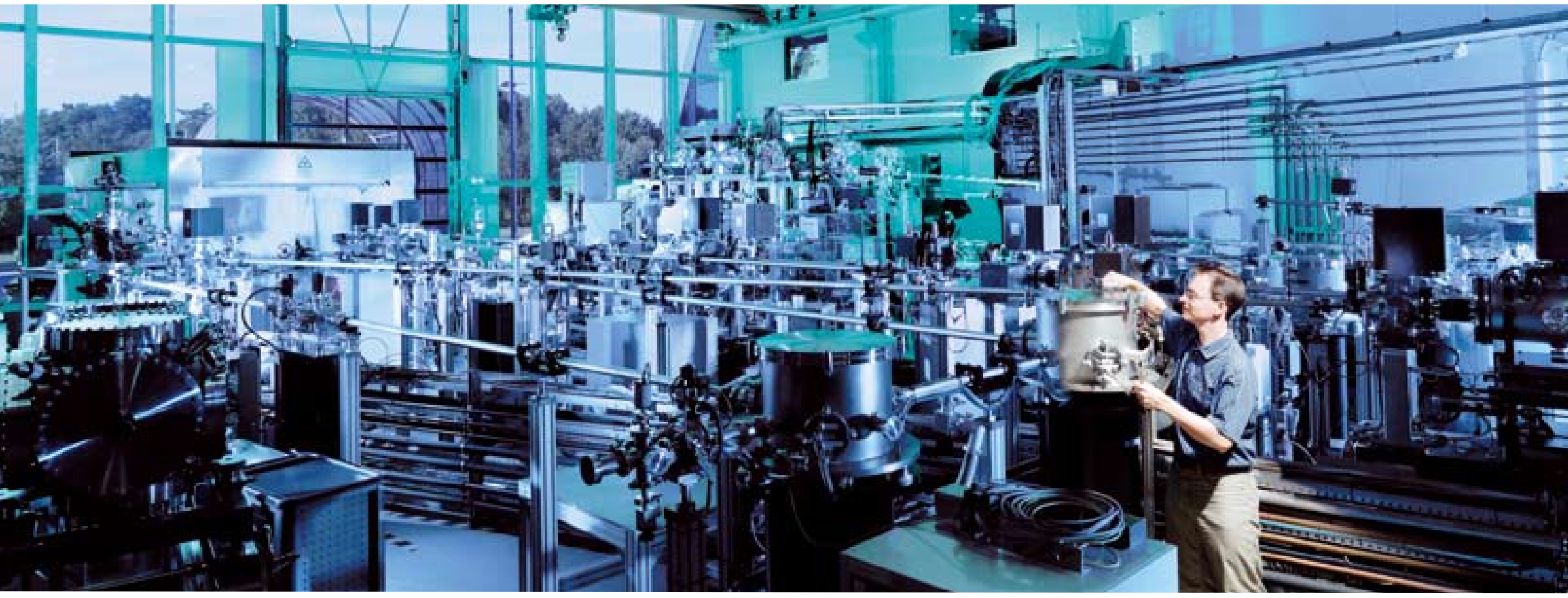
HIGH LIGHTS.

DESY generates pulses of brilliant light for a deeper insight into the structure of matter



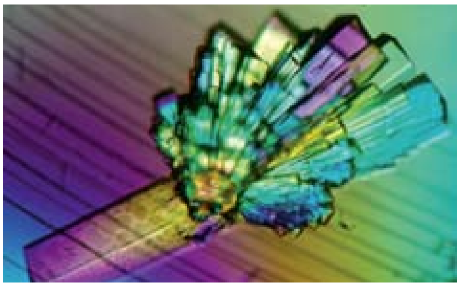
Particle accelerators generate a special kind of light that can illuminate tiny details of the microcosm. Here at DESY scientists from around the world use this light to investigate the atomic structure and reactions of promising new materials and biomolecules that might one day serve to make groundbreaking new drugs. DESY's unique spectrum of light sources makes it one of the world's leading centres for science with photons.

Accelerator | Photon Science | Particle Physics

Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

Work in the FLASH experimental hall at DESY

CONTENTS.


DESY.

Insight starts here

DESY is one of the world's leading accelerator centres for investigating the structure of matter. DESY develops and builds large particle accelerators and conducts research in the fields of photon science and particle physics – this combination is unique in Europe.

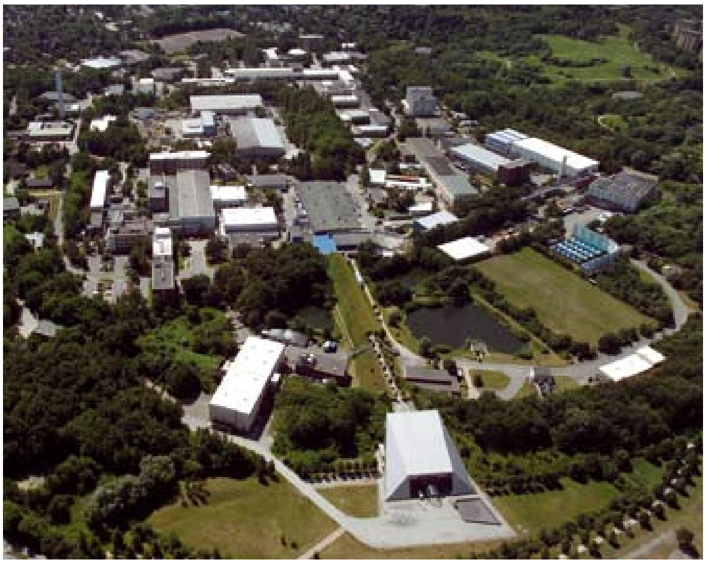
DESY carries out fundamental research in a range of scientific fields and focuses on three principal areas:

> Accelerators:
DESY develops and builds large facilities that accelerate particles to extremely high energies.

> Photon science:
Physicists, chemists, geologists, biologists, medical researchers and material scientists use the special light from DESY's accelerators to study structures and processes in the microcosm.

> Particle physics:
Scientists from around the world use DESY's accelerators to investigate the fundamental building blocks and forces of the universe.

The spectrum of research at DESY is correspondingly diverse – as is the cooperation with partners both national and international. All in all, some 3000 scientists from 45 countries come to Hamburg each year to work at DESY. The research programme is not restricted to the facilities in Hamburg and Zeuthen. Indeed, DESY is closely involved in a number of major international projects, including the European X-ray free-electron laser XFEL in Hamburg, the Large Hadron Collider LHC in Geneva, the neutrino telescope IceCube at the South Pole and the International Linear Collider ILC.



DESY facts and figures

- **Deutsches Elektronen-Synchrotron DESY**
- **A research centre of the Helmholtz Association**
- **A publicly funded national research centre**
- **Locations: Hamburg and Zeuthen (Brandenburg)**
- **Employees: 1900, including 200 in Zeuthen**
- **Budget: 170 million euros (Hamburg: 154 million; Zeuthen: 16 million)**

Computer simulation of particle acceleration

Accelerators

The development of particle accelerators involves special challenges for both humans and machines. Time and again it is necessary to push back the frontiers of science and technology. Over almost 50 years DESY has accumulated vast experience of accelerator development and is now one of the world's leading authorities in this field. DESY focuses on two principal areas of research:

- The development of light sources for science with photons in order to enable structures and processes to be observed on extremely small space and time scales. To this end, particles are first accelerated and then deflected by means of large magnetic structures in such a way that they emit a special form of radiation.
- The development of increasingly powerful accelerators for particle physics research in order to accelerate particles to ever greater energies and thereby obtain deeper insights into the very heart of matter and the origin of the universe.

Photon science

The intense form of radiation generated by particle accelerators can illuminate even smallest details of the microcosm. It reveals the structure and reactions of materials and biomolecules. Scientists from around the world conduct experiments with this special light at HASYLAB, the Hamburg Synchrotron Radiation Laboratory at DESY. Both the existing and planned light sources offer excellent research opportunities:

- The DORIS III particle accelerator provides radiation suitable for a whole range of experimental purposes. This includes the analysis of catalysts and semiconductor crystals as well as research leading to the development of new drugs.
- Unique experimental opportunities are provided by the new free-electron laser FLASH, which generates extremely intense short-wavelength laser pulses.
- From 2009, researchers at DESY will have access to the world's best storage ring-based X-ray radiation source, PETRA III.
- The forthcoming European X-ray laser XFEL will complement the unique range of light sources in the Hamburg region.

Particle physics

On the trail of quarks, supersymmetry and extra dimensions – particle physicists at DESY inquire into the very structure of our world.

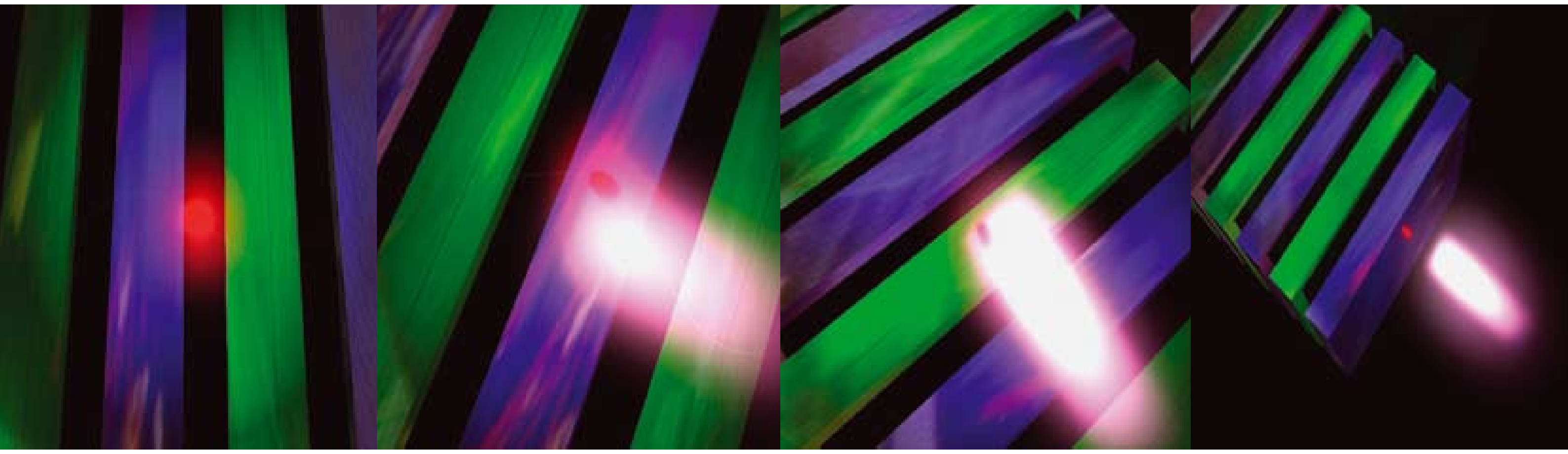
- Using data recorded with the "super electron microscope" HERA, an underground accelerator six kilometres in circumference, scientists investigate the structure of the proton and the fundamental forces of nature.
- Researchers will have unique opportunities to decipher the mysteries of matter, energy, time and space with the next major projects in the field of particle physics, in which scientists from DESY are also participating: the Large Hadron Collider LHC in Geneva, which is the world's most powerful accelerator, and the forthcoming International Linear Collider ILC.
- Using the neutrino telescopes AMANDA and IceCube at the South Pole, DESY researchers and their colleagues gaze into the vast expanses of the cosmos in search of ghost particles from space.

Meanwhile scientists in the field of theoretical particle physics are working at DESY to try and piece together the big picture that corroborates the host of experimental findings.

BEAM POWER.

Lighting up research

It's difficult today to imagine life without X-rays: For over 110 years this high-energy form of radiation has played a key role not only in medicine and materials sciences but also in fundamental research. The rapid improvement of X-ray sources has opened up new areas of application and unforeseen fields of research. Today this intense light, as generated by particle accelerators, is used by scientists all over the world for a variety of experiments. With its unique range of light sources, DESY is one of the leading research centres in the field of photon science.



A light for every purpose

Enormous progress has been made since the 1960s, the period when particle accelerators were first used to generate synchrotron radiation, particularly as a result of improvements to the electron storage rings. Indeed, the brilliance of the light from these sources has increased by a factor of 1000 every ten years! The ever improving quality of such X-rays has opened up completely new research opportunities for scientists – in areas such as the environmental sciences, for example, or even archeometry, the investigation of archaeological remains using scientific methods.

Pioneering experiments at DESY

From the very beginning DESY has been at the forefront of this extremely exciting development. A series of pioneering experiments have been carried out at DESY accelerators, including the first use of synchrotron radiation in the field of biology in 1971, the first measurements of Mößbauer spectra using synchrotron radiation (1984), the first direct measurement of phonons with X-rays (1986) and the first investigations of magnetism by means of X-ray absorption spectroscopy (1987). Most of these projects have been performed in close collaboration with university-based research groups. At the same time, this period also saw the introduction of the extremely successful policy of enabling major research institutions, such as the European Molecular Biology Laboratory EMBL, to set up their own outstations at DESY's synchrotron radiation sources. Each year more than 2000 scientists from around the world use the light sources at DESY to conduct experiments in the field of science with photons.

Light of the future

Modern synchrotron radiation sources are set to play a key role in the field of nanotechnology and related research. This is because they provide intense, tunable and very coherent X-rays on the nanometre scale. PETRA III, the world's best synchrotron radiation source in the hard X-ray range, is scheduled to go into operation in 2009. In conjunction with the DORIS III storage ring, which is especially suitable for experiments requiring a high photon flux and is therefore an ideal partner to PETRA III, this will provide the national and international user community with a unique combination of synchrotron radiation facilities.

Today's light sources are primarily suited for investigating equilibrium states of matter. Yet researchers also dream of being able to observe physical or biological systems as they work – i.e. to progress from still images to proper films. For this, however, the X-ray pulses generated by the storage rings are still too weak and, critically, too long compared to the time scales on which the processes of nature take place. The type of radiation required to record images at such a high temporal resolution can only be produced by totally new types of X-ray sources: X-ray lasers based on linear particle accelerators will achieve this goal. Again, DESY is one of the pioneers in this field.

Since 2005 researchers have had access to FLASH at DESY, to date the world's only free-electron laser in the soft X-ray range. Initial experiments with this facility have already yielded groundbreaking results that are now setting new standards for scientific investigation. Meanwhile, the European X-ray laser XFEL, which is being developed and prepared with strong participation of DESY, is scheduled to go into operation in 2013. With its unique combination of extremely high peak brilliance and very high average brilliance, the XFEL will break new ground in a vast range of exciting areas of both science and technology and yield first-time answers to thrilling scientific questions – despite the fact that similar facilities in Japan and the USA are scheduled to commence operation some three years earlier. Indeed, a further key advantage over competing facilities is that DESY is already successfully operating and using FLASH, the prototype for the XFEL, which will ensure that the European user community is ideally prepared for carrying out research with the new XFEL.

"With its many years of experience in science with photons and in accelerator development, and with its range of exceptional facilities together with the newly opened interdisciplinary Centre for Free-Electron Laser Science CFEL in Hamburg, DESY will continue to uphold and even extend its position at the very forefront of photon science."

Jochen Schneider

Prof. Dr. Jochen R. Schneider
DESY Director for Photon Science

LIGHT FLASHES.

How light originates from particles

The light produced by the DESY accelerators provides a broad spectrum of research opportunities for scientists working in physics, chemistry, geology, biology, materials science and medicine. The versatile radiation is generated by minuscule particles when they are accelerated to almost the speed of light.

In ring-shaped accelerators – so-called storage rings – the particles race around their circular path at almost the speed of light. In the process, they are accelerated towards the centre of the ring. Like the riders on a merry-go-round who are kept on their circular path by the chains of the carousel, the particles are deflected toward the centre by magnetic fields, thus ensuring that they continue to follow the curves of the storage ring. As a result of this radial acceleration, the particles emit a considerable part of their energy in the form of an intense, tightly collimated beam of light when passing through these bending magnets in the curves of the ring. It was back in 1947 that Floyd Haber, a technician at General Electric, first noticed a blinding light produced by an electron accelerator. As the accelerator was of the design called a synchrotron, this new type of light was henceforth known as synchrotron radiation.

Fact file: synchrotron radiation

The light from accelerator-based light sources

- **is extremely bright and intense**
- **consists of ultra-short flashes**
- **is tightly collimated and, in the case of a free-electron laser, even has laser-like properties**
- **contains all the colours of the electromagnetic spectrum ranging from infrared to X-rays**
- **is precisely calculable**
- **is linearly and elliptically polarized.**

Light from the ring

Synchrotron radiation is electromagnetic radiation with wavelengths ranging from infrared via visible and ultraviolet light to X-rays. Early experiments in the 1950s already revealed the extraordinary properties of synchrotron radiation and its suitability for investigating a whole variety of materials. Most valuable of all, synchrotron radiation is extremely intense, a property of special relevance for the X-ray region. The radiation from storage rings is of an intensity several orders of magnitude greater than that from conventional X-ray tubes. Moreover, the beam is very tightly collimated. Similar to sunlight – and unlike laser light, which is monochromatic – synchrotron radiation contains a continuous spectrum of wavelengths. Unlike a laser pointer, for instance, which emits a continuous beam, a synchrotron radiation facility produces a rapid sequence of ultra-short pulses of light, since the particles circulate in the storage ring in small bunches. This enables researchers to observe dynamic processes on the microcosmic scale. In addition, synchrotron radiation is polarized – i.e. the light oscillates only within certain planes. This property can be utilized for investigating magnetic materials, for example. Thanks to all these advantages, synchrotron radiation has become a major research tool.

Magnetic slalom

In today's storage rings synchrotron radiation is generated not only by means of the bending magnets used to hold the particles on their course, but also in long special magnet structures. These so-called wigglers and undulators consist of a series of alternating north and south magnetic poles. When electrons travelling at the speed of light race through this sequence of magnets, they are forced to follow a slalom course. Due to the large number of alternating magnetic poles, the electrons emit a much more intense beam of light than that produced within a single bending magnet. The use of a wiggler generates synchrotron radiation that is up to 100 times as intense as that produced with bending magnets. With an undulator, the light at certain wavelengths is as much as a thousand times as intense, since the wave trains interfere constructively with one another and are thus mutually reinforcing.

The straight and narrow

As next-generation light sources, free-electron lasers (FELs) produce radiation of an intensity several orders of magnitude greater than that from storage rings. Moreover, the radiation has the properties of laser light and is generated in ultra-short pulses, which opens up unique experimental opportunities.

Instead of a ring-shaped accelerator such as a storage ring, the new FEL radiation sources utilize a linear accelerator to boost the electrons to high energies. The accelerators for the FLASH and XFEL free-electron lasers are superconducting. This enables the generation of an extremely fine and homogeneous electron beam of extremely high quality, which is an absolute prerequisite for operating a facility of this kind in the X-ray region. Once the electrons have been accelerated to high energies, they travel through a long undulator, a recurring sequence of magnets that causes them to follow a rapid slalom course. In accordance with the SASE principle of self-amplified spontaneous emission, the radiation pulses emitted by the electrons as they pass through the undulator increasingly reinforce one another, thus resulting ultimately in the production of extremely short and intense X-ray flashes with laser-like properties.

Experiments with light

Stainless steel beam pipes under ultra-high vacuum serve to transport the synchrotron or FEL radiation from the magnetic structures in the accelerator – where it is generated – to the experimental stations, where the actual experiments are located. If required, so-called monochromators select the desired wavelength out of the beam spectrum. This beam then illuminates the sample – e.g. a crystal – and the subsequent reaction is captured by a variety of detectors. Powerful computers installed at the experimental stations and sophisticated programs are used to analyse the results. Each station is equipped for a specific experimental purpose and measuring method. ●

BROAD SPECTRUM.

Radiation sources at DESY

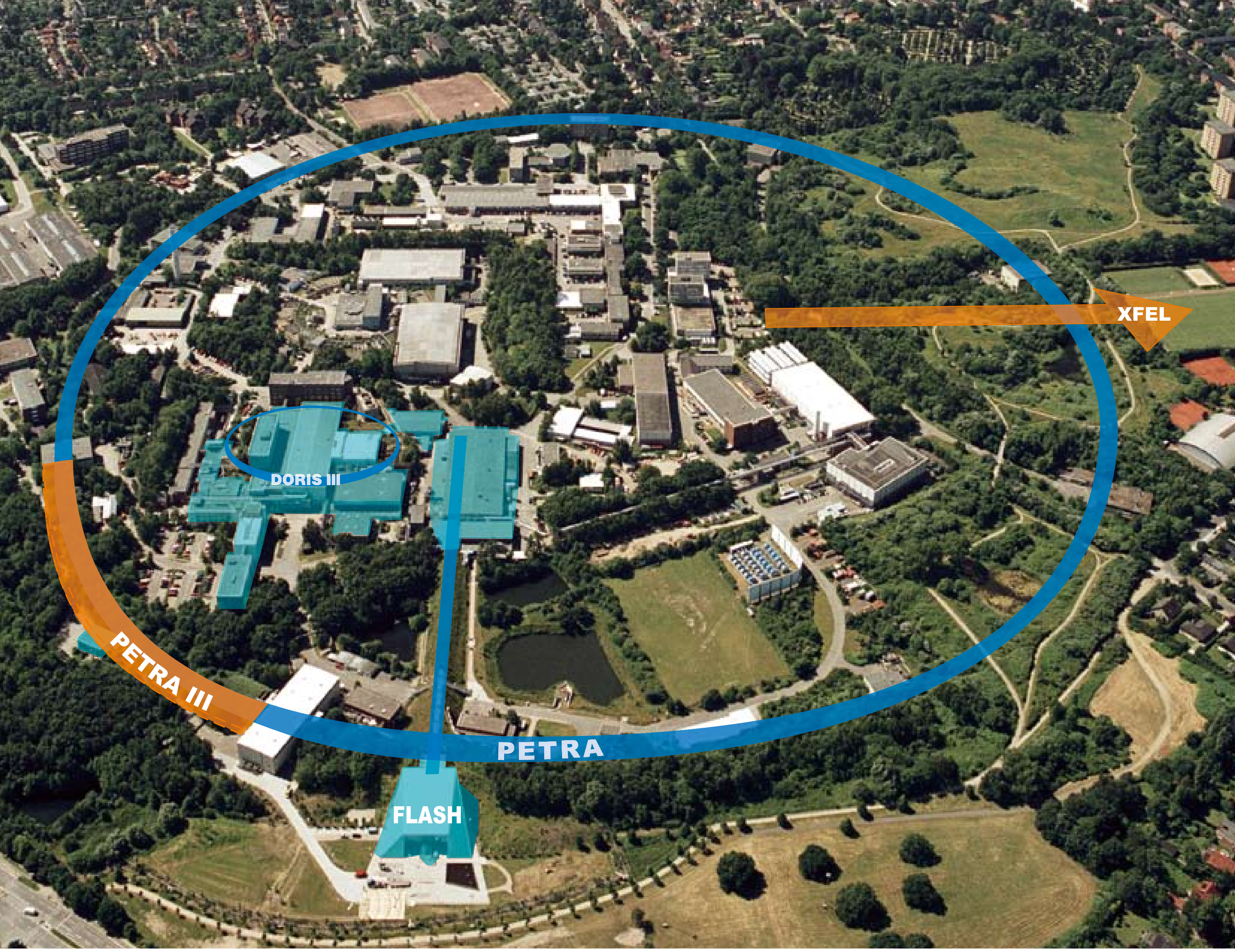
With its outstanding diversity of light sources, DESY is one of the world's leading centres for science with photons. Other similar research institutes typically have just one accelerator available as a light source, which is set up to provide specific radiation properties. At DESY, however, both the existing and planned light sources complement one another perfectly. Scientists working at DESY therefore have access to exactly the type of radiation they need for their experiments.

DORIS III

Almost 300 metres in length, the DORIS III storage ring has been in operation since 1974. Initially it was used in parallel for particle physics experiments and research with synchrotron radiation. However, since 1993 – following appropriate modifications – it has been solely operated to generate synchrotron radiation. DORIS III, the reliable "workhorse" among the DESY light sources, has a total of 36 experimental stations, with 45 alternately operated instruments, mostly for X-rays but also for ultraviolet radiation. This radiation is produced in the curves of the storage ring as positrons accelerated in DORIS III fly through the bending magnets that serve to hold the particles on their course. In addition, radiation of much higher intensity is generated when the particles race through long sequences of special magnets, so-called wigglers and undulators which force the positrons on a rapid slalom course.

PETRA III

For a number of years, the 2.3-kilometre-long PETRA storage ring was mainly used for particle physics experiments; it also provided test experimental stations with hard X-rays for science with photons. In the future, however, PETRA will be dedicated solely to generating light. In summer 2007 work began on the modification of the facility. Scheduled for completion in 2009, it will commence operation under the new name of PETRA III as one of the most brilliant storage ring-based X-ray radiation sources worldwide. Almost 300 metres of the ring are being completely rebuilt and a new experimental hall is being constructed. Current plans envision 14 experimental stations with up to 30 instruments. Here, once again, the installation of several specially adapted undulators delivering X-ray radiation of an especially high brilliance will guarantee excellent research opportunities for users from around the world.



FLASH

The latest addition to the range of light sources on offer at DESY is the FLASH free-electron laser, which commenced user operation in summer 2005. FLASH will remain unrivalled worldwide until 2009. The 260-metre-long facility is the world's first light source to deliver laser radiation in the X-ray range with high peak brilliance and ultra-short light pulses – and it does so at the shortest wavelengths ever achieved with a free-electron laser. Initial usage of this facility has already resulted in some spectacular new experiments, and the scientific interest is correspondingly intense. FLASH offers a total of five experimental stations, where different instruments can be set up as required. At the same time, the operation of FLASH generates important knowledge for the forthcoming XFEL X-ray laser and similar light sources worldwide.

XFEL – the European X-ray laser

An absolute highlight in the genuine sense of the word is the forthcoming European X-ray free-electron laser XFEL, which will generate extremely intense, ultra-short pulses of laser light in the X-ray range at wavelengths substantially shorter than even the light generated by FLASH. The XFEL will therefore open up a whole new realm of highly promising research opportunities for almost all the natural sciences. The 3.4-kilometre-long facility extends from DESY in Hamburg to the Schleswig-Holstein town of Schenefeld in the Pinneberg district, where the research campus will be located, comprising an experimental hall and space for ten experimental stations. There is also room here to build, if required, a second experimental complex with ten additional stations. The XFEL was approved in principle in February 2003 and is to be realized as an independent European project. At the beginning of June 2007 the German research ministry gave the go-ahead for construction of an initial version with six experimental stations, to be funded by Germany and international partners. The start of commissioning is scheduled for 2013.

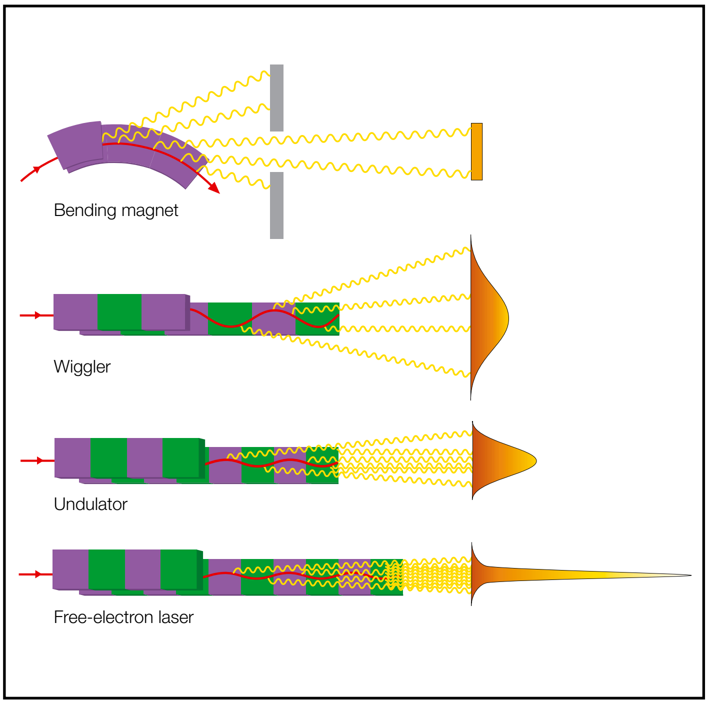
FAMILY TREE.

The dynasty of light sources

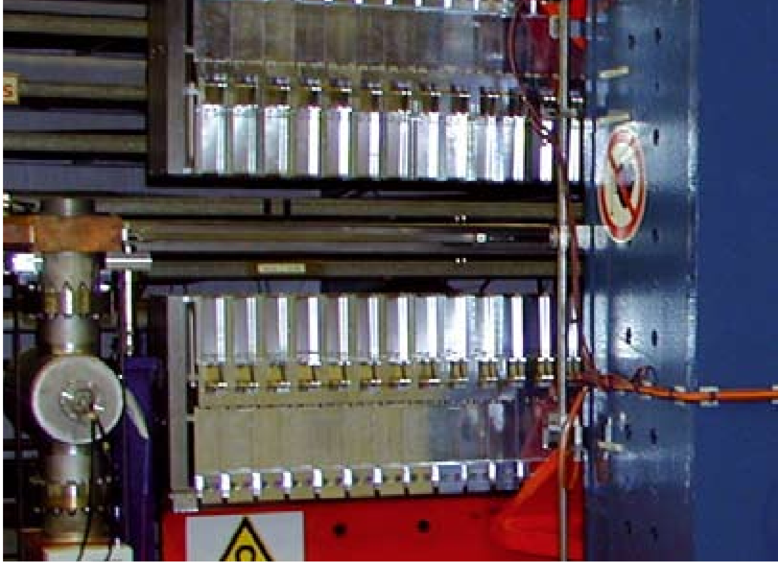
There is big demand for different light sources. Today around 40 000 researchers worldwide use the radiation from particle accelerators to investigate a whole range of materials, and this trend is set to increase. Numerous innovations in the field of materials research would have been inconceivable without the use of this intense light, and almost 90 percent of all the protein crystal structures submitted to the global Protein Data Bank PDB have been deciphered with the help of synchrotron radiation. Light sources such as the world's most powerful storage rings ESRF in France, APS in the USA and SPring-8 in Japan are heavily overbooked, and demand continues to grow. The development of new and internationally competitive radiation sources is therefore high up on the list of priorities at accelerator centres.

The second generation – DORIS III

An important benchmark of the power and quality of a light source is its brilliance. This is a measure of not only the number of photons generated in a specific wavelength range but also the smallness of the light source and how tightly the beam is collimated. The greater the brilliance of the radiation, the larger the variety of experiments for which it can be used. Equally important, the amount of time required for the measurements strongly depends on the brilliance of the light source.



Generation of radiation in various types of magnet structures



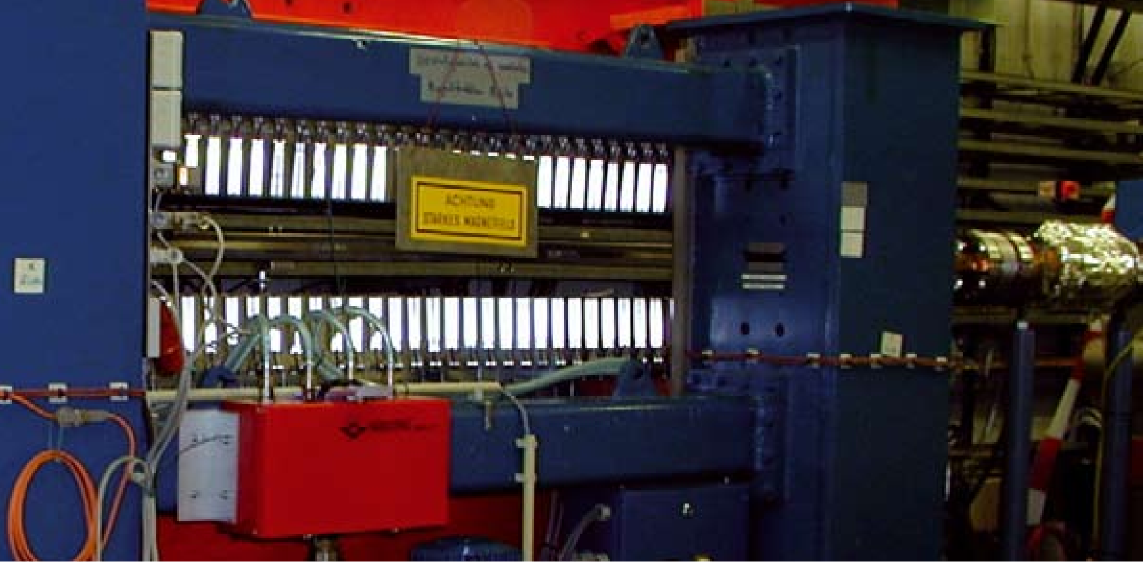
The DORIS III storage ring at DESY, which since 1993 has been used solely to generate synchrotron radiation, is a second-generation light source. Unlike their predecessors, the second-generation accelerators are fitted not only with bending magnets but also with special magnet structures – predominantly wigglers – that result in the generation of as much as a thousand times more light. Owing to the relatively large cross section of the electron beam in the accelerator, this type of source delivers a fairly broad light beam that is ideal for investigating samples several centimetres or millimetres in size or even entire workpieces of the kind that is common in the field of materials research.

The third generation – PETRA III

When it comes to smaller samples in the millimetre-to-micrometre range, or experiments necessitating highly collimated radiation, the light sources of the second generation no longer suffice. This is the realm of the third generation, the first representatives of which went into operation in the 1990s: storage rings that were custom-built for generating radiation and which, due to a small beam cross section in the accelerator and the systematic use of undulators, are able to produce light of a brilliance several orders of magnitude greater than their predecessors.

Experiments at this type of light source attain a spatial resolution in the sub-micrometre range. Because a certain proportion of this highly brilliant radiation also displays coherent, laser-like properties – i.e. its oscillations are exactly in phase with one another – it can also be used to conduct experiments that were impossible at second-generation sources. Upon completion of the source PETRA III, which is scheduled to go into operation in 2009, DESY will have available the world's best third-generation radiation source for hard X-rays.

In their attempts to attain ever higher brilliances and even synchrotron radiation with genuine laser properties, light source developers soon ran up against a fundamental problem. In a storage ring, electrons circulate for hours on end, emitting light several million times per second as they pass



Wiggler in the storage ring DORIS III

through the bending magnets, wigglers and undulators. Each time an electron emits a light particle, however, it is thrown slightly off track. For this reason, the particle beam can only be collimated to a certain degree. In a storage ring it is therefore close to impossible to produce a beam much finer than is already achievable at third-generation light sources. In other words, there seemed to be a limit to the maximum brilliance achievable.

The fourth generation – FLASH and XFEL

It was the most recent advances in the development of powerful linear accelerators for particle physics research that brought the decisive breakthrough. They paved the way for the fourth-generation light sources – the free-electron lasers. In a linear facility the electrons only pass through the accelerating section and the subsequent undulator once. As a result, there are less perturbating effects which means that a much finer beam can be generated. Thanks to a special amplification process in the undulator, this beam can then be made to produce extremely intense flashes of radiation with laser-like properties.

The free-electron laser FLASH, which commenced user operation at DESY in summer 2005, has played a pioneering role in this field. Although free-electron lasers in the infrared and visible light ranges had already been developed some years before, FLASH was the first facility of this kind to produce radiation in the ultraviolet and soft X-ray range. In general, the shorter the wavelength, the finer the structures that can be detected using that type of radiation. The short-wavelength X-rays are such a highly coveted research tool because their wavelength is so short that they can be used to observe individual atoms.

The successful user operation of FLASH along with initial groundbreaking experiments has given major impetus to the development of X-ray lasers of extreme brilliance. Several such facilities are currently under construction worldwide, including the European X-ray laser XFEL in Hamburg and Schleswig-Holstein, which is scheduled to go into operation in 2013. With their superior brilliance, laser-like properties and, most importantly of all, extremely short pulses some 10 000 times faster than those generated by synchrotron radiation sources, free-electron lasers open up totally new research opportunities, particularly in the X-ray range, which would have been inconceivable at third-generation light sources.

Always the right light

The different types of light sources therefore provide radiation with highly varied properties that are especially suited to specific kinds of investigations. In other words, the light sources complement rather than compete with one another, since each specific application requires a specific type of light, depending on the field of research, the method of investigation, the nature of the sample under examination and the aim of the experiment.

At DESY, for example, experiments that call for a high photon flux and a light beam in the millimetre range are best served by the DORIS III synchrotron radiation source. Meanwhile, users wishing to examine samples at a spatial resolution in the micrometre range have access at the PETRA III storage ring to intense radiation of a spectrum extending far into the hard X-ray range. In turn, the FLASH free-electron laser enables completely new kinds of experimentation with extremely intense, ultra-short laser pulses in the ultraviolet and soft X-ray range. And, following its completion in 2013, the European X-ray laser XFEL will generate laser pulses of an even higher brilliance in the hard X-ray range. Together with the XFEL, the light sources at DESY therefore provide the perfect research tool for every application – a key competitive advantage in favour of science with photons in Europe.

X-RAY VISION.

Experimental facilities at HASYLAB

HASYLAB, the Hamburg Synchrotron Radiation Laboratory, supports and coordinates science with photons at DESY. Each year DESY's unique experimental facilities attract over 2000 researchers to Hamburg from around 300 universities and research institutes right across the world. These visiting scientists come from as many as 36 countries, ranging from Armenia to the USA. Some research centres have permanent outstations at HASYLAB or operate their own experimental stations for such fields as structural molecular biology and materials research.

The Hamburg Synchrotron Radiation Laboratory offers much more than just beamtime at light sources. In addition, it is also a genuine service provider to the research community. HASYLAB employees provide advice and support to visiting researchers. Whether assistance is required with a technical problem on a piece of equipment, with a search for information in the library, or even with the complete realization of an experiment – guest scientists at the Hamburg laboratory can expect to receive full expert support for all their research needs. This is another reason why HASYLAB enjoys such an excellent reputation among researchers working in the field of science with photons.

The HASYLAB cooperation model

If scientists from a university or institute, either in Germany or abroad, wish to use the DESY light sources, they must first submit an application for beamtime along with an explanation of their research project. Following approval by an international panel of experts, they can conduct experiments for a certain period time at one of the HASYLAB experimental stations. Such usage is free of charge, provided that the researchers grant the scientific community access to their results, as is customary in the field of fundamental research.

For industrial companies wishing to carry out applied research, HASYLAB offers a special cooperation agreement. In such cases the company concerned contracts to pay a fixed yearly fee towards the costs. In return, it receives fast and flexible access to beamtime and has the support of a special service team during experiments. Afterward the company can utilize the results solely for its own purposes. ●

External partners at the DESY light sources

- The Centre for Free-Electron Laser Science (CFEL), a cooperation between DESY, the Max Planck Society (MPG) and the University of Hamburg
- The European Molecular Biology Laboratory (EMBL), Hamburg outstation
- The GeoForschungsZentrum (GFZ), Potsdam
- The GKSS Research Centre, Geesthacht
- The Institute of Experimental Physics, the Institute of Laser Physics and the Institute of Mineralogy and Petrography of the University of Hamburg
- The Max Planck Society (MPG), Research Unit for Structural Molecular Biology
- Research groups from the Universities of Aarhus (Denmark), Kiel, RWTH Aachen and TU Darmstadt
- In preparation: Helmholtz Group on Structural Biology led by the Helmholtz Centre for Infection Research

Light sources at DESY

DORIS III

- Ring accelerator for electrons and positrons
- Length: 289 metres
- Dedicated synchrotron radiation source since 1993
- 36 experimental stations with 45 alternately operated instruments

PETRA III

- Ring accelerator for electrons and positrons
- Length: 2304 metres
- Now being upgraded to the world's best storage ring-based X-ray source
- Scheduled start of user operation: 2009
- 14 experimental stations with up to 30 instruments

FLASH

- Free-electron laser based on a superconducting linear accelerator that uses TESLA technology
- Total length: 260 metres
- Generates extremely brilliant laser light in the vacuum ultraviolet (VUV) and the soft X-ray range using the SASE principle (wavelengths tunable between 6 and 60 nanometres)
- In user operation since 2005
- Five experimental stations

XFEL

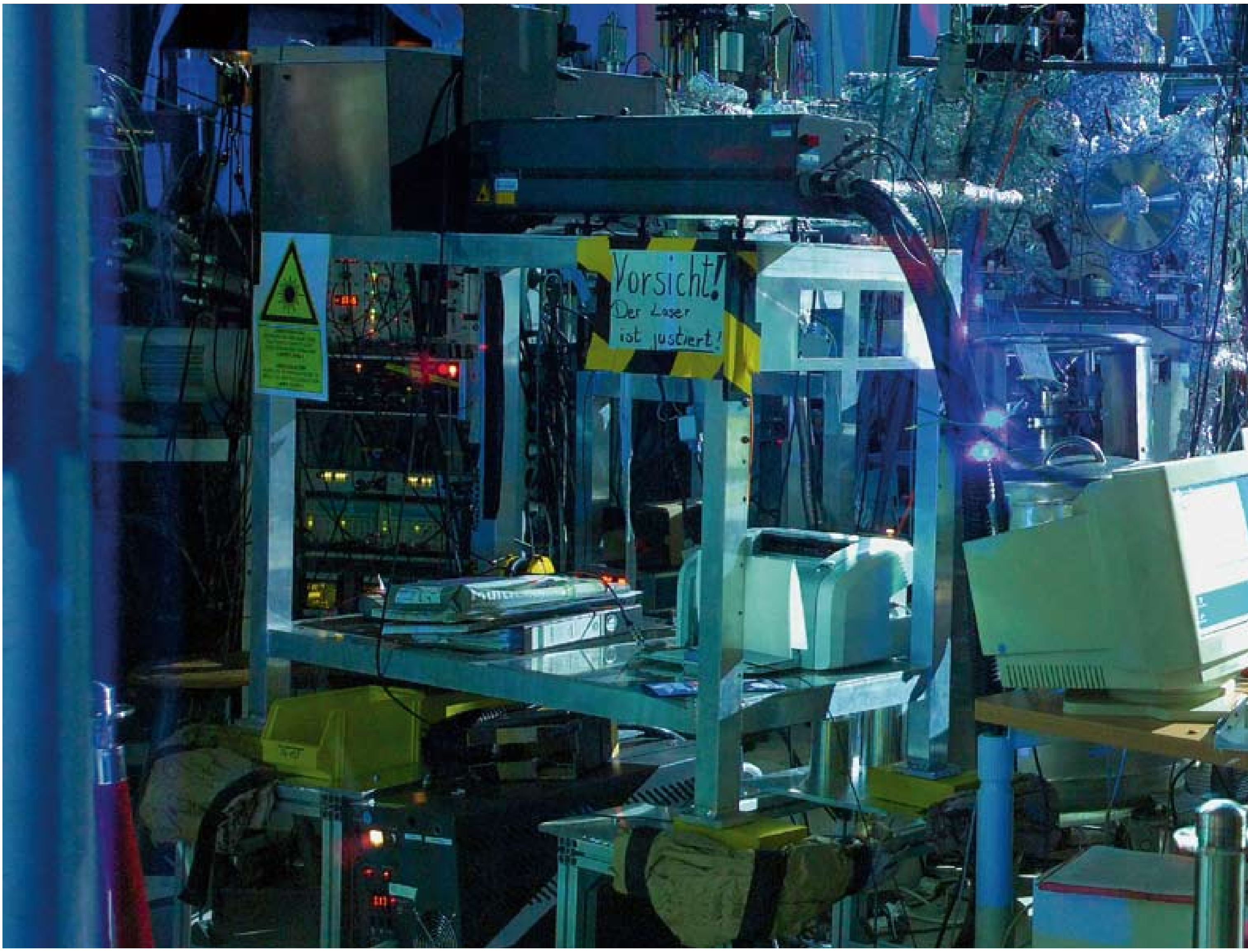
The European X-ray free-electron laser

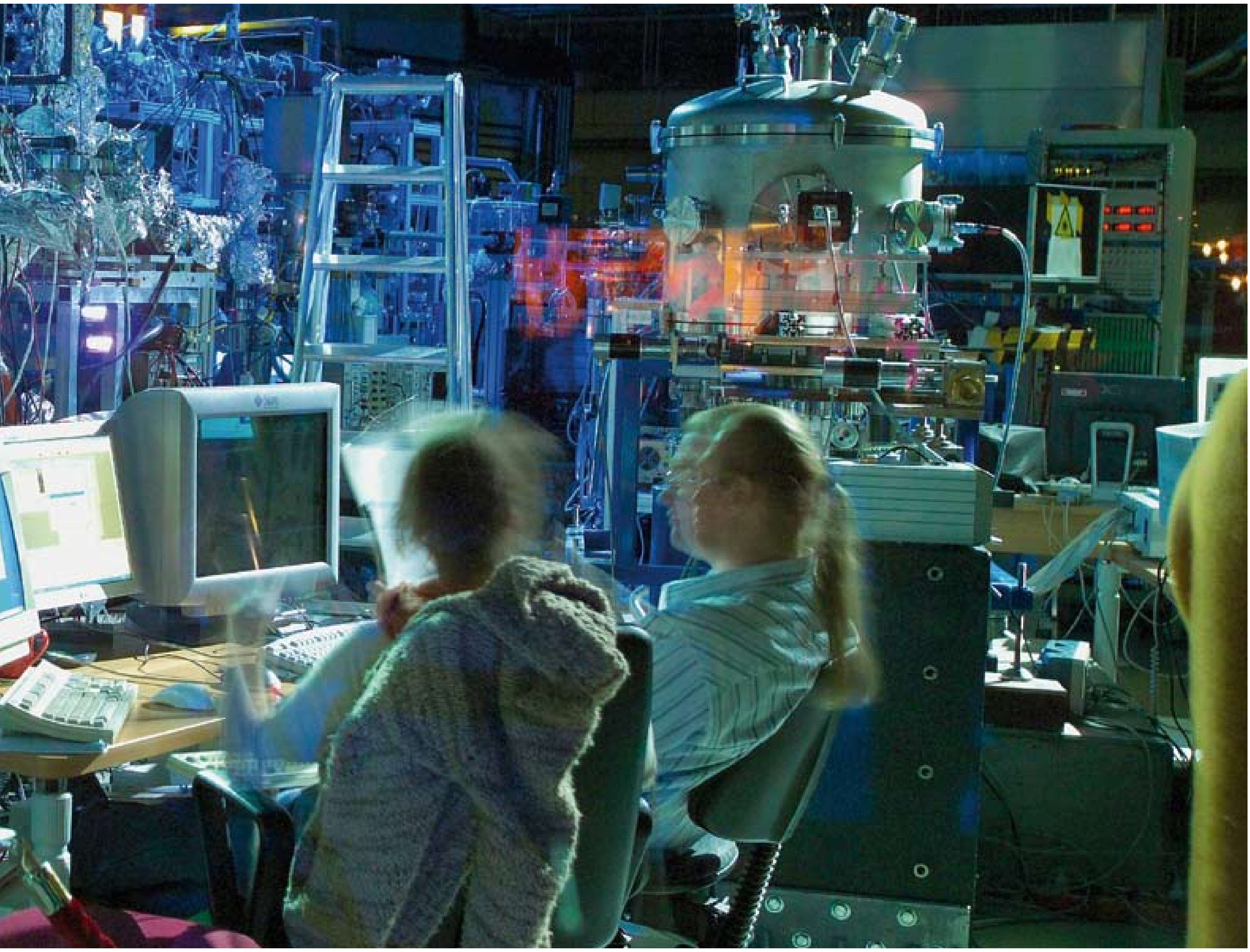
- Under construction as a European project with strong DESY participation
- Free-electron laser based on a superconducting linear accelerator that uses TESLA technology
- Total length: approximately 3.4 kilometres
- Generates extremely brilliant laser light in the X-ray range using the SASE principle (wavelengths tunable between 0.085 and 6 nanometres)
- Scheduled start of commissioning: 2013
- An underground experimental hall with room for ten experimental stations
- Scope to build a second, equally large experimental complex

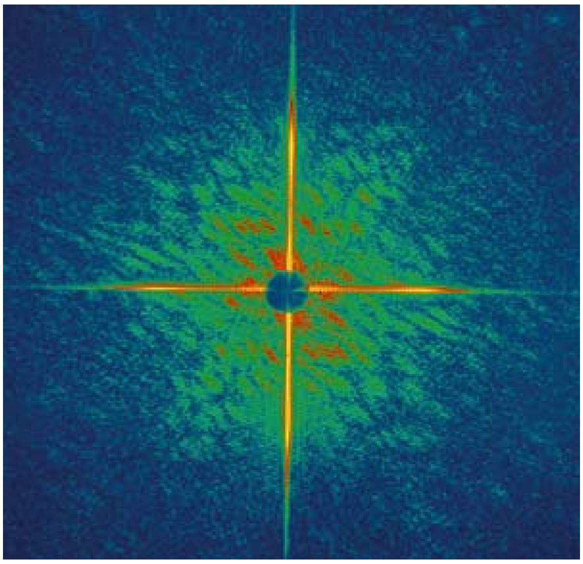
KNOWLEDGE MATTERS.

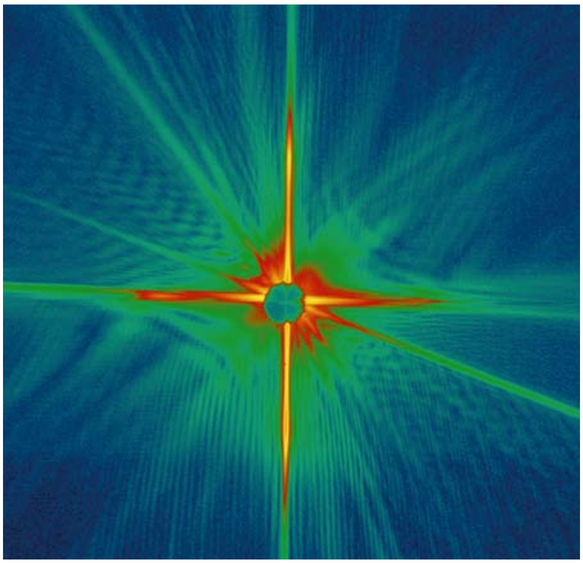
Examples from research

The intense light generated by the accelerators at DESY offers deep insights into matter. This brilliant type of radiation is suitable for examining substances as varied as semiconductor crystals, nanomaterials and proteins, the very building blocks of life. Selected research projects show a small excerpt from the broad spectrum of experimental opportunities that attracts scientists from around the world to the FLASH and DORIS III accelerators at DESY in Hamburg.









Top: Diffraction image of a sample, recorded with a single ultra-short, extremely intense and coherent laser pulse from the FLASH free-electron laser
Bottom: Diffraction image of the same sample after its destruction by the first laser pulse

FLASH IMAGE.

„FLASH, what a picture!“

“FLASH, what a picture!” was the cover story of the 12 December 2006 issue of *nature physics*. What so excited the *nature* editors was an image produced at the new FLASH facility, featuring two tiny stick figures beneath an equally tiny sun. This might sound anything but sensational. However, this “flash diffraction image” was a significant breakthrough in experimental methods. In one of the very first experiments at FLASH, the researchers had succeeded in using a single laser flash to obtain a detailed diffraction image of the sample, which was only a few micrometres in size, before it was destroyed by the intense light. And there was another reason for their excitement: The small stick figures and their sun were engraved in a thin membrane. This meant that the sample was not crystalline, yet a single laser pulse was sufficient to obtain a meaningful image.

This first application of the flash diffractive imaging method demonstrates that it should soon be possible to use single ultra-short, extremely intense laser pulses to record images of nanoparticles, or even of individual large macromolecules. The new method therefore holds the promise of extraordinary capabilities for studying the dynamics of nanoparticles and the structure of large biomolecules, viruses, or cells, without the need to first subject the sample to a complex crystallization process, as is the case in conventional structural analysis using X-rays.

Imaging methods are often limited by the fact that the radiation used to create the image also damages the sample, or that insufficiently strong signals are recorded by the detectors. One way to avoid this is to crystallize the molecules to be studied, so that many of them can be examined simultaneously. But there is a problem with this method. In most cases it is very difficult to crystallize the material. Especially in the life sciences this is a significant limitation, because biomolecules are especially difficult or even impossible to crystallize.

However, there is a way to circumvent the problem. Researchers need to record the image before the sample can be destroyed by the radiation, preferably by using a light pulse of such intensity that a single flash is sufficient to deliver the required signal. This approach also has the advantage that no crystallization is necessary. Flash diffractive imaging only requires a single molecular complex to be irradiated with a single ultra-short, very intense X-ray laser pulse. Using a large number of these diffraction images, it then becomes possible to determine the spatial arrangement of the atoms. Thanks to FLASH, the international team of researchers has now been able to prove that this method actually works.

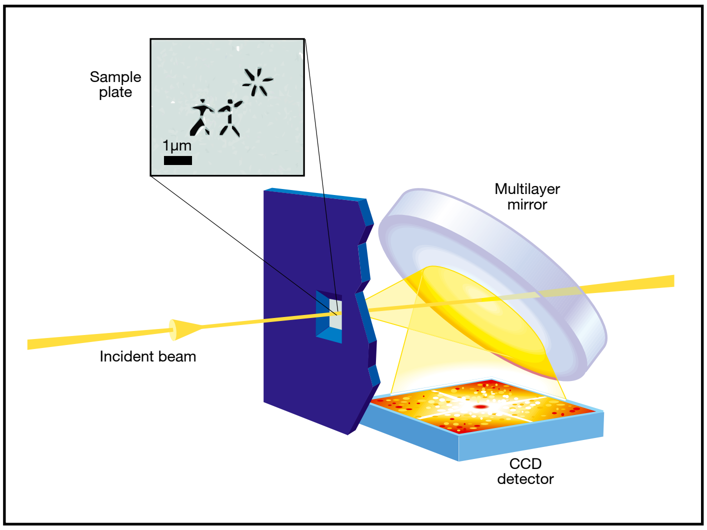
The flash diffractive imaging principle heralds a revolution in structural research in the natural sciences – particularly when images with very high temporal and spatial resolution are required. Since the new imaging method requires no lenses, it can be extended to provide resolution on an atomic scale as soon as X-ray lasers with even shorter wavelengths become available. As a result, the FLASH experiment also backs up the high hopes for revolutionary new experimental capabilities that are being placed in the future generation of hard X-ray free-electron lasers, such as the Linac Coherent Light Source LCLS at Stanford (USA) or the European XFEL facility in Hamburg.

> Deutsches Elektronen-Synchrotron DESY, Germany
> Spiller X-ray Optics, USA
> Stanford Synchrotron Radiation Laboratory, Stanford Linear Accelerator Center SLAC, USA
> Technical University of Berlin, Germany
> University of California, Davis, USA
> University of California, Lawrence Livermore National Laboratory, USA
> University of Uppsala, Sweden

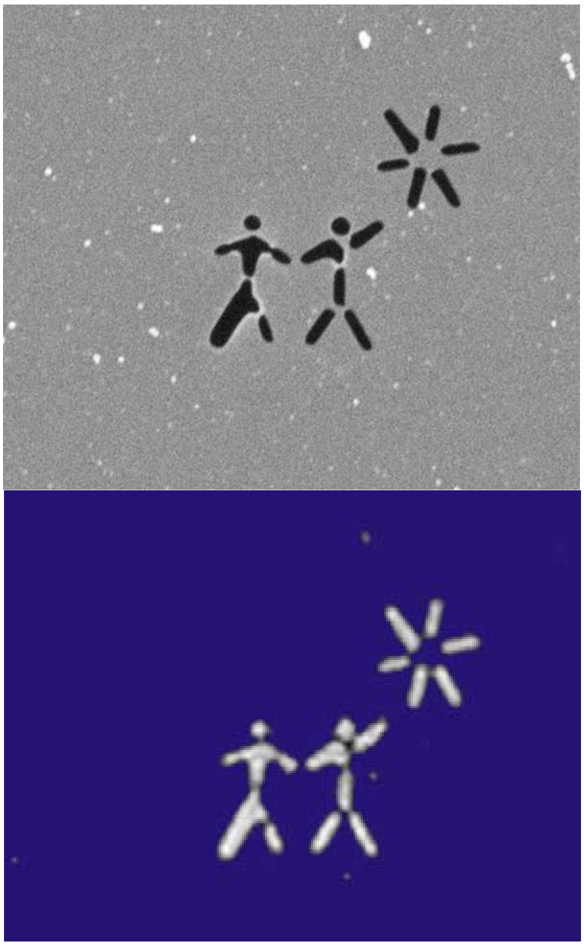
The experiment in detail

To create the diffraction image, the researchers illuminated a thin membrane into which a three-micrometre-wide pattern – of two cowboys under a sun – had been cut, with a FLASH light pulse of 32 nanometres wavelength and only 25 femtoseconds duration. The energy of the laser pulse heated the sample to about 60 000 degrees Celsius, causing it to vaporize. But the team succeeded in recording a diffraction pattern before the sample was destroyed. The image derived from the diffraction pattern by special mathematical methods showed no discernible sign of radiation damage, and it was possible to reconstruct the test object to the maximum possible resolution. Damage to the sample did not occur until after the ultra-short laser pulse had passed through it.

> micrometre: **millionth of a metre**
> nanometre: **billionth of a metre**
> femtosecond: **quadrillionth of a second**



Schematic representation of the flash diffractive imaging experiment at the FLASH free-electron laser



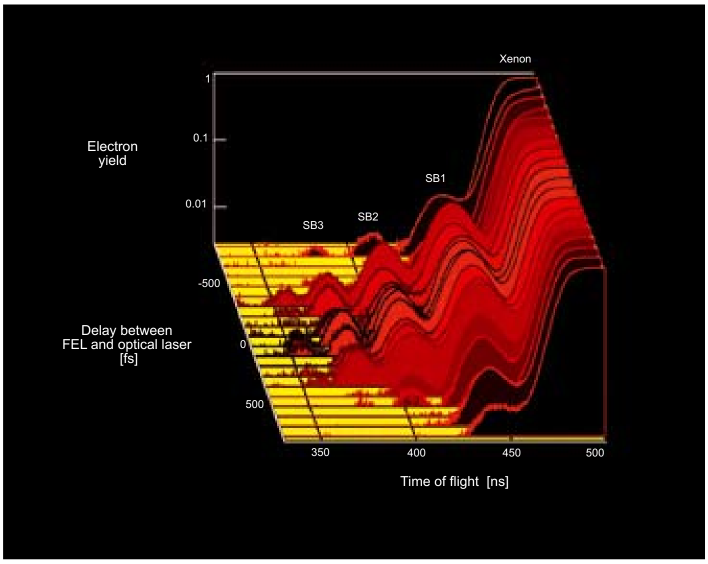
Top: The sample under the scanning electron microscope – two stick figures under a sun, cut into a membrane with a thickness of just a few nanometres
Bottom: Reconstruction of the pattern from the recorded diffraction image

SNAP SHOT.

High-speed photography with FLASH

When very fast reactions have to be tracked with high temporal resolution, somewhat like in a movie, the "pump-and-probe" technique is the method of choice. Here, two ultra-short light flashes are used. The first one triggers a photochemical reaction, the second one probes that reaction immediately afterwards. A series of such snapshots made with different time intervals between the first and the second light pulse can be viewed in sequence to show how the reaction unfolds.

The ultra-short light pulses from the FLASH free-electron laser provide scientists with entirely new opportunities in this context. Certain reactions could, for instance, be triggered by a flash from an optical laser and then probed with the FLASH radiation, or vice versa. But this requires that one important condition is met. To ensure that the snapshot is always taken at a precisely defined moment and to achieve the maximum temporal resolution attainable, the two laser pulses must be synchronized. In other words, the time interval between them must be adjustable with a precision that approximates the duration of the pulses, i.e. a few femtoseconds (quadrillionths of a second).



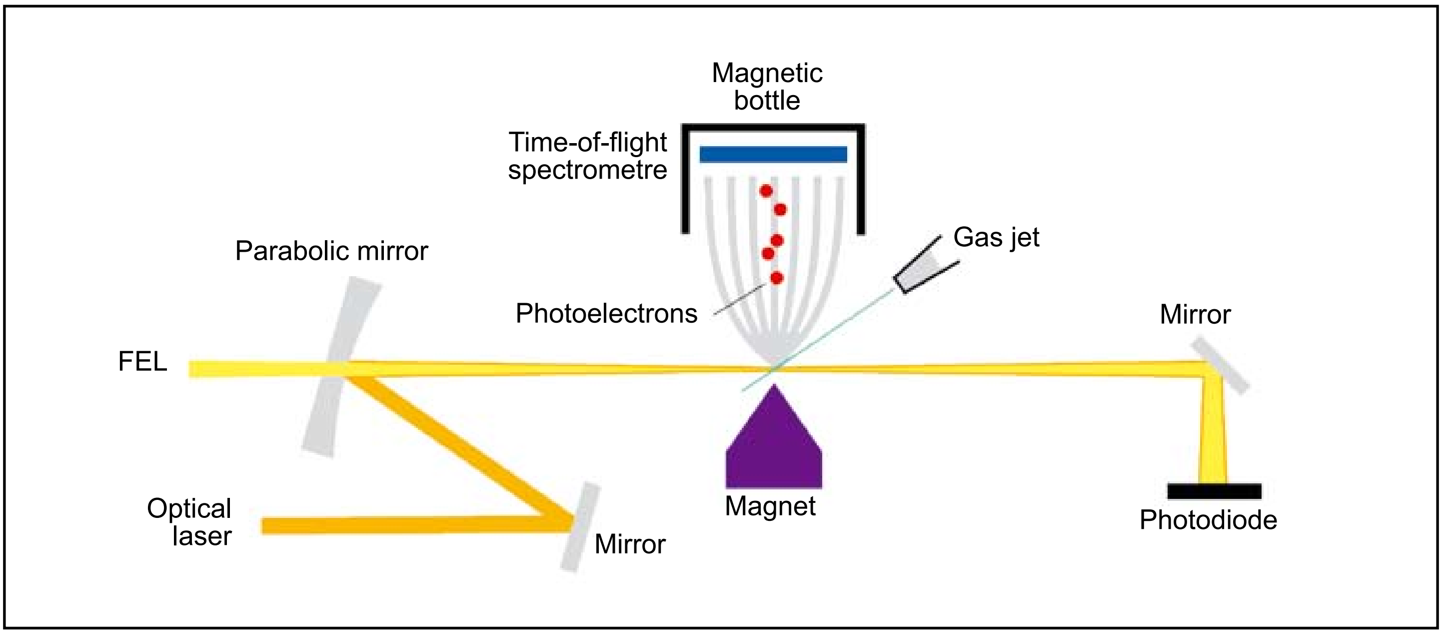
Characteristic sidebands (SB) in the energy spectra indicate the degree of temporal overlap between the light pulses of FLASH and those of an optical laser.

An international team of scientists succeeded in creating these conditions at FLASH. The researchers combined light pulses from an optical laser in the infrared or green range, respectively, with the ultra-short pulses from the FLASH facility and irradiated rare gas atoms such as xenon or helium. They controlled the time intervals between the light flashes by "detouring" the optical laser beam through variable distances, thereby achieving a controlled delay. In a process called photoionization, the combined light pulses caused the rare gas atoms to eject electrons whose energy distribution was then measured by a detector.

Since the electrons are irradiated with photons from two different pulses, they can absorb varying amounts of energy. In the measured energy spectra, this results in characteristic sidebands – for instance, of electrons that have absorbed both a FLASH photon and a laser photon. Since the shape and intensity of these sidebands depend on the temporal overlap between the two light pulses, the profile of the measured spectra enables the scientists to determine the relative time delay between the two laser pulses – an essential prerequisite for conducting time-resolved experiments at FLASH.

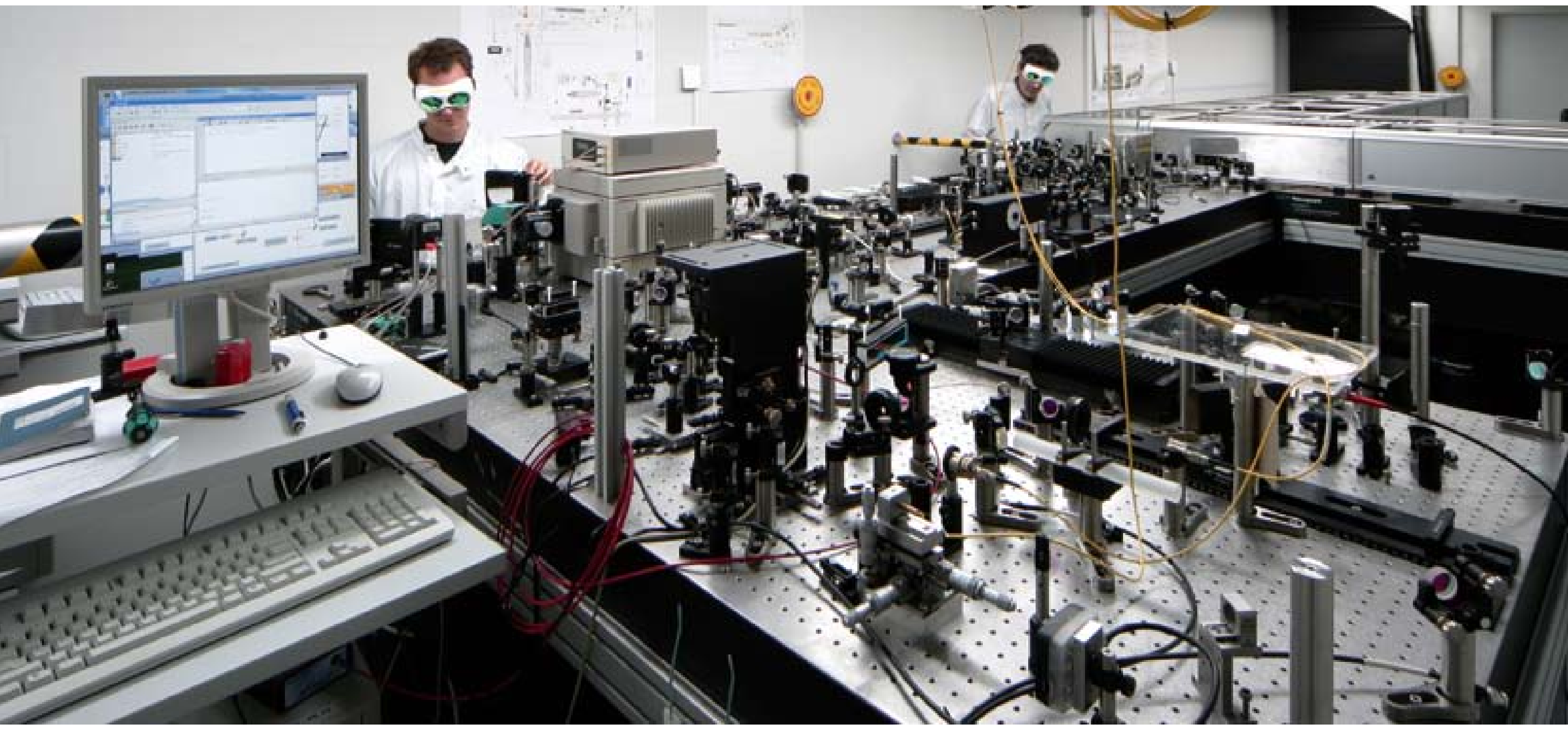
The researchers even succeeded in measuring the sidebands using single FLASH pulses, i.e. not by averaging over a large number of pulses. They were thus able to determine the time interval between the FLASH pulse and the optical laser pulse with a precision of better than 50 femtoseconds. Through this successful combination of two very different types of lasers they clearly demonstrated the potential of pump-and-probe experiments using a short-wavelength free-electron laser and an optical laser – experiments that could be successfully performed even with single light pulses from the FLASH facility.

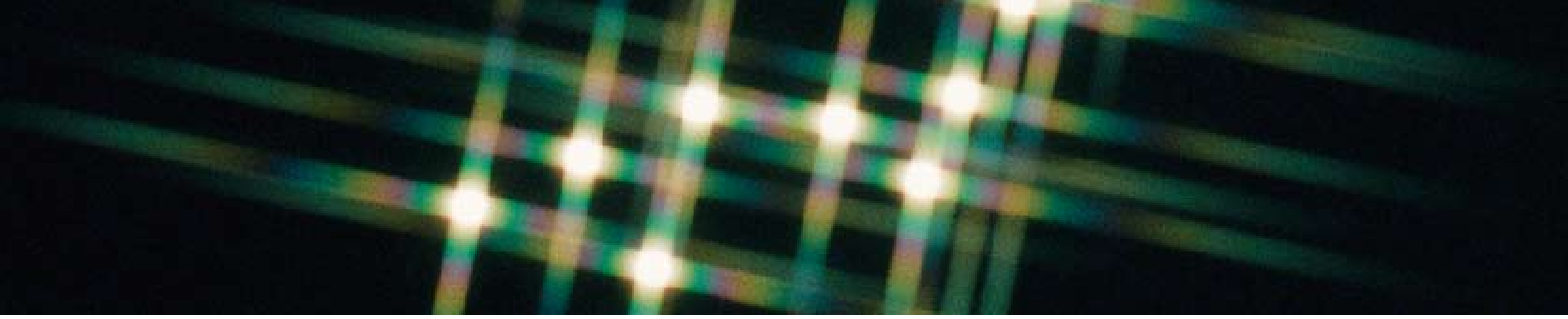
> **Deutsches Elektronen-Synchrotron DESY, Germany**
> **Dublin City University, Ireland**
> **LIXAM/CNRS, Centre Universitaire Paris-Sud, Orsay, France**
> **Queen's University Belfast, UK**
> **Université Pierre et Marie Curie, Paris, France**



Schematic diagram of the experimental setup

At FLASH, an additional optical laser system can be synchronized with the light pulses of FLASH for time-resolved studies of very fast reactions using the pump-and-probe technique.



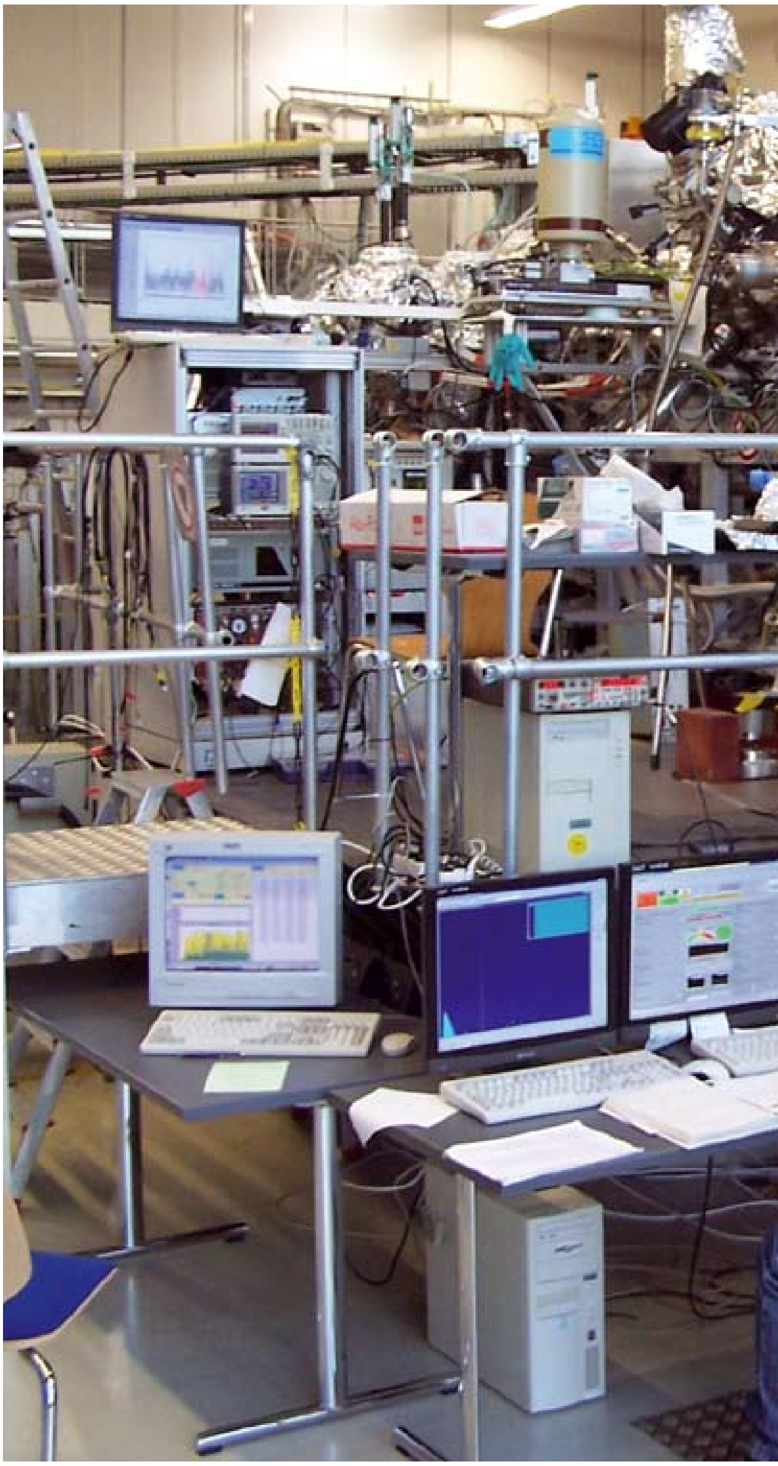


STAR FIRE.

Stellar material under the X-ray eye of FLASH

Taking X-rays of stellar material with a laser – this feat was achieved by scientists from the Max Planck Institute for Nuclear Physics in Heidelberg, the University of Hamburg and DESY using X-ray laser pulses from FLASH. Unlike their colleagues who rely on satellites and telescopes, the researchers studied the luminous plasma of stellar atmospheres right there in the laboratory. At a temperature of about one million degrees Celsius in a special apparatus, they generated highly charged iron ions, such as those that occur in the sun's corona.

Under such extreme conditions, atoms lose most of their electrons. Of its 26 electrons, an iron atom, for example, retains only the three that are most strongly bound to the nucleus. These remaining electrons exhibit extraordinary properties. They stay close to or even within the atom's nucleus, and consequently are most strongly affected by its electromagnetic field. This results in shifts of the atomic spectral lines, which also occur in the neutral atom in a weaker form but are difficult to discern in the complex interplay of many electrons. These phenomena are described by quantum electrodynamics (QED), currently the most exact of all physical theories and a key element of our present understanding of physics. Now the precise measurement of highly charged ions makes it possible to experimentally check important theoretical predictions of QED – which explains the immense interest of physicists in this laboratory-generated starfire.



The scientists created the highly charged ions in a special ion trap – an Electron Beam Ion Trap (EBIT). A sharply focused electron beam ionizes the atoms inside the EBIT until they reach the desired charge. During this time, the ions remain trapped by strong electrical and magnetic fields. Using this technique, the researchers produced several million highly charged ions, concentrated within the volume of a human hair. The tiny ion cloud targeted by the X-ray pulses of FLASH was five centimetres long but a mere 250 micrometres thick. Using the technique of resonance fluorescence spectroscopy, the scientists were able for the first time to excite a spectral line of these ions and to measure it precisely. They used the fluorescence signal to determine the energy of an electronic transition of an iron ion with a 23-fold positive charge to an

accuracy of a few millionths. Even in this initial experiment, the precision of the measurement already exceeded the accuracy of the theoretical prediction. The researchers were therefore able to not only obtain precise information about the structure of this largely unknown stellar material, but also check important predictions of QED. The precision of the measurement is expected to be increased a hundredfold in the future.

This experiment would not have been possible without FLASH. Since highly charged ions both absorb and emit radiation with comparably short wavelengths, it wasn't possible to cause these ions to fluoresce until the X-ray laser pulses of FLASH were available to excite them. In addition, the wavelength of the X-ray radiation that FLASH generates can be varied. As a result, it meets all the essential requirements for the application of resonance fluorescence spectroscopy. In the future, the physicists intend to go one step further and measure how long an electron remains in the excited state. In highly charged ions, that is only a few quadrillionths of a second. Since the FLASH pulse is about as short as the time the electron dwells on the higher electronic level, this time can be determined using the ultra-short X-ray pulses of FLASH.

Studying highly charged iron ions at FLASH

SUCCESS STORY.

The DORIS III radiation source

For more than 30 years, scientists have conducted research using the very intense light from the DORIS storage ring at DESY. DORIS has been in operation since 1974 – initially both for particle physics and for research with synchrotron radiation. In 1990 and 1991 the storage ring was expanded to make room for seven additional magnet structures, so-called wigglers and undulators. This modified machine, DORIS III, has been used exclusively as a source of synchrotron radiation since 1993.

The results of this period have been substantial. Time and again, the scientists and engineers at DORIS were able to develop new methods and instruments and to achieve breakthrough results that opened new fields of research. In many cases, what began as a local test experiment developed into a successful experimental method that ultimately established itself worldwide as a standard method used in research and industrial applications.

Research at an experimental station at DORIS III

KEY ROLE.

Using DORIS III to decode tuberculosis proteins

To this day, tuberculosis remains one of the deadliest threats to global health. Two million deaths are caused annually by the microorganism *Mycobacterium tuberculosis*. About one third of the world's population is latently infected, and the number of strains of the pathogen that have developed a resistance to existing medications continues to increase. *M. tuberculosis* is so dangerous because it conceals itself within the immune cells of the human body. Its survival there is ensured by the activity of certain key molecules. The scientists are therefore studying the functions of tuberculosis proteins to determine their atomic structure in order to find potential weak points of the bacterium as well as new inhibitors. Researchers from the Hamburg outstation of the European Molecular Biology Laboratory (EMBL) on the DESY campus, in collaboration with the Max Planck Institute for Infection Biology (MPI-IB) in Berlin, used the light from the accelerator DORIS III to decode the structures of more than 40 gene products from *M. tuberculosis*.

One of the proteins essential for the survival of the tuberculosis pathogen is LipB, which is important because it activates some parts of the cellular machinery that drives the bacterium's metabolism. The research department of the MPI-IB in Berlin has specialized in the biology of infection with *M. tuberculosis* and its survival strategies in immune cells. During their studies, the scientists became aware of an increased presence of LipB in acutely infected cells in patients who were infected with multidrug-resistant strains of the bacterium – a clear indicator that this protein plays a part in the pathogenesis. That makes it an especially interesting target in cases where traditional medications are no longer effective. One of the highlights has been the 3D structure determination of this protein. The structural image of the molecule suggests possible approaches for developing new antibiotics.

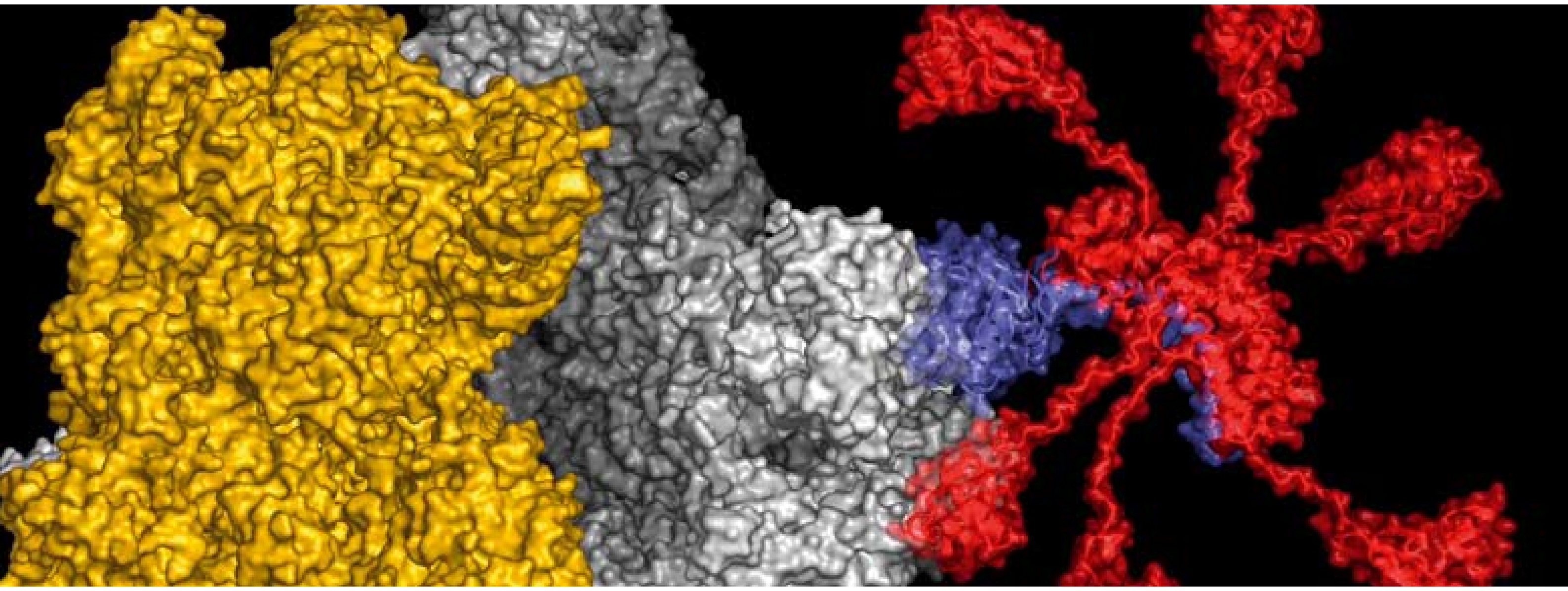
After purifying and crystallizing LipB, the scientists of EMBL in Hamburg used highly energetic synchrotron radiation from the DORIS III storage ring to create a structural image of the protein – a kind of engineering drawing of its atomic blueprint. This provided important indicators about the way it works. The function of the enzyme was revealed by an ultra-high-resolution image of the active site of LipB. In collaboration with researchers of the University of Illinois in the USA, the team at EMBL subsequently discovered how LipB attaches specific fatty acids onto other proteins.

LipB consequently presents a promising target for medications, because it is part of a vitally important signal chain. Unlike other organisms, *M. tuberculosis* has no other backup mechanisms that could assume the role of LipB. An inhibitor that could block the active site of LipB would therefore shut down vital processes without which the pathogen could not survive or replicate – a very effective strategy for a pharmaceutical agent. Now the scientists are searching for substances that could perform that function. At the same time they are continuing their search for other potential target proteins that would be sensitive to medications. Current activities here are focusing on the structures of molecules that help *M. tuberculosis* to persist in its dormant state and thus provide potential targets for medications.

Simplified atomic structure of LipB, a protein that is important to the survival of the tuberculosis pathogen

CONTROL CENTRE.

The world's smallest fishing rod in the light of DORIS III



The genetic alphabet has only four letters, but the way these letters are arranged in sequence is the key to the entire blueprint of life. This is the design according to which proteins – the building blocks of life – are made. Proteins are produced in so-called ribosomes, specialized macromolecular complexes that are present in any cell. Scientists at the Max Planck Society and other institutions are taking a very close look at ribosomes. One of their tools is the intense light from the DORIS III storage ring. As a result, they have been able to map the atomic structure of an important control centre of the machinery of protein synthesis in living cells. This brings us a significant step closer to an understanding of how this important control centre functions.

With a diametre of approximately 25 billionths of a millimetre, even the simple ribosomes from bacteria are gigantic molecular machines. They consist of more than 50 protein components and three long ribonucleic acid molecules, which comprise a large and a small ribosomal subunit. A specific module of the ribosome handles each particular task in the translation of the genetic information encoding a specific protein blueprint into an appropriate chain of protein building blocks (amino acids).

To avoid errors in the synthesis of proteins – some of which involve several thousand building blocks – the individual modules and their particular tasks must be perfectly matched. The ribosome therefore uses a number of control proteins, referred to as translation factors, which only attach themselves to the central machinery at specific times. Some of the translation factors function as molecular switches. They carry small, highly energetic molecules, which are chemically split during a phase in the process. This release causes a change in the three-dimensional structure of the factors, which is sensed by the ribosome and triggers the next step in the process. The capture of the translation factors and the actuation of the molecular switches are coordinated by a special control centre in the ribosome. Whereas the component parts of the control centre have been known for some time, very little has been understood about how it works – until now.

To understand this function, the scientists used a combination of different physical and biochemical methods including protein crystallography with X-rays from the DORIS III storage ring. They obtained a detailed three-dimensional image of the atomic structure of this ribosomal region by growing crystals of parts of the control centre and investigating their X-ray diffraction pattern. They also analysed the physical connection between the control centre and the large ribosomal subunit. As though they were putting together a three-dimensional jigsaw puzzle, they then proceeded to work out how all of the substructures fitted into the envelope of the ribosome that had been visualized using electron microscopy.

Connected to the large ribosomal subunit – right next to the spot where the translation factors get attached – is a long, mobile stalk from which up to six flexible molecular chains are suspended, each of which has a spherical head. Lending credence to earlier studies which had suggested that these heads represent the initial docking stations for the translation factors, the structure resembles a molecular fishing rod with six lines, each with its own bait, which the ribosome can employ to “fish” for translation factors. The researchers also suspected that the heads might be able to reach factors already attached to the ribosome in order to actuate their switches.

They tested these hypotheses by causing selective changes in the fishing rod. To begin with, genetic techniques were used to cut off the bait. As expected, the fishing lines without bait were unsuccessful in fishing for factors. What’s more, the switching processes were slowed down by a factor of 1000. Then the scientists made selective changes in the surface building blocks of the heads that were able to make contact with the translation factors, and this was shown to interfere with their function. The results demonstrated that a considerable number of such building blocks must function in unison to capture the factors and actuate the switches.

The ability to synthesize proteins is a fundamental element of all life on earth. That’s why ribosomes with similar structures occur in all organisms, from the bacterium to the human being. However, the bacterial ribosomes differ in certain details from those of higher organisms. Some antibiotics, for instance, inhibit protein synthesis in bacteria but not in humans, animals or plants. There are also differences in the control centre of the ribosome. A more precise knowledge of the different translation processes could therefore form the basis of new developments, for instance for drugs against infectious diseases.

- Lomonosov University, Moskow
- Max Planck Research Unit for Structural Molecular Biology, Hamburg
- Max Planck Institute for Biophysical Chemistry, Göttingen
- University of Witten-Herdecke

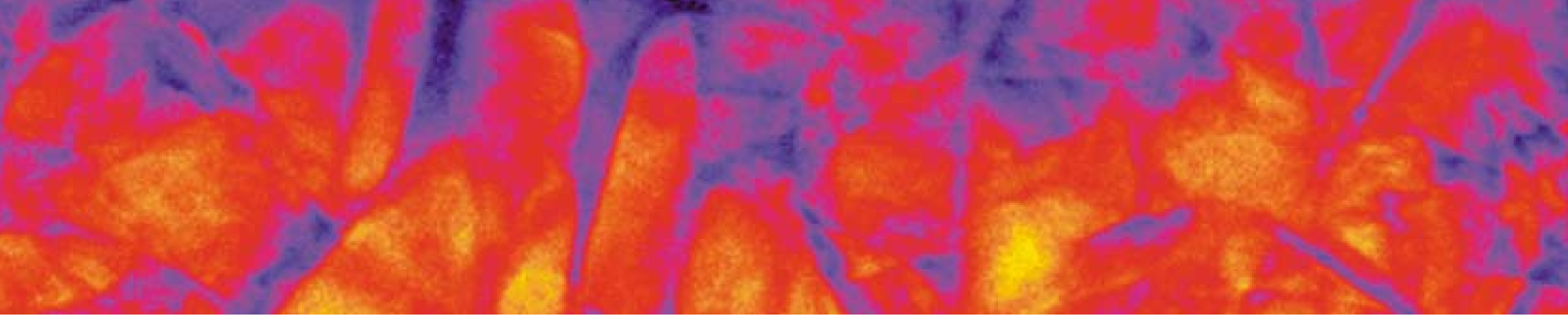
Ribosomes are the protein factories of living cells. Radiation from the DORIS III storage ring can be used to decode their complex structure.

The challenge of structural biology

The intense X-ray light from particle accelerators is indispensable when the aim is to investigate the complex structures of biomolecules, such as proteins, in detail. At DESY, scientists from the European Molecular Biology Laboratory (EMBL), the Max Planck Society (MPG) and other institutions are using protein crystallography at the DORIS III storage ring to study a great variety of biomolecules.

The principle is the same as in X-ray structural analysis of a mineral. An intense X-ray beam is directed at a crystal, whose building blocks are arranged in a regular lattice formation and diffract the X-rays in a characteristic manner. Researchers can deduce from the recorded diffraction pattern how the individual atoms in the crystal lattices are arranged. But in proteins this method encounters a major problem. Proteins are large molecules that are normally dissolved in water and resist being formed into a solid crystal. Even with very sophisticated processes, proteins only form very thin crystals. The only way to study the structure of these tiny and fragile formations is by examining them with the intense X-ray light from the accelerator.

But the results are worth the effort. Protein crystallography makes it possible to obtain detailed knowledge of the structure of large, complex biomolecules – which provides researchers with important information toward understanding the biological function of a protein. For molecular biologists, crystallography is therefore an indispensable tool they can use, for example, to learn how proteins interact in the creation of the great diversity of cell types in the human body – or how to tailor-make new drugs accordingly.



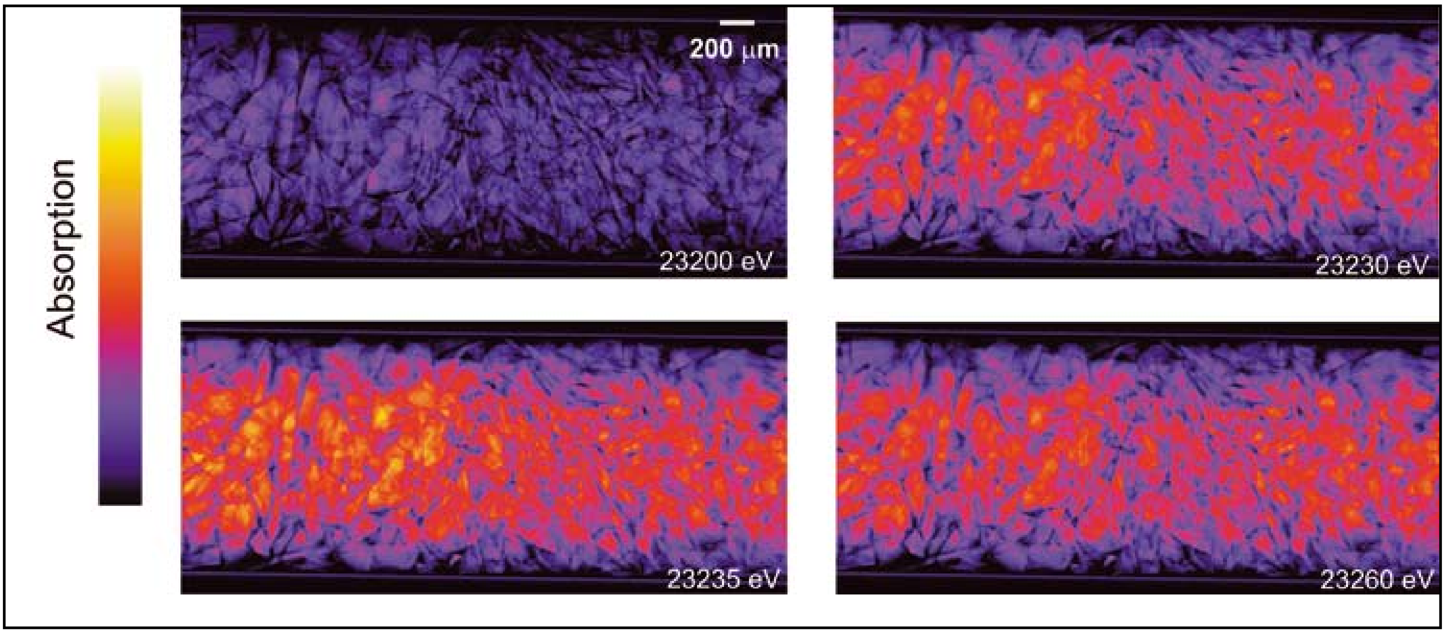
MICRO REACTOR.

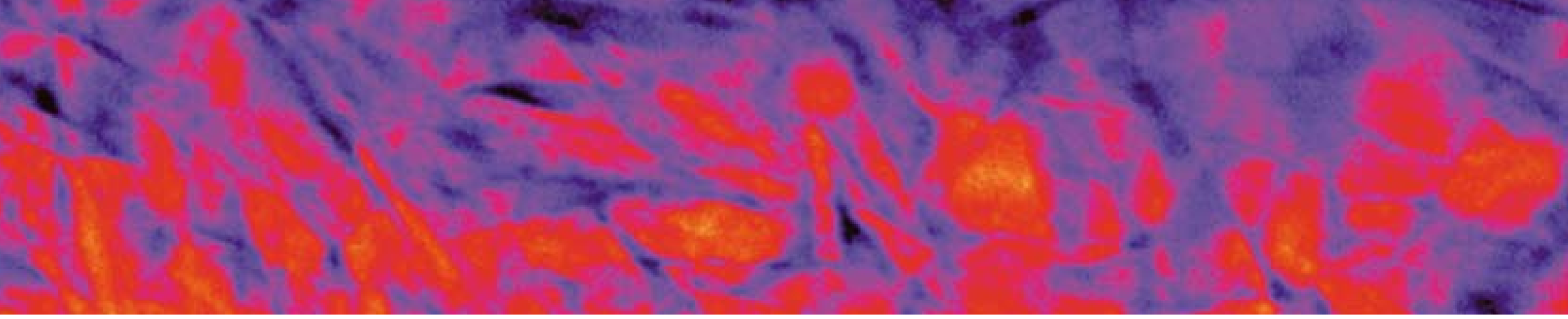
Catalysts under the X-ray eye of DORIS III

“A catalyst is a substance that changes the rate of a chemical reaction without itself being consumed.” So says the sober dictionary definition. But without catalysts many technical processes wouldn’t work at all. An estimated 90 percent of all chemical products require at least one catalytic step in their production. Without the presence of the catalyst, the chemical reaction would be much slower or wouldn’t occur at all. Today’s chemical industry would therefore be inconceivable without catalysts. Catalysts are also important in protecting the environment. They help save energy, reduce undesirable by-products, or convert unavoidable hazardous substances into less hazardous ones, as in the catalytic converter of your car.

Exactly how such catalytic reactions occur in atomic detail can be elucidated with the intense X-ray pulses of DORIS III. The intense X-ray radiation can be used to study catalysts even in the gaseous or liquid phase or under very high pressure. An important question in this context is how the active structure of the catalyst changes during the course of the reaction – for instance, if the composition of the gas or the temperature vary markedly along the length of the catalyst. That subject had hardly been studied in the past. By using an X-ray camera, a group of researchers from the Swiss Federal Institute of Technology (ETH) Zurich, the Technical University of Dresden and DESY has now succeeded in recording the structural changes occurring in a rhodium catalyst during the

A microreactor, in which methane gas reacts with oxygen, exposed to the X-rays of DORIS III at four different energies

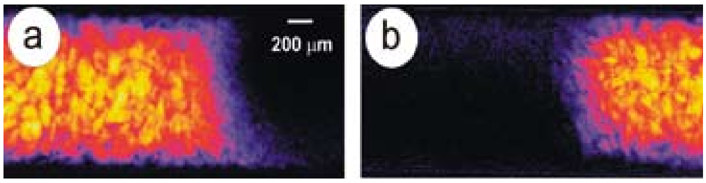




partial oxidation of methane. This reaction is considered to be one of the promising processes for the production of hydrogen, and for gas-to-liquid technologies used to produce liquid methanol or other fuels from natural gas. These products are much easier to transport than natural gas.

The researchers passed gaseous methane and oxygen through a microreactor – a small glass tube filled with rhodium catalyst material and fitted with different analytical instruments. While the reaction of methane with oxygen progressed inside this reactor, the scientists exposed the microreactor to X-rays from the DORIS III storage ring and recorded the transmitted radiation with an X-ray camera. The results revealed drastic changes in the rhodium cluster structure along the length of the microreactor. The scientists found an excess of oxidized rhodium particles in the inlet part of the microreactor, and an increased amount of reduced rhodium particles in the rear part – a pattern that remained stable for hours and only began to change with a variation in the temperature or in the gas flow rate. This characteristic distribution indicated that the methane in the fore and rear portions of the microreactor doesn't undergo the same process during the reaction. While in the first part the catalytic oxidation of methane prevails, methane reforming dominates in the second part. This means that the reaction mixture in the first portion brings the catalyst bed to the required temperature, while in the second portion the intended reaction occurs, forming hydrogen and carbon monoxide. This so-called syngas – for synthesis gas – is extremely well suited for industrial processes to create methanol, or fuels via the Fischer-Tropsch synthesis.

Such structural insights into the way catalysts work are useful in many areas, for instance in materials research, environmental sciences, electrocatalysis or sensor technology. The method used in this experiment is especially useful for all *in situ* analyses, in which the reaction process is studied directly where it occurs.



The rhodium catalyst material in the microreactor tends to be more oxidized at the entry side (a) and more reduced at the exit side (b) – an indication that methane and oxygen in the front and rear portions of the microreactor react via different processes.

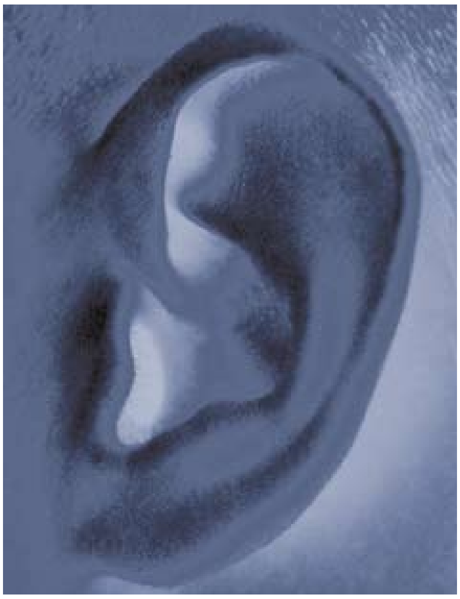
Helixes and implants – X-ray imaging in 3D with DORIS III

Deaf patients whose auditory nerve is still functioning can be successfully treated by inserting a cochlear implant into the inner ear. Conventional hearing aids do amplify sound, but are of little use to patients whose cochlea – a small organ within the inner ear that's shaped like a snail shell – is unable to process the amplified sound. A cochlear implant bypasses the non-functioning part of the cochlea and delivers sound signals directly to the auditory nerve. This procedure requires the insertion of a long chain of electrodes into the helical cavity of the cochlea. With the help of a digital signal processor, the electrodes transmit the sound signals recorded by a microphone as electrical signals directly to the sensory cells, i.e. the auditory nerve.

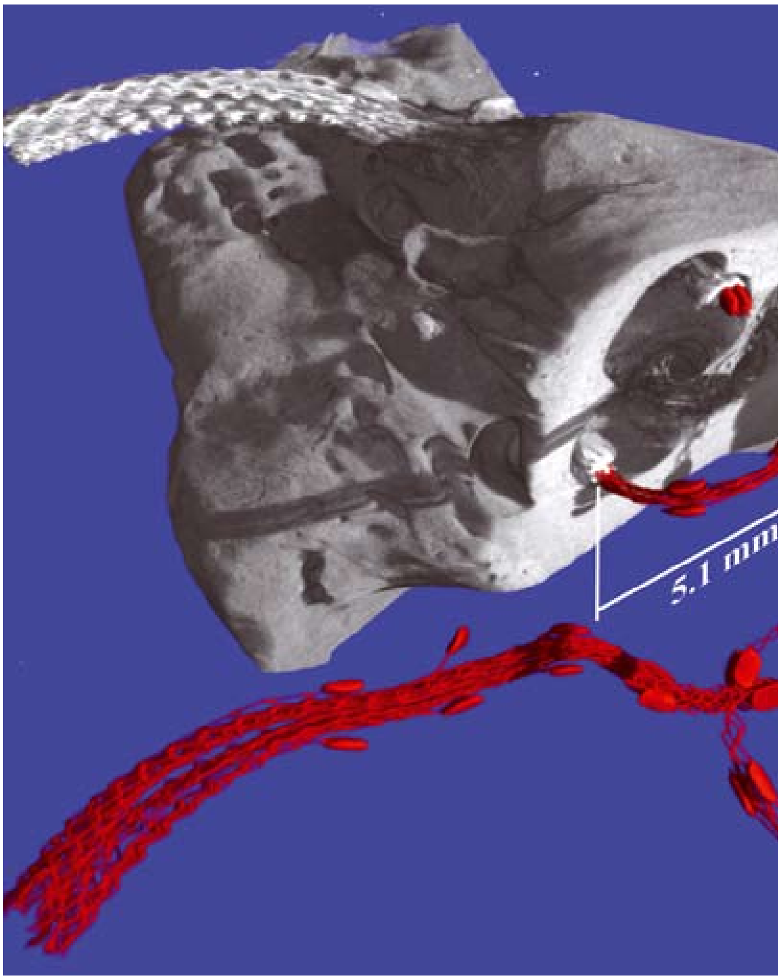
It's very difficult for physicians to obtain reliable data about exactly how the electrodes are integrated into the bone that contains the inner ear – the hardest bone in the human body. Conventional histological studies, in which thin tissue sections are analysed on a microscope, supply only limited information, because the electrodes have to be removed before such sections can be made. But by using microtomography with synchrotron radiation a team of scientists has now succeeded for the first time in visualizing the entire electrode system of a cochlear implant, the structure of the inner ear and the entire temporal bone simultaneously – non-destructively and in 3D.

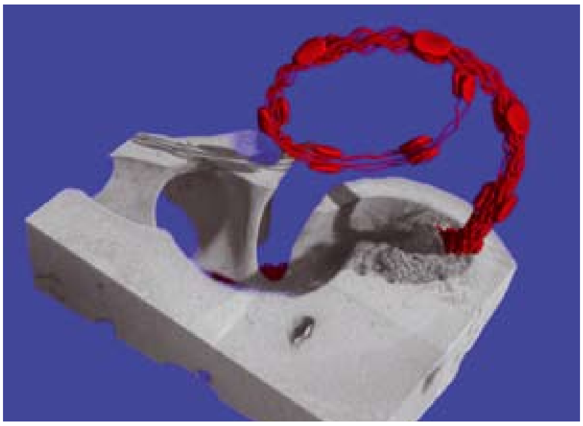
To achieve this, the researchers removed the implant together with the surrounding tissues after the patient had died, fixated the sample and stained it to improve the density resolution of the soft tissues. Then they studied the sample with X-rays from the DORIS III storage ring. The recorded tomograms were then assembled by a computer to form a three-dimensional image.

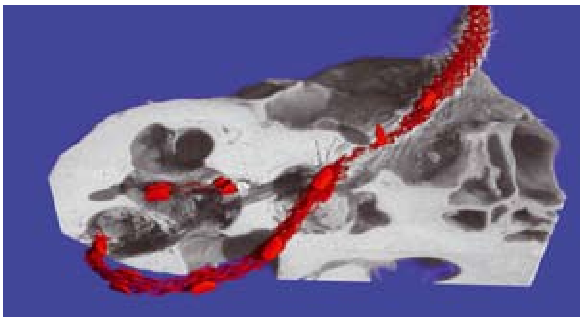
The result was remarkable. The 12 electrode pairs, the interconnecting platinum wires and the silicon matrix in which they were embedded were all clearly visible in the 3D image. The surrounding bony tissues can be displayed with various degrees of transparency, so that the interface between bone and implant can be studied in detail and the complex, characteristic shape of the electrode array can be visualized. It corresponds to the spiral shape of the cochlea, which, in humans, comprises two and a half turns. The 3D image allows the position of the implant in the inner ear to be precisely determined and viewed from all angles. What's more, the three-dimensional data set, which was obtained in an entirely non-destructive manner, makes it possible to obtain virtual sections of the sample in any desired plane. This provides the best possible preliminary information to precisely guide a subsequent histological examination.

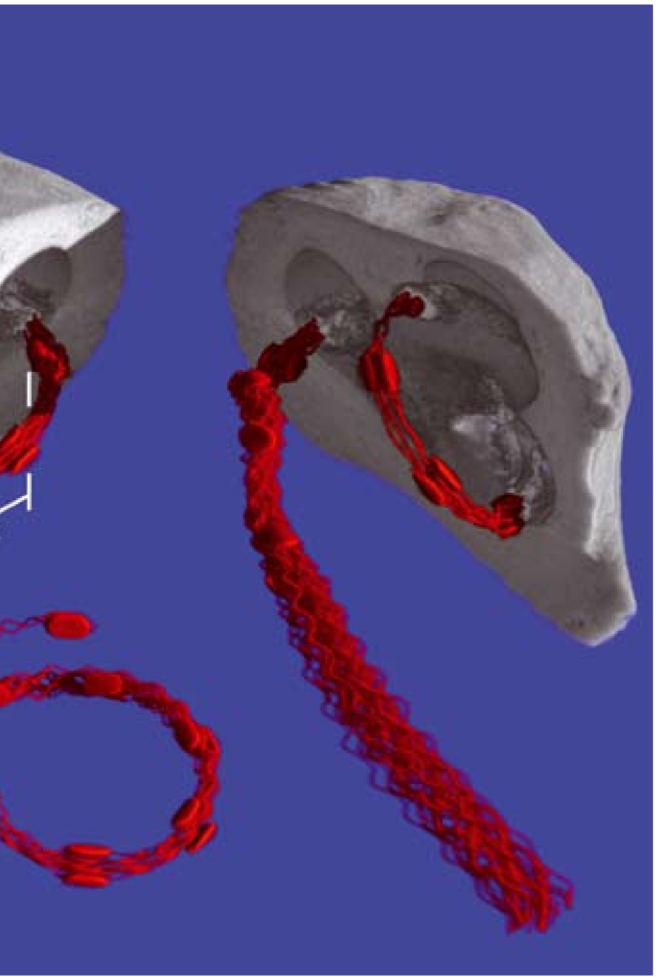


Microtomography with synchrotron radiation simultaneously reveals the electrode system of a cochlear implant, the structure of the inner ear and the temporal bone. The 3D images show not only the exact location of the implant, but even the distribution of new bone formation.









Microtomography with synchrotron radiation has thus proven to be an unrivalled experimental method for studying complex three-dimensional structures that consist of dissimilar, bony and soft tissues. The resolution of just a few micrometres makes it possible to analyse the structures of the inner ear in detail and to localize the electrode array of the implant with high precision. What's more, the method can even show the formation of new bone and soft tissue that might interfere with the function of cochlear implants. As a result, the obtained data provide an important basis for developing realistic models for the propagation of the electric current generated by the implant, to help improve the design of cochlear implants.

> **Biomaterials Science Center (BMC), University of Basel, Switzerland**

> **GKSS Research Centre Geesthacht, Germany**

> **MED-EL, Innsbruck, Austria**

> **Medical University of Innsbruck, Austria**

Microtomography – 3D X-ray imaging in miniature

Three-dimensional X-ray imaging is a standard procedure in modern hospitals. Conventional computed tomography (CT) operates according to the following principle: The patient is positioned within the circular opening of a tomograph. An X-ray device revolves around the patient and makes images of successive layers of a portion of his or her body. A computer then combines the data from all these images into a 3D image of that portion of the body's interior.

The researchers at the DORIS III storage ring are pushing at the boundaries of this method. In microtomography with synchrotron radiation – much as in conventional CT – they create a series of two-dimensional absorption images of a sample. These X-ray images are then combined into a 3D image by a computer. The big difference is that in this method the scientists achieve a resolution that is a thousand times finer than with a conventional CT system. While hospital devices visualize details with a precision smaller than a millimetre, the new method clearly reveals details smaller than one micrometre. What makes this astonishing spatial resolution possible is synchrotron radiation. Microtomography requires maximum light intensity in minimum space – which is just what the tightly collimated and extremely bright X-ray beam from the DORIS III accelerator delivers.

MULTI TALENT.

Using DORIS III to explore the properties of versatile materials

Without the achievements of materials research there wouldn't be any mobile telephones. The same goes for digital cameras, laptops and all of today's other portable electronic devices. Enormous progress has been made in recent years in the development of new materials – especially in the fields of power supply, data storage and data processing. Magnetic materials have played a particularly important role in driving progress forward. But media with special electrical properties are also continuing to gain in importance.

Of particular interest are innovative materials that combine magnetic and electrical properties in unique ways. Known as multiferroics, these materials could herald the next major breakthrough in storage technology. Such special materials have been subjected to a detailed study by a team of researchers from the Hahn-Meitner Institute (HMI) in Berlin, the Max Planck Institute for Solid State Research in Stuttgart and DESY, using neutron scattering and X-ray scattering with the intense X-ray beam from the DORIS III storage ring.

Ferromagnetic materials have been known for ages, the most well-known examples being the metals iron, cobalt and nickel. Below a specific temperature, these materials become magnetized, i.e. they possess a spontaneous, stable magnetization. This can be influenced and thus switched by an external magnetic field. If the material remains magnetized for a long time even without an external magnetic field, it is referred to as a permanent magnet – familiar examples are horseshoe magnets and refrigerator magnets.

A phenomenon analogous to ferromagnetism also occurs in the electrical context. Below a characteristic temperature, ferroelectric materials exhibit a spontaneous, stable electrical polarization that can be switched by an external electric field. Such materials were discovered early in the past century. Since electrical polarization is most often associated with a change in material structure, such materials are increasingly being used as sensors or actuators, for instance in the injection systems of diesel engines.

The experimental station at the DORIS III storage ring is equipped with a high-field cryomagnet.

Magnetism is of fundamental importance above all in data storage on hard discs or other storage media. In general, data are “written” onto a magnetic storage medium using magnetic fields. Then they can be decoded by a reading head that is also controlled by an external magnetic field. Recently, non-volatile storage devices based on ferroelectricity have also become available. This type of storage medium is known as FeRAM (for ferroelectric random access memory). In these devices, two different polarization states of a ferroelectric crystal are used that are switched by an external electric field. The advantage is that the write process is substantially faster than in magnetic storage devices.

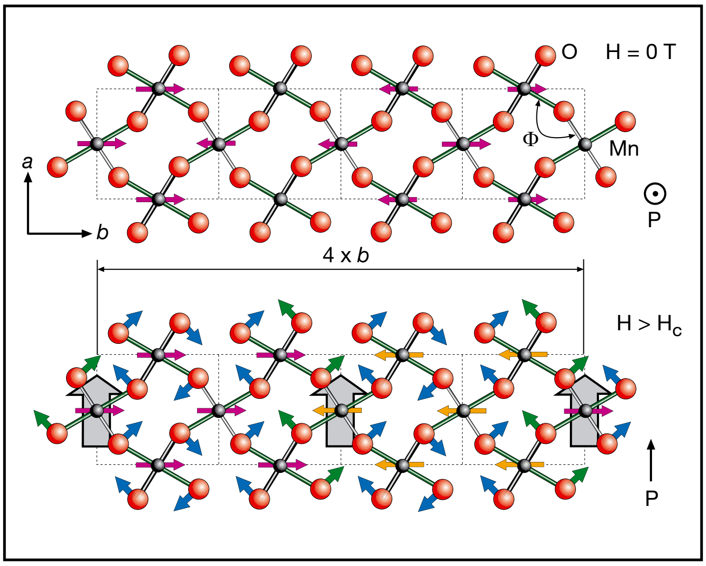
If a single storage medium could be developed with both of these material properties, it would become possible to pair an electric write process with a magnetic read process in order to combine the advantages of both storage types and circumvent their specific disadvantages – and thereby to create, once again, a substantially faster data storage medium.

Materials have been recently discovered or developed that actually have both ferromagnetic and ferroelectric properties. Two such multiferroic materials were studied in detail by the team from the Hahn-Meitner Institute, the Max Planck Institute for Solid State Research and DESY: the two manganese oxides $TbMnO_3$ (terbium manganite) and $DyMnO_3$ (dysprosium manganite). The researchers investigated on the one hand the ordering of the magnetic moments – the spins – of the manganese atoms in the crystal lattice, using neutron diffraction at the HMI. On the other hand, they also analysed the distortions of the crystal structure using X-ray diffraction at the DORIS III storage ring at DESY.

When the crystals are cooled below a certain critical temperature, the magnetic moments of the manganese atoms arrange themselves into a spiral pattern, and the structure of the crystal lattice changes as well. These changes are accompanied by the creation of characteristic diffraction patterns in the neutron radiation reflected by the crystal (“magnetic” reflections caused by the spin ordering) or in the reflected X-rays (“structural” reflections caused by the physical arrangement of the atoms in the crystal lattice). At the same time, the spontaneous ferroelectric polarization occurs. The electric polarization is thus closely linked to the structural distortion and the spiral spin ordering.

While ensuring that the temperature remained constant, the scientists then applied an external magnetic field to the crystals. They observed that as the field was applied a change occurred in the coupling between the polarization and the distortion of the crystal lattice. Additional structural reflections at the positions of the magnetic reflections indicated that a linear coupling had occurred, which had not been observed previously. As the magnetic field was increased, the positions of the magnetic and structural reflections in the diffraction patterns of the $TbMnO_3$ crystal initially remained constant, before suddenly shifting when a specific field was reached. At the same instant, the polarization changed direction. The initial thinking was that the phase transition from one particular crystal structure to another caused the switch in the polarization. But since such a phase transition did not occur in the $DyMnO_3$ crystal, the scientists were able to disprove this hypothesis. Instead, the structural phase transition appears to be a secondary effect. The intensity and direction of the electric polarization are evidently directly dependent on the ordering of the magnetic moments of the manganese atoms in the crystal, which suggests a magnetic phase transition at high magnetic field.

So far, the coupling of ferromagnetic and ferroelectric properties has only been observed at very low temperatures, and such materials are therefore not yet suitable for specific applications. But the investigation of such multiferroics has already yielded promising information about the relationships between the two effects, which – materials researchers hope – will in the long run lead to the development of multiferroic materials with higher critical temperatures, and to the hoped-for breakthrough leading to new applications.



The crystal and magnetic structure of $TbMnO_3$ in the *a*-*b* plane.
Top: Model of the spin structure of the manganese atoms without an external magnetic field above the critical temperature. The polarization P is directed out of the image plane. Bottom: Model of the spin structure of the manganese atoms in a magnetic field exceeding the critical value. The large arrows in the ferroelectrically active areas indicate the new direction of the polarization.

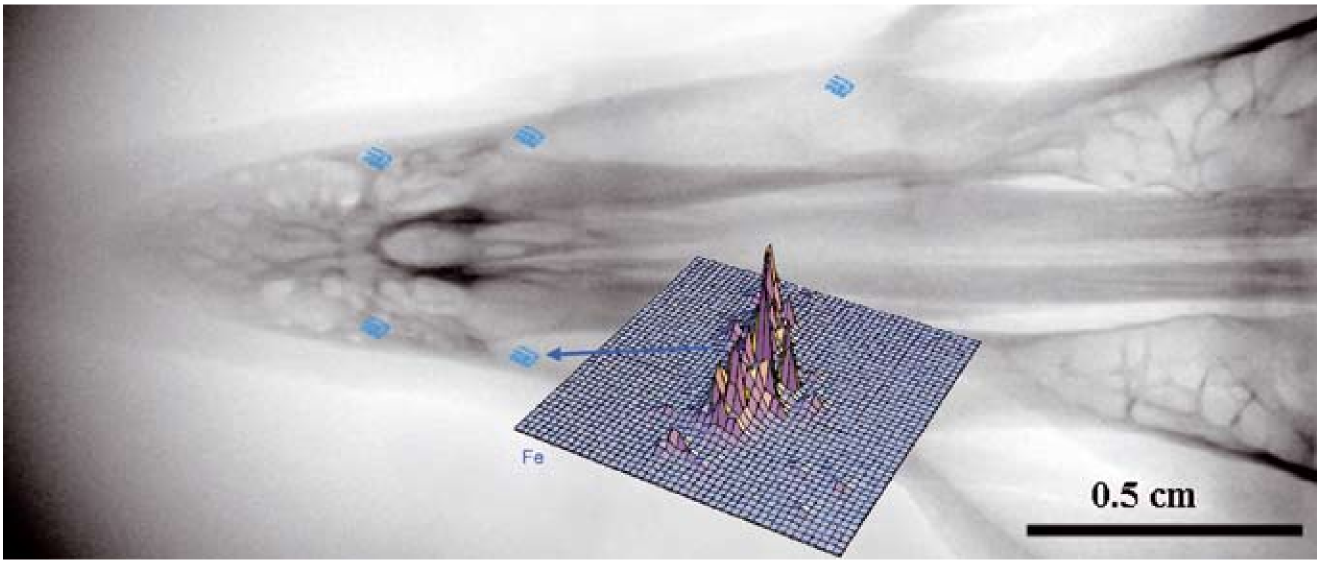
MAGNETIC SENSE.

DORIS III uncovers navigation system in pigeons' beaks

A homing pigeon always finds its destination. The position of the sun aids its sense of orientation, and even highways and intersections provide it with optical landmarks. But that's not enough to keep it precisely on course. Birds can achieve this feat because they are also endowed with a magnetic sense, the underlying mechanism of which researchers from the University of Frankfurt are now exploring in collaboration with DESY and the Technical University of Darmstadt. It's conceivable that iron crystals in the bird's beak could sense the direction and magnitude of the earth's magnetic field and direct the pigeon accurately to its home base.

The researchers on the team got their first indications that the beak might contain magnetic receptors from microscopic examinations of thin tissue sections. As it turned out, the skin lining the upper beak is crisscrossed by a complex network of nerves containing innumerable fine branches known as sensory dendrites. At six different locations in the beak, the researchers found iron oxides with magnetic properties in these dendrites.

The investigations continued at DORIS III in Hamburg. Here, the team used X-rays from the storage ring to determine the distribution and exact quantity of the iron oxides. They also



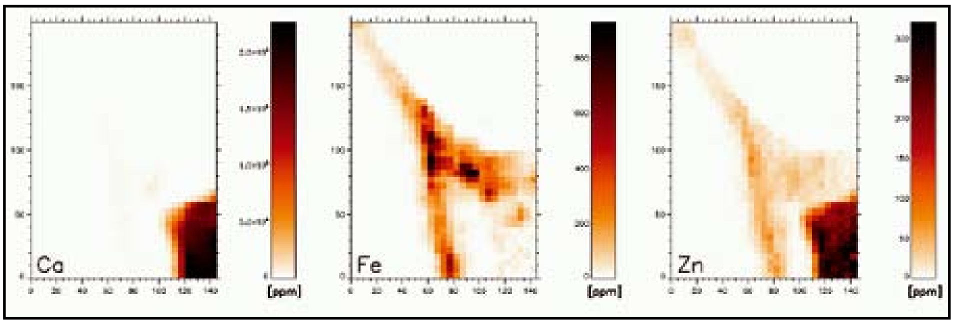
X-ray image of a pigeon's beak, with insert of an X-ray fluorescence analysis diagram. The X-ray beam from the DORIS III accelerator scans the thin tissue section and provides information about how much iron, for instance, is contained at which points in the skin of the beak.

determined their chemical composition. The analysis revealed that tiny metal platelets made of maghemite were arrayed like dominos in the dendrites of the beak skin. Now and then, small spheres containing magnetite interpose themselves between these bands. This combination acts as a functional unit. Homing pigeons use it much like a three-axis magnetometre to register the minutest variations in the direction and magnitude of the earth's magnetic field – independent of their motion and posture. Since these variables differ with the geographical position, birds can use them at any time to determine their location – which enables them to travel back thousands of kilometres to a specific place.

A possible signal chain might function as follows: If a pigeon deviates from its course, it is likely that the inhomogeneous local field, which is amplified by the maghemite platelets, undergoes a change. A magnetic pull or push force is thereby exerted on the small, magnetite-containing spheres. This triggers a signal in mechanical receptor channels, which is conducted to the brain. As a result, the pigeon can sense the change in direction and make appropriate course corrections. The researchers noted identical findings in the beaks of robins, garden warblers and even domesticated chickens. Perhaps this capability will turn out to be a universal sensory system in birds.

In further studies, scientists will explore these phenomena in greater detail. In particular, the focused X-ray beams generated by the forthcoming PETRA III light source at DESY will be fine enough to investigate the different crystals individually. This will contribute to a more precise understanding of how the natural magnetic field receptors work, and how the iron-containing cellular compartments of the dendrites interact. The measuring method used in this context can also be very useful in many other areas such as biomedicine, environmental analysis and the materials sciences.

The significance of the tiny iron oxide crystals extends far beyond the astonishing orientation sense of the birds. Such particles could, for instance, find many different uses in nanotechnology – for example, to selectively administer drugs, or even for data storage. But before potential applications can be explored in detail, a significant problem needs to be solved. Although birds have been producing such crystals for millions of years, scientists haven't yet been able to create them artificially.



X-ray fluorescence analysis can be used to measure the distribution of different chemical elements in a sample with high resolution – in this case the concentration of calcium, iron and zinc within a dendrite in a pigeon's beak.

BRILLIANT RING.

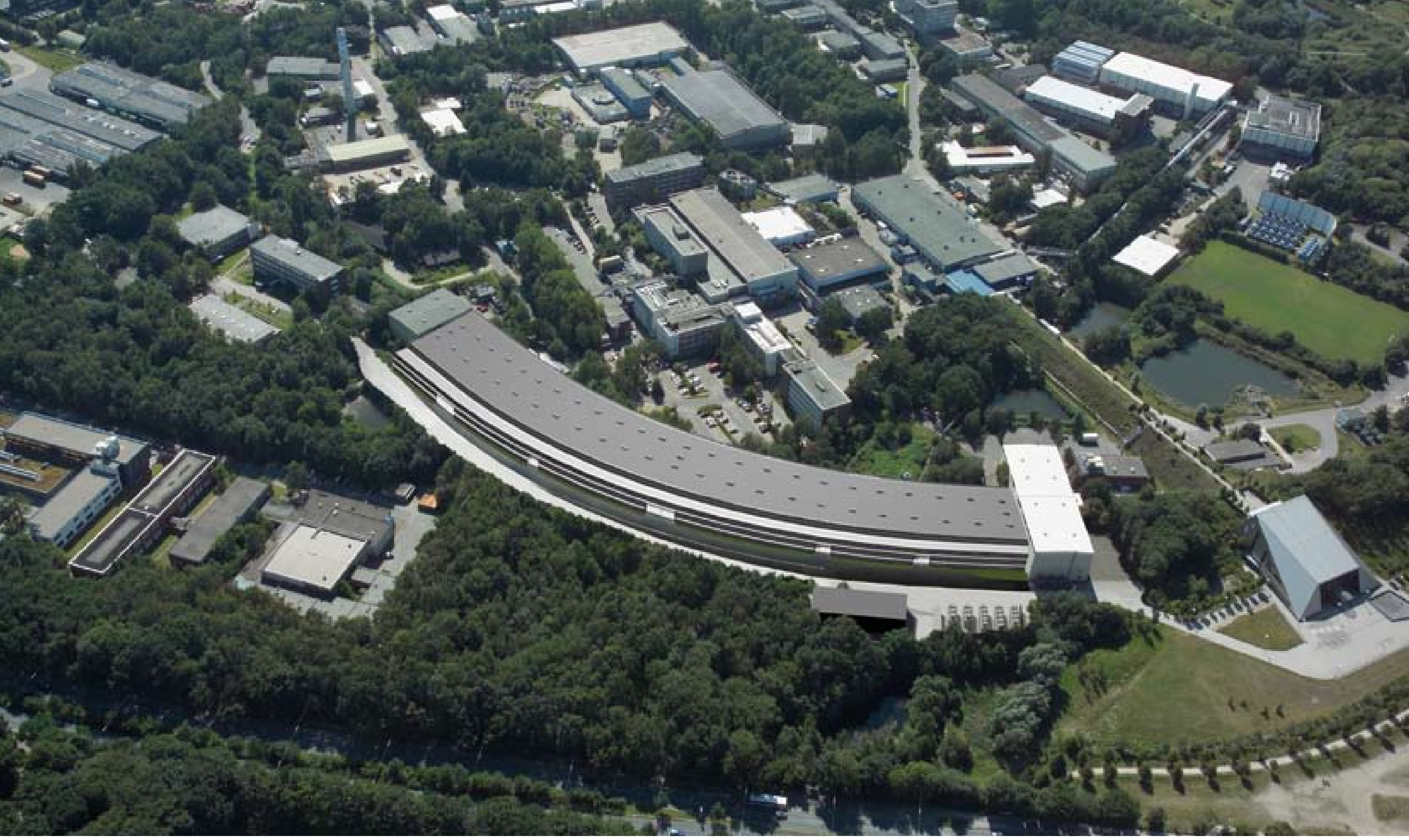
PETRA III – a jewel with many facets

Scheduled for completion in 2009, PETRA III will be one of the most brilliant storage ring-based sources of X-ray radiation in the world. As the most powerful light source of its kind, it will offer scientists outstanding experimental opportunities with X-rays of an exceptionally high brilliance. In particular, this will benefit researchers investigating very small samples or those requiring tightly collimated and very short-wavelength X-rays for their experiments.

Of the roughly 3000 scientists who use the sources of synchrotron radiation that exist in Germany, more than 2000 travel to Hamburg every year to conduct research using the light sources at DESY. Tried and proven for many years, the dependable DORIS III synchrotron radiation source supplies millimetre-thin light beams with a high photon flux but comparatively low brilliance. However, the demand among researchers for a finer and more intense X-ray beam of higher brilliance continues to grow. In Europe such radiation is available most notably at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France. But this source alone can’t meet the very high demand among users.

With the FLASH free-electron laser that has been operating at DESY since 2005 and the planned European X-ray laser XFEL, scientists will have access to unprecedented experimental capabilities. The temporal resolution, brilliance and coherence of the X-ray laser radiation are setting new standards. But these innovative radiation sources are not well suited to ensure the basic scientific supply of intense X-ray radiation. An increasing number of users around the globe, both in the natural sciences and in industrial laboratories, will continue to need powerful storage ring-based radiation sources in the future. And these sources must be internationally competitive in order to buttress the high standing of Germany and Europe as research venues.

DESY has therefore decided to convert the 2.3-kilometre-long PETRA storage ring, which has long been used for particle physics, into a powerful radiation source. The facility will create very brilliant short-wavelength X-rays – with a performance that will actually surpass that of its worldwide competitors. As a result, PETRA III will perfectly complement the range of existing and planned European radiation sources.



Architectural study for the new experimental hall of PETRA III

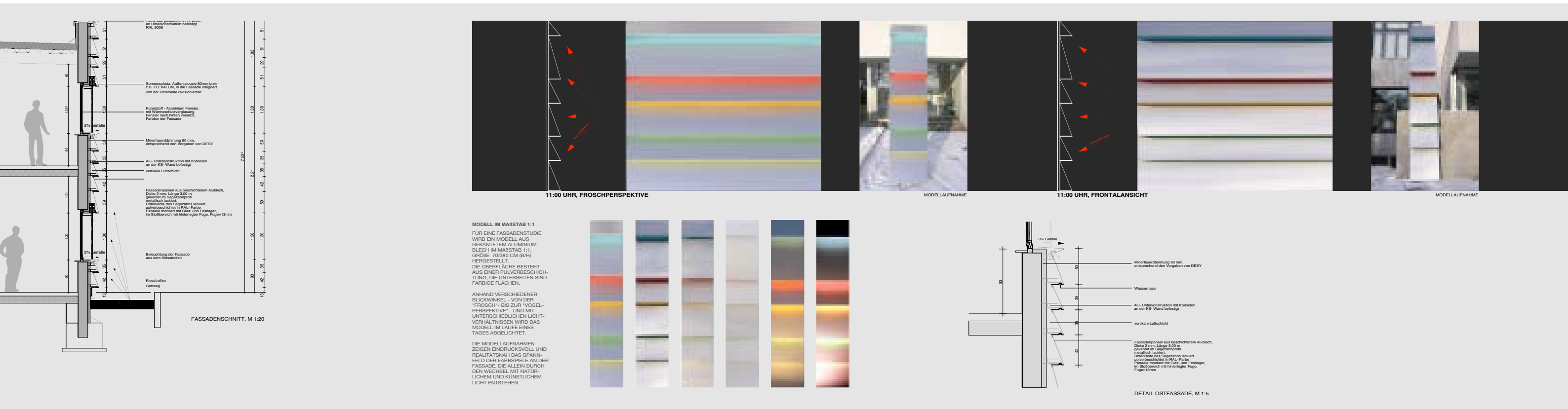
Conversion to a brilliant radiation source

To convert it to a brilliant radiation source, it will be necessary to completely rebuild nearly 300 metres of the 2.3-kilometre-long PETRA ring and to erect a new experimental hall. The plans call for 14 experimental stations with up to 30 instruments. Excellent experimental capabilities are ensured by the installation of undulators – long arrays of magnets that generate X-ray radiation of exceptionally high brilliance. In simple terms, this means that a very large number of photons will be emitted from a very small area to form an extremely collimated beam of X-rays. As a result, PETRA III will deliver a photon flux within an area of a single square millimetre that is as high as DORIS III presently produces on several square centimetres! The new radiation source will commence user operations in 2009. >

Brilliance

Brilliance characterizes the quality of the radiation, and consequently the performance of a radiation source. It is a measure of the number of photons (particles of light) generated within a defined range of wavelengths. The brilliance is greater, the smaller the radiation source and the more tightly collimated the emitted radiation beam.

Façade study for PETRA III



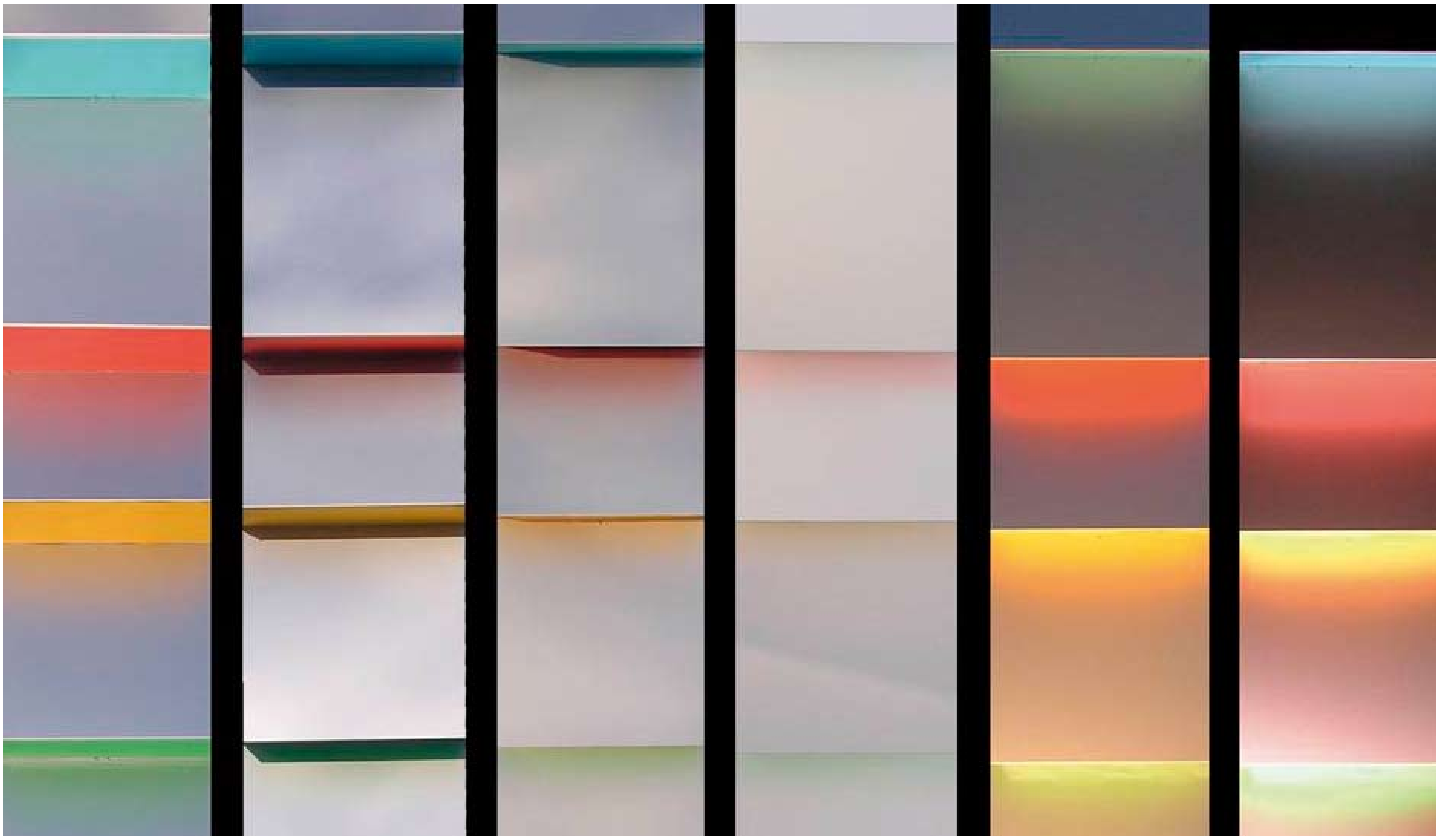
World-class research in a futuristic setting

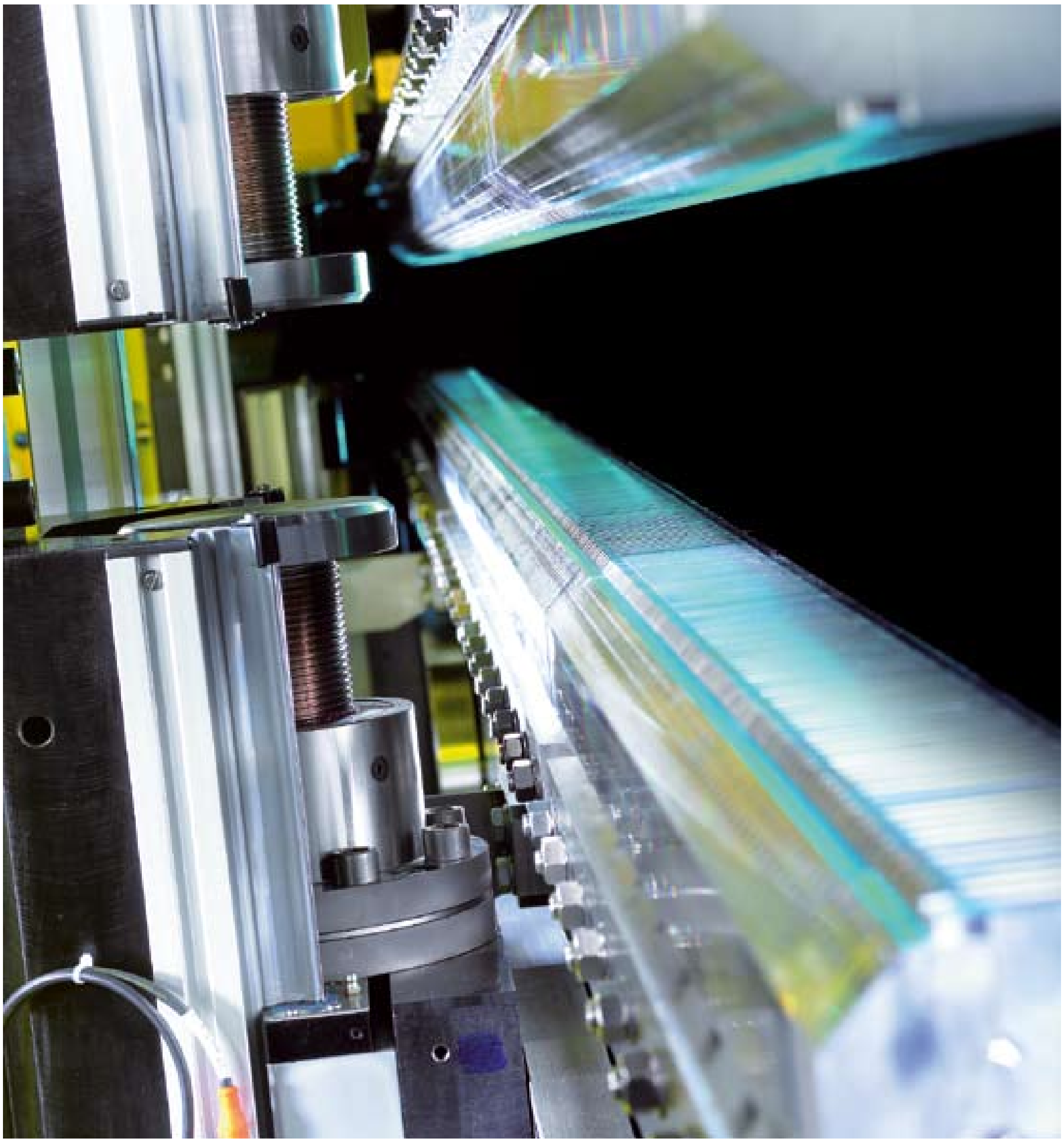
The new experimental hall of PETRA III will be an impressive 280 metres in length, and its shape will conform to the curved contour of the accelerator ring. An area of about 10 000 square metres will contain 14 experimental stations that can accommodate up to 30 experiments – with the measuring equipment located on the ground floor and the evaluation rooms on the first floor.

To ensure that the high-precision measuring equipment isn't affected by mechanical vibrations, a special technique is being employed in the construction of the experimental hall. The hall floor is cast as a single one-metre-thick concrete slab that will support both the accelerator and the experiments. The slab is isolated from the vibrations of the rest of the building. To also minimize the influence that the building could exert through the ground on the hall floor, the building is supported on sleeved piles extending 20 metres below the surface. Anchored in concrete at that depth, these supports are surrounded by a thin bubble-wrap foil that acts as low-friction casing, thus preventing direct contact with the upper layers of the soil. This allows any force acting on the piles to be transferred deeper into the ground and thus reduces distortions at the surface.

The architect's plans for the façade provide for a modern design that underscores the unusual shape of the hall. It will be composed of light saw-toothed metal panels. The upper surface of these aluminium sheets is smooth and has a natural aluminium colour, but the lower surfaces are finished in different colours. As a result, daylight striking the facade creates a play of colours on the metallic surfaces that keeps changing with the time of day. Continuous bands of windows further accentuate the building's curved shape. The overall visual impression is that of a 280-metre-long arc traversed by bands of different colours that also change with the angle of view. The building is thus an avant-garde structure that perfectly complements the advanced research being conducted inside.

Façade elements for the PETRA III hall





View along one of the undulators for PETRA III

Excellent outlook for research

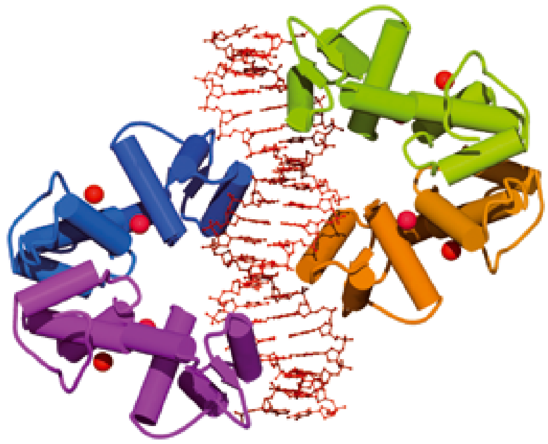
A hair-thin, brilliant X-ray beam such as the one produced by PETRA III gives researchers vital advantages. For example, even minuscule material samples can be studied and the arrangement of their atoms precisely determined – or molecular biologists can explore the atomic structure of tiny protein crystals. The demand for such information is enormous. The structure of proteins generated according to the genetic blueprint is at the very top of the researchers' wish list. An important application will be the development of new drugs that can be targeted precisely at the location where a pathogen attacks.

Because of this excellent outlook, the European Molecular Biology Laboratory (EMBL) and DESY are extending their collaboration, which has already endured more than 30 years, to cover PETRA III as well. By 2010 the Hamburg outstation of the EMBL will construct EMBL@PETRA III, an integrated research facility for structural biology at DESY. Its state-of-the-art experimental stations will enable researchers to utilize the extraordinary properties of the storage ring for innovative applications in the life sciences – for example, to make advances in protein crystallography and small-angle X-ray scattering of biological materials. In the new facility, all the steps involved – from high-throughput protein crystallization and sample preparation to data processing – can be performed under one roof. This advance will decidedly speed up the research on molecules that make the difference between human health and disease.

PETRA III also opens many different opportunities in the field of materials research. For certain applications, materials researchers need highly energetic photons with high penetration power – for example, to test welding seams or to check production parts for signs of fatigue. The PETRA III storage ring will generate especially high-energy radiation at up to 100 000 electron volts with high brilliance – a decisive advantage for many experiments. >

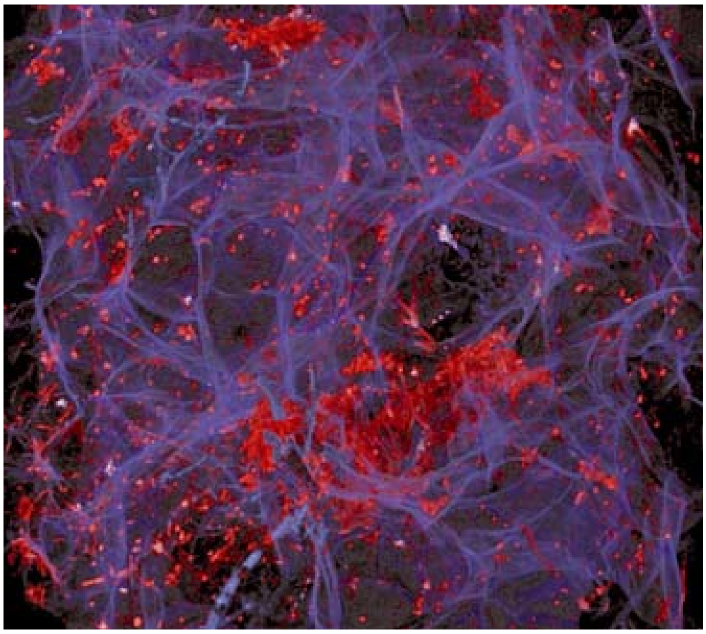
The challenge of structural biology

To decode and understand the building blocks of life, ever larger and more complex molecules are now being studied – whose crystals diffract X-rays less and less. A prime example is the exploration of the ribosome (see page 26). The more complex the structure, the more intense must be the X-rays used to examine it. The big challenge of the future is to explore the way a complete cell operates at the molecular level. Modern synchrotron radiation sources such as PETRA III will make important contributions in this quest.



New materials in 3D

In recent decades, computed tomography (see page 30) has become an established technique in the materials sciences too, and a standard method for the examination of inner structures of materials. Spatial resolution and image contrast in particular have been continuously improved. The high-brilliance X-rays from PETRA III will make it possible to study structures in different materials with an accuracy of less than one micrometre in high-speed exposures. As a result, even fast process sequences, such as foam formation, can be studied in serial 3D images. Special contrast techniques can be used to visualize even low-contrast objects three-dimensionally and non-destructively, and to analyse them quantitatively. As an example, X-ray microtomography can be used to study the integration of cells into biocompatible materials non-destructively, and thus to gain knowledge about the best way to create 3D cellular substrates.



Microtomogram of a material that could be used in the future as a 3D substrate for the growth of cell cultures. The artificial bone structure (blue) consists of a protein-based, open-pored ceramic foam. Coloured red are the cells – only a few micrometres in size – that have grown in the substrate.

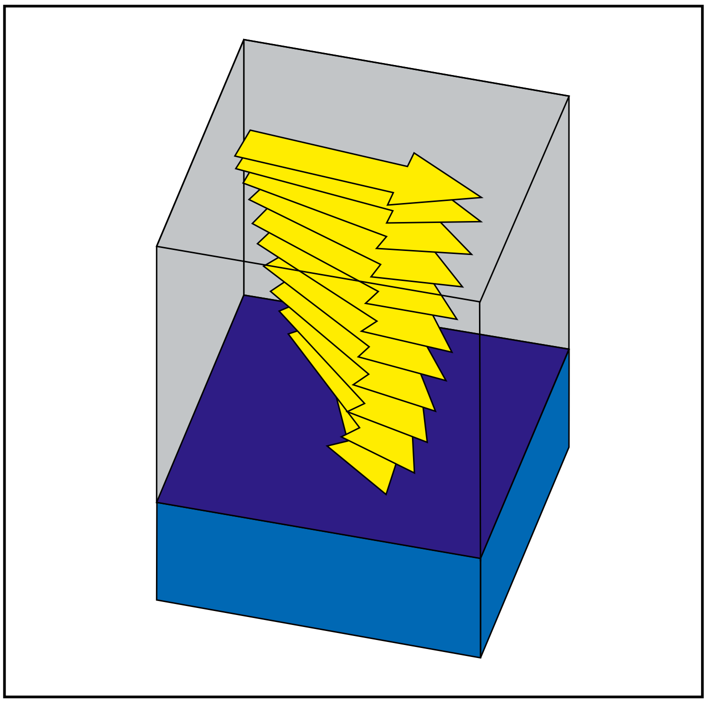
Chemical analyses on a microscopic scale

The optical microscope enables scientists to view the microcosm. But as a rule it doesn't reveal which chemical elements the visualized structures comprise. Focused X-rays at PETRA III will provide the capability of chemically analysing a sample on a very small scale. This method will produce three-dimensional microscopic images of the element distribution – even when less than one in a million particles consists of the element in question. It will also be possible to visualize chemical bonds and crystal structures. This method is non-destructive and fast, so that even growth processes can be studied. These capabilities will be useful in many diverse applications in biomedicine, environmental analysis and materials sciences.

Such methods were for instance useful in studying the magnetic sense of birds (see page 34). In the past it was impossible to seperately study the crystals involved in this phenomenon, which are composed of two different iron compounds. But the focused X-ray beams of PETRA III will be so fine that the different crystals can be individually measured to gain an even better understanding of the magnetic sense in birds.

Nanomagnets for data storage

Ultra-thin magnetic films have become indispensable when more data must be stored in ever less space. The magnetic storage density of commercially available hard disks has presently reached values of 20 gigabits per square centimetre, and thus makes it possible to store and play full-length movies on devices the size of a credit card. This property is physically based on magnetic structures that are 10 000 times smaller than the diametre of a human hair. The stored information is contained in the orientation of tiny, closely packed nanomagnets. In writing information on such storage media, it must be possible to change this orientation in an instant without influencing neighbouring nanomagnets. The way this process unfolds depends on what these structures are made of. To further develop and optimize these types of storage media, scientists must therefore be able to view the inside of such nanostructures. This will become possible with the highly brilliant X-rays of PETRA III.

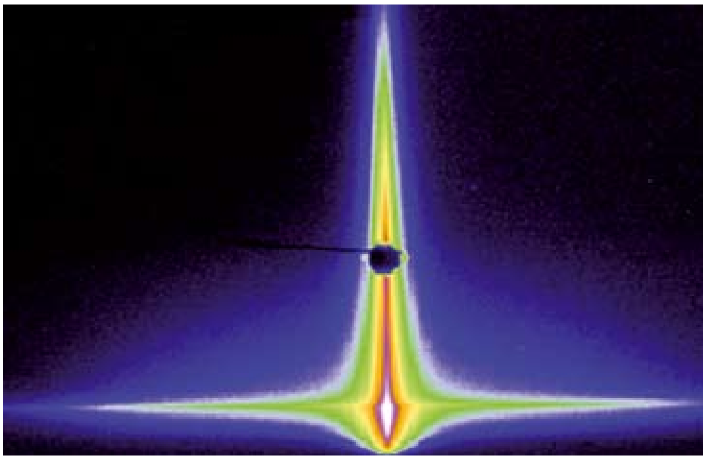


Fan-like orientation of the magnetic moments within an iron layer ten nanometres (billionths of a metre) in thickness, which is bonded to a magnetically hard layer (blue).

Tailor-made surfaces

Focused X-rays at PETRA III will be up to 1000 times finer than a human hair. Such nanobeams will create many entirely new opportunities for studying materials, especially surfaces.

In many cases, the microstructure of surfaces determines their properties and function. Examples include water- and dirt-repellent coatings, catalytic surfaces and materials whose optical properties can be precisely selected by placing tiny, nanometre-sized particles of noble metals on the surface. The shape and arrangements of these particles determine the colour and brightness of the surface in visible light. This technique can, for example, be used to create forgery-proof identification. The nanobeams of PETRA III will enable scientists to determine the structure and arrangement of such particles on surfaces with great precision. What's more, it will become possible to watch and understand the creation, growth and distribution of nanoparticles on surfaces in real technical production processes – an important requirement in the pursuit of further improvements of these methods.



Spatial distribution of X-ray radiation scattered by a surface. Such measurements are useful for reconstructing the shape and distribution of nanoparticles on the surface.

FRONT RUNNER.

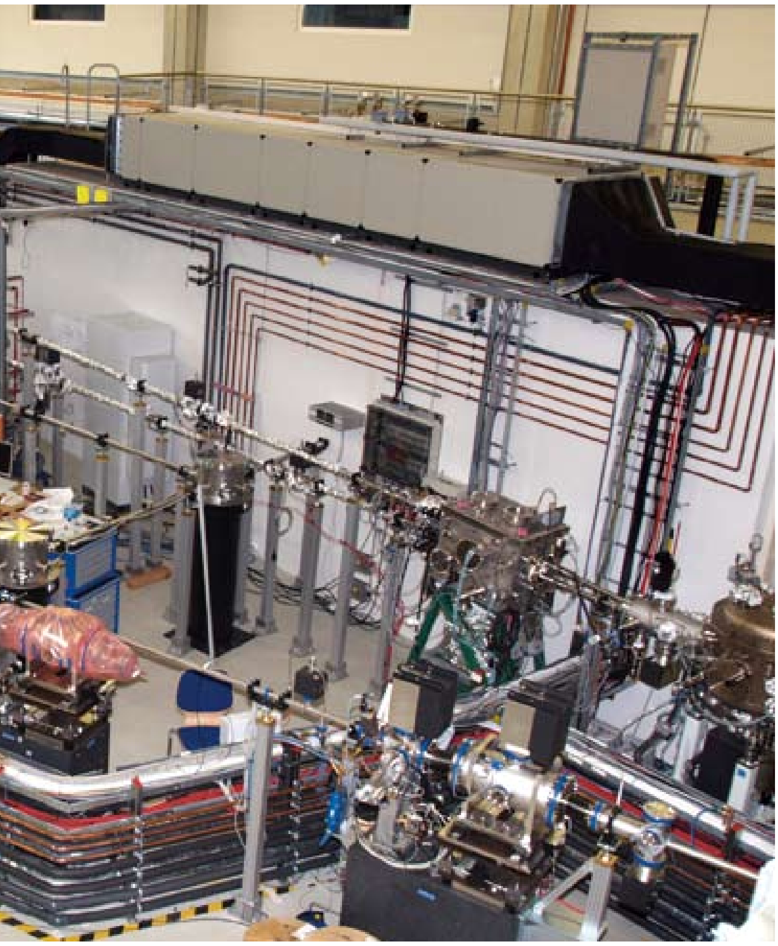
FLASH – world record laser flashes

Since 2005, researchers at DESY have had access to a unique new light source: FLASH, the world's first and, until 2009, only free-electron laser in the soft X-ray range. Among current light sources FLASH is an absolutely pioneering facility with a performance that surpasses not only the best synchrotron radiation sources but also the very latest laser systems in the X-ray range.

While it is true that synchrotron radiation sources also deliver tightly collimated radiation, FLASH generates light with real laser properties, i.e. which is perfectly collimated. In the X-ray range, conventional lasers can only deliver low-intensity beams. In contrast, the peak luminosity of the FLASH radiation is several orders of magnitude higher, even than that of the most advanced synchrotron radiation sources. In addition, since the laser radiation from FLASH is emitted in ultra-short flashes, it provides the researchers using the new DESY facility with experimental capabilities not available from any other radiation source on the globe.

Builders of radiation sources on several continents have been competing for years to develop the first high-performance laser for the X-ray range. In this race, the international FLASH team is clearly out in front: The 260-metre-long free-electron laser at DESY is presently the world's only laser facility that delivers fast pulsed, powerful and ultra-short light flashes in the soft X-ray region. Even during the first measuring period from 2005 into 2006, FLASH set a new record of 32 nanometres (billionths of a metre) – the shortest wavelength ever produced with a free-electron laser. In 2006 the FLASH team bettered that record with a wavelength of only 13.1 nanometres – and, on top of that, at a laser power that exceeded anything even the world's largest plasma X-ray laser facilities can produce.

Beamlines and experimental stations in the FLASH hall



In the summer of 2007, FLASH was expanded further with the aim of reducing the wavelength of the generated radiation to the planned design value of six nanometres. This will enable DESY to retain its worldwide leadership until 2009, when the LCLS (Linac Coherent Light Source) free-electron laser in Stanford (USA) goes into operation with even shorter wavelengths in the hard X-ray region.

In demand

The FLASH facility at DESY is being used for research with short-wavelength ultraviolet radiation and soft X-rays. User time at the initial four of five experimental stations is in great demand – just a year after the start of user operations, the facility was already threefold overbooked. Even during the first measuring period, the high hopes that the researchers had placed on the revolutionary new experimental capabilities of the free-electron laser were already confirmed (see pages 16–23). Consequently there are many prospective users interested in other projects at FLASH, for instance in the fields of physics, chemistry and molecular biology.

However, FLASH is not only in demand as a new kind of research instrument. The facility is also playing an important pioneering role for the larger free-electron lasers to come, such as the LCLS in Stanford and the European X-ray laser XFEL, which will generate X-ray flashes in the hard X-ray region. At FLASH, scientists, technicians and engineers are testing the superconducting accelerator technology which will be used in the XFEL as well as the special magnet arrangements for generating the X-ray flashes, the optical components, experimental setups and detector systems. Operating FLASH is also helping them to gain valuable experience with the electronic processing of large data volumes. Furthermore, FLASH is presently the world's only radiation source where researchers can explore new experimental methods for the future X-ray lasers.

Unique experimental capabilities

The extraordinary properties of the FLASH radiation provide researchers in virtually all natural sciences with unprecedented experimental capabilities. The peak luminosity of FLASH for instance exceeds that of the most advanced synchrotron radiation sources by a factor of ten million, and consequently opens the door to previously impossible studies, for example of processes in astrophysics using extremely diluted samples. The radiation is laser-like, i.e. coherent, and the wavelength can currently be adjusted between 13 and 60, later between 6 and 60 nanometres. Of special importance is also the extremely short duration of the radiation pulses, which last only 10 to 50 femtoseconds (quadrillionths of a second). Scientists will be able to use this radiation much like an ultra-fast stroboscope to actually watch fast processes such as the formation of chemical bonds or the processes involved in magnetic data storage as they actually unfold. The high energy of the radiation makes it possible to produce in the laboratory energy densities in matter that can otherwise only be found in the far

Taking stock: successes in the first measuring period

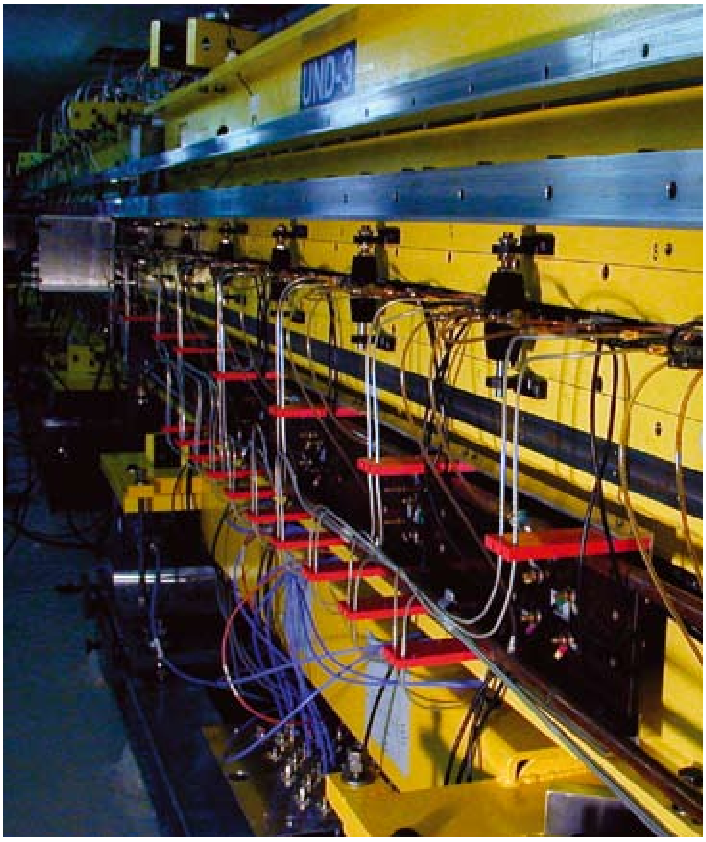
In the HIXSS experiment, the intense laser light from FLASH is used to explore catalytic processes on solid-state surfaces.

The FLASH free-electron laser at DESY is an absolute novelty: For the first time, experiments can now be conducted with highly intense, pulsed laser radiation at short wavelengths in the soft X-ray region. In other words, the researchers involved have ventured into entirely unexplored territory for which there was no prior data that they could rely on.

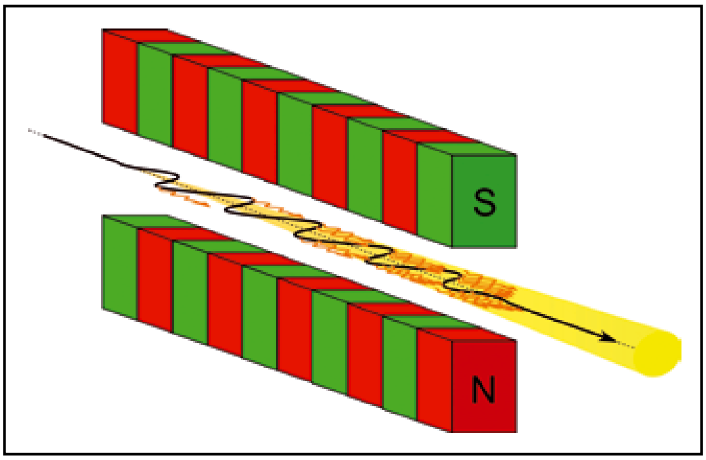
Most of the groups of scientists arriving at FLASH for the first measuring period (2005–2006) came equipped with entirely new instruments designed specifically for the special properties of this laser radiation. Despite the complexity of the equipment and initial teething troubles of a new radiation source that hadn't been completely run in yet, the researchers were highly satisfied and returned home happily with new data by the diskful.

The early experiments ranged from the generation and measurement of plasmas, investigations of gases and clusters to initial studies of experimental methods for complex biomolecules – methods of the type intended to be used at the European X-ray laser XFEL, among others. As expected, the X-ray pulses of FLASH were shorter than 50 femtoseconds. Some groups were already able to use them for the first time to actually watch processes as they unfolded with extremely high temporal resolution – much as in a slow-motion film. The investigation of such time-resolved processes using short-wavelength radiation ranks among the most important new applications this type of X-ray laser will offer in the future (see pages 16–23).

SASE – the principle



So how does a free-electron laser work? During their slalom run through a periodic array of magnets (the undulator) the electron bunches emit radiation (photons) of a distinct wavelength. The photon beam propagates in a straight line so that it overlaps with the electron bunch. It imprints its periodic structure on the electron bunch, so that the initially homogeneous charge density distribution becomes periodic – a chain of tiny individual charge "disks" regularly separated by a single wavelength. Now all the electron disks emit radiation in synchronism, and the light can amplify itself to form high-intensity laser radiation.



reaches of the cosmos. FLASH thus also opens a new door to the exploration of open questions in plasma physics. The wavelength region around 13.5 nanometres is of particular interest as well, because radiation of this wavelength is required in the semiconductor industry for EUV (extreme ultraviolet) lithography, which will be used to manufacture the next generation of microprocessors.

Fundamentally important for the life sciences is the wavelength region between 2.3 and 4.4 nanometres, known as the "water window." In the water window, carbon atoms in matter are highly opaque to the radiation, while the surrounding water is transparent and therefore remains invisible. This wavelength region is covered by a special, less intense portion of the FLASH laser radiation, the so-called third and fifth harmonics (i.e. radiation with wavelengths of the corresponding multiple of the fundamental laser frequency), which presently attain wavelengths of 4.4 and 2.8 nanometres, respectively. This enables biologists to perform previously impossible studies – such as generating holographic images of cellular systems with the aid of a single radiation pulse from the FLASH facility.

Technology for tomorrow's accelerators

With respect to technology too, FLASH is advancing far into new territory. The free-electron laser's operation is based on the innovative SASE principle of self-amplified spontaneous emission. In this special amplification process, electrons from a particle accelerator fly through an undulator – a periodic array of magnets – which causes them to follow a high-speed slalom course, forcing them to emit flashes of radiation. These flashes reinforce each other in accordance with the SASE principle to form short-wavelength, high-intensity laser flashes.

A distinguishing feature of FLASH is the use of superconducting accelerator technology to propel the electrons to the required high energy. The technology used to achieve this was developed and tested by the international team of the TESLA Collaboration between 1992 and 2004 at DESY. The accelerating elements, the resonators, which are cooled to minus 271 degrees Celsius, conduct electric current loss-free, so that practically all of the electric power they consume can be transferred to the particles – an extremely efficient acceleration method. What's more, the superconducting resonators deliver a very thin and homogeneous electron beam of extremely high quality. A particle beam with such special properties is a prerequisite to operate a free-electron laser in the X-ray region.

Two other large projects are based on the superconducting TESLA accelerator technology: the European X-ray laser XFEL, whose linear accelerator is roughly 1.5 kilometres long, and the future major project of particle physics, the International Linear Collider ILC, which is currently being planned in a worldwide cooperation. Its two accelerating sections will be up to 20 kilometres long and will also be equipped with superconducting resonators. Scientists and engineers can therefore gather valuable information for both projects from the operation of the 120-metre-long linear accelerator of FLASH. Participation in the FLASH project is also of considerable interest to industrial companies that can leverage the acquired technical know-how to qualify for participation in the construction of the XFEL and other linear accelerators around the globe.

The undulator section in the FLASH tunnel

LIGHT HOUSE.

XFEL – an outstanding facility for European science

The X-ray free-electron laser XFEL, a European project currently being built with strong participation of DESY and scheduled to go into operation in 2013, promises to be a genuine landmark facility. As the only light source of its kind in Europe, the XFEL will produce extremely intense, ultra-short pulses of laser light in the hard X-ray range – i.e. at wavelengths substantially shorter than even the light generated by FLASH. The XFEL will likewise set new standards in terms of brilliance and therefore promises to open up a whole new realm of previously undreamed-of research opportunities for science and industry alike.

The invention of lasers in the infrared and visible regions has triggered a real revolution in science and technology during the past 40 years. At the same time, the use of synchrotron radiation generated by ring accelerators in the ultraviolet as well as in the soft and hard X-ray regions since the 1960s has led to great experimental advances and discoveries in nearly all the natural sciences. With the construction of powerful X-ray lasers such as the XFEL, natural scientists of all disciplines are hoping to add the next chapter in the success story of the laser – and at the same time to revolutionize research with X-rays.

Today, X-ray lasers that produce radiation with even better properties than those of synchrotron radiation are being built. The generated radiation is many times more brilliant, coherent, is emitted in pulses shorter than 100 femtoseconds (quadrillionths of a second), and has a peak power of several gigawatts.

View into the tunnel of FLASH, the prototype for the XFEL, during a maintenance shut-down

The main building on the XFEL research campus with the underground experimental hall in the planning stage: The photon tunnels, from which the laser-like X-ray flashes of the XFEL are led to the experimental stations, terminate in this subterranean hall.

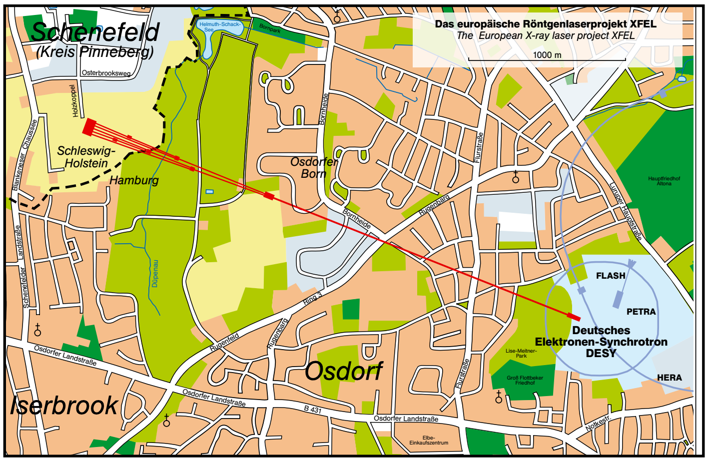
Holograms of molecules

The shorter the wavelength of the radiation, the smaller the structures that can be examined with it. That's why X-ray radiation is of such great value to researchers. Its wavelength is so short that samples can be studied with atomic resolution. Furthermore, if these X-rays also have laser properties, they can be used to make holographic images with atomic resolution – i.e. images in which the spatial arrangement of the atoms, for example in a crystal, can be imaged three-dimensionally.

With conventional X-rays, researchers have to use a detour to obtain a spatial image of a crystal's structure. To accurately determine the structure of a sample that way, a great deal of information about the molecule in question must already be known and fed into computer programs. With the aid of these inputs and of complex mathematical methods and computer algorithms, the 3D structural arrangement of atoms can then be reconstructed. With laser-like radiation, in principle no prior information is required, since the spatial information about the positions of the different atoms in the crystal is already contained in the X-ray images. They must "only" be processed to be visualized on the computer. That, however, can require other, very complex algorithms. On the computer display, the resulting 3D image of the sample structure obtained from the hologram can then be rotated freely and viewed from any angle. >

The location of the XFEL

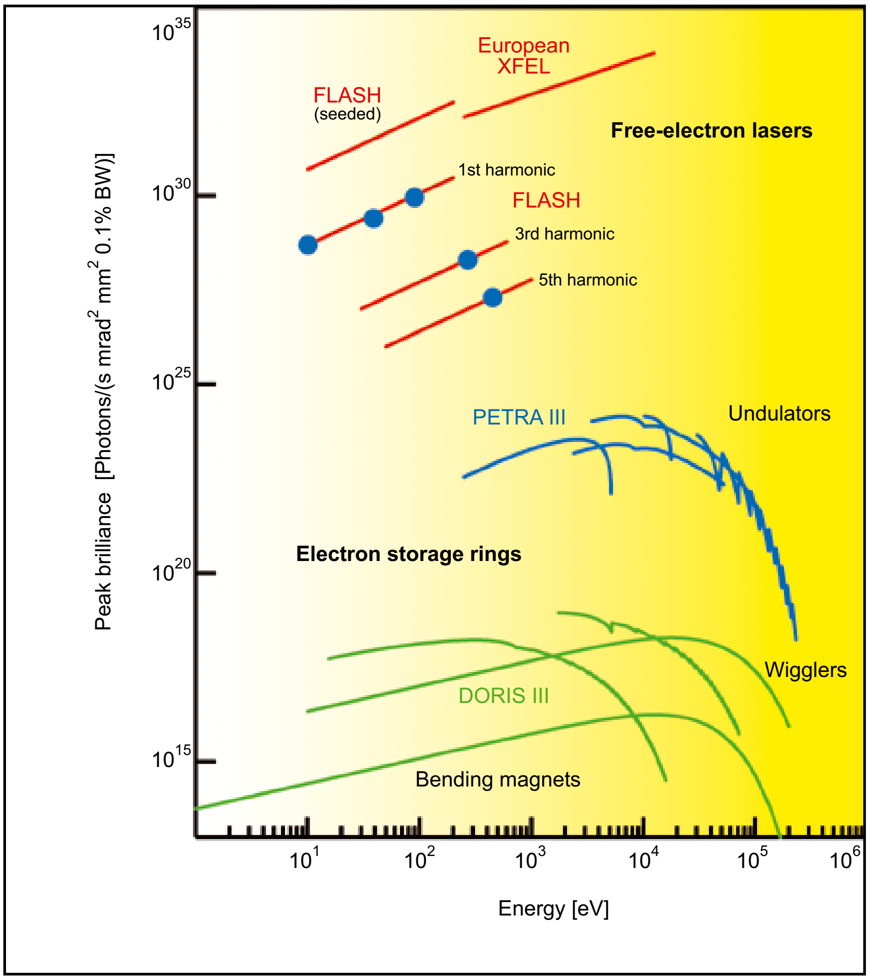
The 3.4-kilometre-long European XFEL facility with its three sites will be located in the German Federal States of Hamburg and Schleswig-Holstein. The XFEL begins at the DESY site in Hamburg-Bahrenfeld, extends to the northwest, and ends in the city of Schenefeld (Pinneberg district, Schleswig-Holstein), which borders on Hamburg. This is where by 2013 the new research campus will be built, including an underground experimental hall with space for ten experimental stations. The location has been chosen so that a second, equally large experimental complex could be built if needed. The central supply station will be located on the DESY grounds in Hamburg to support the effective utilization of the existing infrastructure. This is also where the underground tunnel begins for the linear accelerator that will deliver electrons travelling at almost the speed of light for the generation of the X-rays.



Superlative laser light

As radiation source of the future, the XFEL X-ray laser will set new standards:

- **Its peak brilliance is a billion-fold higher than that of even the most advanced X-ray synchrotron radiation sources, and the average brilliance is ten thousand times higher.**
- **Its temporal resolution is orders of magnitude better than that of any synchrotron radiation source available today. Each laser flash is shorter than 100 femtoseconds (100 quadrillionths of a second). That is the time scale on which chemical bonds are formed, and on which groups of molecules shift their positions.**
- **The wavelength of its X-ray radiation is so short that even atomic details can be visualized. It can be varied from six nanometres down to less than one-tenth of a nanometre (billionth of a metre).**
- **Its X-ray radiation has laser properties, i.e. it is coherent. As a result, holographic experiments for example can be conducted on an atomic length scale.**



Unrivalled intensity

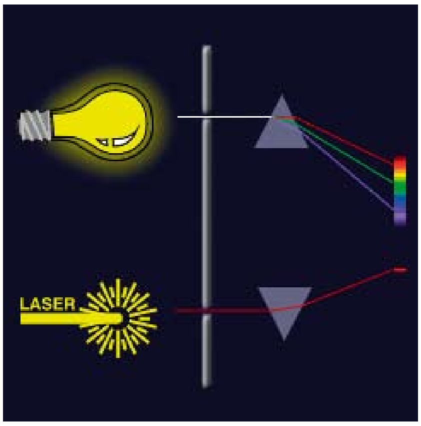
The extremely high intensity of the X-rays from the XFEL has several advantages. Not only can experiments that take several days now be completed at the XFEL in seconds or even microseconds; it will also be possible to use the high-intensity X-ray flashes to study highly diluted samples, such as very fine gas jets or even individual molecules or atoms. The high intensity furthermore opens entirely new opportunities to create and study exotic states of matter such as plasmas – hot, ionized gases such as exist for instance in the interior of stars. The high intensity of the XFEL makes it possible to create matter under such extrem conditions with a single, ultra-short X-ray flash and to study it with a second flash following immediately.

The extreme brilliance of the XFEL radiation provides exciting opportunities for creating diffraction images of individual molecules with just a single X-ray flash, without having to first go through the complex process of growing a crystal from these molecules. This will eliminate a substantial obstacle particularly in molecular biology: Many structures that are extremely important in research, such as membrane proteins or viruses, can only be grown into crystals with great difficulty or not at all, which has been making it very difficult to study their structure in great detail.

Laser – a special kind of light

> **Monochromaticity**

Sunlight or even a flashlight beam consists of a large number of wave trains with differing wavelengths, i.e. colours, that, together, appear more or less white to the human eye. Lasers on the other hand, only generate light of a single wavelength as a rule.



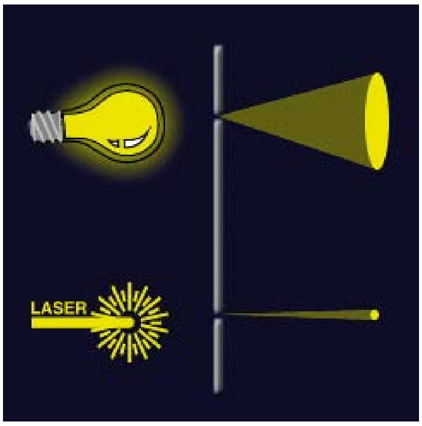
> **Coherence**

To describe any form of electromagnetic radiation in precise mathematical terms, it is helpful to think of it as composed of individual wave trains. Such a wave train is characterized by a distinct wavelength, its length and its position.

In the case of a laser beam, the individual wave trains can be very long, and adjacent trains oscillate synchronously. This property is referred to as coherence, and is indispensable when the aim is, for instance, to create 3D images of objects.

> **Emittance**

Emittance is defined as the product of beam area and divergence. The smaller the emittance, the less divergent the beam is for a given source area. Unlike light such as is emitted, for instance, by a light bulb, laser beams have a low emittance: They don't diverge very much.



> **Brilliance**

Brilliance is a measure of the number of photons generated in a specific wavelength region. The smaller the radiation source and the more tightly collimated the emitted radiation beam, the higher is the brilliance. The brilliance of a laser is far greater than that of the sun.

Atoms in a storm of flashes

Since the flashes of the European X-ray laser XFEL, at less than 100 femtoseconds, are extremely short in duration, they are ideally suited for obtaining the equivalent of slow-motion films of fast processes, such as chemical reactions, movements of biomolecules or the formation of solid-state materials: Femtoseconds are the temporal order of magnitude on which changes occur at the atomic level as two molecules react with each other. By using ultra-fast lasers, researchers can therefore obtain stop-motion images of the molecular structures as they form during the reaction – without any motion-blurring in the images as would be the case with longer laser pulses, i.e. at longer exposure times. Viewed in series, such images provide a motion picture of the reaction as it unfolds. With the ultra-short X-ray laser flashes of the XFEL, such films can be made with unprecedented temporal resolution and with the reacting molecules visualized with atomic-scale spatial resolution.

Light of the future

With the extraordinary properties of its radiation, the European X-ray laser XFEL represents a significant step forward compared to even the most advanced synchrotron radiation sources. Nearly all the natural sciences – from physics, chemistry and materials science or geological research all the way to the biosciences – will benefit from its unique capabilities. In the longer term, the outlook is also extremely promising for industrial and medical applications. The facility will, however, not replace the existing X-ray sources, but open entirely new avenues for research and for breakthrough experiments that cannot be performed at even the most advanced facilities existing today. >

A project in the making

Things started happening very fast once the German Federal Ministry of Education and Research (BMBF) had given the green light for the European XFEL facility in February 2003. In the same year the 100-metre-long TESLA Test Facility at DESY was extended to 260 metres and expanded to become the VUV-FEL free-electron laser – the user facility and pilot facility for the XFEL which is now called FLASH. All technological aspects of the XFEL were developed, tested and thoroughly studied at this facility. As the world's first free-electron laser for short-wavelength radiation, FLASH has been setting one wavelength world record after the other, proving that the principle of the free-electron laser really is capable of producing intense laser radiation in the X-ray region. The successful user operation of FLASH since the summer of 2005 and the first groundbreaking experiments have impressively confirmed both the feasibility and the research potential of the even more powerful X-ray laser XFEL.

On the organizational side too, the preparations for the XFEL got off to a quick start. On the initiative of the BMBF, an international steering committee was established in February 2004 with the mission of working out the details of the participation of European countries in the XFEL facility. The committee is composed of high-ranking government representatives of countries that are interested in participating. In April 2005, DESY submitted an application for the planning approval procedure for the construction and operation of the XFEL to the State Office for Mining, Energy and Geology (LBEG) Clausthal-Zellerfeld, which has jurisdiction in this matter. In the summer of 2005 the European XFEL project team was appointed to prepare the establishment of an independent European XFEL organization, to be named XFEL GmbH (company with limited liability). In September 2005, the first interested countries signed a Memorandum of Understanding, which will serve as a basis for international collaboration until an international agreement has been signed. Other countries soon followed. Today the list of signatories comprises Denmark, France, Germany, Greece, Hungary, Italy, Poland, Russia, Spain, Sweden, Switzerland, the United Kingdom and the People's Republic of China. Bilateral negotiations are currently underway at the government level between Germany and each of these countries about the nature and extent of their participation in the XFEL.

Things really came together for the XFEL in the summer of 2006. In July, the European XFEL project team submitted the Technical Design Report to the international steering committee: On its 580 pages, around 300 authors from 71 institutions in 17 countries detailed all scientific and technical aspects of the research facility. In this context, the total construction cost of the facility including the first ten experimental stations was estimated at 986 million euros (based on 2005 price levels). And on 20 July 2006, the LBEG Clausthal-Zellerfeld issued the planning approval for the XFEL. This comprises all individual approvals required by law for the construction and operation of the XFEL facility.

The official go-ahead for the XFEL was given on 5 June 2007. The construction of a starting version with six experimental stations can now begin. Altogether, 75 percent of the required construction cost in the amount of 850 million euros (based on 2005 price levels) will be born by Germany, the rest by the international partner countries. The independent European XFEL research organization (XFEL GmbH), in which all of the participating countries are represented, is due to begin its work in 2008. The partners remain committed to the eventual completion of the full version of the facility. Construction will start at all three project sites in the spring of 2008, so that commissioning of the European XFEL can begin by the end of 2013.

New technologies for new light sources

The performance of light sources for science with photons continues to improve. In a few years, with the development of X-ray lasers like the European XFEL, researchers will have access to radiation whose brilliance surpasses that of today's sources by orders of magnitude. But even the brightest beam of light with the shortest flashes is of little use unless it can be precisely controlled and focused, unless its properties can be selectively adjusted – and unless, upon completion of the reaction in a sample, the generated reaction products can be studied with a maximum of accuracy and temporal resolution.

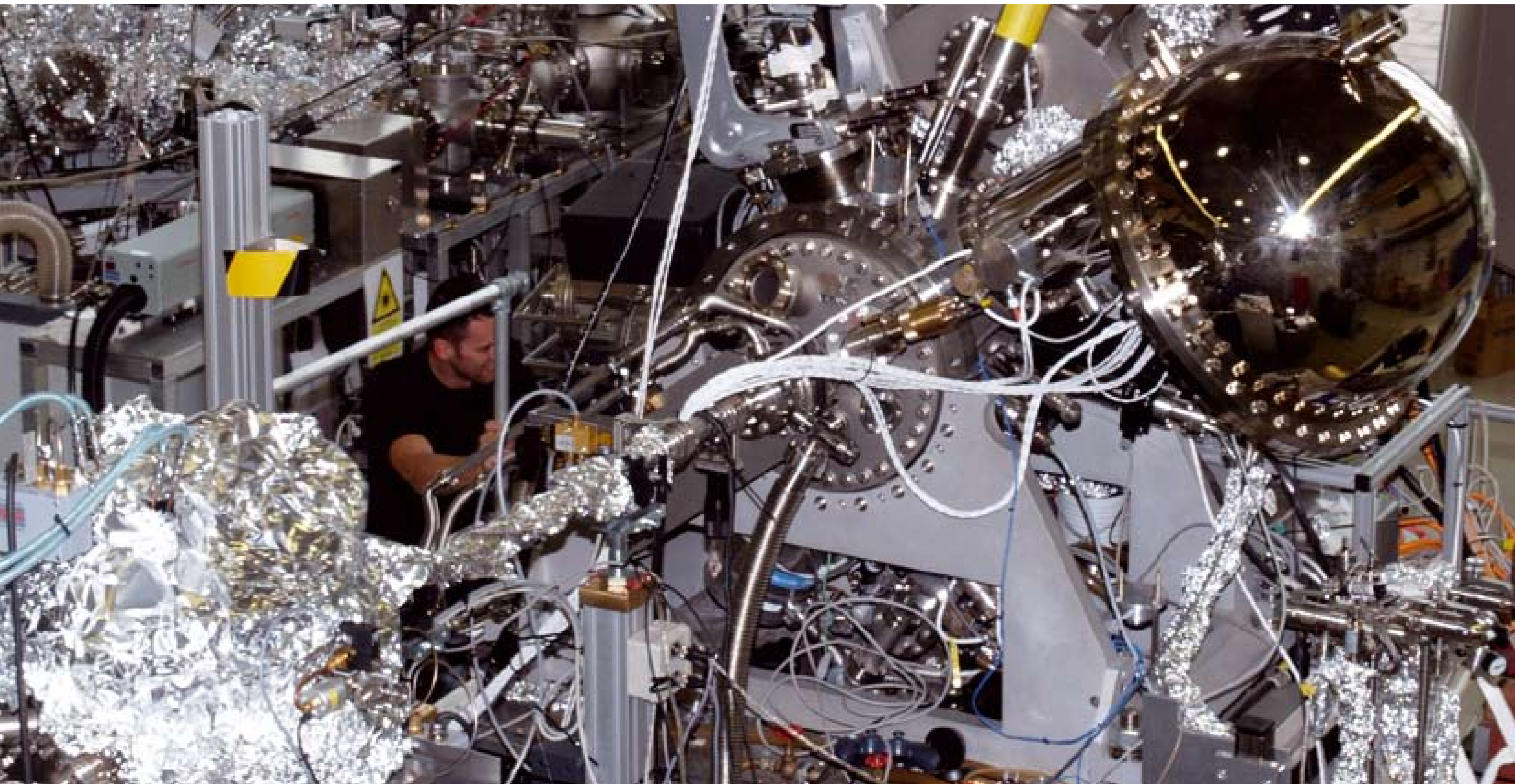
Exactly this enormous boost in the performance of the future sources poses particularly difficult challenges for the researchers – because at present, virtually no instruments exist that are designed to work with such a beam. And the best experiment is only as good as the weakest link in the chain from the radiation source via the actual measuring setup all the way to the scientists' computer.

The development of such innovative instruments can take years. Intensive work is therefore already under way at DESY and at research facilities around the globe on new concepts for beamlines as well as optical elements such as monochromators, gratings and mirrors that direct the beam from the accelerator to the experimental station. A particularly difficult challenge is posed by the detectors needed to monitor the X-rays and identify the different reaction products. These instruments must be endowed with extremely high spatial and temporal resolution to take full advantage of the special properties of the XFEL's laser beam.

Ten times per second, the XFEL will generate a train of 3000 X-ray pulses, each with a duration of only 100 femtoseconds, spaced 200 nanoseconds apart. The "quiet" time interval between these individual pulse trains lasts 99.4 milliseconds. Ideal detectors should therefore be able to process a repetition rate of 5 MHz, i.e. five million pulses per second. The detector systems should be capable of detecting every single X-ray pulse, and of enabling the experiments to utilize each of the 30 000 pulses per second – a challenge that remains unresolved so far. Of course such fast detectors will also generate data volumes that far exceed anything previously encountered in science with photons. In this context too, new data acquisition and analysis systems will have to be developed to manage such an enormous dataflow.

In order to fully exploit the benefits of the intense light from future X-ray lasers, researchers will thus have to venture far into unexplored territory – to develop both the required instruments and the appropriate experimental methods. DESY in conjunction with international partners has therefore launched a series of tendering processes, and has also proceeded independently to establish a detector group. In these developments, the researchers benefit especially from synergies with the particle physics programme at DESY, since the development of specialized detectors and data acquisition systems has always been a central aspect of experimental particle physics.

To exploit the full potential of the new radiation sources, equally sophisticated detectors will be needed. The photo shows a detector used in a FLASH experiment.



We would like to thank everyone who has helped in the creation of this brochure for their active support.

IMPRINT.

Publisher
Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

Hamburg location: Notkestraße 85, D-22607 Hamburg
Tel.: +49 40 8998-0, Fax: +49 40 8998-3282
desyinfo@desy.de, www.desy.de

Zeuthen location: Platanenallee 6, D-15738 Zeuthen
Tel.: +49 33762 77-0, Fax: +49 33762 77-413
desyinfo.zeuthen@desy.de

Hamburg Synchrotron Radiation Laboratory: hasylab.desy.de

Author
Ilka Flegel, Textlabor, Jena

Realization and editing
Ute Wilhelmsen
Wiebke Laasch
Ilka Flegel, Textlabor, Jena

Design
Jung von Matt/brand identity GmbH, Hamburg

Layout
Heike Becker

Translation
TransForm GmbH, Cologne

Printing
Schneider Druck e.K., Schenefeld

Copy deadline
August 2007

Photographs and Graphics
DESY
Michael Bogumil, Hamburg
EMBL
Peter Ginter, Lohmar
Dirk Günther Grafik Design, Hamburg
Kontor B3, Hamburg
Max-Planck-Arbeitsgruppen für Strukturelle Molekularbiologie, Hamburg
Option Z, Thomas Plettau, Frankfurt
Dirk Rathje, Hamburg
Christian Schmid, Hamburg
Manfred Schulze-Alex, Hamburg

Page 3, 39: Babcock Noell GmbH, Würzburg
Page 18–19: Henry N. Chapman et al., Nature Physics 2, 839 (2006)
Page 20: Michael Meyer et al., Physical Review A 74, 011401(R) (2006)
Page 22–23: Max-Planck-Institut für Kernphysik, Heidelberg
Page 26: Max-Planck-Institut für Biophysikalische Chemie, Göttingen
Page 28–29: Reprint with permission from: Jan-Dierk Grunwaldt et al., Journal of Physical Chemistry B, vol. 110, issue 17, pp 8674–8680 (2006), Copyright © 2006 American Chemical Society
Page 30–31: Felix Beckmann, GKSS, Geesthacht
Page 34: Gerta Fleissner, Jörg Habersetzer, Frankfurt (X-ray image); Gerta Fleissner, Frankfurt, Gerald Falkenberg, DESY (inset)
Page 35: Gerta Fleissner, Frankfurt, Gerald Falkenberg, DESY, Gerta Fleissner et al., Naturwissenschaften 94:631 (2007)
Page 36–38: dinsefeestzurl architekten, Hamburg
Page 40: Astrid Haibel, GKSS, Geesthacht (microtomogram, BAM/BESSY)
Page 46: Antoine Devouard, Agentur R.E.A.

Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

The Helmholtz Association contributes to solving major challenges facing society, science and the economy with top scientific achievements in six research areas: Energy, Earth and Environment, Health, Key Technologies, Structure of Matter, Transport and Space.

With 25 700 employees in 15 research centres and an annual budget of approximately 2.3 billion euro, the Helmholtz Association is Germany's largest scientific organization. Its work follows in the tradition of the great natural scientist Hermann von Helmholtz (1821–1894).

www.helmholtz.de