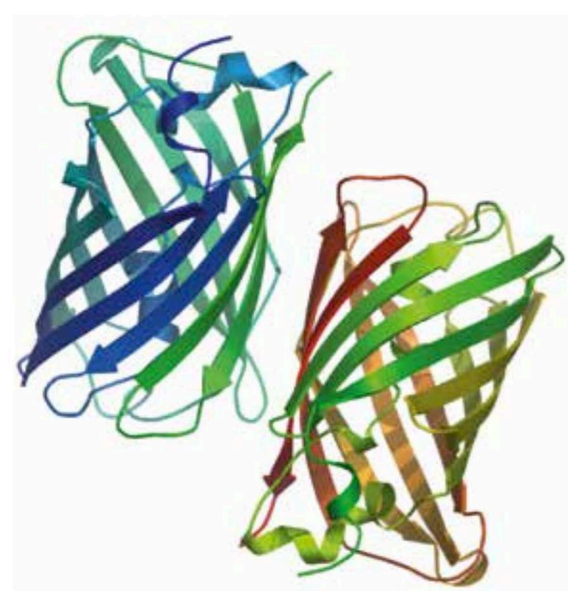
who had just taken two big steps up the career ladder," he recalls. But the promotion had its own pitfalls. PETRA III – now one of the most powerful X-ray sources in the world – did not yet exist back then. Instead, the experts had to make do with the considerably smaller storage ring DORIS. However, as Wilmanns explains, "it was clear that DORIS was no longer competitive at an international level." The management of EMBL was therefore considering closing down its Hamburg site – for lack of a long-term perspective. "So there was a danger that my job would amount to little more than winding down the operations," says Wilmanns.

But that is not how things turned out – thanks to a far-reaching decision. At the start of the 2000s, DESY drew up plans to convert the storage ring PETRA, which had until then primarily been used for particle physics research, and turn it into a dedicated radiation source. "This presented the prospect of a research facility that could claim to be a world leader," says Wilmanns. "And in the end, that is what it has become."

Today, EMBL Hamburg operates three beamlines at PETRA III, which are available to structural biologists from all over the world. The measuring station T-REXX is a comparatively recent addition – allowing time-resolved X-ray crystallography to be carried out. With it, researchers can observe enzymes as they go about their business, tracking the various stages of a reaction in great detail. "A real highlight," according to Matthias Wilmanns. "There's nothing like it anywhere else in the world." For example, his team has studied an enzyme called glutamine amino-transferase, which inserts nitrogen into chemical compounds in a highly complex reaction, making this an interesting molecule for pharmaceutical companies and the chemical industry.

Later, Wilmanns took on an additional position: Until the end of 2017, he was the founding director of the Centre for Structural Systems Biology (CSSB) on the Bahrenfeld campus. Supported by ten partner institutions, it focuses on a highly topical issue – studying infectious diseases. "More and more bacterial pathogens are becoming resistant to antibiotics," explains the biologist. "And more and more people in Germany are dying of such multiresistant germs." The CSSB partners are trying to counteract this by working out the fundamental processes involved in an infection. How exactly does it proceed, and how can it be stopped? "With ten different partner institutions working under the same roof at the CSSB, this leads to collaborations that would never have come about before," says Wilmanns. Thus, one team recently refined a method for isolating certain membrane proteins in order to be able to study them.

Matthias Wilmanns certainly hasn't ever regretted moving to Hamburg in 1997, despite the uncertain prospects at the time. "I have been able to participate in some fantastic developments here," he says. "I really feel very privileged."



Examples of representations of protein structures, as calculated by supercomputers from the complex diffraction patterns created by protein crystals exposed to X-rays.

Picture: Gesine Born

Research group leader Kay Grünewald uses cryo-electron microscopes, among other techniques, to study the structural cell biology of viruses.

Frosty cameras

Cryo-electron microscopes allow cells and viruses to be examined at high resolution without destroying them – a perfect complement to PETRA III

In the basement of the Centre for Structural Systems Biology (CSSB), the biologist Christoph Hagen opens a heavy door. Behind it stands a large block stretching all the way up to the ceiling, with a filigree assembly inside – a cryo-electron microscope. This imaging technique is a real high-flyer in biomedical research: For some years now, it has enabled scientists to take pictures of cells, viruses and biomolecules at astonishing resolution and to reveal ever new details about how they work.

The principle behind the electron microscope has been around for quite a time. An electron beam strikes a sample and is able to scan it in far greater detail than the light beam of a conventional microscope – meaning that much smaller structures can be imaged. In the past, this technique was only of limited use for biological samples, because these were often simply destroyed by the electrons.

Then scientists came up with a number of tricks to get around this problem. "The samples first need to be vitrified, that is converted into a glass-like state," explains Hagen. He works at the Heinrich Pette Institute, the Leibniz Institute for Experimental Virology, one of the CSSB partners. "To achieve this, we freeze the cells using liquid nitrogen so quickly that no ice crystals can form that might destroy the cells." The procedure is both effective and non-destructive. When the snap-frozen cells or viruses are unfrozen again, most of them come back to life.

"The resolution could be increased by a factor of ten, so all of a sudden you could even see individual atoms"

Christoph Hagen, Heinrich Pette Institute

Another milestone followed in 2012 – known in professional circles as the "resolution revolution". "The cameras designed at the time could detect the electrons directly and with very high precision," explains Hagen. "This meant the resolution could be increased by a factor of ten, so all of a sudden you could even see individual atoms." In 2017, the Nobel Prize for Chemistry was awarded for the development of this technique, which is now being used by more and more research teams.

The CSSB has invested millions to procure several such devices, which perfectly complement protein crystallography as conducted at the storage ring PETRA III. Christoph Hagen and his boss Kay Grünewald are particularly interested in developing a better understanding of the processes by which infections take place. "We infect cells, with the herpes virus for example, and use the cryo-electron microscope to study the different stages of the infection," says Hagen. "You can only really understand viruses if you look at them inside a cell – after all, that's their actual state of life." One can also learn a lot about the way a cell works by confronting it with a virus – this important fundamental research will allow infectious diseases to be controlled more effectively in the future.

The pioneer machine

The free-electron laser FLASH was the first to produce ultrashort X-ray laser pulses and laid the foundations for “filming” chemical reactions

FLASH is a real pioneer. When it went into operation in Hamburg in 2005, it was the world’s first ever free-electron laser in the X-ray range. It is based on a superconducting linear accelerator, over one hundred metres long, which accelerates up to 8000 electron bunches per second until they are travelling at close to the speed of light. Afterwards, these bunches pass through an undulator – a magnetic structure that forces the electrons to follow a slalom course, causing them to emit high-intensity laser pulses in the soft X-ray and vacuum ultraviolet range. At five measuring stations, these laser pulses can be used round the clock to analyse a wide range of samples – atoms, molecules, surfaces and solids, such as magnetic materials and organic solar cells. “The ultrashort pulses in the femtosecond range can be used to follow elementary processes over time, for example to observe the sequence of events during a chemical reaction,” says FLASH physicist Elke Plönjes-Palm.

“The ultrashort pulses in the femtosecond range can be used to follow elementary processes over time, for example to observe chemical reactions”

Elke Plönjes-Palm, DESY

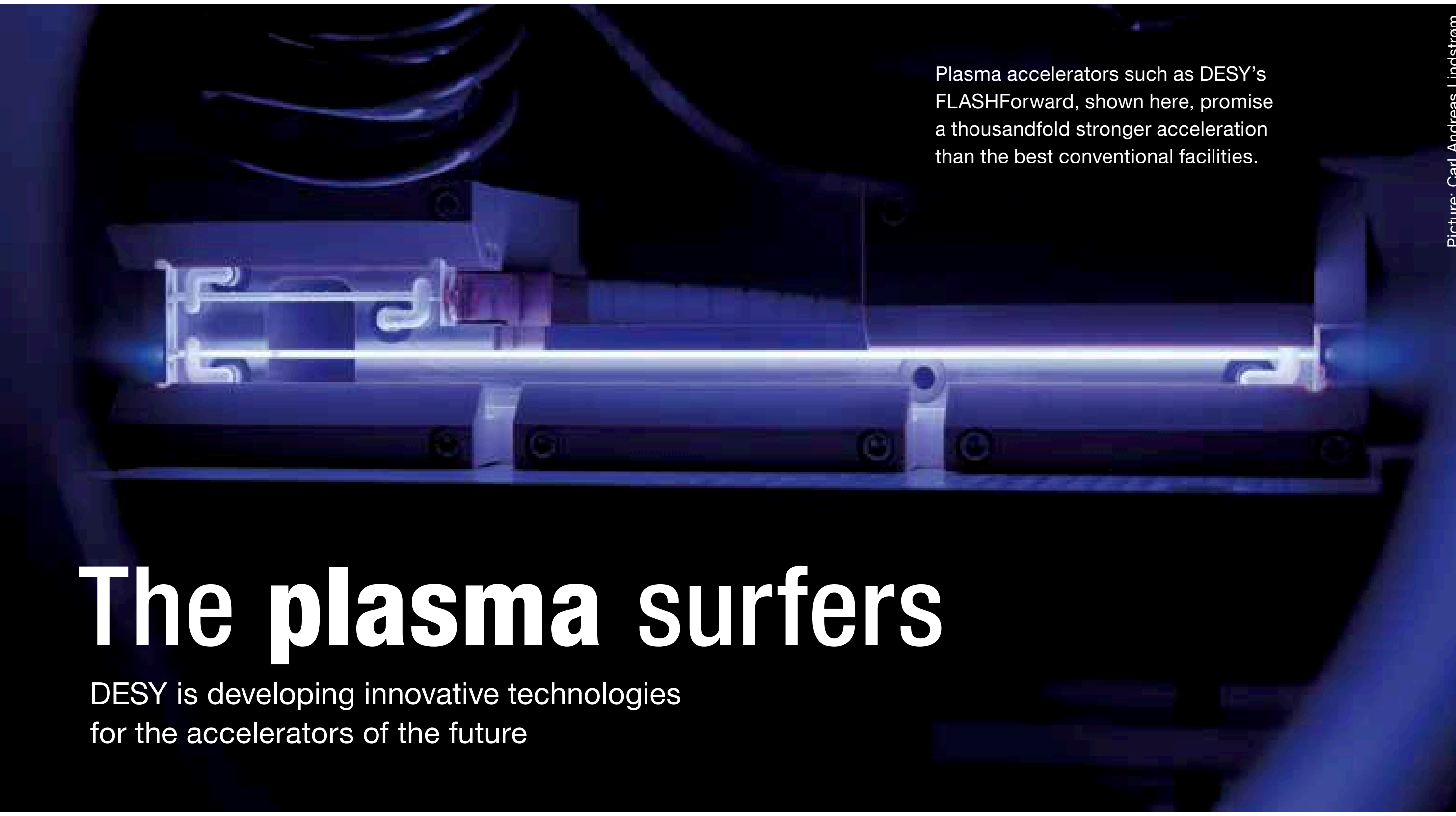
To increase the capacity of the facility, a further undulator line, known as FLASH2, went into user operation in 2016 together with a new experimental hall. For this purpose, some of the electron bunches are deflected towards the new undulator. The latter then supplies X-ray pulses to three measuring stations in turn. A fourth station is currently being set up. Now, a further upgrade programme is to once again expand the possibilities offered by FLASH and ensure that it continues to remain a world leader. The project, called FLASH2020+, comprises three elements:

Picture: Gesine Born

DESY physicist Elke Plönjes-Palm is an expert for FLASH.

- Part of the FLASH accelerator is to be replaced by new, more powerful modules. This will allow electrons to be accelerated to even higher energies in the future, producing X-ray pulses of shorter wavelengths – this is useful when studying magnetic materials, for example, in which elements such as iron, cobalt and nickel can be specifically excited and examined.
- The original FLASH1 is to be fitted with a new, modern undulator that allows the wavelength of the laser pulses to be altered during an ongoing experiment, which is already possible at FLASH2 – a feature from which many experiments stand to benefit.
- At the moment, the X-ray pulses are produced using a technique known as SASE. This leads to slight differences in the pulse duration and wavelength from one shot to the next – a drawback for some experiments. For this reason, FLASH1 will in future resort to “seeding”, where a conventional laser fires light pulses into the undulator, which affect the process of X-ray generation in such a way as to produce distinctly more uniform and cleaner X-ray pulses.

The upgrade programme is to begin in 2021 and will take place in several stages. It stands to be completed by 2024.



Plasma accelerators such as DESY's FLASHForward, shown here, promise a thousandfold stronger acceleration than the best conventional facilities.

Picture: Carl Andreas Lindstrom

The plasma surfers

DESY is developing innovative technologies for the accelerators of the future

Today, particle accelerators are often gigantic – the linear accelerator for the European XFEL X-ray laser, for example, is almost two kilometres long. Yet scientists at DESY are already involved in a range of projects aiming to develop new and innovative technologies for tomorrow's compact and space-saving accelerators.

In today's accelerators, radio waves are fed into special metal tubes called cavities. Particles can ride these waves much as a surfer rides ocean waves. However, this technique has its limits: "The maximum voltage of the cavities is limited to some 50 megavolts per metre," explains Ralph Aßmann, leading scientist for accelerator research at DESY. To propel the particles to high energies, a large number of cavities needs to be combined in series – this makes the facility correspondingly long.

Significantly higher accelerating voltages can be achieved using a technique that is still comparatively young: plasma acceleration. "The aim is to reach 50 gigavolts per metre, around one thousand times higher than today's peak values," says Aßmann.

This would allow accelerators to shrink: "Theoretically, a 100-metre accelerator could be replaced by a machine that would fit inside a laboratory basement," says Jens Osterhoff, head of DESY's plasma acceleration group. The underlying principle is that short, powerful laser pulses or, in the case of the DESY project FLASHForward, high-speed electron bunches plough their way through a plasma – an ionised state of matter made up of electrons and atomic cores. "When the pulse enters the plasma, it drives the electrons in the plasma along in front of it, like a snow plough, creating a wake, like a ship," explains Osterhoff. "This produces extremely strong electric fields within a very small region, which can accelerate the electron bunches enormously."

In 2006, at the Lawrence Berkeley National Laboratory in

Picture: Heiner Müller-Elsner

"Theoretically, a 100-metre accelerator could be replaced by a machine that would fit inside a laboratory basement

Jens Osterhoff, DESY

the USA, a research team headed by Wim Leemans, now director of the accelerator division at DESY, was able for the first time to accelerate electrons to energies of one giga-electronvolt (GeV) using laser plasma acceleration. In the

Picture: Thomas Schuster

“KALDERA will move laser plasma acceleration a big step closer to practical applications”

Andreas Maier, DESY

Picture: Gesine Born

Wim Leemans
Director of the Accelerator Division

“DESY is world leader in large-scale accelerators for science and advanced accelerator technology. In order to meet the challenges of the future, we are planning to upgrade PETRA III to PETRA IV, a unique 3D X-ray microscope – with outstanding potential for industrial users and applications in energy research, information technology, mobility and medicine. Complementing this, we are continuing to develop free-electron X-ray lasers and testing entirely new concepts for compact particle accelerators for future applications, for example in medicine.”

meantime, the record is 8 GeV over a distance of 20 centimetres, also set by the Berkeley group. A conventional accelerator would have to be more than 100 metres long to achieve these energies. At the same time, scientists at DESY have made important progress in producing particularly stable electron beams using laser plasma acceleration, which marks an important step towards future applications.

“Building on the achievements in Berkeley and DESY’s unique strengths, we are going to move plasma accelerators forward so it can be used in practical applications,” says Osterhoff. “We are initially focusing on developing plasma accelerators that can drive a new generation of compact free-electron lasers and high-energy X-ray sources for medical imaging. On top of this, we are exploring ways of making these accelerators more powerful and more reliable.”

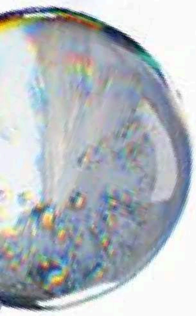
With this goal in mind, DESY is currently setting up a new and unique research infrastructure called SINBAD (Short Innovative Bunches and Accelerators at DESY), in addition to its FLASHForward project. With it, DESY will be perfectly placed to achieve a far more detailed understanding of the physics behind this new technology, while also developing it for a broad range of applications. Within SINBAD, scientists are already now testing two innovative technologies, in the form of ARES, an accelerator for producing ultrashort electron bunches, and AXIS, an accelerator that uses short-wave terahertz radiation instead of the usual radio waves.

In future, SINBAD will also house the new KALDERA laser, capable of firing more than a thousand ultra-intense light pulses per second. Until now, plasma accelerators have been limited to a few electron bunches per second, putting them at a distinct disadvantage towards other accelerator technologies available today. KALDERA is to make plasma accelerators competitive and open up new opportunities.

“KALDERA will move laser plasma acceleration a big step closer to practical applications,” says Andreas Maier, leader of the KALDERA project. “One of our goals is to demonstrate that laser plasma accelerators can be used to drive a free-electron laser.”

Plasma technology and innovative lasers as realised with KALDERA will allow more compact and less expensive X-ray sources to be built. Among other things, these could be used in industrial settings for testing materials. Another field of application could be X-ray screening of shipping containers. Today, this is done using conventional accelerators – in the port of Hamburg, for example. The accelerators are stationary, so the containers have to be moved through a gantry-like rig. Plasma accelerators would allow such devices to be mobile – the scanner would come to the container instead of bringing the cargo to the scanner. Mobile scanners like this could also be used to inspect road bridges.

These future X-ray sources could be equally interesting in the field of medicine. Here, they would enable new diagnostic techniques, such as X-ray fluorescence. This could be used to detect tumours that are so small that they are missed by present-day methods – the prognosis for the patients concerned would be improved accordingly. In its efforts to develop plasma acceleration to a point where it can be used in practical applications, DESY is proving to be an important partner within the international research community and can play an important part as a centre of excellence for European projects such as EuPRAXIA or the ALEGRO consortium.



The water institute

Water is life – but what in fact is water? How does it react in detail, and how does it shape the processes of life? What part does it play in the universe?

Picture: Gesine Born

"Water is a fairly simple molecule, but very special in its own particular way"

Melanie Schnell, DESY

Although it is truly ubiquitous and, in a sense, a very mundane molecule, water continues to present a number of puzzles to scientists. How exactly does it affect the important processes on which life is based, such as the behaviour of proteins? What happens on a microscopic level when water molecules affect chemical reactions, for examples during corrosion? And what role does water play in the distant reaches of the universe, for example inside remote giant planets? A new, interdisciplinary institute planned on the DESY campus – the Centre for Molecular Water Science (CMWS) – is to explore questions like these.

"Water is a fairly simple molecule, but very special in its own particular way," explains the chemist Melanie Schnell, a leading scientist at DESY. She and her colleague Gerhard Grübel are coordinating the project. "Special bonds between water molecules, for example, are the reason why it only boils at 100 degrees Celsius." If it weren't for these hydrogen bonds, water would be a gas already at room temperature. Experts have long been fascinated by such idiosyncrasies. "Over recent years, we noticed that a wide range of research groups in DESY's surroundings were interested in the subject of water," Schnell recalls. "At some point, we came up with the idea of bringing this shared interest together in a joint centre – a kind of scientific grass-roots initiative." The researchers involved all have one thing in common: They use the Hamburg X-ray sources PETRA III, FLASH and European XFEL to study the details of how water, the object of their interest, behaves.

Picture: Gesine Born

"Virtually every institution on the DESY campus is involved in the CMWS"

Gerhard Grübel, DESY

The CMWS wants to shed light on water and its properties from many different angles: Special experimental setups are designed to put water quite literally under pressure and thereby create exotic ice crystals, which should otherwise only exist deep inside giant planets. The question of how water molecules affect the folding of proteins is of special interest in biology: Does a protein molecule adopt a different shape when there is water around? Research groups working in the field of chemistry want to find out, among other things, how catalytic reactions are influenced by the water molecule – this is important for electrolysis, for example, a key part of climate-friendly hydrogen generation.

Melanie Schnell is particularly fascinated by one question: "What role does water play in interstellar space?" This has to do with an observation that has puzzled scientists for some time now. They have found that an astonishing variety of different molecules exists in the depths of space – even amino acids, the building blocks of life. The question is: How was it possible for them to form there? Where did the corresponding chemical reactions take place?

The answer could be connected with the countless little granules of ice drifting about in outer space, according to astronomical observations. "We suspect that the chemical reactions in which these different compounds are formed take place on these granules," says Schnell. The idea is that molecules encounter the drifting ice granules, freeze onto them – and can then react with other molecules also stuck to the granules. "This would make ice a kind of interstellar catalyst," notes Schnell. "We want to test this hypothesis at the new centre." In concrete terms, her team intends to simulate conditions in space in the laboratory and then use high-intensity pulses from the DESY X-ray laser FLASH to examine the processes in detail.

"Virtually every institution on the DESY campus is involved in the CMWS in one way or another," Gerhard Grübel is pleased to report. "And we have received so much encouragement from even further afield that it could almost be described as a European centre." More than 30 groups from different institutes around Europe and beyond have expressed a concrete interest. Collaborations have already been established in the context of an "Early Science Programme", and the experts are holding regular workshops to share their ideas. First of all, a laboratory is being set up where the samples can be prepared; later, the centre is to have its own building on the campus.

Picture: istockphoto.com/Artem_Egorov

The nano combiner

Robert Blick trains his sights on structures that are no larger than a speck of dust, but have huge potential for the technologies of the future

Robert Blick squeezes into his overalls, slips into protective boots and dons a hood. “This is necessary to avoid contaminating the cleanroom,” explains the professor of physics. “Human beings are the biggest source of dust here.” The cleanroom is the centrepiece of the Center for Hybrid Nanostructures (CHyN), a recent addition to the campus in Bahrenfeld, launched by Universität Hamburg in 2017. The experts here study structures that are just a few millionths of a millimetre across and that could prove to be important for the technologies of the future. “More specifically, the CHyN studies nanomaterials that are composed not of one but of several classes of substance,” explains Blick. “We combine semiconductors with biomolecules, with two-dimensional carbon or with superconductors, for example.”

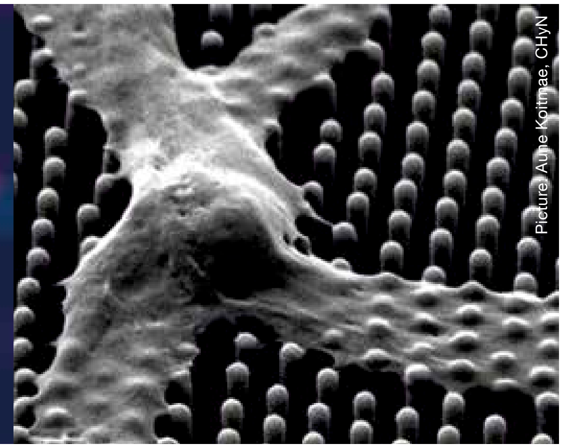
Hybrid materials like these could one day serve many different purposes: as processors for future quantum computers, as special-purpose chips for DNA analysis, or in retinal implants that

The cleanroom at the Center for Hybrid Nanostructures (CHyN) covers an area of over 300 m² and is divided into three areas, in which more than 30 users can work simultaneously.

Picture: Gesine Born

Working together with Swedish scientists, for example, the experts at the CHyN have grown nerve cells on nanowires, containing a type of solar cell. When light is shone on this hybrid structure, an electric voltage is produced, which activates the cell function.

Picture: Aune Koitmae, CHyN



Picture: Aune Koitmae, CHyN

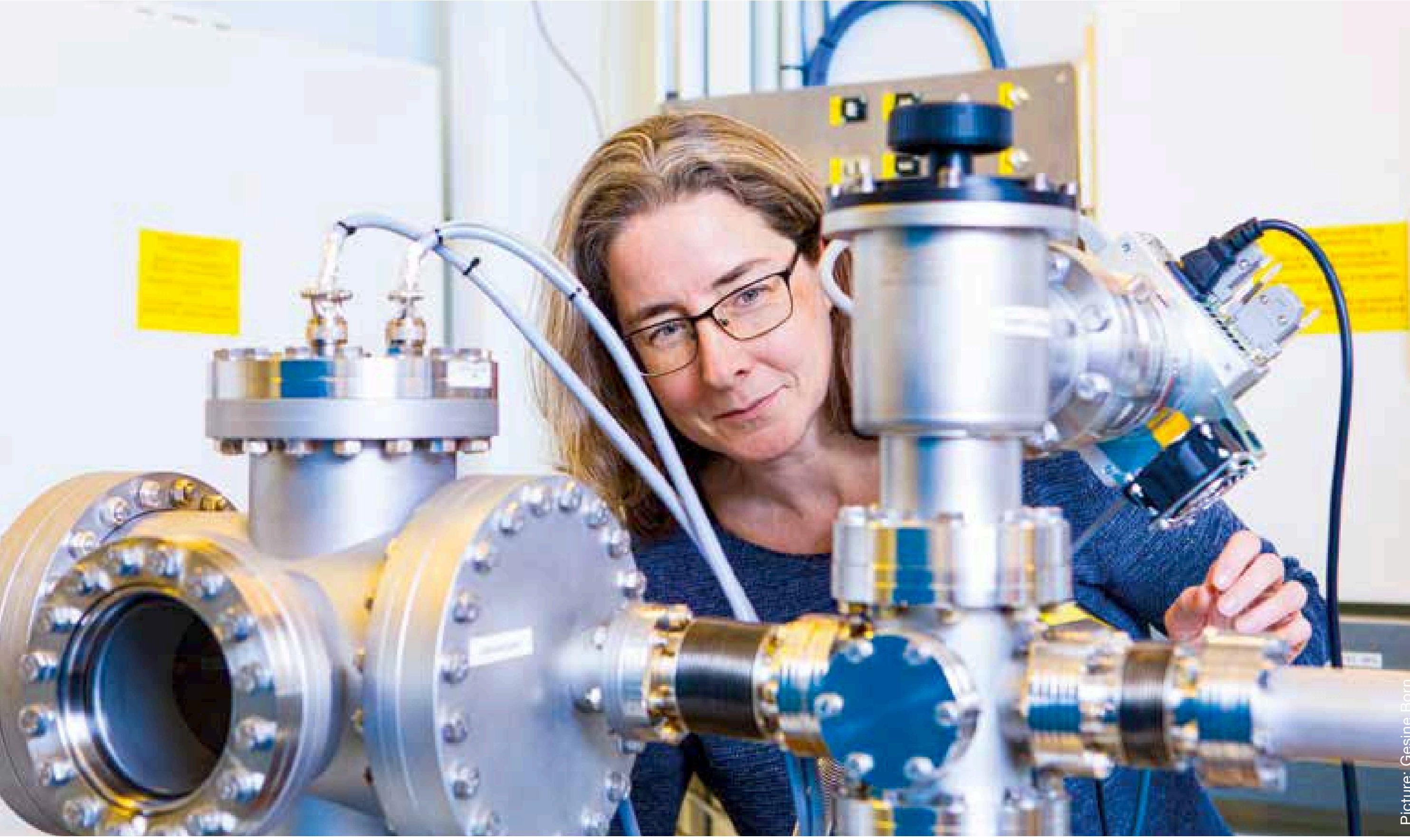
> "We combine semiconductors with biomolecules, with two-dimensional carbon or with superconductors, for example"
>
> **Robert Blick, CHyN**

could restore the eyesight of the visually impaired. Building the prototypes is tricky, however. The structures are so tiny that even a single grain of dust can put them out of action. The work therefore needs to be conducted in an extremely clean environment: the cleanroom.

> "Human beings are the biggest source of dust here"
>
> **Robert Blick, CHyN**

You enter it through an airlock. Robert Blick pushes a button, and a few seconds later, a powerful air shower blows any remaining dirt from his overalls. He points to the floor, which is covered in air vents – a total of 628 circular apertures are sucking away the air. Sophisticated filter systems clean it, and fans blow the clean air back into the room from the ceiling – without producing any appreciable turbulence. "There are only a few dust particles here per litre of air," explains Thomas Finger, the technical supervisor of the cleanroom. "That's a ten thousandth of what you'd find in a normal laboratory." Inside the cleanroom, one high-tech device stands next to another: air exhaust systems for chemical preparation, a high-precision etching system and a box for making nanostructures. This technique is much like potato printing, but on a nanometre scale. "We offer all the standard techniques used in the semiconductor industry," explains Robert Blick. "But compared with a chip factory, we are much more flexible." One highlight is the electron beam writer: It can produce extremely fine structures, the smallest of which are no more than eight nanometres across. Even the tiniest vibrations would ruin the production process, so the entire device stands on its own, damped foundations.

The cleanroom cost nine million euros to build – and is in great demand throughout the entire campus. "This is a fantastic environment for our students to come up with new ideas," says Blick. "And in the context of the cluster of excellence 'CUI: Advanced Imaging of Matter', DESY is using our cleanroom to develop piezoelectric nanomembranes for high-precision measuring techniques, for example." Soon, start-ups are to begin using the cleanroom, among them a company that is developing special-purpose chips for analysing human cells. "Hamburg offers start-ups a fantastic setting today," says Blick, "and there is quite a bit of investment capital around nowadays too."



Picture: Gesine Born

The biophysicist Arwen Pearson from Universität Hamburg is in charge of HARBOR.

The protein tamers

In order to watch biomolecules in action, they first need to be trapped – which is not that easy

Biologists have long been regular visitors of the DESY campus. In most cases, they use the X-ray flashes from PETRA III to determine the exact shape of proteins – the more accurately the shape of these molecules is known, the more precisely you can determine how they work and what role they play in a living organism. However, biologists have been rather more hesitant in using another interesting property of the Hamburg X-ray sources: "DESY's X-ray sources also enable detailed time-resolved measurements," says Arwen Pearson, a biophysicist at Universität Hamburg. "This allows us to watch reactions between proteins and other substances, just like in a movie."

There is a good reason why biologists have made relatively rare use of this possibility until now. The experiments are tricky and require special experimental techniques. As of 2020, a new institute from the university is developing and refining such techniques on the campus in Bahrenfeld: The Hamburg Advanced Research Centre for Bioorganic Chemistry, or HARBOR for short, will provide the necessary infrastructure to carry out time-resolved experiments on biomolecules.

A key focus will be the development of so-called "photocages". These are artificial chemical tags that inhibit protein function. The trick is that it only takes a suitable pulse of light to shatter the tag. Once free of its bonds, the protein can go into action. This cunning mechanism serves as the starting signal for a time-resolved measurement: When the light pulse hits not just one but millions of inhibited proteins, they are all released from their molecular fetters at the same time and become active in synchrony, as a vital enzyme for example. This "synchronised ballet" of the proteins can then be filmed using X-ray pulses from PETRA III or the European XFEL. The resulting molecular movie reveals the details of what the biomolecules are up to. "At HARBOR, we want to develop photocages that can be used flexibly for all kinds of proteins," "DESY's X-ray sources enable detailed, time-resolved measurements that allow us to watch reactions between proteins and other substances, just like in a movie"

Arwen Pearson, Universität Hamburg

says Pearson. This calls for an interdisciplinary approach: Biologists identify biomolecules that could be of interest, chemists construct suitable photocages, and physicists use laser instruments to test how much light at which wavelength is most suitable for slipping the leash quickly and efficiently. The building housing HARBOR takes this need into account: Its ground floor contains ultrafast lasers and rooms for chemical analysis, while synthesis and biochemical laboratories populate the upper floors. Meanwhile, theoreticians simulate the various processes on the computer to identify suitable candidates.

"The new centre will be open to biologists from all over the world, in order to support their experiments here at DESY," says Arwen Pearson. "They can test and characterise their samples in the HARBOR laboratories so that they can carry out the best possible experiment at PETRA III or the European XFEL."

Take the study of membrane proteins, for example. These are lodged in the cell's membrane and are responsible, among other things, for allowing vital substances to enter and leave the cell. The interesting question is how a membrane protein selectively allows just one substance to pass, rather like a molecular Open Sesame.

Some time ago, a research group headed by the biochemist Henning Tidow from Universität Hamburg studied the way in which certain membrane proteins move iron into pathogenic bacteria. "This iron is essential for the bacterium," explains Tidow. "If we could prevent it from being absorbed, we might have a new antibiotic." In the meantime, his team has managed to unravel important details of this process by – in simple terms – taking still shots of the iron transfer. "We don't yet understand the precise details of the process," says Tidow. "That is why we are now planning to conduct experiments using time-resolved techniques. The new opportunities provided by HARBOR are likely to be extremely useful in this respect."

With HARBOR, Universität Hamburg is seeking to combine excellent physics with excellent life sciences. Henning Tidow leads one of the research groups.

Picture: private

Picture: Sprinkenhof GmbH / Nickl & Partner Architekten AG

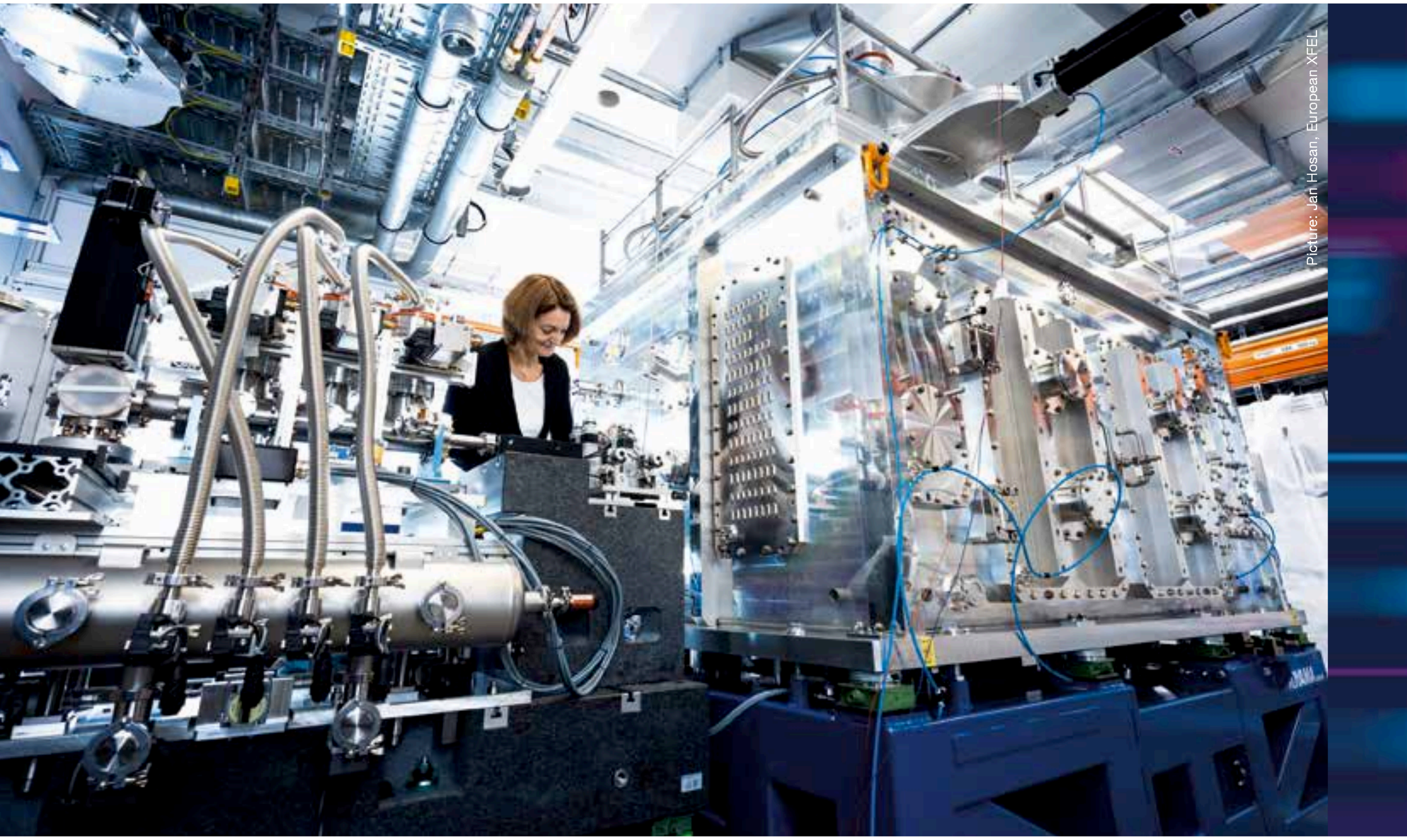
The planet simulator

X-ray laser flashes from the European XFEL are simulating events deep inside the Earth

How does matter react under extreme conditions, such as extremely high pressures or temperatures? A new measuring station at the European XFEL X-ray laser can provide answers. The HED (High Energy Density) beamline has recently gone into operation. The extreme conditions are created, among other things, by two lasers. They bombard a material sample with superstrong pulses, putting it into an exceptional state. Immediately afterwards, the ultrashort X-ray flashes from the European XFEL hit the sample and capture the events at a level of detail never achieved before.

Another device for creating extreme conditions is the diamond anvil cell: It compresses tiny samples, creating the kind of pressures found deep inside the Earth. This allows geoscientists to simulate conditions inside our planet and learn important information about the Earth's core and mantle.

As part of a user consortium called HIBEF (Helmholtz International Beamline for Extreme Fields), experts are planning a range of experiments at the European XFEL. For example, they want to examine iron samples – iron is the main component of the Earth's core. Their plan is to use an initial X-ray flash from the European



Picture: Jan Hosan, European XFEL

The HED measuring station is used to study matter under conditions of very high pressure and temperature or in very strong electromagnetic fields, like those encountered inside exoplanets or in high-density plasmas.

View into the tunnel of the X-ray laser: The tunnel system housing the European XFEL begins 3.4 kilometres away, on the DESY site in Hamburg.

Picture: Jan Hosan, European XFEL

XFEL to melt the iron as it is compressed in the diamond anvil cell. The subsequent flashes will then precisely measure the sequence of events – before the molten iron can react with the cell. "This is only possible at the European XFEL," DESY scientist Cornelius Strohm points out. "It is the only facility able to provide a sufficiently large number of high-energy X-ray pulses in quick enough succession." The results should help to clarify an important geoscientific question: Where exactly does molten iron exist in the Earth's core, and where are the boundaries with the solid phase?

"With the European XFEL, we can now push ahead to the very centre of an impact"

Hanns-Peter Liermann, DESY

The simulation of meteorite impacts is another item on the agenda. During an experiment, special actuators ensure that the pressure between the diamonds increases very abruptly. The X-ray pulses from the European XFEL can help identify the crystal forms that are created in the process. Experts then compare these with mineral samples found in meteorites or near old asteroid impact craters. The results of the simulations can help them to estimate the size and nature of the impact more accurately. "So far, we have only been able to simulate the outer perimeter of an asteroid impact," explains DESY mineralogist Hanns-Peter Liermann. "With the European XFEL, we can now push ahead to the very centre of an impact."

Another object of research is ice – though a rather exotic version of it. The pressure inside giant planets is so tremendous that ice can form even at high temperatures. In this case, however, it does not adopt the familiar snowflake shape, but instead occurs in unusual crystal forms. A range of theories predicts that further, hitherto unknown types of ice crystals should exist inside planets. Experts now want to test this hypothesis with their experiments at the European XFEL – also in collaboration with the new Centre for Molecular Water Science (CMWS) on the DESY campus. "These experiments are an entirely new field for us," says Liermann. "We are very excited, because we have no idea what to expect."

Picture: Marta Mayer

DESY researcher Hanns-Peter Liermann is in charge of the beamline for extreme conditions at DESY's X-ray source PETRA III.

Quick as a flash

At the Max Planck Institute for the Structure and Dynamics of Matter, every fraction of a second counts

> "With the help of light, we can create states of matter that do not otherwise exist"
>
> Andrea Cavalleri, Director at the MPSD

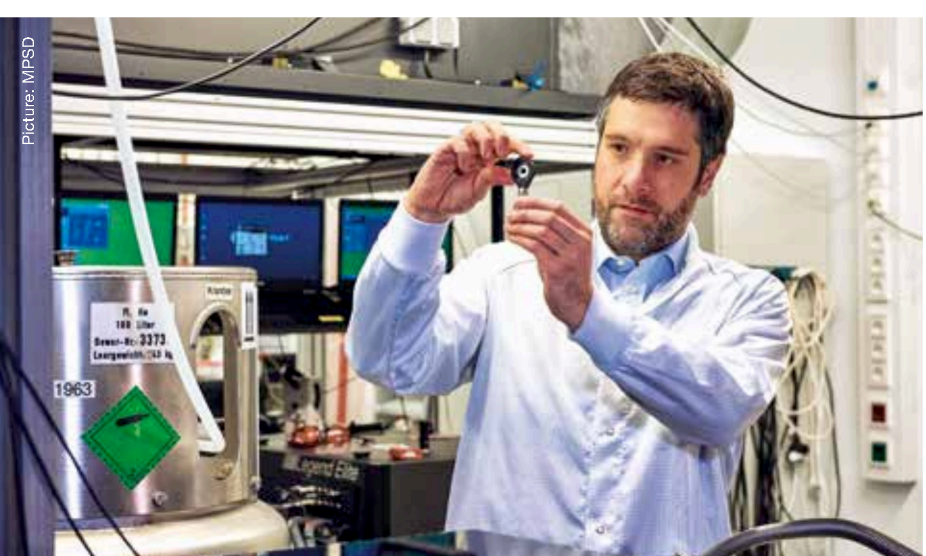
Electrons travelling through a crystal; atoms absorbing and re-emitting light; and molecules reacting chemically with each other. All these processes happen over incredibly short times – within pico-, femto- or even attoseconds. Studying such extremely rapid events is one of the key focuses on the Bahrenfeld campus. An important protagonist in this endeavour is the Max Planck Institute for the Structure and Dynamics of Matter (MPSD). To observe the high-speed activities within the microcosm, its experts use special tools – ultrashort pulses from special lasers and from X-ray sources such as the European XFEL.

"With the help of light, we can create states of matter that do not otherwise exist," says Andrea Cavalleri, director at the MPSD. "These are ultrafast processes that arise extremely quickly, but are over just as quickly." Among other things, his team is examining the origins of a fascinating physical phenomenon: superconductivity. Electrical current can flow through superconductors with zero resistance – provided the superconducting material is cooled to low temperatures, often close to absolute zero, which is at minus 273 degrees Celsius.

For decades, physicists have been trying to find materials that are superconductors at comparatively high temperatures. Although they have made some progress, their dream of finding a material that has no electrical resistance without having to be cooled at all is still not in reach. A room-temperature superconductor would offer tremendous technical potential, for example for transporting electrical power efficiently over large distances. In contrast to today's materials, it would not need to be elaborately cooled.

Some time ago, the MPSD physicists did indeed succeed in turning certain ceramic materials into superconductors at room temperature using ultrashort laser flashes. However, the effect lasted only a few millionths of a microsecond. "The laser light can activate the microscopic processes that are responsible for superconductivity," explains Cavalleri. Analyses using an X-ray laser furnished an explanation: The laser flashes lead to brief displacements of the crystal lattice, thereby strengthening superconductivity. This finding improves our theoretical understanding of the phenomenon and could in future contribute to the development of new, improved materials.

"We are collaborating closely with other institutions on the Bahrenfeld campus, including CFEL, DESY and the Center for Optical Quantum Technologies at Universität Hamburg," Cavalleri points out. "There is a lively exchange of ideas and personnel, for example in developing innovative laser technologies and new theoretical concepts."

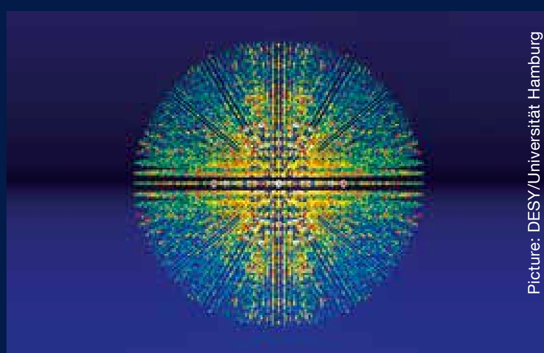


Picture: MPSD

Andrea Cavalleri is the director of the Condensed Matter Dynamics Department at the MPSD.

Doubly excellent!

The German federal government and states are pursuing an excellence strategy to promote outstanding collaborations between universities and non-university research institutions. Universität Hamburg has won funding for four such clusters of excellence in the latest round of the competition, and DESY plays a major role in two of them. Not least thanks to its clusters of excellence, Universität Hamburg has been awarded the title of University of Excellence.



Dance of the molecules

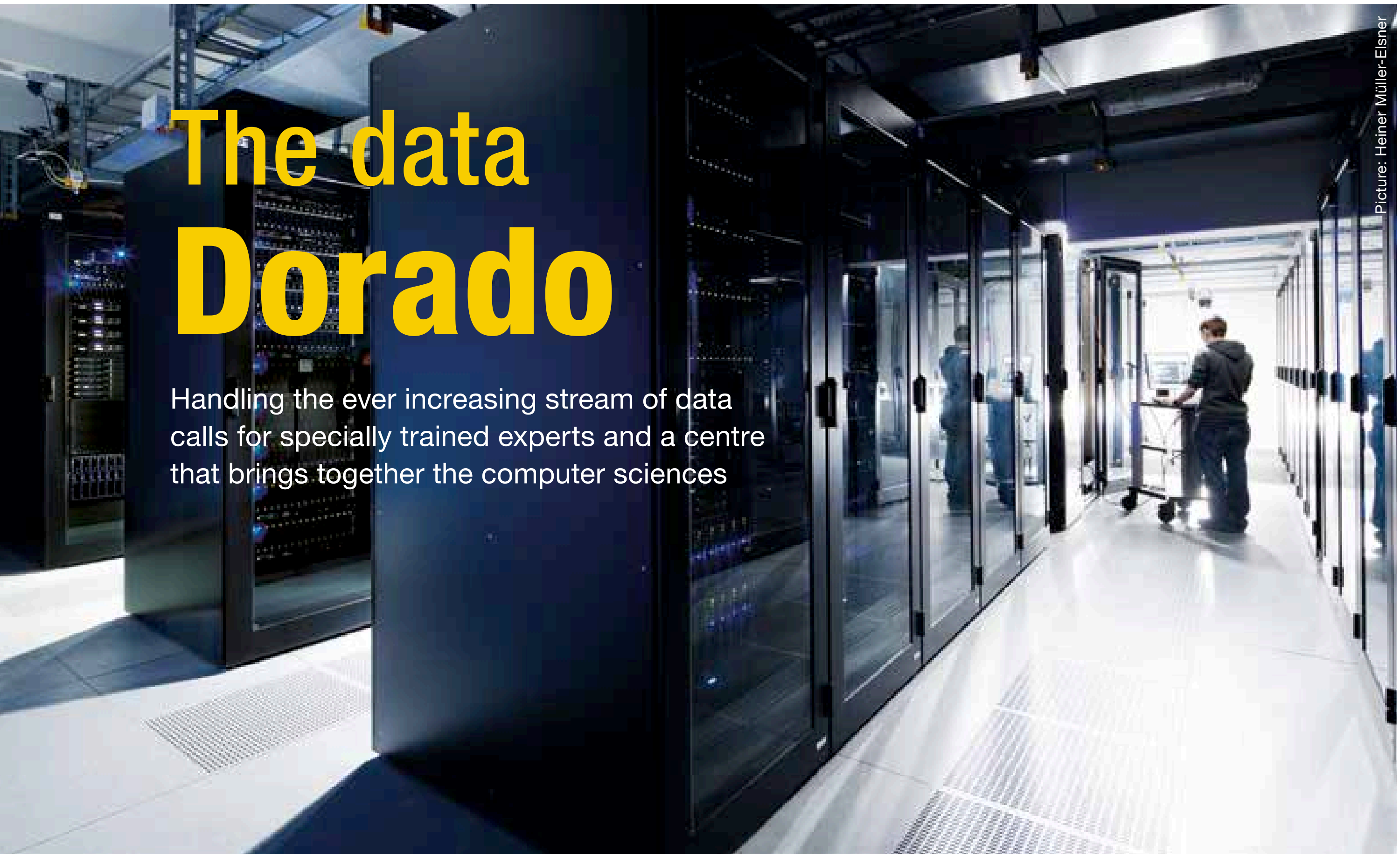
Nature can be extremely complex on the elementary scale – at the level of atoms and molecules. Countless building blocks interact with each other, and the processes involved take place at incredible speeds within time spans in the range of femtoseconds (quadrillionths of a second). The more detail with which this dynamic "dance" can be observed, the better the behaviour of matter can be understood.

Today, tools are available, many of them at DESY, with which these processes can be observed in great detail: Specialised laser facilities like the European XFEL produce ultrashort pulses that allow the events taking place on the microscopic stage to be precisely tracked. Since January 2019, the cluster of excellence "CUI: Advanced Imaging of Matter" has been pursuing the goal of refining these tools, developing new methods for detailed investigations of the microcosm and studying the dynamics on all time scales. The central question is how the microscopic events determine the properties of materials, and how this knowledge can be used to create new functionality. Universität Hamburg, the Max Planck Institute for the Structure and Dynamics of Matter, the European XFEL and DESY are all involved.

Early development of the universe

The universe was created some 13.8 billion years ago in the big bang. But the details of how that big bang unfolded remain a mystery. Since January 2019, the cluster of excellence "Quantum Universe", in which Universität Hamburg and DESY are both involved, has been devoting itself to studying the early childhood of our universe.

Today's large universe follows the laws of Einstein's general theory of relativity. But at the beginning of time, the universe was so tiny that quantum phenomena must also have played a dominant part. The problem is that a theory of "quantum gravity" that combines Einstein's theory of relativity with quantum theory does not yet exist. The cluster of excellence is pursuing a number of different approaches to developing such a theory – whereby string theory is one of several promising candidates. One focus lies on the Higgs boson, first detected in 2012, whose precise investigation will allow some fundamental questions to be answered. Another focus is the ominous dark matter, which marks the interface between cosmology and particle physics and which might consist of undiscovered particles. Gravitational waves too could grant us a glimpse back into the juvenile universe and the laws that governed it.



Picture: Heiner Müller-Elsner

The data Dorado

Handling the ever increasing stream of data calls for specially trained experts and a centre that brings together the computer sciences

Sharper and sharper images lead to bigger and bigger image files. The phenomenon is familiar from digital and smartphone cameras: While file sizes of a few hundred kilobytes used to be considered large, it is now perfectly normal for a single picture to contain many megabytes of data. The reason for this increase is the rapid technological developments that have made both camera chips and memory chips more and more powerful over the years.

This trend is also found in research – in the scientific cameras known as detectors. At the gigantic LHC accelerator near Geneva, they record what happens when ultra-high-speed particles collide. At free-electron lasers such as the European XFEL in Hamburg, they take high-resolution X-ray images. And in telescopes, they pick up even the faintest twinkle of the stars. “Our detectors are becoming better all the time and producing larger and larger files,” says Nina Rohringer, a leading scientist at DESY. “As a result, there is a rising surge of data that needs to be processed and analysed.”

This poses a problem for researchers: Many of them do not have the necessary expertise to handle such huge amounts of data, to manage “big data” quickly and efficiently. “This requires new programs and algorithms, which already analyse the data during the experiment itself, for example,” explains Rohringer. At X-ray lasers, for instance, the measurements need to be processed while the experiment is taking place, to check whether everything is going as planned or whether adjustments need to be made.

Developing this type of software calls for proven experts who know their way around the physical methods used and who also have a solid understanding of computer science. In order to train such experts, Nina Rohringer coordinates a new graduate school by the name of “Data Science in Hamburg – Helmholtz Graduate School for the Structure of Matter”, or DASHH for short. Apart from DESY, its main partners are Universität Hamburg and the Hamburg University of Technology.

“DASHH is meant to provide a favourable environment where motivated young scientists can pursue their doctoral studies,” explains Rohringer. The interdisciplinary graduate school, which is designed for 15 students a year, covers the fields of structural biology, particle physics and physics using X-ray sources. “To some extent, these different fields use the same methods,” explains the physicist. “The same software procedures that have proven useful in particle physics can also be helpful in structural biology or astrophysics.”

All DASHH graduate students are supervised by two experts – one from the fields of computer science or mathematics and one from physics or biology. On top of this, there are seminars and colloquia on numerous topics connected to data science, in some cases in cooperation with the Helmholtz Information & Data Science Academy (HIDA). "We have received many applications, also from abroad," Rohringer is happy to report. "Our graduates are likely to be in strong demand, as data specialists at research facilities for example."

It is not only the next generation of scientists that is profiting from the new graduate school, however. Established research personnel is also benefiting: As Nina Rohringer notes, before the programme was launched, she had little contact with her colleagues in the departments of mathematics and informatics at the two partner universities. "But in the course of our talks, we quickly realised that there could be a lot of synergies if we worked together in the future. That's just wonderful."

As a result, Rohringer's own research has seen lots of new impulses. For example, she has launched a joint project with a mathematician from the university to develop a software program that can simultaneously process and analyse X-ray measurements taken using two different techniques. "The graduate school means we now have better ties with the university and the university of technology," says Rohringer. "There is a lively exchange of ideas – which for me is a true bonus."

In future, the graduate school could be embedded in a larger framework. As part of its "Strategy 2030", DESY is planning to set up a Center for Data and Computing in Natural Sciences (CDCS) to strengthen computer science on the campus. "Our mission is, more than ever, to work on an interdisciplinary level," explains Volker Gülzow, head of the DESY IT department. "We want to bring together scientists who are using facilities such as PETRA III, the European XFEL or the LHC with scientists in the fields of computer science and mathematics."

The CDCS too will be about finding the most effective way of handling the ever-increasing volume of data in science. How can the relevant signals be extracted from the vast sea of measured values, for example? "In order to analyse the huge amounts of data from the experiments, but also accruing during accelerator operation, we need fast algorithms, for example from the fields of machine learning and automatic image recognition," says Gülzow. To develop these innovative software tools, the CDCS will be bringing together experts from different faculties – in a new building specially designed for the collaboration.

Picture: Gesine Born

"Our graduates are likely to be in strong demand, as data specialists at research facilities for example"

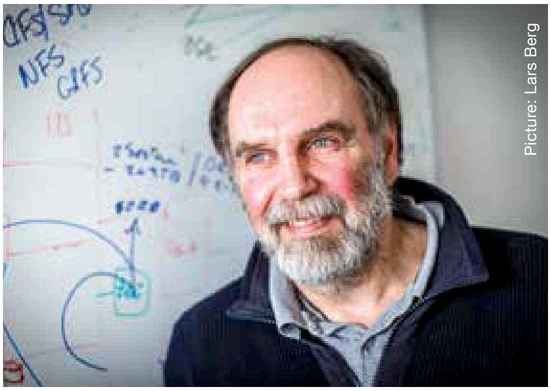
Nina Rohringer, DESY

Data streams from on-campus experiments converge at the DESY computing centre, alongside data from the European XFEL and CERN.

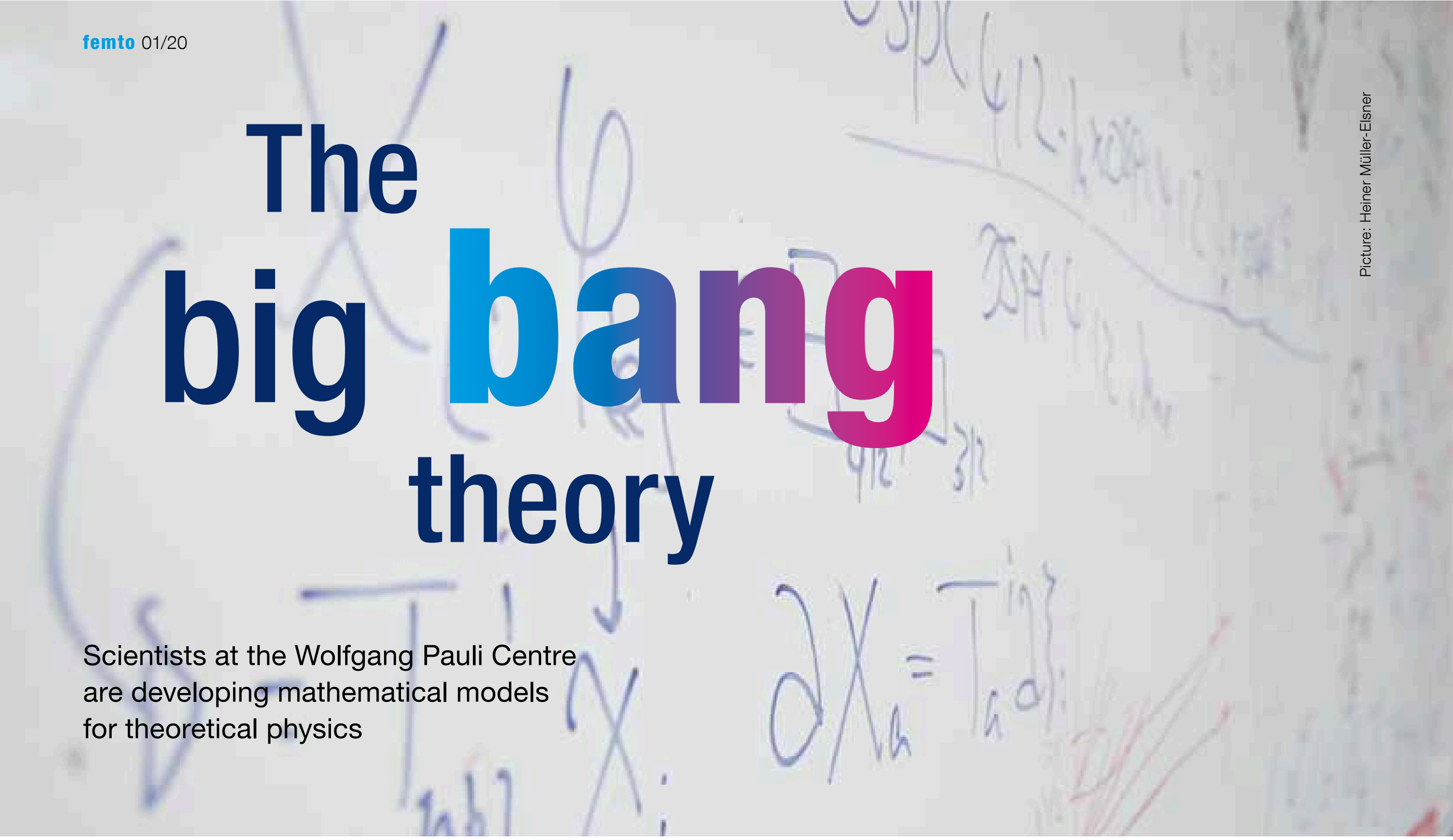
Picture: Heiner Müller-Elsner

"Our mission is, more than ever, to work on an interdisciplinary level"

Volker Gülzow, DESY



Picture: Lars Berg



Picture: Heiner Müller-Elsner

The big bang theory

Scientists at the Wolfgang Pauli Centre are developing mathematical models for theoretical physics

Most physicists seek to unravel the secrets of nature using elaborate experimental setups: They peer down microscopes, gaze into space with observatories, or fire tiny particles down huge accelerators. Others, however, rely on pencils, paper and computers: Theoretical physicists draw up mathematical models that aim to describe our world in terms of numbers and equations. Their most famous representative was Albert Einstein – his theory of relativity is still considered one of the mainstays of modern physics.

These two branches cannot get by without each other. Theoretical physicists often give experimental physicists crucial clues as to what they might look for; and conversely, solid measurement data are the acid test for physical theories: A number of plausible models has gone up in smoke after incorrectly predicting the outcome of experiments.

DESY and Universität Hamburg share a long tradition in theoretical physics. For decades, their experts have been drawing up and refining models for particle physics and cosmology. But in recent years, new areas have been added: “Theoretical physics is experiencing an upsurge in Hamburg,” explains the DESY physicist Volker Schomerus. “New topics have emerged, for example in the fields of laser physics, quantum optics and theoretical chemistry.”

To take this trend into account, DESY founded the Wolfgang Pauli Centre for theoretical physics in 2014, together with Universität Hamburg. Its mission is to create a framework in which the different aspects of the field can be brought together under a single roof. “The transfer of ideas and methods is particularly important in theoretical physics,” says Schomerus. “You often find that methods from one field can also be applied in other fields.”

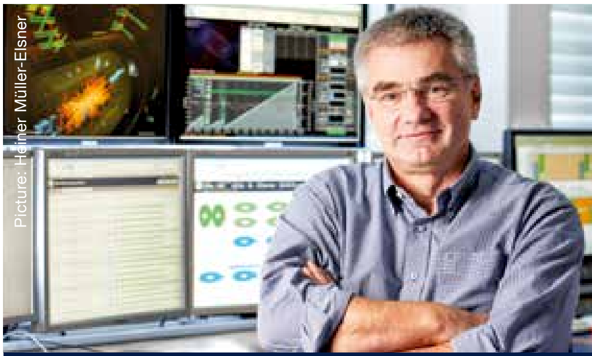
One example is the study of phases. In addition to the “solid”, “liquid” and “gaseous” phase states, physicists know of other, more exotic states of matter – the topological phases or orders. These are found in condensed matter physics and in

> “We want to turn the centre into one of the world leaders in theoretical physics, creating an institution that is unique in Europe”
>
> **Volker Schomerus, DESY**

chemistry, but they are also relevant to the early stages of the universe and to particle physics. “These states of matter behave differently from the ones we are familiar with, and they obey new rules,” Schomerus explains. “Describing them mathematically is very demanding.” They are being studied, among other things, within the two clusters of excellence “Quantum Universe” and “CUI: Advanced Imaging of Matter”.

A further example is so-called tensor networks, originally developed in the field of quantum optics. They represent a new way of packaging information about the states of a quantum system as effectively as possible. At the Wolfgang Pauli Centre, different areas complement each other: String theory – a model known from particle physics – is successfully examining the question what happens when information falls into a black hole – a problem that already haunted the famous physicist Stephen Hawking. The ideas and concepts developed in the process can in turn be useful for another field, the development of algorithms for quantum computers, a future generation of computers that promises to be extremely powerful. “The Center for Optical Quantum Technologies at Universität Hamburg is working on the components of such a quantum computer,” says Volker Schomerus. “And particle theoreticians can develop algorithms that will actually run on such systems.”

Over the coming years, the Wolfgang Pauli Centre is to be expanded substantially. “We want to turn the centre into one of the world leaders in theoretical physics, creating an institution that is unique in Europe,” Schomerus points out. In concrete terms, this means that the virtual institute is to become a physical one: A new building is planned, which from 2024 onwards will serve as a central meeting point for the experts – and as a melting pot for new ideas.



Picture: Heiner Müller-Elsner

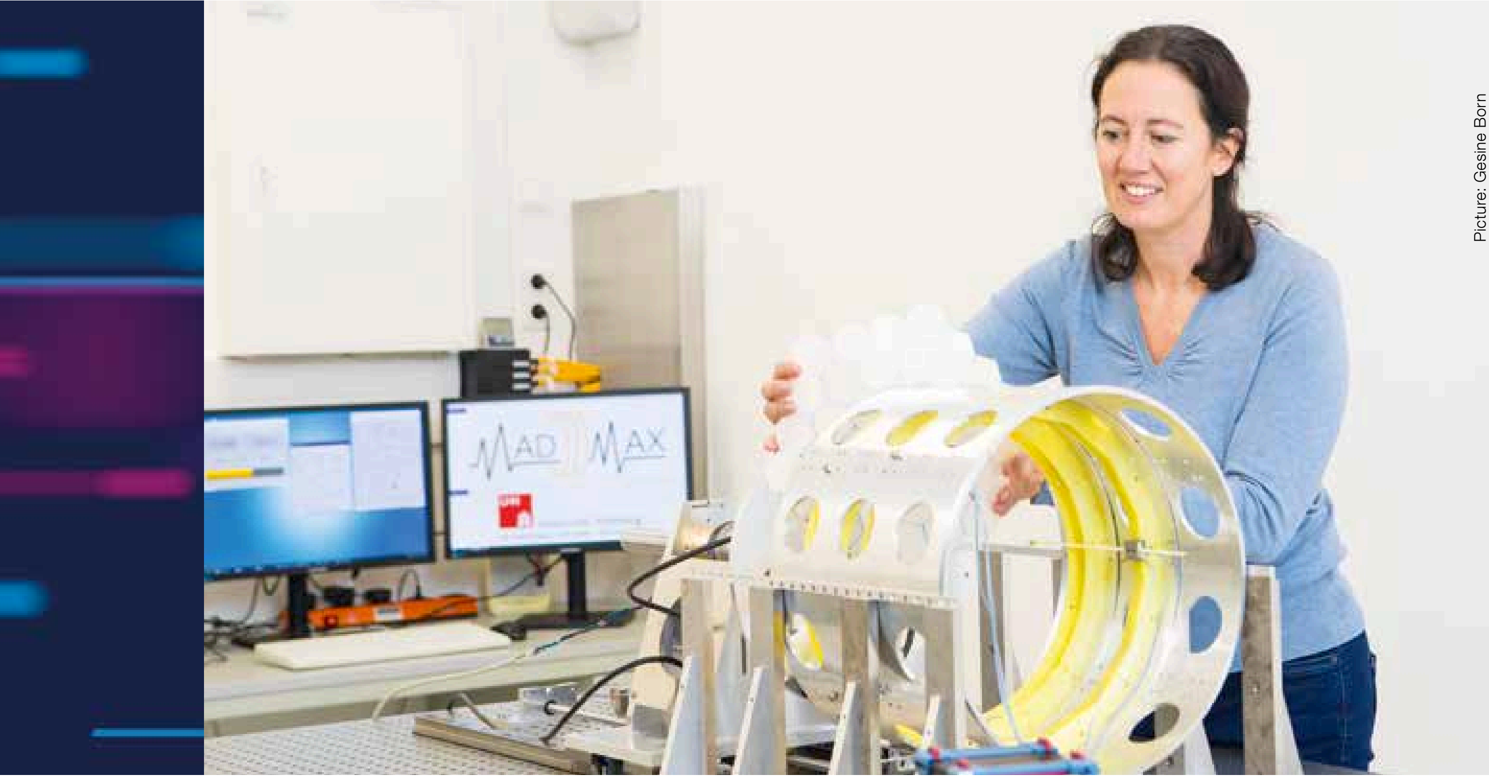
Joachim Mnich
Director in charge of Particle Physics

“Our universe continues to pose many riddles: What is dark matter? Where is the antimatter? What exactly is the origin of the mass of elementary particles? What is the common origin of all fundamental forces? Our particle physicists are working on the front line both in the major experiments around the world and on theoretical models. Thanks to its excellent infrastructure and expertise, DESY is the national laboratory for particle physics and in strong demand as a partner for international collaborations.”

Picture: Heiner Müller-Elsner

“The Center for Optical Quantum Technologies at Universität Hamburg is working on the components of a quantum computer, and particle theoreticians can develop algorithms that will actually run on such systems”

Volker Schomerus, DESY



Picture: Gesine Born

Very versatile

Erika Garutti develops detectors for applications ranging from exploring the universe to diagnosing cancer

Whenever Erika Garutti wants to enter her new laboratory, she has to get past a solid wall of reinforced concrete, three metres thick. Inside the bunker stands a second building – a cube with a massive metal door. The professor of physics at Universität Hamburg heaves it open and points to the walls. "Fine copper netting is embedded in the walls, shielding the inside from any type of electromagnetic radiation," she explains and laughs: "This is the quietest room in Hamburg." No mobile phone will ever start ringing here – the radio waves simply cannot get inside.

The research bunker on the Bahrenfeld campus is called SHELL, short for Shielded Experimental Hall. Its inside is completely new, funded by the cluster of excellence "Quantum Universe" at Universität Hamburg. The conditions here are perfect for Garutti's experiment: In a project named MADMAX, an international team is hoping to track down the axion, a particle whose existence is so far just hypothetical. This tiny oddball could be the answer to one of the biggest mysteries in physics: dark matter. According to the prevailing scientific opinion, this invisible form of matter holds together galaxies and has also played a key role in the evolution of the universe. However, it remains completely unclear what dark matter is made of. Theoretical physicists have proposed dozens of candidates, one of which is the axion – und MADMAX could track it down within a few years.

> "Motors capable of doing that still have to be developed"
>
> **Erika Garutti, Universität Hamburg**

"When I first heard about this project, I immediately thought: That's right up my street, I'd like to be a part of that," Garutti recalls. "Unfortunately, I'd misunderstood that this was not about a type of detector I was familiar with, but a completely different kind." Nevertheless, she accepted the challenge, and now she and her team are developing a detector that is meant to record the ghostly particles. The idea is that, using a total of 80 discs made of a material called lanthanum aluminate, placed in an evacuated tank and cooled to the temperature of outer space, axions might be made to transformed into microwaves on being exposed to a strong magnetic field. Detecting these extremely weak microwaves requires special radio antennas – a huge metrological feat.

"This is the quietest room in Hamburg"

Erika Garutti, Universität Hamburg

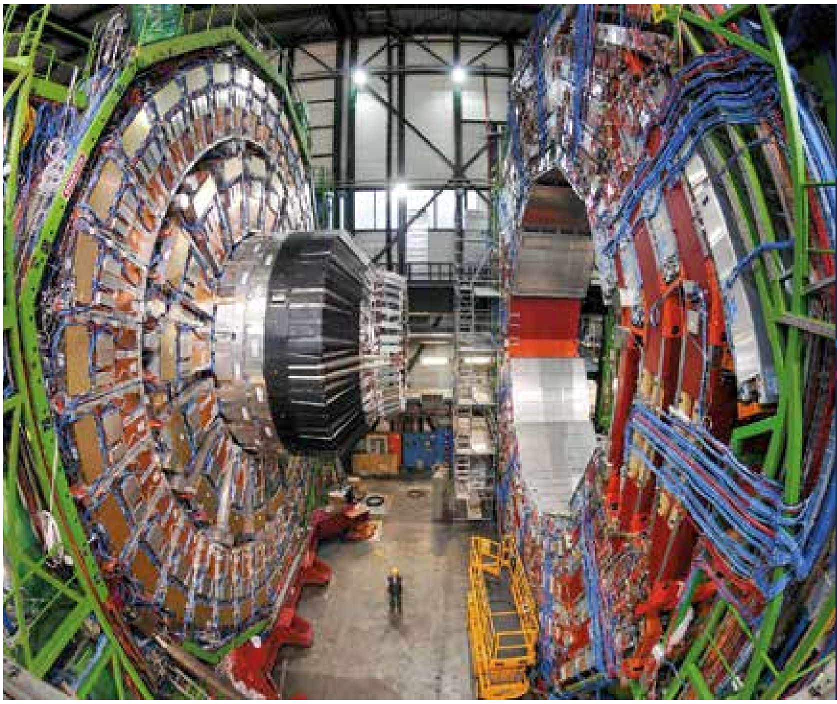
"The disks weigh six kilograms, and we need to position them inside the vacuum tank to within ten micrometres," explains Garutti. "Motors capable of doing that still have to be developed." The technology is so sophisticated that the experts first intend to test it using a small prototype. Garutti opens a drawer and takes out one of the test disks, the size of a vinyl record. "We want to try them out in this room at the end of 2020, followed by further tests at CERN in Geneva," she explains. "The actual, full-scale experiment will then take place at DESY, in one the underground halls of the former HERA accelerator. It could begin in 2025." This makes Hamburg a major centre for axion research: In addition to MADMAX, further experiments are to hunt for these ghostly particles over the coming years, including DESY's ALPS II experiment.

Erika Garutti then goes on to speak about her other projects. Her team is currently developing special silicon counters for the CMS detector at CERN. This is located at the LHC, the world's largest accelerator, where it analyses whether exotic particles, such as the Higgs boson, are formed during collisions between ultrafast protons. Over the coming years, the LHC will be upgraded to produce substantially more collisions and hence more data. Accordingly, the CMS detector must also be upgraded, among other things by installing higher-performance silicon counters to record the trajectories of the particles created during the collisions. "We are currently testing our newly developed counter at a test beam here at DESY," Garutti reports. "By 2026, the fully refurbished CMS detector should power up."

But the detector technology that the physicist is working on is not only intended to serve pure fundamental research; it could also be used in medicine. Together with doctors and biochemists, Garutti's team has created the basis for a novel type of endoscope, as part of an EU project. The new device is to combine two different imaging techniques – ultrasound and PET (Positron Emission Tomography). One day, this technology could help doctors to perform minimally invasive surgery on pancreatic tumours. The endoscope could be navigated around the body using ultrasound, while PET could be used to locate the cancer cells. "The closer the PET detector is to the pancreas, the more precisely the tumour can be identified and located," explains Garutti.

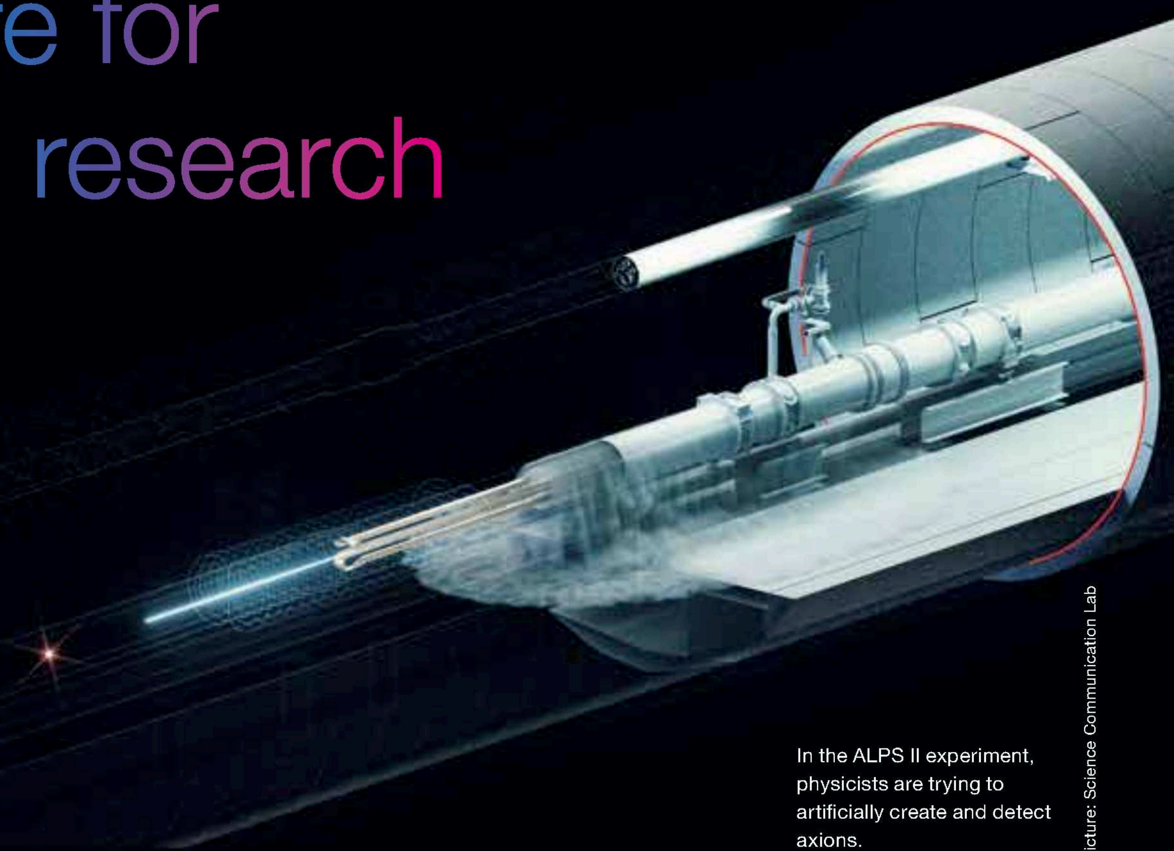
Her team is developing a miniaturised PET detector based on the silicon counter technology. "The prototype works, so the principle is feasible," says Garutti. "What we haven't managed to do so far, though, is to install the PET detector inside an ultrasound endoscope – this will have to be done by a company." Although several manufacturers of endoscopic devices have expressed an interest, in the end they were not prepared to pursue the unfamiliar PET technology. Nevertheless, a number of results from the project have made it to the market – new biomarkers, for example, which specifically bind to pancreatic tumours, and special chips for reading out silicon counters, which are now used in a range of laboratories and are marketed by a spin-off company created specifically for that purpose. And Erika Garutti is far from having written off the basic idea of a new type of endoscope. "Doctors remain very interested," she says. "I still believe that one day industry will seize upon the idea."

The Compact Muon Solenoid (CMS) is one of the two gigantic particle detectors at the LHC that was used to discover the Higgs boson.



Picture: CERN

Centre for axion research



In the ALPS II experiment, physicists are trying to artificially create and detect axions.

Picture: Science Communication Lab

MADMAX is to trap axions using lanthanum aluminate.

Picture: Universität Hamburg, Kervin Saint Pere

Picturer: Universität Hamburg, Kervin Saint Pere

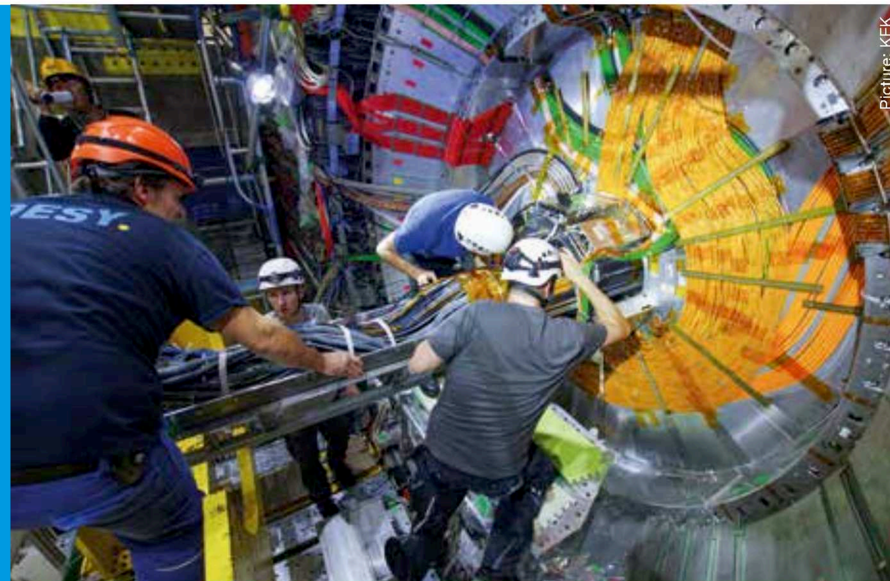
BRASS is lying in wait for the terahertz waves produced by axions.

An as yet undiscovered particle could solve one of the biggest mysteries in physics: Some theoretical physicists suppose that the axion could explain dark matter. This mysterious type of matter is over five times more abundant in the universe than the matter we are familiar with, and its gravitational force appears to be what holds galaxies together. If the axion does in fact exist, there could be prolific amounts of it throughout the universe, forming dark matter. On the research campus in Bahrenfeld, several experiments are setting out to prove the existence of these hypothetical exotic particles. This will make Hamburg a widely recognised centre for axion research.

One of the experiments is called ALPS II, and it is currently being set up in the underground tunnel of the former accelerator HERA. It will be based on 24 of HERA's old magnets, specially modified and lined up over a distance of 300 metres. The idea is to direct a high-precision laser beam through twelve of these magnets, reflecting it back and forth between mirrors. The hope is that axions will occasionally form inside this magnetic field. These would be able to pass through a lightproof wall, behind which the other twelve magnets will be positioned. The axion could then be converted back into light in their magnetic field, an event that would be registered by highly sensitive detectors. Data collection is due to begin in 2021. If ALPS II succeeds in detecting an axion, this would be a real sensation: It would be the first discovery of a particle beyond the Standard Model of particle physics.

Two further axion experiments are currently being prepared at the new SHELL laboratory run by Universität Hamburg. Its three-metre-thick concrete walls mean that it is largely shielded from all outside interference. One of the two rooms inside contains the test bench for MADMAX, which hopes to detect axions using disks made of lanthanum aluminate. In the room next door, the BRASS experiment is being set up. This uses reflectors with a diameter of two and a half metres, installed in chambers whose walls are partially magnetic. The idea is that if an axion strikes one of these walls, it could be converted into an electromagnetic wave in the gigahertz to terahertz frequency range. The large area of the reflector would allow it to register several of these waves at the same time and focus them on a high-sensitivity detector that would record them – using a technology adopted from radio astronomy. To further increase the measurement sensitivity, several of these chambers are to be operated in parallel.

On top of this, experts at DESY are already tinkering with plans for a further experiment: the International Axion Observatory (IAXO). This is to track the sun during the course of the day and thereby detect axions that may form inside the sun. A prototype called babyIAXO could go into operation in just a few years.



Picture: KEK

Precision work: An international research team installs the vertex detector in the “antimatter search engine” Belle II in Japan.

Detector development at DESY

Detectors are among the most important tools in particle physics. They observe what happens during collisions in an accelerator and are able to detect exotic particles like the Higgs boson. DESY is developing important components for ATLAS and CMS, the biggest detectors at the LHC in Geneva. Both these “particle cameras” are to be upgraded over the coming years in order to supply substantially more data.

In concrete terms, DESY is manufacturing the so-called end caps – large components, over two metres across, consisting of thousands of individual sensors. The Detector Assembly Facility (DAF) was recently opened in order to assemble and test these devices. The facility consists of two buildings fitted with ultramodern cleanrooms. To begin with, the DAF will be used for the upgrade of ATLAS and CMS, later it will help to develop new high-performance detectors. DESY is also involved in another accelerator experiment: The research programme at Belle II in Japan started in March 2019. The detector is located at the SuperKEKB accelerator, which produces huge quantities of particles called B mesons. Belle II observes the decays of these short-lived particles. Experts are hoping this will provide answers to one of the most exciting questions in physics: why there appears to be far more matter than antimatter in the universe.

The vertex detector is installed right at the heart of Belle II. It measures the precise position at which the particles created in the collisions are formed. Its innermost part was developed in Germany – a highly sensitive pixel detector the size of a soda can, which was thoroughly tested at DESY before being shipped to Japan.

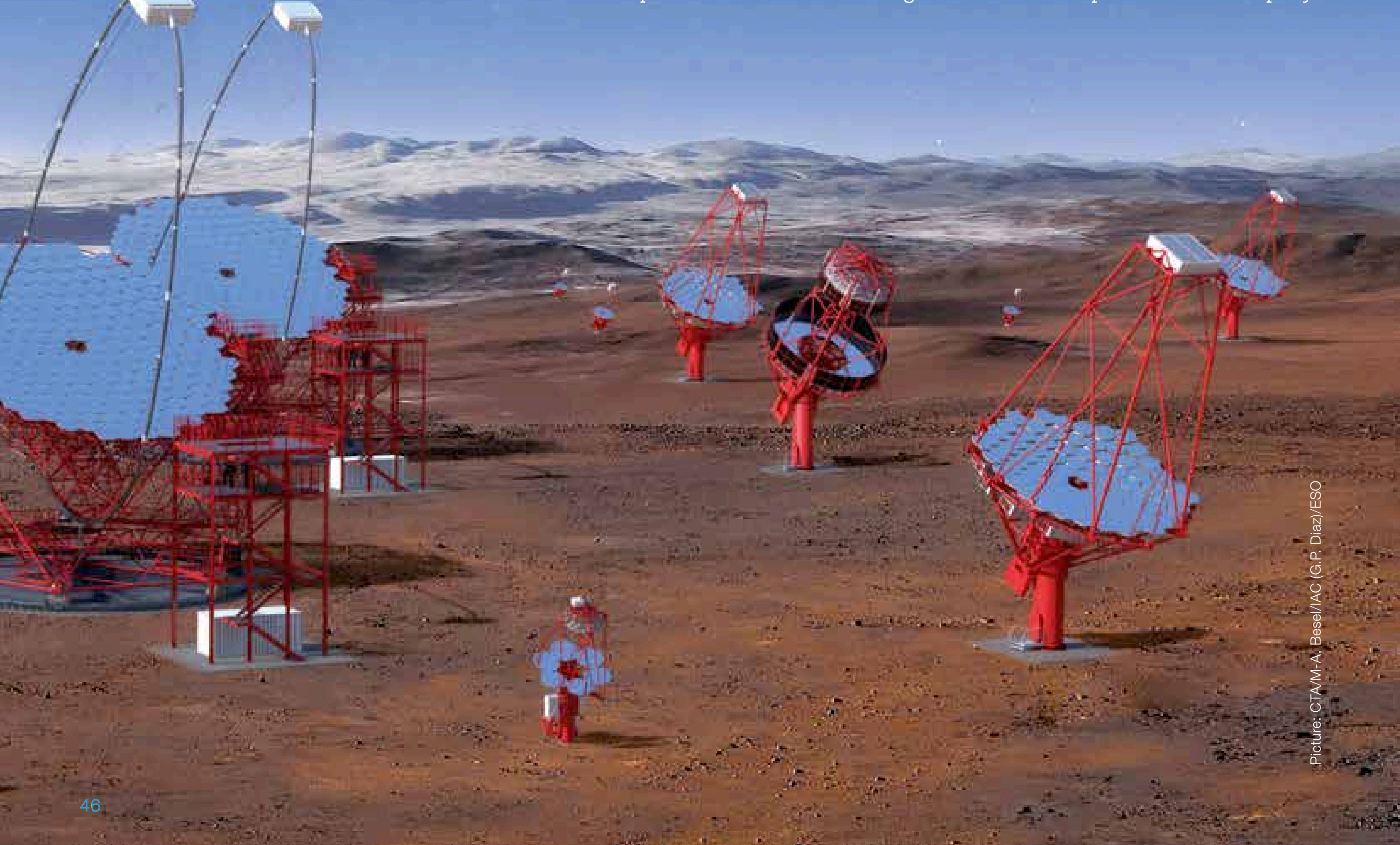
The astroparticle physics hub

At DESY's site in Zeuthen, near Berlin, scientists are searching for "cosmic messengers" that can afford new insights into our universe

Since the beginning of 2019, astroparticle physics has been a dedicated research division at DESY. Two major international projects, in which DESY's Zeuthen site on the outskirts of Berlin is instrumentally involved, are central to its work: In the Antarctic, the giant detector IceCube is lying in wait for neutrinos from space; while in Chile and on the Canary Islands, an international team is setting up the Cherenkov Telescope Array (CTA), the largest observatory of its kind anywhere in the world.

"CTA is to consist of around one hundred individual telescopes and will look for gamma rays from space," explains DESY physicist Markus Garczarczyk. Gamma rays are extremely high-energy electromagnetic waves that are produced, among other things, in supernova explosions and collisions between stars. CTA exploits the fact that, when such a gamma-ray pulse strikes Earth's atmosphere, it triggers an avalanche of particles. These in turn produce faint blue flashes of light, known as Cherenkov radiation. Several telescopes distributed across a site register this light. The observational data allows the scientists to calculate the direction from which the gamma-ray pulse arrived as well as its strength.

The CTA team wants to use these measurements to bring to light new details about supernovae, binary stars and black holes. Which mechanisms are able to accelerate particles to such extremes that they emit such high-energy gamma rays? In addition, the observatory is to search for traces of dark matter. And perhaps it can contribute to a better understanding of dark energy, the mysterious energy that appears to be causing the universe to expand ever more rapidly.



Picture: CTA/M-A. Besel/IAC (G.P. Diaz)/ESO

CTA will consist of different types of telescopes, most of which should be ready by 2025. The largest of these have a mirror diameter of 23 metres. Additional medium and small telescopes specialise in specific energy ranges. In order to be able to observe the whole sky, two sites are planned – one on the Canary Island La Palma, the other in Chile. DESY has a one quarter share in CTA and is responsible, among other things, for developing the control software and for building the 40 mid-sized telescopes. In addition, Zeuthen is to become the site of the Science Data Management Centre, making it the gateway to CTA for the scientific world: The centre will process the plethora of observational data and make it available to the scientific community.

The world's largest neutrino detector is located at the South Pole. This inhospitable place offers ideal conditions for detecting neutrinos, ghostly elementary particles that race through space in vast numbers but scarcely interact with matter along the way. For scientists, they can serve as cosmic couriers carrying unique messages. Tracking them down calls for a huge detector – IceCube, deployed inside the three-kilometre-thick ice cap at the South Pole. On very rare occasions, a neutrino will collide with an atomic nucleus in the ice, producing a bluish glow that can travel through the ice unimpeded. Distributed throughout a volume of one cubic kilometre of ice are more than 5000 sensors, each the size of a basketball, that capture the light signals. ››

Christian Stegmann
Director in charge of Astroparticle Physics

"As a result of some spectacular research results, astroparticle physics has developed into a promising field of research for DESY in recent years – particularly at our campus in Zeuthen, where we bring together outstanding expertise in the field of neutrino and gamma-ray astronomy as well as in theoretical astroparticle physics. The aim of our global collaboration is to gain a better understanding of the role of high-energy particles and processes in the development of the universe. We are on the threshold to a golden age of astronomy with a range of different cosmic messengers. The combination of gamma rays, cosmic neutrinos and gravitational waves offers us completely new insights into the origins and evolution of our universe."

The new building to house the CTA Science Data Management Centre will give DESY's Zeuthen campus a new face.

"That would give us one telescope in the south and one in the north, which would be ideal for astronomy"

Marek Kowalski, DESY

Installation began in 2005 and took until 2010. Three years later, IceCube succeeded in recording the first two cosmic neutrinos, and in the meantime it has registered more than 100. In September 2017, it achieved a special measurement: IceCube had picked up a high-energy neutrino whose direction of origin could be determined with great precision. In response, telescopes all around the world took a closer look at the region in question and discovered a special object: a blazar, a black hole in the constellation Orion that accelerates huge amounts of matter, including neutrinos, and hurls them out into space.

This means that scientists now have a new early warning system that can tell them when something exciting is happening in the universe. Colliding dead stars, supernovae, cosmic particle accelerators – in future, neutrinos will be able to reveal additional details about such extreme processes. In order to exploit the possibilities more completely, the experts are planning to expand the IceCube detector. "It will no longer be one cubic kilometre in size, but ten cubic kilometres," explains DESY physicist Marek Kowalski.

To this end, another 10 000 sensors are to be sunk into the Antarctic ice. This would allow neutrinos with even higher energies to be picked up. "IceCube-Gen2" could go into operation some time around 2025. By then, a second detector, called KM3NeT and stationed in the Mediterranean, could also start listening for neutrinos. Since it would cover a different part of the sky from that monitored by IceCube, the two would complement each other. "That would give us one telescope in the south and one in the north," says Kowalski, "which would be ideal for astronomy."

IceCube is installed beneath the ice at the Amundsen–Scott South Pole Station, where computers collect and filter the data from the detectors before sending them on to be analysed.

Picture: Sven Lidstrom, IceCube/NSF

The particle hunter

Markus Ackermann travels to the South Pole in search of cosmic neutrinos

There is no other place like it." When Markus Ackermann thinks of the Antarctic, it brings back some special memories. The physicist normally works at DESY's Zeuthen site but has travelled to the southern end of the world many times, to spend weeks doing research there. The Amundsen–Scott South Pole Station is operated by the USA. In the Antarctic summer, which lasts from November to February, some 130 experts throng to it – polar researchers, geoscientists, climatologists and astrophysicists like Ackermann. He is a member of the team that runs IceCube, a huge detector in the Antarctic ice that is looking out for cosmic neutrinos.

"Just getting there is an adventure," he reports. "You fly from New Zealand to McMurdo Station, a kind of logistics centre for the Antarctic." First, you have to take a training course about living and surviving in the Antarctic, before you travel on to the South Pole in a US transport plane. The planes can only fly to the station during the three months of the Antarctic summer. During the remaining dark months, an overwintering team holds the fort – and has to fend for itself.

On landing at the station, you first need to acclimatise. "The South Pole lies on a layer of ice three kilometres thick," Ackermann says. "To begin with, you tend to be rather short of breath." Another thing that takes some getting used to is that daylight goes on round the clock, with the sun always at the same altitude. "You lose all sense of the time of day," says Ackermann.

> "The South Pole lies on a layer of ice three kilometres thick. To begin with, you tend to be rather short of breath"
>
> Markus Ackermann, DESY

"There is no difference between day and night shifts." Also, the air at the South Pole is so dry that static charge keeps building up – you are constantly receiving small electric shocks. And then there's the cold: Even at the end of December, when the sun is at its highest, it never gets warmer than minus 20 degrees Celsius. Time and again, outdoor temperatures drop to minus 30 or even minus 40 degrees. Even brief excursions into the snow desert can be a strain. And in cloudy conditions, the horizon between the ice and the sky vanishes almost completely. "The only thing you see when you look into the distance is white nothingness," recalls Markus Ackermann. "After four weeks, I was just longing for the colour green – for surroundings that included plants and some signs of nature." So, as exciting as every research trip to the South Pole may have been, he has always been happy to return to his office at home – which lies right on the picturesque shores of the lake Zeuthener See.

Picture: Gesine Born

The enablers

Hundreds of experts help to ensure that DESY's infrastructure is ideally set up for the campus of the future

DESY is an internationally outstanding venue for top-class research and is undergoing extremely exciting and dynamic developments. One prerequisite for this is a highly effective infrastructure that provides scientists from all over the world with a professional setting, offering services ranging from a broad spectrum of organisational and technical support through to library, canteen and guest services. The DESY experts in personnel management, procurement, construction and building management need to focus on needs and solutions, and must deal with the challenges of a growing campus that encompasses many different collaborations and institutions. With its accelerators, DESY has always gone to the very limit of what is technologically achievable. To do so, its in-house workshops construct purpose-built equipment, ranging from highly specialised electronic measuring and control devices through to precision mechanical components. A high-performance IT infrastructure that is capable of coping with the rapidly growing volume of data involved in scientific analyses is also crucial in all areas.

Providing the services that support the research activities at the two DESY sites, in Hamburg and Zeuthen, means that the living and working conditions in all the relevant areas must constantly be checked and adjusted to take account of potential improvements. This includes state-of-the-art laboratories and offices, sustainability issues as well as the social and family needs of employees and guests.

"In the mechanical engineering training at DESY, I learn a wide variety of manufacturing techniques and am thus excellently prepared for future tasks"

Willi Herhold, Mechanics Workshop

"It is exciting to work with people from all over the world at DESY"

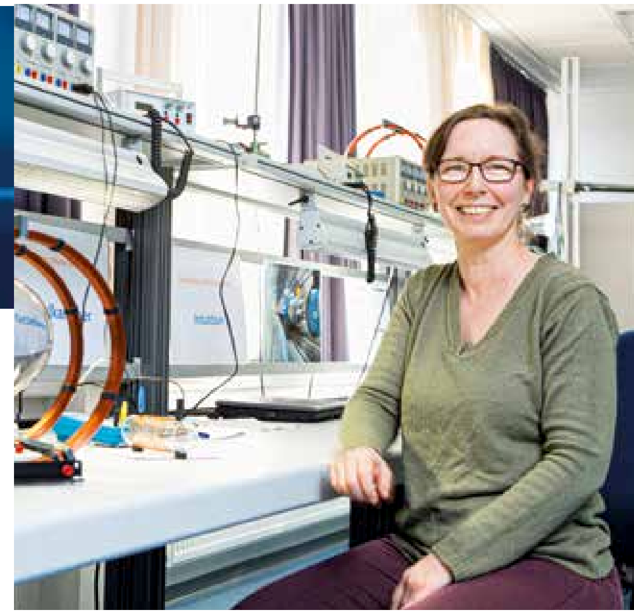
Sandra List, Secretariat

"As a purchaser at DESY, I am faced with exciting and challenging procurement projects every day"

Stefan Frank, Purchasing and Materials Administration

"With our development department, I am working to expand the Zeuthen campus as part of DESY into an influential research location"

Stefan Klepser, Deputy Director Astroparticle Physics



"In the DESY school lab, I am overjoyed, day after day, to see children and young people become entranced with the incredibly exciting world of research"

Karen Ong, School Lab

The personnel development, vocational training and recruitment staff work together hand in hand to continue to win over the best talents for DESY and ensure the on-going development of its employees' professional and personal potential. DESY is also involved in promoting young scientists on many different levels – starting with children and teenagers, who are given exciting glimpses into the natural sciences at the school labs in Hamburg and Zeuthen, through to a wide range of offers for young academics as well as the opportunity to do highly qualified training courses in a range of technical vocational professions. At the same time, DESY opens its doors to interested members of the public almost every day – whether in the form of guided tours, scientific lectures or the open day that is held once every two years and that fills tens of thousands of visitors with enthusiasm for DESY's research.

"At DESY, we take the health of our employees very seriously"

Natascha Peleikis, Health Management

"I appreciate DESY's excellent networking with other laboratories in Europe and the growing interest in EU-funded projects, especially among young scientists."

Ute Krell, EU Office

Pictures: Gesine Born

City of science

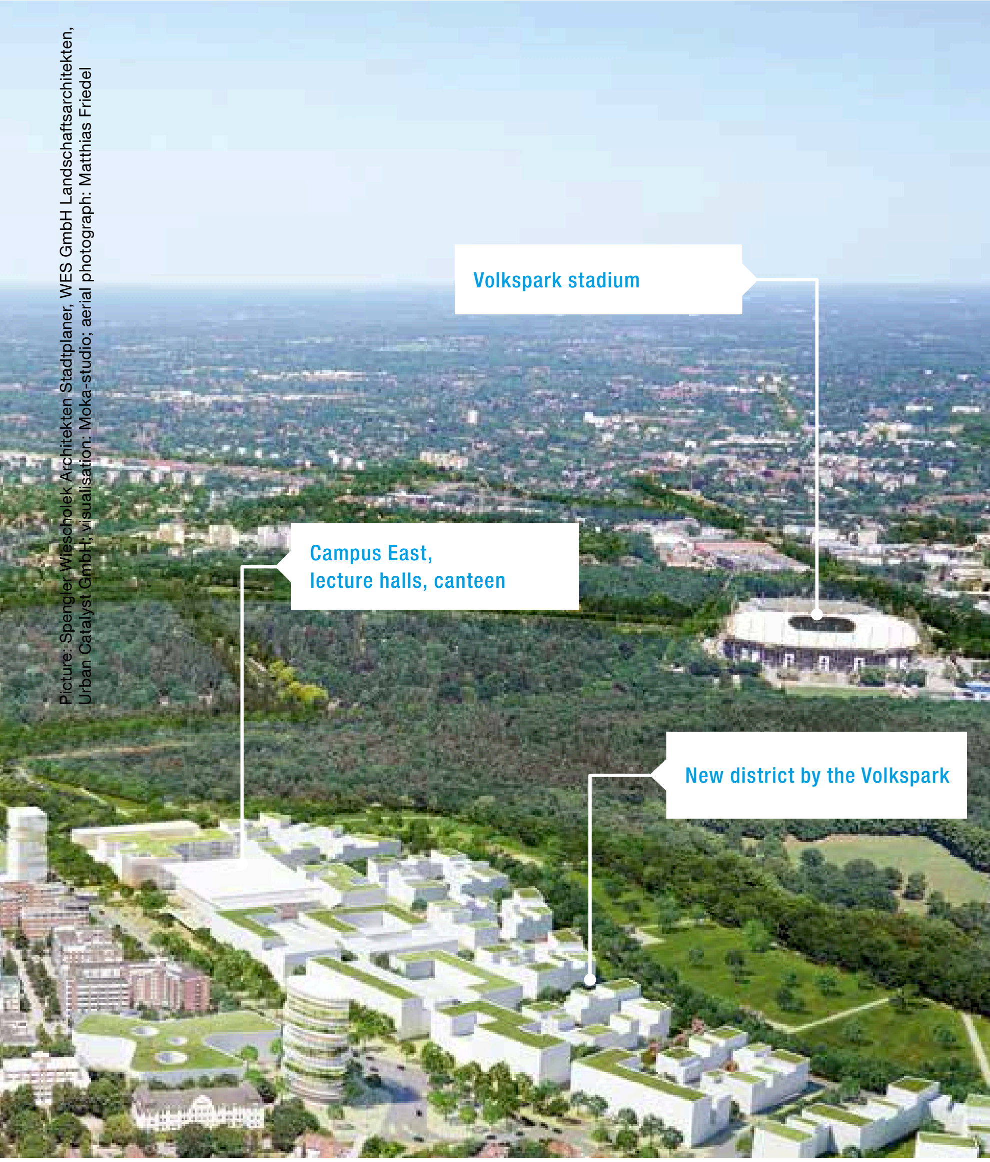
Together with DESY and Universität Hamburg, the City of Hamburg is planning to establish an innovative district by the name of Science City Bahrenfeld, bringing together science, business and quality of life

From the time it was first set up, DESY has successfully acted as an initiator of and partner for cooperations. Over the years, a number of different institutions have settled on the research campus in Bahrenfeld, including institutes from Universität Hamburg and the Max Planck Society. In future, this development will be expanded even further. For example, an Innovation Centre is currently being set up for start-ups and founders of businesses. This is a first milestone for a ground-breaking new venture: Over the next few decades, a new science district is to be created in the form of the Science City Bahrenfeld, a unique undertaking in Germany. The project seeks to closely link science, business and housing in the new district and become a model of modern urban development.

For start-ups…

The Innovation Village, which opened its doors at the beginning of 2019, already now offers young high-tech companies some 1000 square metres of office space, workshops and laboratories. They are used primarily by young scientists who are developing ideas arising from DESY's fundamental research and turning them into marketable products. The new Innovation Centre – a joint venture between DESY, Universität Hamburg and

Picture: Spengler Wiescholek Architekten Stadtplaner, WES GmbH Landschaftsarchitekten, Urban Catalyst GmbH; visualisation: Moka-studio; aerial photograph: Matthias Friedel



DESY lies at the heart of the Science City Bahrenfeld.

Picture: Heiner Müller-Elsner

Christian Harringa
Administrative Director

"In developing the campuses in Hamburg and Zeuthen, DESY is making a crucial contribution towards developing excellent venues for doing science, linking research, innovation and residential housing in close vicinity. In this way, we are not only providing attractive working conditions for the already more than 2500 DESY employees from over 60 different nations; we are also supporting the sustainable development of pioneering urban campus concepts. In future too, we want to win over the best minds for DESY and actively support young talents. To this end, we are creating the best possible conditions with the construction of the Science City Bahrenfeld in Hamburg and the national hub for astroparticle physics in Zeuthen."

the City of Hamburg – will add another 2600 square metres in 2021. The centre will offer start-ups in the fields of life sciences, biotechnology, nanotechnology and intelligent materials ideal conditions for development – including the possibility of collaborating with teams involved in top-class research and using the world's leading X-ray sources, located just round the corner.

"The Innovation Centre is an important component of our vision for a new science district: the Science City Bahrenfeld," Katharina Fegebank, Hamburg's Senator for Science and Deputy Mayor, pointed out at the ground-breaking ceremony for the new building. "It offers intelligent minds the necessary infrastructure to turn scientific insights into spin-offs and products. This benefits both Hamburg as a science hub and its citizens – because the future of a site depends on a successful exchange between science, society and business, and on converting new ideas into concrete products and services." ››

For teaching and research…

The Science City Bahrenfeld is to cover an area of some 125 hectares surrounding the DESY campus. The underlying concept rests on several pillars: It envisions a further expansion of DESY, for example the upgrade of PETRA III to PETRA IV, an ultramodern X-ray source with great innovative potential. Citizens who are interested in science will also benefit: As from 2023, the new multi-purpose building DESYUM near the entrance to the campus is to become a central point of contact for visitors, employees and guest researchers. It will also house DESY's new visitor centre. Two storeys will be set aside as a multipurpose area for different events and an exhibition providing information about the research carried out at DESY.

Several departments from Universität Hamburg are also to move to the Science City Bahrenfeld. More than 5000 students of physics, chemistry, nanoscience and biology would benefit from modern lecture halls and laboratories as well as from the close proximity of leading international research facilities and experts. In addition, plans are being developed for numerous new institutes and collaborations on and around the DESY campus, such as the Center for Data and Computing in Natural Sciences (CDCS) for scientific computing and the interdisciplinary Centre for Molecular Water Science (CMWS).

> "The future of a site depends on a successful exchange between science, society and business, and on converting new ideas into concrete products and services"
>
> **Katharina Fegebank, Hamburg's Senator for Science and Deputy Mayor**

The planned multipurpose building DESYUM will be the central point of contact for visitors, employees and guest researchers. It will also house DESY's new visitor centre.

The Innovation Centre will offers some 2600 square metres of office and laboratory space for business founders and start-ups.

For innovation…

Furthermore, the new district will ensure a close interlinking of science and business: The Innovation Park Altona will offer start-ups and research-oriented companies a setting that is both creative and productive. Also, an integrated Technology and Start-up Centre for life sciences, biotechnology, nanotechnology and new materials will create a space where ideas arising from science can become innovations for businesses, through close and regular cooperation. The Technology and Start-up Centre is to be established at two sites, on the DESY campus and in the Innovation Park Altona.

“Housing, science and innovative business are at the heart of an urban development plan that is unique in Hamburg”

Dorothee Stapelfeldt, Hamburg’s Senator for Urban Development

For everyone...

Finally, some 2500 new flats are to be built in the immediate vicinity, on the former harness race-course and the adjacent areas to the east. The neighbouring Volkspark, Hamburg’s biggest recreational park, and sports facilities as well as access to the urban railway network, innovative transport concepts and the expansion of recreational and leisure spaces will make the Science City Bahrenfeld an attractive place to live. “Housing, science and innovative business are at the heart of an urban development plan that is unique in Hamburg,” Hamburg’s Senator for Urban Development Dorothee Stapelfeldt pointed out when the concept was presented.

This will make the Science City Bahrenfeld a unique district in Germany for international top-class research, for the high-level training of the next generation of scientists and for the transfer of research findings to business and society. The concept has been developed jointly by the Hamburg authorities of science, economics, environment and energy, urban development and housing, the district administration of Altona, DESY and Universität Hamburg.

Picutre: Werner Bartsch

Arik Willner
CTO, Associate Director for Innovation

“Innovation and technology transfer have become enormously important at DESY. Based on the fundamental research we carry out, we develop new ideas, applications and products, which benefit science, business and society equally. We are a dependable and interesting partner for industry and enable new high-tech start-ups to be established. Together with our local partners, we are expanding our sites in Hamburg and Brandenburg to become hotspots for ideas and innovation.”

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Building boom

Today, there are 267 buildings on the DESY campus in Hamburg-Bahrenfeld – an ever-growing little research town. When the eponymous particle accelerator DESY went into operation in 1964, the research centre got by with 25 buildings, less than a tenth of the number existing today. The grounds and the layout were much more straightforward back then. In addition to the 267 existing building, five new ones are currently under construction: the Innovation Centre, the Centre for X-ray and Nano Science, the Max Planck Institute for the Structure and Dynamics of Matter, the Hamburg Advanced Research Centre for Bioorganic Chemistry and a school lab to be run by Universität Hamburg. Further buildings are already being planned.

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The DESY research centre

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

DESY is a member of the Helmholtz Association, Germany's largest scientific association.

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