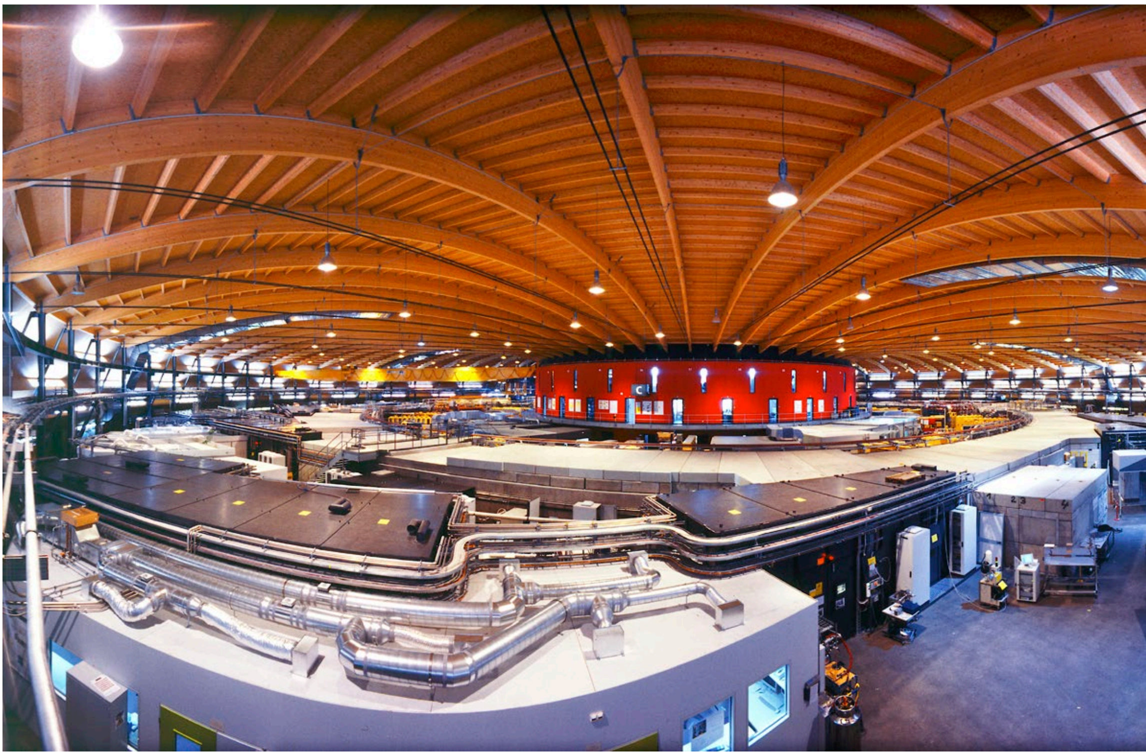
PAUL SCHERRER INSTITUT
PSI

Project SLS 2.0



An upgrade of strategic importance

for the Paul Scherrer Institute

SLS 2.0

The upgrade of the Swiss Light Source SLS

The Swiss Light Source SLS has been providing extremely bright, highly bunched X-ray light since 2001. Researchers use it to investigate the tiniest structures down to the atomic level and develop new drugs and materials. In order to remain among the world‘s best in the future, PSI is planning an upgrade of this large research facility, which is unique in Switzerland, under the name SLS 2.0.

In the UFO-shaped building that houses the Swiss Light Source SLS, researchers from PSI and from all over the world conduct cutting-edge research. For example, they study the electronic properties of novel materials, determine the structure of medically relevant proteins, and make the structure of a human bone visible at the nanometer level. After two decades of operation, during which SLS has set international standards, the facility is to be modernised so that it continues to meet researchers' needs.

To investigate the smallest of structures, the researchers need X-ray light with a very short wavelength. This is produced at SLS with the help of electrons, that is, negatively charged elementary particles. A particle accelerator brings the electrons to almost the speed of light before they are guided into a storage ring with a circumference of almost 300 metres – hence the circular shape of the building. In a pipe evacuated to a high vacuum, well shielded by thick concrete walls, the electrons take a spin around the storage ring roughly a million times per second.

Magnets steer the particles along the circular path. With each change of direction, the electrons generate X-rays, so-called synchrotron light. This light is collimated until a very intense X-ray beam arrives at the research stations. The upgrade project SLS 2.0 aims to make the synchrotron light brighter at the source and to focus the beams even tighter. This is made possible by the latest technologies, some of which were developed at PSI.

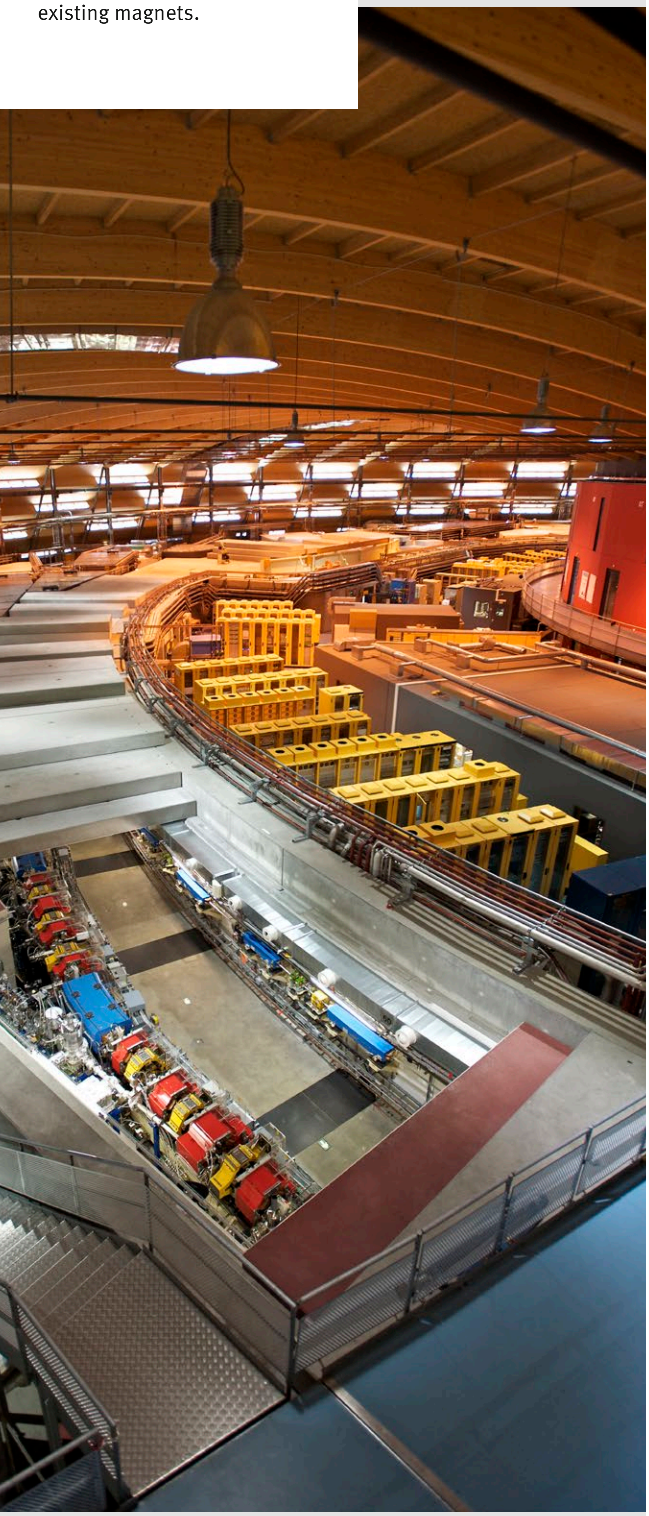
Making the most of synergies

With the existing SLS and the X-ray free-electron laser SwissFEL, which went into operation in 2017, PSI and Switzerland have established a leading position in research with X-rays. The planned upgrade of SLS will reinforce this position. The two facilities enable different experiments and complement each other ideally.

SwissFEL generates extremely intense and extremely short flashes of X-ray light. The researchers use it to study ultrafast processes in atoms and molecules. But the X-ray light pulses are so intense that they quickly destroy most samples under examination. This problem is compensated for by measuring techniques that are so fast they can record the condition of samples before their destruction.

With SLS, on the other hand, samples can usually be observed non-destructively over a longer period of time. Most experiments at SLS use a continuous X-ray beam. Time-resolved measurements with pulsed radiation are also possible here, though the pulses are significantly longer and less intense than at SwissFEL. In exchange, the scientists at SLS have the ability to work at up to 20 research stations simultaneously, while at SwissFEL it is only possible to conduct two to three experiments in parallel. Thus, the options at these two large research facilities complement each other. With SLS 2.0, the synergies between SwissFEL and SLS are being further expanded.

View into the SLS electron storage ring set for renovation; clearly visible are the red, existing magnets.



More magnets, softer curves

As viewed from the outside, the distinctive SLS facility will not change much, but the inside of the electron storage ring is to be completely rebuilt. That's because the quality of the synchrotron light is strongly dependent on details of the electron path in the storage ring. The magnets do not steer the particles on a perfectly circular path; rather, the electrons fly along a polygon. If this polygon has more angles, the resulting synchrotron beams are qualitatively better for research. That is why significantly more magnets than before are to be installed in SLS 2.0. These will guide the electrons onto a better circular path with softer curves. In addition, the metal pipe in which the electron beam circles the ring will be even narrower than before. For that, a new kind of vacuum technology is required.

The measures taken as part of the renovation are intended to ensure that the synchrotron beam that finally arrives at the SLS research stations has a value 40 times better than the current one. In certain cases, further improvements to the beamlines can improve the so-called brilliance by a factor of a thousand. This means: The diameter of the beam shrinks, so the beam becomes even finer with the same intensity. And it will also remain highly collimated for an even longer distance, which means that the beam will barely have expanded even after several metres. Depending on the experiment, the data quality will improve between three and 1,000 times, or even more.

Representative applications

of the Swiss Light Source SLS

With the aid of synchrotron light, the structure of proteins can be elucidated, images can reveal the finest tissue structures, and fundamental research questions can be answered. SLS 2.0 will yield even deeper insights and make researchers' work more efficient.

State-of-the-art research is carried out at SLS. The SLS 2.0 upgrade will ensure that the large research facility has a brilliant future.

Custom-tailored medicines

Using SLS, researchers are deciphering the spatial structure of large biomolecules that are involved in all vital functions in our body, such as proteins or the genetic material DNA. To do this, they have to produce crystals of the molecules. When X-ray light hits a crystal, a diffraction pattern is created, from which the structure of the molecule under examination can be calculated. The PSI groups in macromolecular crystallography are among the world's most successful in this field and have, for example, provided crucial data that led to the decoding of the structure of the ribosome. In 2009, this research was awarded the Nobel Prize in Chemistry. The ribosome, which is responsible for the synthesis of proteins, is one of the largest and most important molecules in the cells of all living things.
Elucidating the structure of proteins is also important for medicine and the pharmaceutical industry, since many diseases stem from malfunctions of these biomolecules. Of particular interest to researchers are so-called membrane proteins. These are located in the cell mem-

brane, where they are responsible for the transport of chemicals and signals into and out of the cell. Active agents that dock on the membrane proteins can fight diseases such as cancer, infections, or inflammation. Two-thirds of all newly approved drugs target membrane proteins to bring about desired changes in the body.

The better a drug molecule fits into the binding pocket of a membrane protein, the faster acting and more effective the drug is. Yet as good as the current SLS is in elucidating many protein structures – and thus providing pharmaceutical developers with the information they need – it still has difficulties with certain membrane proteins. That's because these form notoriously tiny protein crystals of around ten thousandths of a millimetre or even smaller. To examine these efficiently, an intense and correspondingly narrow, highly collimated X-ray beam is required. This is exactly what the upgrade ensures: It will make the X-ray light still "brighter and cleaner".

3-D images of the tiniest details

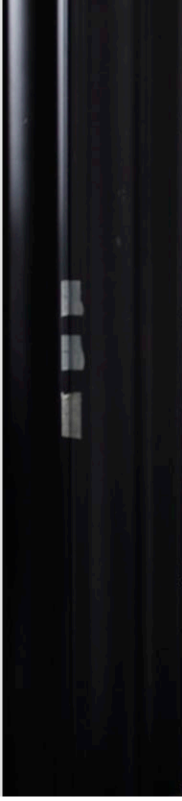
As with a computer tomography scan in a hospital, at SLS 3-D images of the inside of objects can be taken without cutting them open. While the smallest details on medical X-ray images have a diameter of half a millimetre, however, the research station at SLS delivers a resolution a thousand times better: less than a micrometre. So, for example, it is possible to examine tiny changes in the structure of brain tissue that could be related to diseases such as Alzheimer's, Creutzfeldt-Jakob, or amyotrophic lateral sclerosis (ALS).

It is even possible to take 3-D images of objects in motion. In 2014, a film that showed the insides of flying insects caused a sensation. With regard to time-resolved recordings in this size range, SLS holds a world record with several hundred tomograms per second. With SLS 2.0, the X-ray images should be even faster and more precise, so that details of moving objects down to the nanometre range could be made visible. This will enable new experiments and discoveries, for example in energy research with a look inside an operating fuel cell.

Using another imaging method, researchers can already zoom in on objects that are only several micrometres or millimetres in size, down to a resolution of a few nanometres. This method, which does not require a lens, generates hundreds of overlapping scattering images from one sample. From this, an algorithm reconstructs the object. It was first demonstrated at PSI in 2007 that this method works with X-rays, and the researchers in Villigen are world leaders in the further development of the technique. It can be used, for example, to study computer processors down to the smallest detail. The method is also suitable for examining biological samples such as brain tissue and thus for investigating Parkinson's disease, among other things. Focusing on blood vessels, it can be used to study age-related degradation processes that can lead to dangerous rips in the vessel wall. With diabetes, on the other hand, researchers can observe the effects of the disease on connective tissue. SLS 2.0 will give this technique higher resolution and make it several orders of magnitude faster.

Exotic materials for the electronics of the future

With SLS, you can look inside materials and watch the electrons flow, so it is possible, for example, to carry out experiments on a "living transistor". In this way PSI researchers have shown how a component made of gallium nitride, which is already used in smartphones, can be further improved. But they are also investigating exotic materials with completely novel characteristics. Understanding the fundamental physical phenomena should help, among other things, to develop better materials for electronics and information technology. The aim is to obtain faster and denser storage and data transmission while reducing the energy consumption of the electronic components.

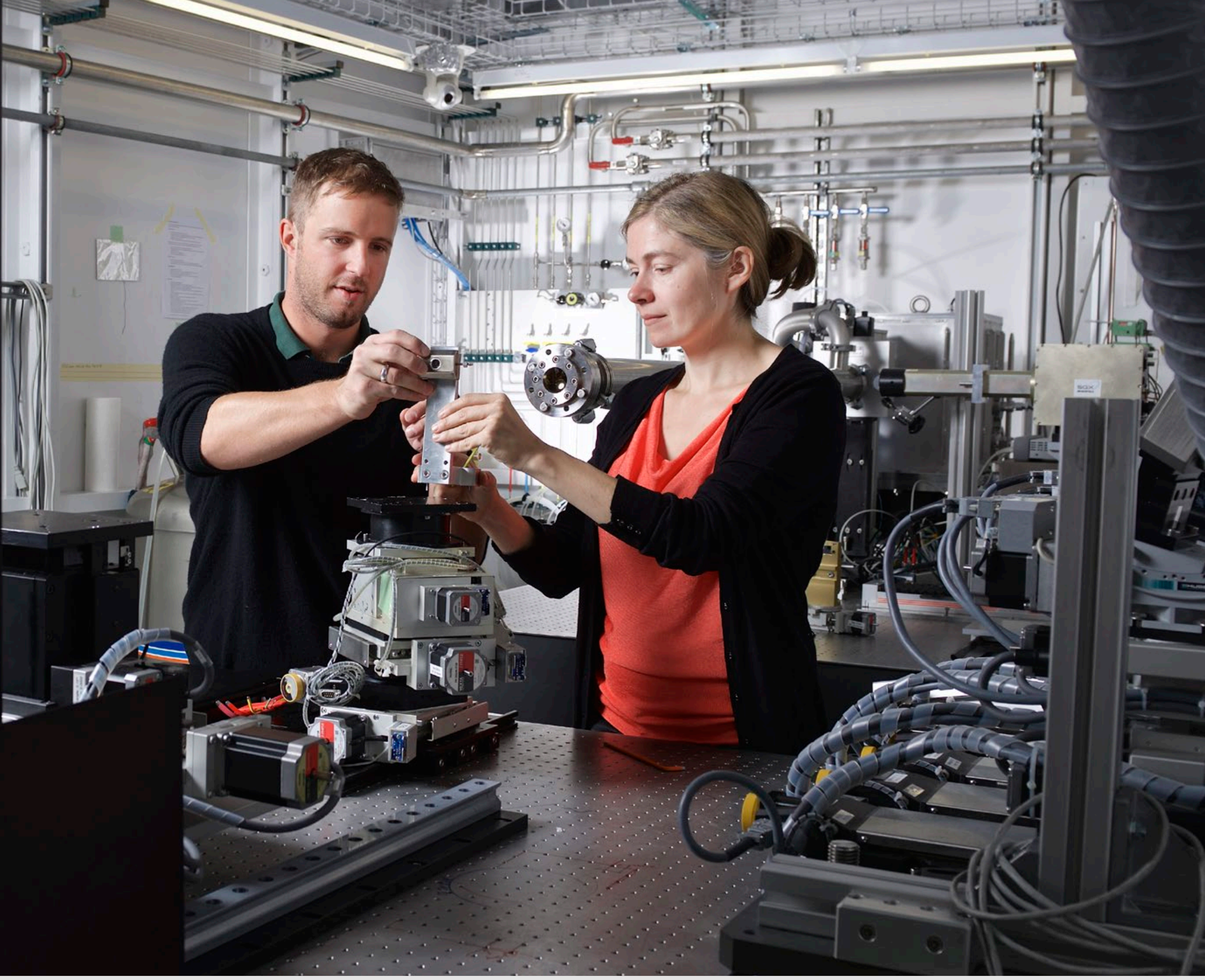


Using the X-ray light from SLS, researchers are investigating catalysts, among other things: materials that accelerate chemical reactions or start them up.

For one special crystal made of aluminium and platinum atoms, PSI researchers demonstrated that it is a material with electronic properties never observed before, which in addition behave differently inside the crystal than on its surface. The sample they examined thus belongs to the class of so-called topological materials, which may be suitable for the construction of fast quantum computers. Also of interest are compounds made of certain metal atoms and oxygen, so-called transition metal oxides. Among them, there are good candidates for especially reliable transistors or superconductors that carry current without loss at temperatures below a certain threshold.
In the investigation of new materials, PSI researchers are among the pioneers in the use of a modern method that is currently developing rapidly: With so-called inelastic X-ray scattering, or RIXS for short, the X-rays trigger transitions between various electronic states in the material samples. These provide information about important processes that are, for example, fundamental to superconductivity or magnetism. RIXS as well as the other methods for examining materials will benefit greatly from the SLS upgrade. Because the electron beam in the storage ring has a smaller horizontal dimension and is capable of better alignment, beamlines with extremely high energy resolution can be built, which will increase the sensitivity of such methods considerably.

More efficient catalysts

Catalysts play an important role in the development of technological solutions for the future of energy, for example in the storage of solar energy in the form of hydrogen. With the help of solar power, water is broken down into hydrogen and oxygen in a so-called electrolyser. PSI researchers keep racking up one success after another in the development of new catalysts. SLS is particularly well suited for the investigation of catalytic processes. The high energy of the radiation makes it possible to X-ray the reactor with a catalyst under real conditions.
For example, studies at SLS helped a group of researchers find out what the structure of a new nanomaterial should look like so that its catalytic properties would become active. After three years of research and several studies carried out at SLS, they succeeded in developing a nanomaterial that efficiently accelerates the breakdown of water molecules and also is a thousand times less expensive than a comparable material.
The upgrade of SLS will make it possible to apply a new examination technique that provides additional information about the material's geometric structure. The researchers will also be able to carry out their measurements more quickly. They are hoping these innovations will yield further important advances in development.



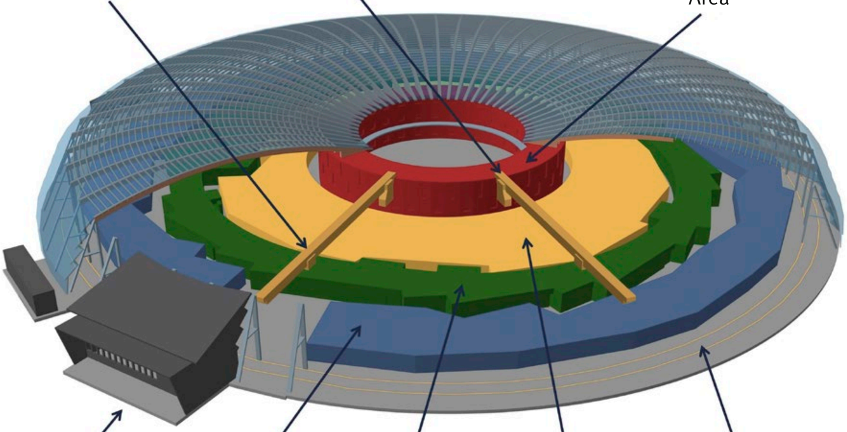
Improving modern manufacturing processes

Experiments with SLS also help in the further development of modern industrial manufacturing processes such as the 3-D printing of metal components using selective laser melting. In this so-called additive manufacturing process, metal powders are applied in layers and selectively melted with the laser, as prescribed by a 3-D computer model. Suitable mainly for prototypes, tools, and components with highly complex geometries, the process is considered especially promising for the future.

Despite substantial progress in recent years, it is still unclear how the many different process parameters affect the final microstructure and thus the material properties. Researchers at PSI developed an apparatus with which they can follow the printing process live. They built a mini-system for selective laser melting and installed it at one of the SLS research stations. Because the X-rays can be used to determine structural and chemical properties at the same time, the researchers were able to observe exactly what happened during the 3-D printing of a titanium-aluminium alloy.

This industry-relevant research in particular will benefit from the SLS upgrade, because the modernisation will bring an order of magnitude better spatial and temporal resolution of the observable processes. Technological progress will enable researchers to perform measurements much faster or more accurately. Thanks to the higher-energy X-rays, they will be able to peer even more deeply into the materials.

Planned expansion and function



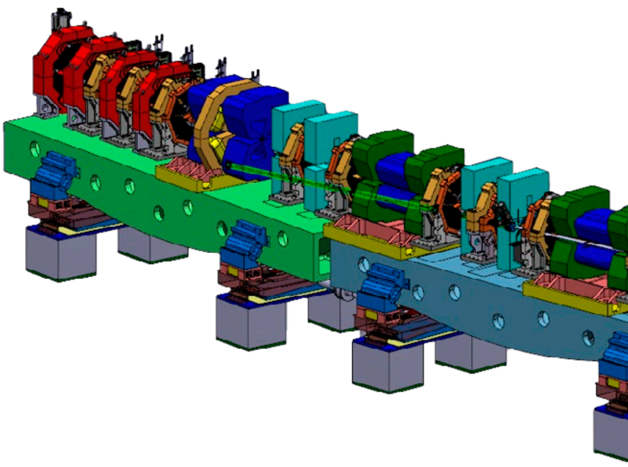
The UFO-shaped building with its main entrance (dark grey) and offices (red) remains intact with the modernisation.

Renovations take place within the technical gallery (yellow) as well as in the experiment area (blue). The beamlines in the experiment area must be dismantled during the renovation and, in part, repositioned slightly when rebuilt.

A second crane (ochre) is to be added to the existing one, enabling faster construction.

The electron storage ring in the accelerator tunnel (green) will be completely modernised.

The circular building of the Swiss Light Source SLS will remain intact during the modernisation of the facility. The storage ring in the concrete tunnel, which runs for almost 300 metres in the middle of the building, is being rebuilt. On their own, electrons would fly straight ahead, but in the storage ring, magnets force the ultrafast particles to follow a circular path. Each time they change direction, they generate X-rays – the synchrotron light. During the renovation, the existing magnets in the storage ring will be replaced by a new configuration with more, smaller magnets of a new type to guide the electrons onto a better circular path with softer curves. In this way, a brighter beam can be generated. A total of 1,007 magnets will be installed in the storage ring of SLS 2.0. So that the magnets can get closer to the electrons, the metal pipe in which the particles circulate will also replaced by a new one that is narrower. Its inner diameter will be just under two centimetres.



The smaller diameter calls for a new vacuum technology, because it would not be possible to achieve a sufficiently good vacuum with the existing pumps, a phenomenon that anyone who has ever sipped through a straw can understand: The thinner the straw, the harder you have to suck. A new type of coating on the inside of the metal pipe absorbs gas atoms – similar to the way a sponge absorbs water. This so-called non-evaporable getter coating is thin, only about 0.5 micrometres, but it lasts for 20 years.

The existing SLS is a third-generation synchrotron source. With the coming magnet arrangement, SLS 2.0 will belong to the fourth and newest generation of these facilities, the so-called diffraction-limited storage rings, or DLSRs for short. In international comparison, the storage ring at PSI is rather small, but thanks to the new technologies, SLS 2.0 will be just as powerful as the other DLSR synchrotrons that are now going into operation worldwide.

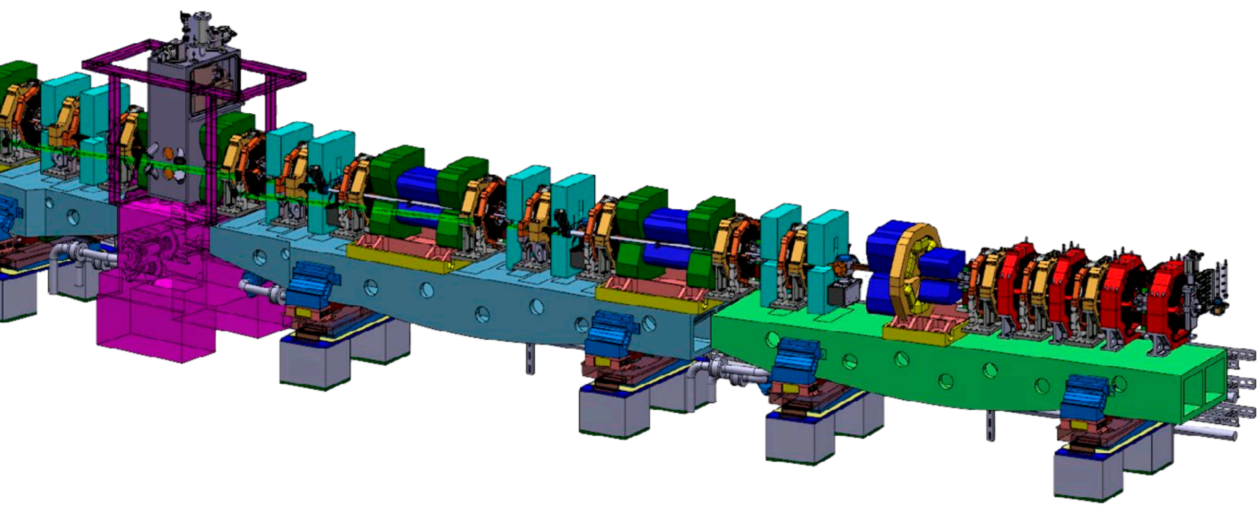
Blue magnets: Deflection magnets
Dipole magnets deflect the electrons in such a way that they do not fly straight ahead but on a circular path. These will be new ultra-strong permanent magnets made of neodymium-iron-boron. These are more compact than present-day electromagnets.

Magnet on a violet base: Superconductor magnet
One out of seven deflection magnets will be made of superconducting material. This creates a stronger magnetic field and thus harder X-rays, which penetrate deeper into samples. The superconductor magnets must be cooled to –268.5 °C.

Red magnets: Quadrupole magnets
Magnets with four poles focus the electron beam. To save space, many of these will also be permanent magnets.

Cyan-coloured magnets: Magnets that deflect outwards
These magnets help to boost the brightness of the synchrotron light – a technique developed at PSI.

One of 12 such components in the SLS 2.0 storage ring. The magnets are mounted on supports borne by concrete bases, to achieve maximum stability.



Beyond the limits of what is possible today

Over the past 16 years (2004-2019), SLS has hosted more than 47,000 visits by 23,661 researchers from all over the world. Around 11,000 research proposals were submitted during this period. For research in Switzerland, this reliable large facility is an extremely valuable resource, for example in structural biology as pursued by the group of renowned molecular biologist Nenad Ban at ETH Zurich. The team investigates the structure and function of biological molecules to understand, among other things, processes that keep us healthy or make us sick.

Nenad Ban is looking forward to the upgrade, which will give the brightness of the X-ray beam a crucial boost. It is particularly important for the molecular biologist that the beam will be even better collimated. There are many elusive biological molecules that have, so far, defied examination. It is often difficult to grow crystals of such samples large enough for structural determination, given the capabilities of X-ray crystallography to date.

«We and all researchers in structural biology worldwide who make the journey to gather data at SLS 2.0 will profit from this upgrade.»

Prof. Nenad Ban, Institute for Molecular Biology and Biophysics, ETH Zurich

The new properties of X-rays arriving at the research stations of SLS 2.0 will make it possible to examine much smaller crystals than before. This is a major advance not only for basic research, but also for pharmaceutical companies. The industry already has direct participation in SLS. One beamline was financed by Novartis and Hoffmann-La Roche together with the German Max Planck Society, with industry and basic research bearing equal shares of the cost. PSI realised another beamline in partnership with Swiss and foreign pharmaceutical companies. With SLS 2.0, the Novartis researchers want not only to elucidate the structure of ever smaller crystals, but also to carry out so-called serial crystallography. This combines measurements of many tiny crystals into one data set. Thanks to the upgrade, SLS will remain an important and often indispensable tool for industrial applications.

«The planned upgrade will be an important contribution to pushing beyond the limits of what is possible today.»

Dr Trixie Wagner, Group Leader, Novartis Institutes for Biomedical Research (NIBR)

Fabia Gozzo founded the start-up Excelsus, based in Park innovaare next to PSI, in 2012. Excelsus has an agreement with PSI for the commercial use of an SLS beamline. Here, Gozzo and her employees inspect the quality of medicines, foods, and chemicals on behalf of industrial customers. The method used, so-called powder diffraction, is very fast and will become significantly faster after the upgrade.

SLS is unique in Switzerland. Researchers from other institutes, universities, and companies travel here to carry out experiments.

Certain examinations require especially high-energy X-rays, which at present cannot be generated at SLS. In such cases, Gozzo has to sidestep SLS to use facilities in the UK or the USA, which is expensive and time-consuming. After the upgrade, this should no longer be necessary, since SLS 2.0 will also deliver so-called harder, that is, higher-energy X-rays.

«If the upgrade makes X-rays with higher energy available, we can concentrate all our activities on SLS and only use other facilities as back-up solutions.»

Dr Fabia Gozzo, CEO, Excelsus Structural Solutions

Many guest researchers travel regularly from abroad to take measurements at SLS. One of these is Marianne Liebi from Chalmers University of Technology in Sweden, who carries out her measurements mainly at SLS because she finds the best conditions there. For example, she examines collagen fibres in bones and uses X-ray technology to look at how they are organised at the nanometre level. The researcher hopes SLS 2.0 will provide even better resolution for her imaging technology. In addition, the measurements should become significantly faster.

«After the upgrade, we will be able to measure more samples in the same amount of time, which is currently one of the limiting factors in our investigations.»

Prof. Marianne Liebi, Chalmers University of Technology, Gothenburg, Sweden

To maintain a leading position internationally, the SLS upgrade is crucial – despite or precisely because of the completion of the X-ray free-electron laser SwissFEL at PSI in 2016. Majed Chergui from EPF Lausanne conducts experiments here that show, for example, how the exchange of electrical charges works in the human body and how one could increase the efficiency of solar cells. The X-ray flashes of SwissFEL reveal ultrafast processes. Without previous tests on a synchrotron source such as SLS, these measurements would hardly make sense or might not be possible at all. In addition, SLS can be used to follow processes of somewhat longer – if still minuscule – duration, for which SwissFEL is unsuitable.

«In addition to experiments at SwissFEL, we will continue to carry out measurements at SLS in the future. Both facilities at this location are important, and they complement each other optimally.»

Prof. Majed Chergui, Laboratory for Ultrafast Spectroscopy, EPF Lausanne

Technical data of SLS 2.0

Circumference of the storage ring:
288 metres (as before)

Number of magnets:
1,007 (previously 388)

Inner diameter of the beam pipe:
18 millimetres (previously 64 x 32 millimetres)

Electron energy:
2.7 giga-electronvolts (previously 2.41 giga-electronvolts)

Maximum photon energy:
80 kilo-elektronvolts (previously 45 kilo-elektronvolts)

Beam quality:
Up to 40 times better than before.
Brilliance up to 1,000 times higher on certain beamlines.

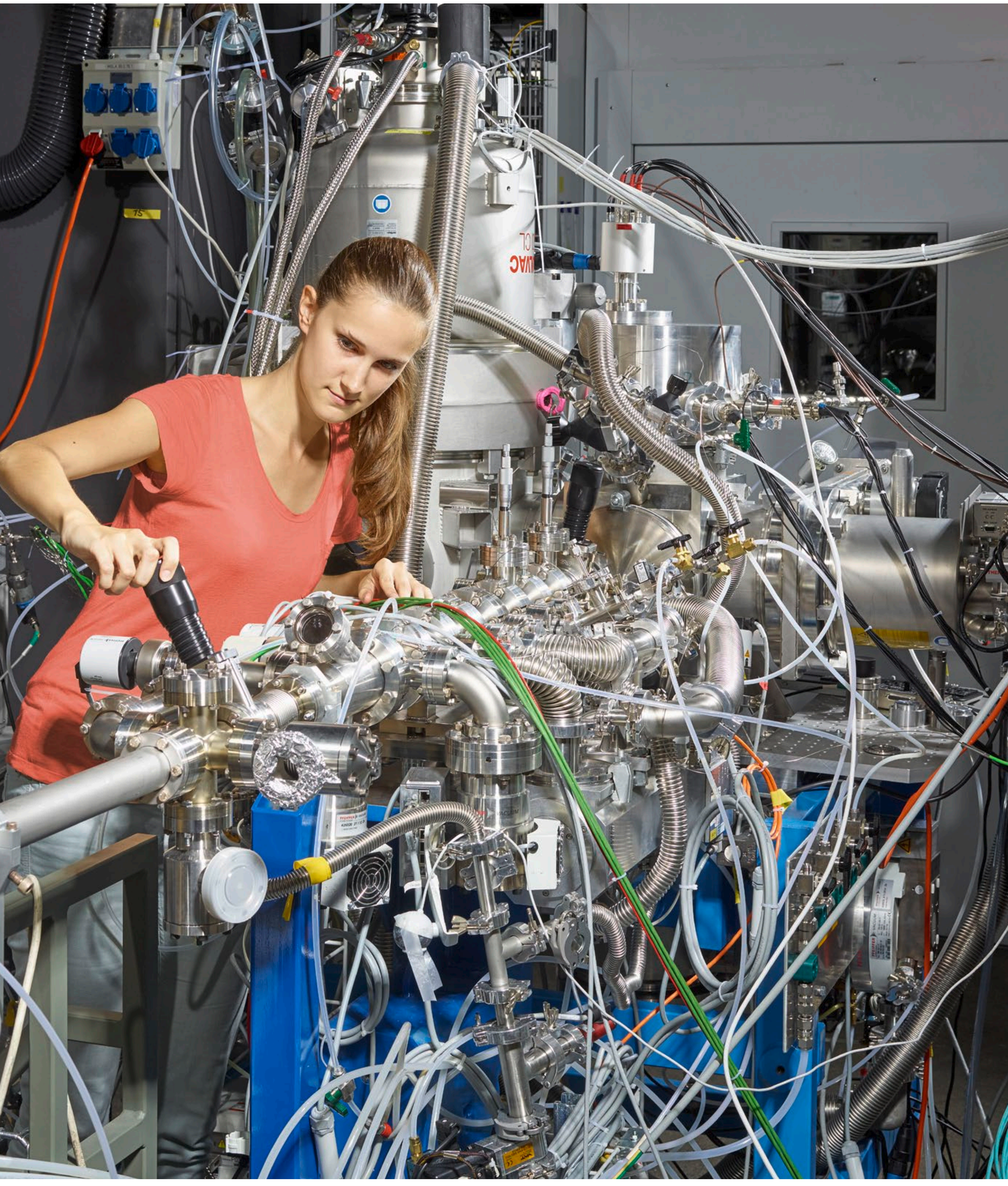
Measurement duration and data quality:
Depending on the experiment, the measurements become faster or the data quality is three to more than 1,000 times better than before.

Time usable for experiments:
Around 220 days a year in 24-hour operation (as before)

SLS 2.0 planning phase:
2017 to 2020

Renovation:
2021-2024. First, the new components are procured and prepared. Then the storage ring is switched off, dismantled, and rebuilt. In this way, SLS is out of operation for the shortest duration possible.
The new commissioning is scheduled to begin in 2024.

Costs:
A total of around 167 million Swiss francs. Funding of CHF 98.7 million has been requested from the federal government. PSI estimates costs of CHF 17 million for hardware and services as well as CHF 51 million in salaries and wages during planning and renovation.



Aerial view of the Paul Scherrer Institute PSI. The circular building in the background is the Swiss Light Source SLS.

PSI in brief

The Paul Scherrer Institute PSI is a research institute for natural and engineering sciences, conducting cutting-edge research in the fields of future technologies, energy and climate, health innovation and fundamentals of nature. By performing fundamental and applied research, we work on sustainable solutions for major challenges facing society, science and economy. PSI develops, constructs and operates complex large research facilities. Every year more than 2500 guest scientists from Switzerland and around the world come to us. Just like PSI's own researchers, they use our unique facilities to carry out experiments that are not possible anywhere else. PSI is committed to the training of future generations. Therefore about one quarter of our staff are post-docs, post-graduates or apprentices. Altogether PSI employs 2200 people, thus being the largest research institute in Switzerland.

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5232 Villigen PSI, Switzerland
Telephone +41 56 310 21 11

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Further information on SLS 2.0

SLS 2.0 Project Leader
Dr. Hans-Heinrich Braun
Tel. +41 56 310 32 41
hans.braun@psi.ch

Scientific Coordinator and Project Leader Photonics
Prof. Dr. Philip Willmott
Tel. +41 56 310 51 26
philip.willmott@psi.ch

Accelerator Project Leader
Dr. Terence Garvey
Tel. +41 56 310 46 37
terence.garvey@psi.ch

Head of the Communication Department
Dr. Mirjam van Daalen
Tel. +41 56 310 56 74
mirjam.vandaalen@psi.ch

Paul Scherrer Institut :: 5232 Villigen PSI :: Switzerland :: Tel. +41 56 310 21 11 :: www.psi.ch

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