

FOCUSSING ENERGY REALISING VISIONS



TWO METHODS – ONE GOAL: TO DISCOVER MORE

Penetrating nature's secrets with
photons and neutrons



Inside view of a neutron detector shielding.

IN BRIEF

Helmholtz Zentrum Berlin (HZB) was founded after merging two longstanding research centres, the Hahn-Meitner Institut (HMI) and the Berliner Elektronenspeicherring Gesellschaft für Synchrotronstrahlung (Berlin Electron Storage Ring Society for Synchrotron Radiation, or BESSY for short), as a way to **pool their expertise** and facilitate the complementary use of neutrons and photons (light particles) for researching the structure and function of matter. With its unique research infrastructure, HZB attracts around 2500 of the most brilliant minds in science and technology to Berlin each year. They come from universities, colleges, and research facilities such as the Max Planck Society and the Bundesanstalt für Materialforschung (German Federal Institute for Materials Research and Testing). They are scientists, medical professionals, archaeologists and even art historians.

Combining photon and neutron experiments allows scientists to gain deeper insights into natural processes than could be achieved by one approach alone.

HZB offers a wide-variety of measurement and instrumentation devices for experiments including extreme condition instruments for low-temperature, high pressure and high magnetic field experiments. This brochure looks at a few examples of important on-going and current research using both neutrons and photons.

HZB: Facts and Figures

HZB is one of 17 centres of the Helmholtz Association. The HZB institute employs approximately 1100 staff members and has a total yearly budget of 110 million euros. Approximately 100 doctoral candidates every year earn their qualifications at HZB and approximately 50 students complete vocational training in one of twelve professions at the institute. Beyond the Berlin-Brandenburg region, the HZB cooperates with more than 400 partners from German and international universities, research institutes and companies.

ONE PLUS ONE IS MORE



THE BER II RESEARCH REACTOR

BER II in Berlin-Wannsee is an internationally renowned **neutron source**. With its 24 experimental stations, experimenters have practically all neutron scattering or neutron radiography techniques at their disposal. Neutrons, being electrically neutral particles, penetrate deeply into the matter that is being examined. The way they are scattered by the material reveals information about the material's characteristics. A detector records the interaction between the neutrons and atoms within the sample, giving the researchers comprehensive insights into the **structure and dynamics of the material**.

All of the instruments enable studies at the highest scientific level. With the renewal of the neutron guides in 2011 and the renovation and modernization of important reactor components, BER II gives the approximately 500 yearly users access to measuring conditions that are unrivalled in the world.

The available sample environment is unique in the world:

Experimenters can make use of high pressures, ultra-low temperatures down to almost absolute zero and extremely strong magnetic fields of up to 17.5 tesla – and starting in 2012, 25 tesla.



BER II at a glance

- Light-water-moderated, open “pool-type” reactor
- Basin dimensions: 200 m³ of water distributed over two basins connected by a channel, each 3.5 metres in diameter and 11 metres deep
- Thermal power: 10 megawatts (around four hundred times less than a typical nuclear power plant)
- 24 fuel rods, each with 322 grams of uranium-235
- 6 fuel elements to accommodate control rods (neutron absorbers) with 238 grams each of uranium-235
- Neutron flux: $1.2 \cdot 10^{14}$ neutrons per square centimetre and second
- 9 beam tubes for thermal neutrons
- Cold source with 9 neutron guides

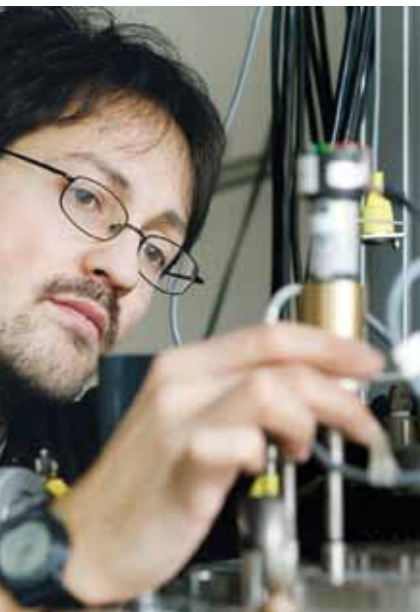


View of the exterior of the synchrotron BESSY II in Berlin-Adlershof.

MICROSCOPE FOR SPACE AND TIME

BESSY II in Berlin-Adlershof is a brilliant source of synchrotron light. This type of light is emitted by electrons when they are accelerated to near the speed of light and rotated around a circular track. The electromagnetic (light) waves emitted by the electrons cover a spectrum from the terahertz range through visible light and up to hard X-rays. This light can sometimes be millions of times brighter than the sun. Using **special magnetic structures**, known as insertion devices, the BESSY II accelerator experts can boost the intensity of the out coming light to extremes. On more than **50 beamlines**, experimenters can adjust the wavelength and oscillation direction of the synchrotron light as well as adjust the energy of the light particles (photons). The ultrafast photon flashes can be directed onto extremely small samples. This allows measuring precision of ten millionths of a millimetre (nanometres) and temporal resolutions of billionths of a second (femtoseconds). Each year more than 2000 researchers from universities, research institutes and industry around the world utilise this facility.

The Physikalisch-Technische Bundesanstalt (**PTB**) also uses the BESSY II synchrotron as a European standard for calibrating light sources and detectors.



BESSY II at a glance

- Circumference: 240 metres
- Bending magnets: 32
- Number of experimental stations (beamlines) for parallel operation: 50
- Number of circulating electrons: 1 to approx. 1000 billion (in up to 400 packets)
- Energy of one electron: 1.72 billion electron volts (GeV)
- Shortest light flash: approx. 2 trillionths of a second (picoseconds)

Preparing an experiment at BER II, where samples will be subject to extremely strong magnetic fields and very low temperatures.

MATERIALS FOR TOMORROW

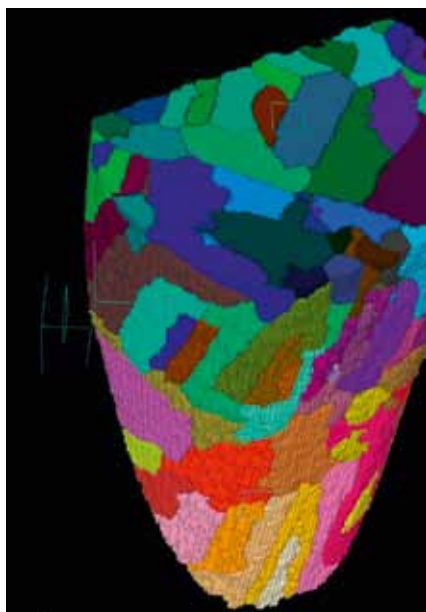
The macroscopic properties of materials can often be understood by studying the nature of their atomic components and structures. By knowing these relationships researchers are able to develop materials or components with desired properties, for example designing materials that are more compact, more flexible, more robust, lighter or more efficient than those we have today.

Researchers therefore systematically scan and illuminate materials with neutrons and synchrotron light. The neutrons penetrate deep into materials and probe the atomic nuclei, while photons interact mainly with the electrons near the surface of the solid. The methods complement each other perfectly. Together, both photons and neutrons allow researchers to study layers near the surface as well as the volumetric properties of materials in a completely non-destructive manner.

Computers of tomorrow: ever faster, ever more powerful

The goal is to produce computer data storage with ever higher-performance densities while simultaneously maintaining lower-energy consumption. However, this can only be achieved by knowing exactly what happens on a hard disk drive surface while data are being written or read. Using neutrons a research team at HZB, partnered with a team from Switzerland, were the first to visualise in 3D the domains of magnetic materials used in a hard disk drive. Their method of choice was **neutron tomography**, performed at the BER II research reactor. Storage devices and computer electronics can be made especially compact and energy-saving by exploiting another property of electrons for writing and storing data: an intrinsic property known as angular momentum, or spin.

Magnetic domains shown
for the first time in 3D.





Understanding magnetism in the micro- and nanocosmos to produce increasingly more powerful computer hard drives, for example.

Spintronics is accordingly the electronics of the future. To plumb the depths of this technology, workgroups at the synchrotron ring BESSY II fire ultra-short laser and X-ray pulses in rapid succession at thin, magnetized metal foils. These pulses are generated by the so-called femtoslicing technique. Femtoslicing at BESSY II is special, because only here user will find femto-second pulses of circularly polarized **X-ray light**. This, combined with neutron measurements, allows researchers to perform ultrafast experiments to build a complete picture of magnetic phenomena.

Lossless current flow

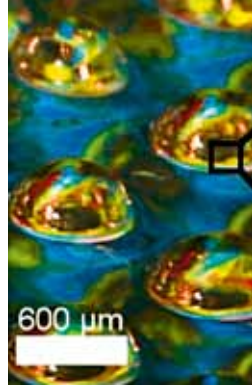
The intrinsic angular momentum of electrons also plays a crucial role in **superconductivity**. Superconductivity lets us transport electrical currents almost completely without any loss or heat, but the materials we know today only enter the superconducting state at extremely low temperatures – an expensive effort. Research groups around the world are trying to explain this effect and are looking for answers how to put this phenomenon to practical use. The aim is to develop materials that transport electric charges at room temperature. This would save billions of euros in energy costs and simultaneously help reduce the environmental burden.



Two examples of successful neutron experiments for high-temperature superconductivity:

- In cooperation with an international group of scientists, researchers at HZB have discovered a universal magnetic signature among all iron-based superconductors, despite the respective materials having different chemical properties.
- In lanthanum strontium manganate – an electric conductor which, similar to high-temperature superconductors, is produced by doping insulating materials – where free electrons briefly behave like a gas. They quickly however, become trapped inside the crystal lattice again. The experiment proves that superconductivity does not exist permanently in this base material.

Lenses for mobile phone cameras, produced with a soft lithography method: the nanostructures on the lens array – a moth-eye structure – create an anti-reflective effect, which improves the optical properties of the lenses.



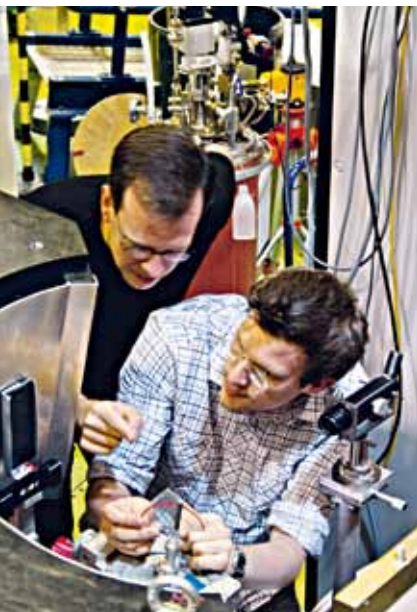
INVESTIGATING QUANTUM PHYSICS IN SOLIDS

A research group using neutrons was the first to detect magnetic monopoles in a solid. Predicted by physicists, these exotic particles possess only one magnetic pole, either north or south. The quasi-particles detected at HZB resemble tubes containing a magnetic field inside them. The researchers showed that magnetic moments inside the material arrange themselves like “spaghetti”, the density and number of these moments can be reduced, and at very low temperatures magnetic monopoles exist at the ends of the tubes.

Another team working with neutrons discovered hidden symmetries in solid matter. These symmetries result from quantum physical properties of the electrons in certain special solids. Their spins arrange themselves into chains only one atomic layer thick. The workgroup was able to excite these chains to resonate like guitar strings, where adjacent strings vibrate in relation to each other at frequencies exactly equalling the famous golden ratio famous in art and architecture.

This property of mathematical symmetry, which has been well known to the particle physics world, was first observed in a solid material at HZB. Such insights prove that some structures exist in solids as entities emerging from the quantum world.

Researchers detect magnetic monopoles in solids.





Researchers at HZB reveal ultrafast processes using femtoslicing.

MATERIALS TESTING

Neutrons and synchrotron light can be utilised as a comprehensive tool set to thoroughly test macroscopic components for breaks, cracks and mechanical stresses. Anything designed to withstand heavy stress and strain can be tested at HZB: crankshafts, drill heads, weld seams, even rocket combustion chambers. Analyses with neutrons and photons can detect weak points early on that could lead to damage or disaster.

Micro- and nanostructures revolutionise the world

Given its very short wavelengths and extraordinarily high intensity, synchrotron light is also ideal for creating micro- and nanostructures using X-ray lithography. These structures can in turn be excellently analysed using neutrons. Magnetic nanostructures are well-suited as data stores, carbon nanotubes for example, can carry extraordinarily high currents.

HZB has special experience in:

- producing parts for micro gear systems and microstructured moulding tools for hot stamping and micro-injection moulding,
- X-ray lithography and masking technology for semiconductor components
- developing and optimising photoresists.

Soft matter and functional materials

Many new research fields are also turning to use both neutrons and photons. Some examples include micro-optics and nano-optics, where photonic crystals are studied, and micro- and nanofluidics, in which highly water-repellent surfaces are analysed and new synthesis processes are developed to produce such surfaces. The researchers at HZB are currently promoting these young, emerging fields in both experiment and theory.

“Spin spaghetti” of Dirac strings

Experiments at the BER II research reactor show that, at temperatures of a few degrees above absolute zero, magnetic moments inside a dysprosium titanate crystal arrange themselves into a network of winding tubes called Dirac strings, where self-manifested magnetic monopoles can be found. Using magnetic fields the researchers can vary the symmetry and orientation of this “spin spaghetti”.

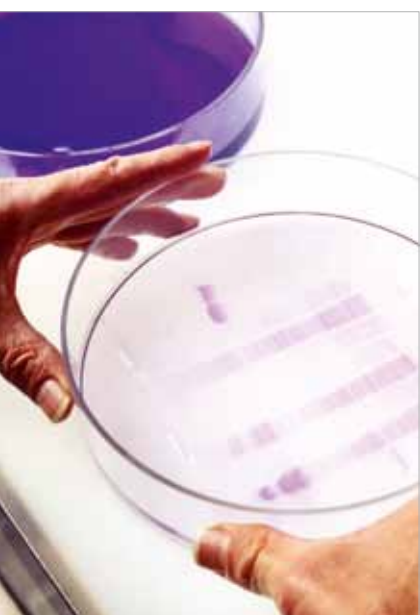
NATURE AND ENVIRONMENT

The basic building blocks of nature – atoms – form a limited ensemble. Diversity comes into the world through their combinations with other building blocks. Many research groups aspire to investigate the secrets of this interplay of nature and to use this knowledge for the benefit of mankind and the environment. They can find the perfect experimental opportunities for this endeavour at HZB and its large-scale facilities.

An important object of study are reaction accelerators known as a **catalyst**. Without them many chemical processes would proceed only very slowly or not at all. What actually happens at the atomic level, where these catalysts play a large role, however is only rarely understood. We need to gain these insights if we want to develop new and improved catalysts. These developments would increase the efficiency of chemical processes and lead to lower energy and material consumption. The processes of a catalyst can be illuminated in detail using the penetrative power of neutrons and synchrotron light.

Fuels of the future

Catalysts are indispensable, one common example of their use is in the processing and synthesis of **methanol**, an important chemical in industry as well as an energy supply. Catalysts made of metal oxides are currently used for this purpose. The same type of catalysts might be used for the chemical fixation of the greenhouse gas carbon dioxide or for the chemical storage and on-board production of hydrogen in fuel cells. Researchers at HZB can precisely explain the complex reaction mechanisms with the help of neutrons and photons.



Gel-chromatographic separation of enzymes.



View of an instrument at BER II, specially designed for studying thin layers of biological samples and soft matter.

Eco-friendly mobility

Catalysts also play a crucial role in the **automotive industry**. In combined tests that use synchrotron light and neutrons, scientists at HZB have joined forces with major car manufacturer to study alternatives to the costly platinum used in catalytic converters: highly porous carbons stored in nanoparticles of selenium and ruthenium.

Another important field of work deals with fuels and the effect of additives within. For example, additives ensure that diesel does not clog filters in winter. Neutron experiments have led to a better understanding of how this works. After only a few years, pure research yielded a marketable product that is now used as an additive in many common fuels. Furthermore, experimenters at HZB have studied the behaviour of glues used in car manufacturing panels and the way soot deposits in engines or propulsion units of aeroplanes.

Functional biology and new materials

Foreign matter introduced into the human body, as often seen in medical treatments, is often rejected by the patient's immune system. At HZB, research groups are working on understanding and minimising the occurrences of rejections. Solid implants could be made much more tolerable, for example, if covered by a layer of the body's own molecules – specifically **lipids**. By performing neutron scattering experiments on model biological systems, researchers are discovering how to make these molecules successfully adhere to implants and also how they behave under body-specific temperatures, pressures and chemicals. Special apparatuses are set up at HZB for this purpose.

New functional materials are also being developed at HZB for **catalysis**. Together with industry, researchers are working on designing and manufacturing **nanocomposites** applied to colloid carrier particles. The functional molecular units of these newly developed materials comprise only a hundred to a few thousand atoms. Their properties are significantly different from the characteristics of a normal-scale solid of the same material consisting of many billions of atoms. The materials developed at HZB are highly sought after as materials for solar energy research and photonics. Given their electronic and optical properties, they are suitable for transmitting, storing and processing information by light particles (photons).

TACKLING DISEASE

For their biological studies, researchers often turn to X-ray crystallography, fluorescence and spectroscopic methods. There are many cases however, where neutrons are ideally suited for these tasks. While X-rays resolve atomic structures due to being scattered at the electrons of crystal lattices throwing strong shadows, neutrons are most sensitive scattered when studying samples that contains a lot of hydrogen. Used together, the two methods yield a richly detailed picture.

On the trail of the scourges of humanity

Medical professionals, biologists and biophysicists come to HZB to use neutrons and X-rays to reveal the causes of **Alzheimer's disease**. They are studying the structure and actions of certain nerve-damaging proteins which are deposited in the brain and blood vessels of patients with Alzheimer's disease and Down syndrome.

The lipid-rich membrane material myelin is also being examined at HZB. It forms a protective sheath around nerve cells. In **multiple sclerosis** patients this protective sheath is attacked by the body's own immune system. Another point of discussion concerns what role myelin plays in the onset of mental disorders such as schizophrenia.

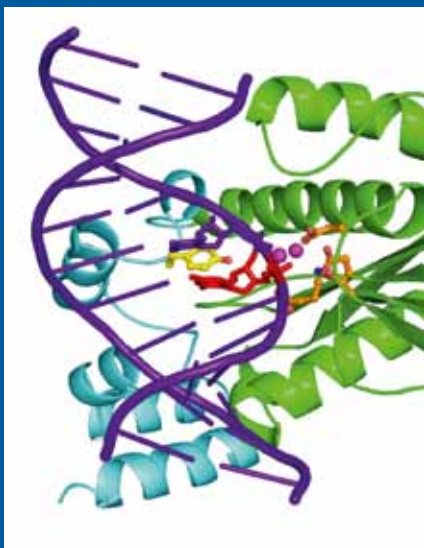
X-ray nanotomography in 3D

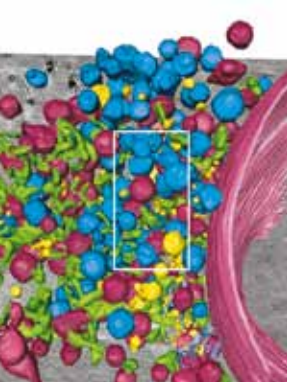
HZB researchers have developed a special **X-ray microscope** for medical and biological studies.



Combating AIDS

At BESSY II, biologists have been able to produce the first three-dimensional images of a molecular complex that plays a critical role in the propagation of human immunodeficiency viruses (HIV). Biologists and medical professionals anticipate new insights into the development of promising AIDS treatments and therapies.





An HZB researcher at the X-ray nanotomography microscope. This device can image the tiniest of cell structures in three dimensions. On the left: A mouse cell with its cell components – the nuclear membrane can be seen as an arc shape.

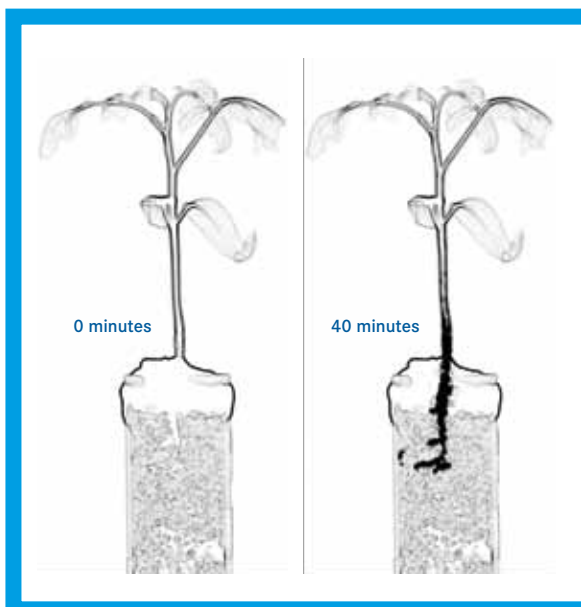
It reveals cell structures as small as 30 nanometres with unrivalled contrast and precision in 3D. The team achieved this outstanding resolution by using an excellent lens and partially coherent light provided by the synchrotron source BESSY II. For these experiments, there is no need to chemically fix, stain or cut the cells, as is typically required. In deep-frozen state, the otherwise intact objects can be investigated in their (natural) spatial structure (3D).

Keeping vessels in shape

Biologically compatible materials and shape memory alloys are often needed for medical devices used in treatments. An example of this are **Stents**. As fine meshed tubes, they are inserted while folded into blood vessels, urethra or the bile duct and then expanded once they reach body temperature. Experiments at HZB have helped to explain the functional mechanism of such shape memory alloys.

How does the tomato plant drink?

Scientists at HZB are not only on the trail of diseases but are also investigating whole natural life processes. Agricultural scientists from Japan and Potsdam are conducting the first studies on how a plant absorbs and distributes water. To do this the experimenters gave the tomato seedlings exclusively “heavy” water to drink at a specific time. Each water molecule has two neutrons more than conventional water. By scanning and illuminating the plant with neutrons, they can literally watch it drink by following the noticeable signature given off from the heavy water.



Rising water in a tomato plant: When scanned and illuminated with neutrons, the “heavy” water (black) stands out.

SECURING THE ENERGY SUPPLY OF THE FUTURE

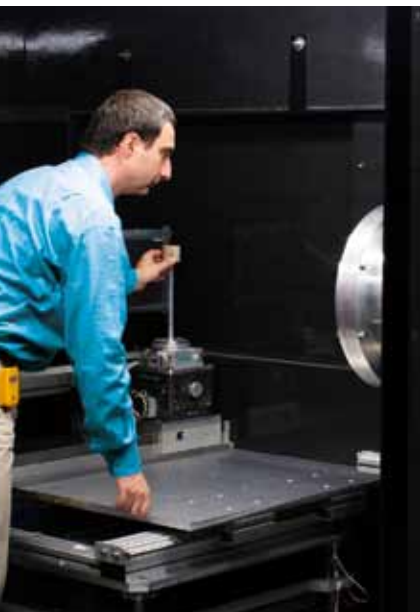
Experts at HZB use the large-scale facilities to test new materials that look promising for sustainable energy production. These include solar cells as well as fuel cells and high-capacity batteries. The aim is to get the future energy supply onto a cost-effective and environmentally sound footing.

Watching fuel cells and batteries at work

Eco-friendly fuel cells obtain heat and electricity from oxygen and hydrogen. Depending on the scientific problem being examined, certain aspects of this complex process can be studied using either neutrons or photons. With synchrotron light for example, technicians and engineers can precisely follow how water is created as a waste product of the reaction. Using neutrons they can even do this while the process is operating – although there is a loss of resolution. Both pieces of information help us understand the exceedingly important **water management** in a cell, which is a prerequisite for producing the most efficient fuel cell possible.

Still, fuel cells are often too expensive for the mass market. One reason is the current day reliance on platinum as a catalyst. Many researchers are striving to find a lower cost substitute. At HZB electrochemists have discovered that nanometre-sized particles of the metal ruthenium could be one such alternative to the pricey platinum. They can precisely determine the ruthenium metal properties using photons from BESSY II.

Using neutrons, scientists can furthermore observe lithium-ion batteries while they charge and discharge and witness the complex chemical reactions taking place inside the cells. With a deeper understanding of these processes, experts soon hope to substantially increase the energy density of batteries, which would make the electric car a true **alternative to the internal combustion engine**.



The all-important water management of fuel cells can be studied in detail using photons and neutrons. A scientist prepares an experiment with neutrons.



Polycrystalline samples of solar absorber materials are produced for experiments with neutrons. A scientist takes a quartz glass ampule with the sample out of the oven in which the Cu(In,Ga)Se_2 compound is cultivated at 900 degrees Celsius from the elements copper, indium, gallium and selenium.

Putting solar cells into perspective

Numerous projects show that the large-scale facilities of HZB are also excellent for investigating solar cells, for example studying materials for inorganic thin-film solar cells. Compounds such as copper-indium (and/or gallium)-sulphide or -selenide, called **chalcopyrites**, are already being used as the light-collecting layer (solar absorber) in thin-film solar cells. However, there is still plenty of research to be done in order to further increase their efficiency. Using neutrons and photons, researchers gain detailed insights into what happens at the boundary surfaces of the individual material layers, how the materials are atomically structured and what processes might hinder the flow of current. X-ray methods are often the methods of choice for this. However, the elements such as copper, zinc and gallium can hardly be distinguished with X-ray analysis – but they can however be clearly identified using neutrons. Neutron experiments therefore allow researchers to study the atomic structure and any defects in semiconductor materials.

Experts expect thin-film solar cells based on chalcopyrite to play a major role in the future photovoltaic market and to contribute to its growth. HZB already holds the **efficiency record** for certain thin-film solar cells of this kind.

The new analytical lab Sissy (Solar cell In-Situ Laboratory at the Synchrotron), currently being established by HZB, will open up entirely new opportunities. The new laboratory is being coupled directly to the BESSY II accelerator ring and will enable unique conditions, not available anywhere else in the world, for studying new types of solar cells using synchrotron light. This will allow developers to observe thin films directly as they grow.

In addition, researchers at HZB are looking into the feasibility of nanoparticle-coated, ultra-thin solar cells. Nanoparticles, which can be studied exceptionally well using neutrons and synchrotron light, can create a surface structure on solar cells that will make them incredibly strong at capturing incident light, thus making light a more fully exploitable energy source.

A flexible thin-film solar cell from HZB.

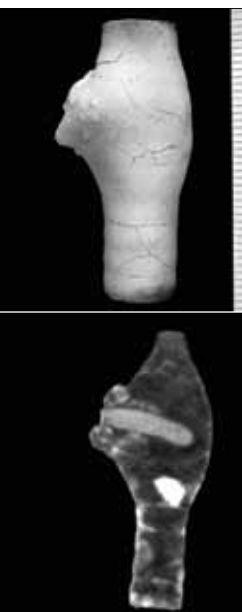




THE ART OF SYNERGY

Historical artefacts can be studied extremely gently and completely non-destructively using neutrons and photons. Accordingly, art historians and archaeologists are frequent visitors to HZB, where they check paintings from famous artists for authenticity. Historians also bring in valuable scriptures by Archimedes or the Qumran Scrolls, which are some of the oldest known documents of the Bible. Others bring parts of sunken ships or cult objects such as the Nebra Sky Disk or the Berlin Gold Hat, an artefact from the Bronze Age that was most probably a calendar. To ensure that these often unique and highly valuable objects are not damaged, let alone stolen, HZB has air-conditioned examination rooms and secure vaults for storing them.

The Nebra Sky Disk: The entirely non-destructive analysis of the circa 4000-year-old cultural object revealed important findings. The oldest known depiction of the starry night sky was apparently created in multiple phases, with materials originating from various parts of Europe. This is evidence of travel that had always been thought impossible for those times.



The worm in the sea lily: The 150 million-year-old, fossilised sea lily revealed its secret to archaeologists from the Humboldt State University Natural History Museum – thanks to neutron tomography: The antique echinoderm was infested with a worm. The worm and sea lily lived together in symbiosis.





(p. 16) The authenticity of old master paintings: It has long been uncertain whether the painting “The Abduction of Rinaldo” from the Berlin Gemäldegalerie collection is an original by French painter Nicolas Poussin (1594 -1665). Tests at HZB have shown that pre-sketched trees were painted over with the same type and with identical colour pigments; for art historians, it was a sure sign that it is an original.

(p. 17) The “Empresses’ Jewels” studied at BESSY II: The individual jewels of pure gold are adorned with many precious stones, pearls and ancient intaglios. From the material composition art historians have been able to draw conclusions about the work steps involved at different points in time.

OF HISTORICAL JEWELS AND DINOSAURS

The most frequently asked questions concern creation, origin and authenticity as well as preservation. Physicists can use neutrons to study metallic materials and reveal hidden layers of paints in paintings or the interiors of archaeological treasures. Using synchrotron light, they can analyse the chemical composition of paintings or art objects in precise detail. For instance, the light from BESSY II was used to study the “Empresses’ Jewels” from the 11th century, also known as the “Gisela Jewels”. Using neutrons, researchers from the Berlin Natural History Museum scanned and illuminated a 270 million-year-old dinosaur skull to obtain information about the prehistoric organism’s hearing system.



Sunken treasures: Treasures found in sunken ships are often covered with a thick layer of limestone. Archaeologists’ attempts to remove this covering may damage the object beneath. Left untouched however, such objects are of no scientific use. Now, tomography with neutrons allows us to gain deep insights into the interior of these objects without destroying them. In cooperation with Palermo University, HZB has studied objects taken from the bed of the Mediterranean Sea. From the richly detailed images, the archaeologists hope to trace back their origin and figure out the best way to restore them.



School pupils are engrossed in an experiment in the school lab.

ACTIVELY ENCOURAGING THE YOUNG GENERATION

HZB offers interested pupils, school graduates, university students, PhD students and postgrad students many opportunities to deepen their education and qualifications.

Sunny Prospects for University Students

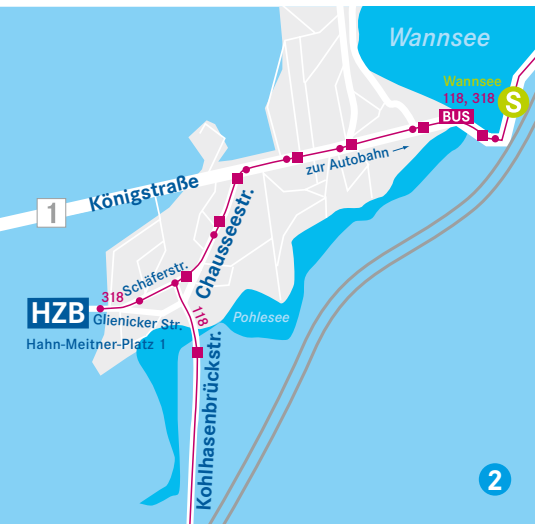
HZB collaborates closely with universities in Berlin and the Brandenburg region. Many of the senior researchers teach there and supervise students on their theses. Each year, a ten-day course on neutron scattering is held at HZB. An international school for photovoltaics and an eight-week, comprehensive **summer student programme** are also offered. The programmes give students a unique chance to familiarise themselves with laboratory work and learn about the large-scale scientific equipment at HZB.

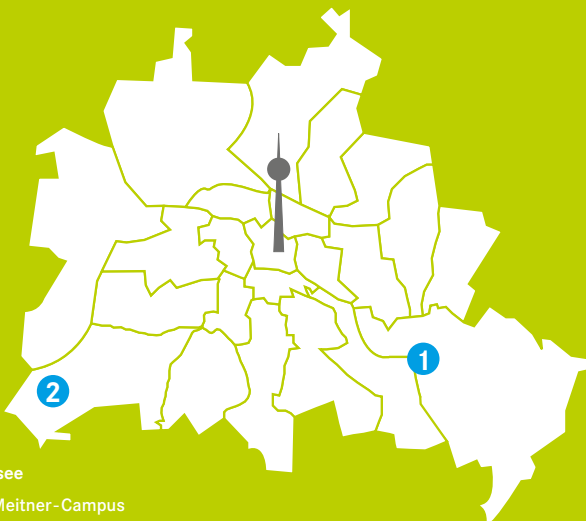
Hands-on Science

In the “Blick in die Materie” (“insight into matter”) school lab, pupils can delve into the fascinating world of physics while learning about the work of a researcher. Young students who are interested can get a taste of the practical side of things during a student internship at HZB.

Successful Start to Professional Life

Young students also have the opportunity to be trained in a forward-looking profession such as computer science, mechanical engineering, administration or environmental and radiation protection.





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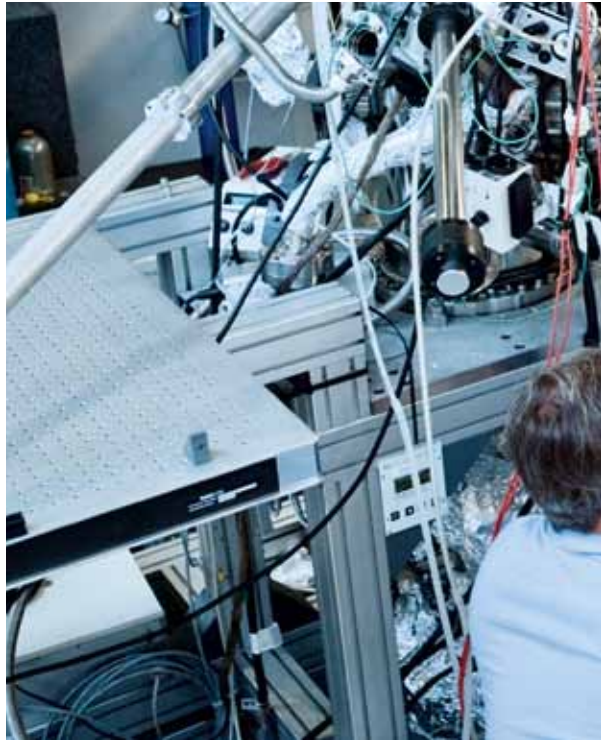
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