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.
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.

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.
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.
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.

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 separately 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 diameter 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.

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.