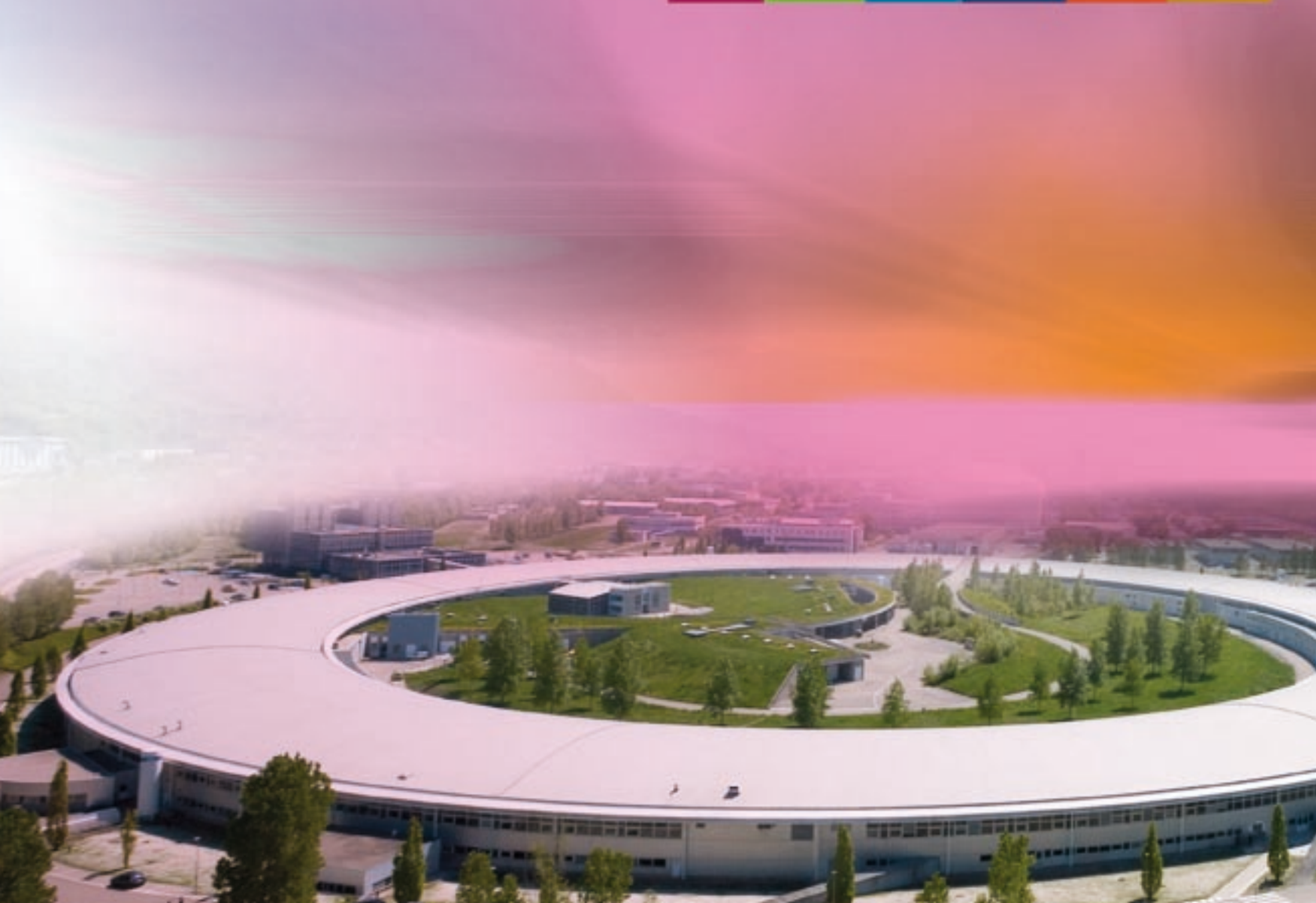
A LIGHT FOR SCIENCE



A Light for Science

Illuminating the world with brilliance

The European Synchrotron Radiation Facility (ESRF) shines a powerful light on a range of world-class science. It provides beams of intense X-rays whose brilliance attracts international researchers from both academia and industry.

A multinational centre of excellence

ESRF, located in Grenoble, France, is a centre of scientific excellence supported and shared by 19 countries. Since opening in 1994, this "supermicroscope" produces the brightest X-rays in Europe to investigate everything from biological molecules, sustainable polymers and nanostructures to archaeological treasures and innovative components for fuel cells.

At ESRF, X-rays with exceptional properties originate from very high energy electrons circulating in a doughnut-shaped accelerator, the "storage ring". From the monitoring of the electron beam to the data acquisition and data analysis of each experiment, cutting-edge technology is developed to ensure that ESRF continues to lead the synchrotron science community in the decades to come.

For better health and improved materials

Every year several thousand researchers come to Grenoble to conduct experiments using the ESRF's 42 highly specialised beamlines, operating 24 hours a day, seven days a week. Being much more than a simple source of bright X-rays, ESRF offers its visiting scientists a full range of support services and world-wide collaborations, for the benefit of science and society.

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X-ray vision

Reaching the nanoscale

Scientists are driven by the quest for knowledge about the world around us: What is our planet made of? What are the processes that sustain life? How can we explain the properties of matter in the widest sense? Will it one day be possible to defeat cancer, use only renewable materials and counteract pollution?

Most of these questions cannot be answered without a profound knowledge of the intimate details of the structure of matter, at the level of the atoms and molecules. However, atoms measure about one tenth of a nanometre (1 nanometre = 1 billionth of a metre = 10^{-9} m), which makes them invisible even to the best light microscopes. In order to "see" atoms, and explore materials beyond their macroscopic properties, one needs a "magic" light with a very short wavelength: X-rays.

The extreme brilliance of synchrotron X-rays

X-rays interact with matter in different ways. They penetrate matter, which is at the origin of their medical applications. But X-rays can also decipher the three-dimensional structure of crystals, a technique called crystallography. For decades, scientists used X-ray tubes to obtain this information, including on biological molecules. As the X-ray beams produced in a synchrotron are orders of magnitude more intense and, like a laser beam, finely focused, data taking is much quicker and new opportunities for research have arisen every year, well beyond the wildest dreams of crystallographers at the advent of the synchrotrons, forty years ago.

At the heart of life

Composed of amino acids, proteins are needed for the structure, function and regulation of the body's cells, tissues and organs. They include enzymes, hormones and antibodies but can also be dangerous, like the protein coatings on viruses that latch onto cells and cause diseases such as the common cold, influenza or AIDS.

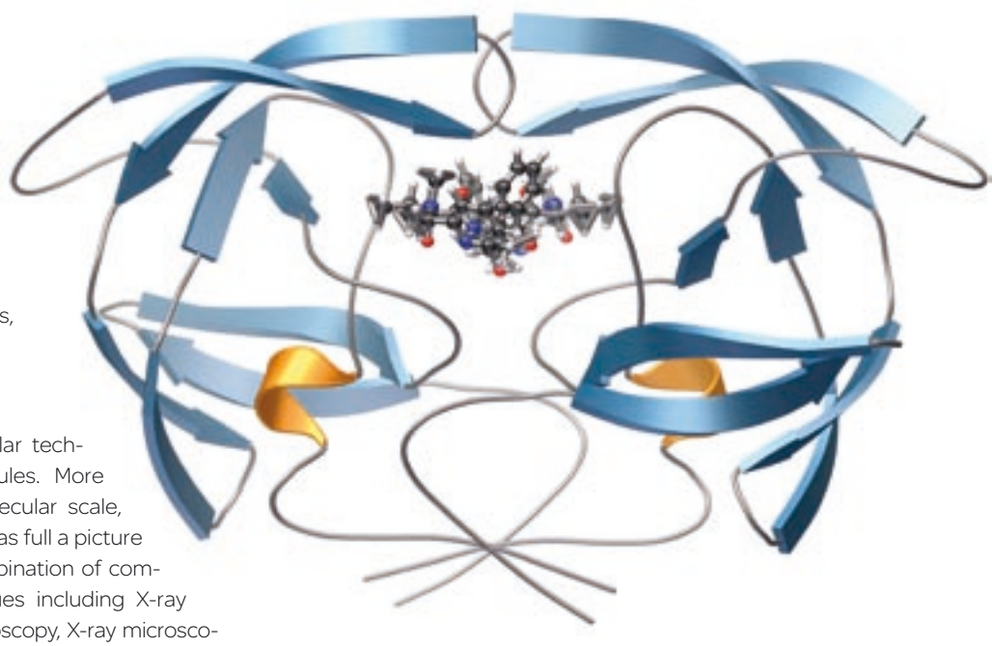
A revolution in structural biology

A link between form and function

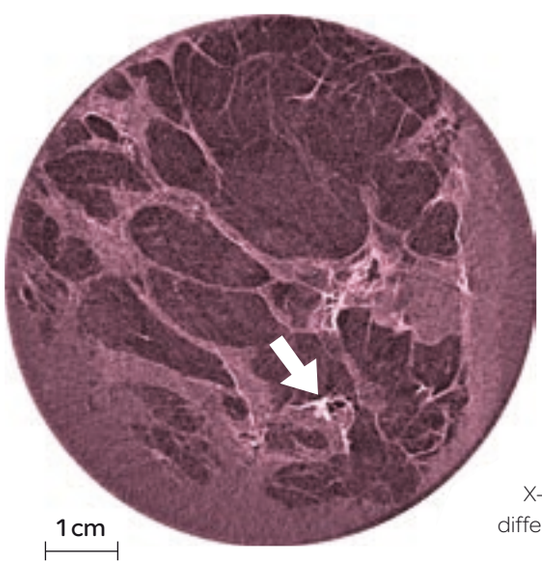
Proteins are large molecules containing up to several hundreds of thousands of atoms. Each of them has a definite shape, called the "3D structure". The atomic details of a protein give invaluable information about its function, and particularly about the active site, where the biological reaction takes place. Synchrotron X-ray beams are a unique tool to explore the whole range of the macromolecules of life: proteins, DNA, RNA, ribosome, nucleosome, viruses...

X-ray techniques to study proteins

X-ray crystallography is by far the most popular technique used to study individual macromolecules. More complex biological systems, at the supra-molecular scale, require a multi-disciplinary approach to provide as full a picture as possible. This is achieved at ESRF by a combination of complementary high- and low-resolution techniques including X-ray small-angle scattering, X-ray absorption spectroscopy, X-ray microscopy and infrared spectroscopy.



3D structure of a protein of HIV-1.



Breast tumour made visible by new synchrotron technique.

Medical research made easier

Making the invisible visible

X-ray computed tomography (medical scanner) is a powerful three-dimensional imaging technique but it hardly differentiates weakly absorbing soft tissues. At ESRF, phase-sensitive X-ray imaging takes advantage of the slight deviation of the coherent X-ray beams when they travel through different densities. As a result it produces a good contrast for soft-tissue structures, making the invisible visible and allowing the early detection of tumours.

Radiotherapy in progress

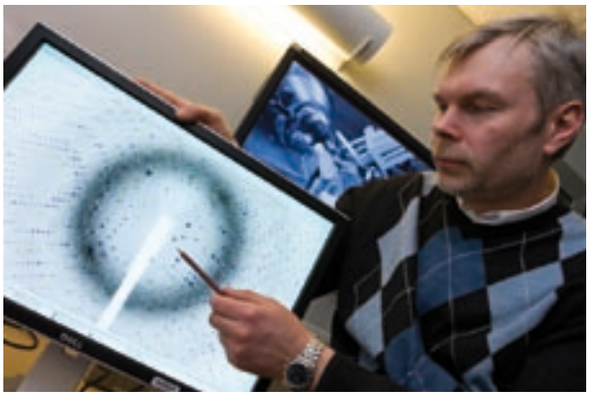
Conventional X-rays used in radiotherapy, although effective in destroying cancerous cells, may damage as well the healthy tissues surrounding the tumour. Synchrotron X-rays, being very intense and focused, can be harnessed to selectively reach and burn the malignant tissues.

X-ray crystallography

Where are the atoms?

X-ray crystallography is an extremely powerful tool for identifying the individual atoms and their positions in materials. The technique is based on the diffraction of X-rays by a crystal. In the case of a protein crystal, identical protein molecules repeat regularly in a three-dimensional lattice. The resulting pattern of light (called the diffraction pattern) relates to the structure of the molecule and reveals how the atoms are arranged.

Of course, protein crystallography is only possible if the protein can be crystallised, which may be very difficult, or even impossible. Using the brilliant synchrotron X-ray beams, it is possible to study tiny or imperfect crystals that would have been dismissed a couple of decades ago. As one biologist user at ESRF put it: "In the old days, you studied what you could study. Today you study what you want to study."



Discussing a diffraction pattern.

Focus

Drug discovery

Protein crystals.

Designing drugs

Drug discovery and development is a high-risk enterprise that requires a long-term vision, considerable technical and strategic experience, and multifaceted expertise. One of the objectives of the pharmaceutical industry today is to design drugs – ligands – that can attack particularly susceptible or favourable sites (usually proteins) in macromolecular complexes.

Synchrotron and speed

This new "structure-based drug design" depends in a large part on high-throughput X-ray crystallography, where lots of samples are put through a synchrotron beamline. Highly automated instruments have therefore become mandatory in the earliest stages of drug discovery, where speed is needed to "screen" a large number of possible ligand-protein structures.

Inspired by nature...

The driving force of the natural sciences is to understand the world around us. Thanks to its ability to observe all sorts of reactions *in situ*, synchrotron light is revolutionising our view of the atomic and molecular world.

Water's hidden depths

Understanding water's properties is crucial for the future of our planet.

Crucial for life

Water is a crucial element for life, agriculture and the environment. We know that water exists in three forms: solid, liquid or gas. But it's what we don't know that is intriguing scientists around the world. Water's surprising properties are providing extraordinary challenges in biology, chemistry and physics, as well as the applied sciences including geology, glaciology and marine science.

A form of ice for gas storage

Scientists are interested in a form of ice called clathrate hydrate, which is found on the ocean floor and in areas of permafrost. These hydrates can trap gas molecules such as carbon dioxide or hydrogen (CO_2 or H_2) inside cages of hydrogen-bonded water molecules. By using X-ray reflectivity to look at the surface of hydrate layer formation, and X-ray diffraction to study samples under pressure, ESRF has obtained unique information about these materials with the potential to trap and store gas in the future.

Microstructure of "snow white", a dry form of snow.

A new dawn for solar power

Studying photosynthesis...

If sunlight powered the world's buildings, a global energy crisis could be averted. Unfortunately, due to the inefficiency of current solar power technology, this energy revolution remains a dream. Even the most advanced designs only convert 40% of the Sun's captured energy into electricity. Fortunately, studying photosynthesis could help. In nature, only one enzyme, photosystem II, is capable of performing the crucial reaction (oxidation of water molecules and production of oxygen) with high efficiency. This enzyme can be found in plants, algae and cyanobacteria and its activity, driven by the energy of absorbed light, has created the oxygen-rich atmosphere we enjoy today.

Photosynthesis: a powerful way to transform Sun's light into energy for life.

... by filming the reaction

Photosystem II has been extensively studied by X-ray crystallography, but a bit more was needed: time-resolved X-ray absorption spectroscopy at ESRF has been used as a complementary technique. Scientists were thus able to follow "online" the whole cycle of the intricate mechanism of water oxidation. Understanding this mechanism is also of key interest for future renewable fuel generation, where electrons from water may be used to reduce protons by artificial photo-catalysts. Solar power would then be used to produce hydrogen gas.

… technology turns green

A body of good ideas

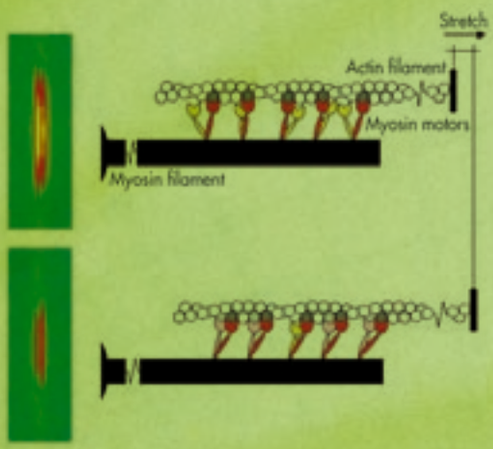
Tough and stiff bones

Bright X-rays not only reveal the human body's ingenuity but can also inspire new technologies and science. Bones, for example, are the body's scaffolding and must be tough and stiff. The secret of bones' remarkable properties lies in their complex structure: a combination of a biopolymer (collagen) and mineral nanoparticles. Using different synchrotron X-ray techniques, scientists can study both the structure of bones and their mechanical behaviour. This can then lead to new and smarter materials.

Biological tissues are excellent models for new materials.

Nanostructured muscles

The study of muscles is equally enlightening. Although muscle contractions are clearly visible to the human eye, they are the sum of billions of microscopic, single-molecule contractions. Researchers found that a synthetic nanostructured polymer containing poly(metracrylic) acid changes molecular conformation as it goes from an acid to an alkaline environment, while submitted to a mechanical force at the same time. They were able to use this innovative approach to construct a simple, chemically driven, artificial muscle by using a reaction that continuously changes the acidity of the surrounding solution.



Studying the reaction of proteins (actin and myosin) when a muscle is stretched.

Cleaner cars with longer lives

Climate change is producing a demand for greener and more environmentally friendly technologies.

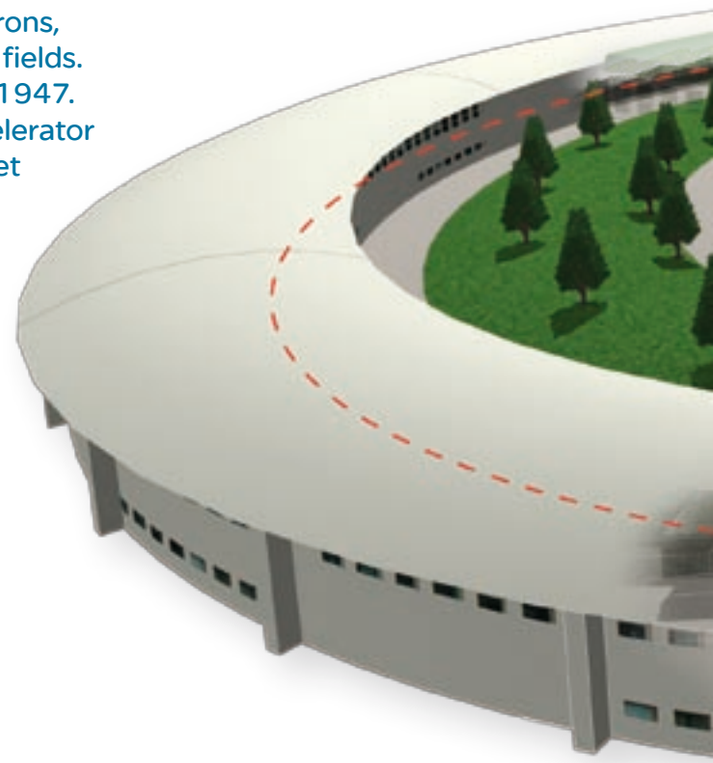
As a result, it has become mandatory to improve the car catalysts that clean up toxic exhausts. Costly metals like platinum are at the core of today's catalysts in the form of nanoparticles on a porous ceramic substrate. When exposed to high temperatures (800°C and above), these nanoparticles bond to each other or sinter, decreasing the active surface area available for catalytic activity.

At ESRF the phenomena of sintering and redispersion of metals have been studied in fine detail. This is possible because the catalytic reaction could be reproduced realistically (a technique called "operando") and the behaviour of the nanoparticles observed *in situ* using X-ray absorption and infrared spectroscopy.

Better catalytic converters for cleaner cars.

How does ESRF work?

Synchrotron light is produced when high-energy electrons, circulating in a storage ring, are deviated by magnetic fields. The first synchrotron radiation beam was observed in 1947. Since then impressive progress has been made in accelerator physics, electronics and computing as well as in magnet and vacuum technologies. Today third-generation synchrotron light sources exploit the latest technical advances to produce very bright beams of X-rays that are in huge demand around the world.



1 The linear accelerator (linac)

Electrons are emitted by an electron gun, a device similar to the cathode ray tubes found in older televisions or computer screens. These electrons are packed in "bunches" and accelerated by a pulsed electric field inside a vacuum where they approach the speed of light.

2 The booster synchrotron

Before entering the giant storage ring the electrons need to reach their final energy of 6 billion electronvolts (GeV). They do this in a 300 metre long, racetrack-shaped booster accelerator. The booster synchrotron contains accelerating radio frequency cavities and bending magnets, which force the electrons to deviate from a linear trajectory into an orbit. The strength of the magnetic field must be increased and carefully synchronised to the increasing energy of the electrons, which is why the accelerator is called a synchrotron. After reaching 6 GeV in about 50 milliseconds, the electrons are sent to the storage ring.

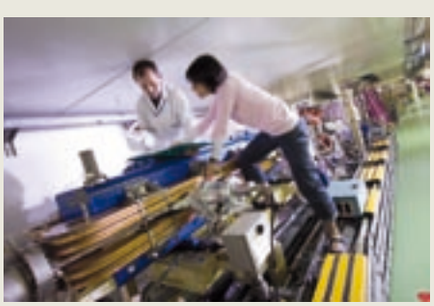
3 The storage ring

The storage ring, at 844 metres in circumference, is where electrons travel for hours close to the speed of light within an evacuated tube at extremely low pressure (around 10^{-9} mbar). As they travel round the ring, they pass through different types of magnets, mainly bending magnets, undulators and focusing magnets.

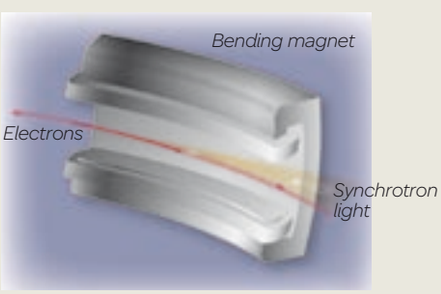
Inside the storage ring

4 Bending magnets

There are 64 bending magnets in the storage ring. Their main function, as in the booster, is to force the electrons into a curved trajectory.

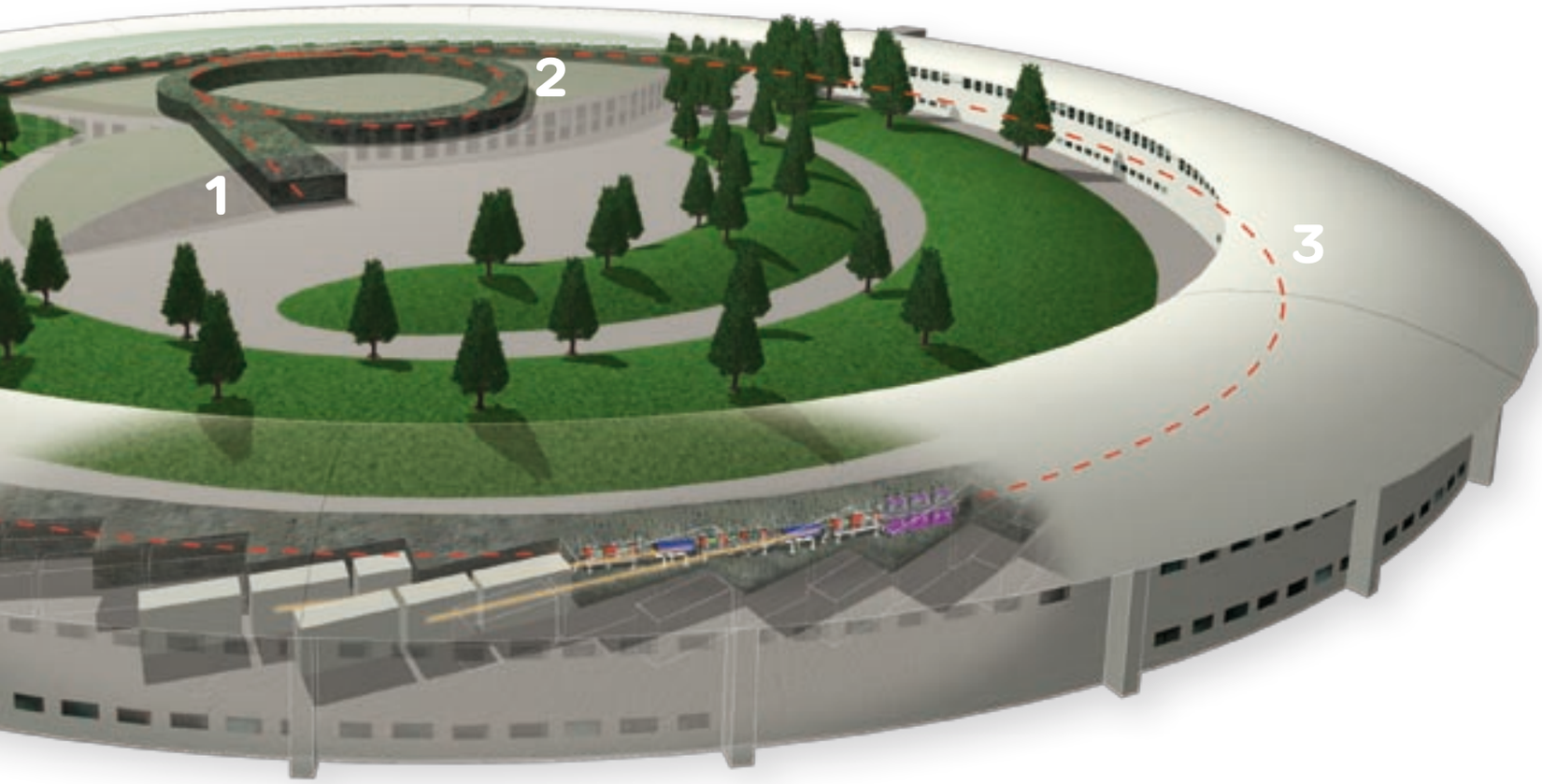


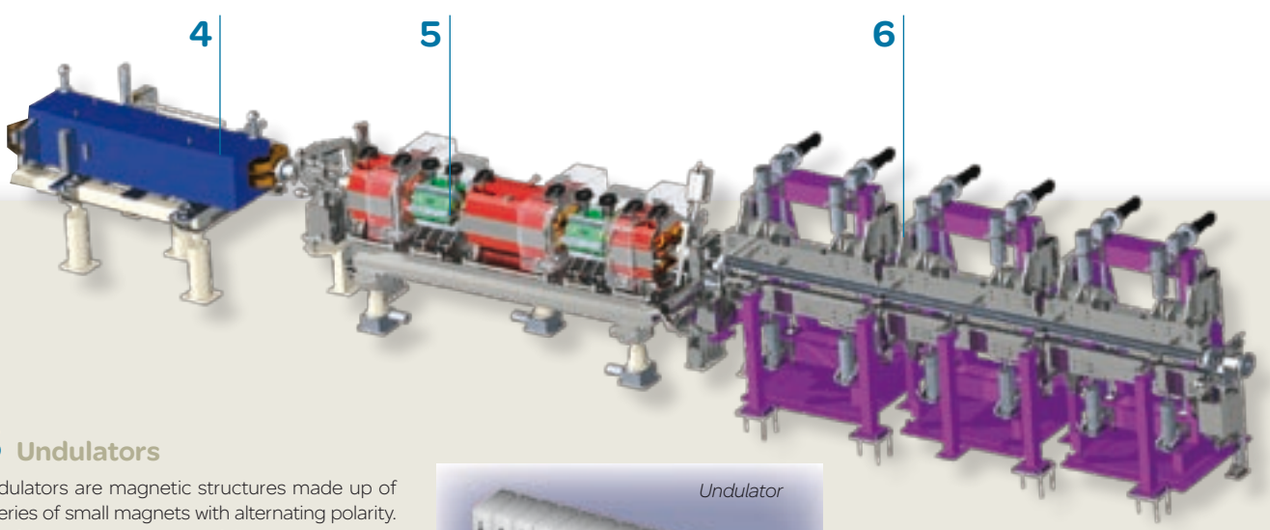
Bending magnets are also a source of synchrotron light. According to Maxwell's theory, electrons, when accelerated, emit electromagnetic waves. Because the electrons are relativistic (very high energy), this light is emitted tangentially to the curved electron beam and is collimated into a narrow, intense beam. It then goes to a beamline in the experimental hall. Synchrotron light emitted from a bending magnet covers a wide and continuous spectrum, from microwaves to hard X-rays.



5 Focusing magnets

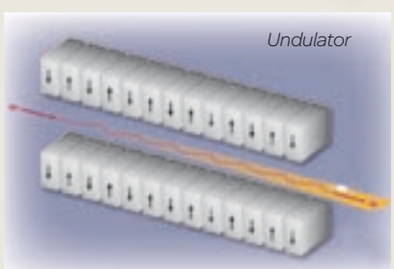
Focusing magnets – also called magnetic lenses – keep the electron beam size as small as possible.





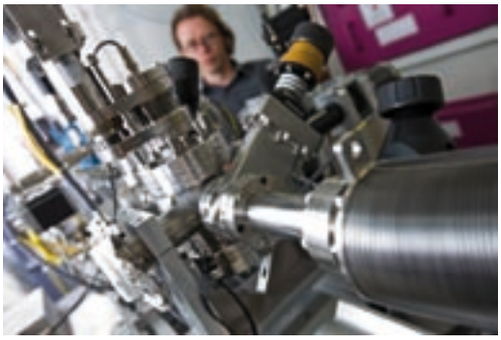
6 Undulators

Undulators are magnetic structures made up of a series of small magnets with alternating polarity. This forces the electrons to follow an undulating, or wavy, trajectory. The beams of radiation emitted at each magnet overlap and interfere with each other to generate a much more intense beam of radiation than that generated by a bending magnet alone. As a consequence, the photons emitted are concentrated at certain energies (called the fundamental and harmonics), thus increasing the brilliance of the beam. By opening or closing the gap of the undulator, the system can be fine tuned to reach the highest brilliance at any desired energy.



Pushing back the frontiers

Each year thousands of researchers, from all over the world, visit ESRF to experiment at the frontier of beamline science and technology. There are 42 highly specialised beamlines in total, each equipped with state-of-the-art instrumentation. Some of the key features of a beamline are described below.



1 X-ray optics

The optical devices found on the beamline (slits, filters, monochromators, mirrors, etc.) condition the photon beam for a specific experiment. The role of a monochromator is to select a specific energy from the wide spectrum of energies available. This is done by diffraction, usually on silicon monocrystals, which need to be cooled to avoid deformation under the high heat load of synchrotron light. A mirror is also an essential optical element, allowing the focusing of the beam onto the sample down to the sub-micrometre scale.

2 The sample work space

The working space around the sample is shared with specialised tools and sample environment devices. Nanofocusing an X-ray beam onto nano-sized objects requires improved instrumentation for sample positioning and viewing, optical tools and beam position monitors. Instruments providing complementary information to the X-ray data, such as microscopes and spectrometers, are essential for particular experiments. Automation in macromolecular crystallography, by using robots as sample changers and positioners, is also reducing the duration of experiments.

# of science

3 Detectors

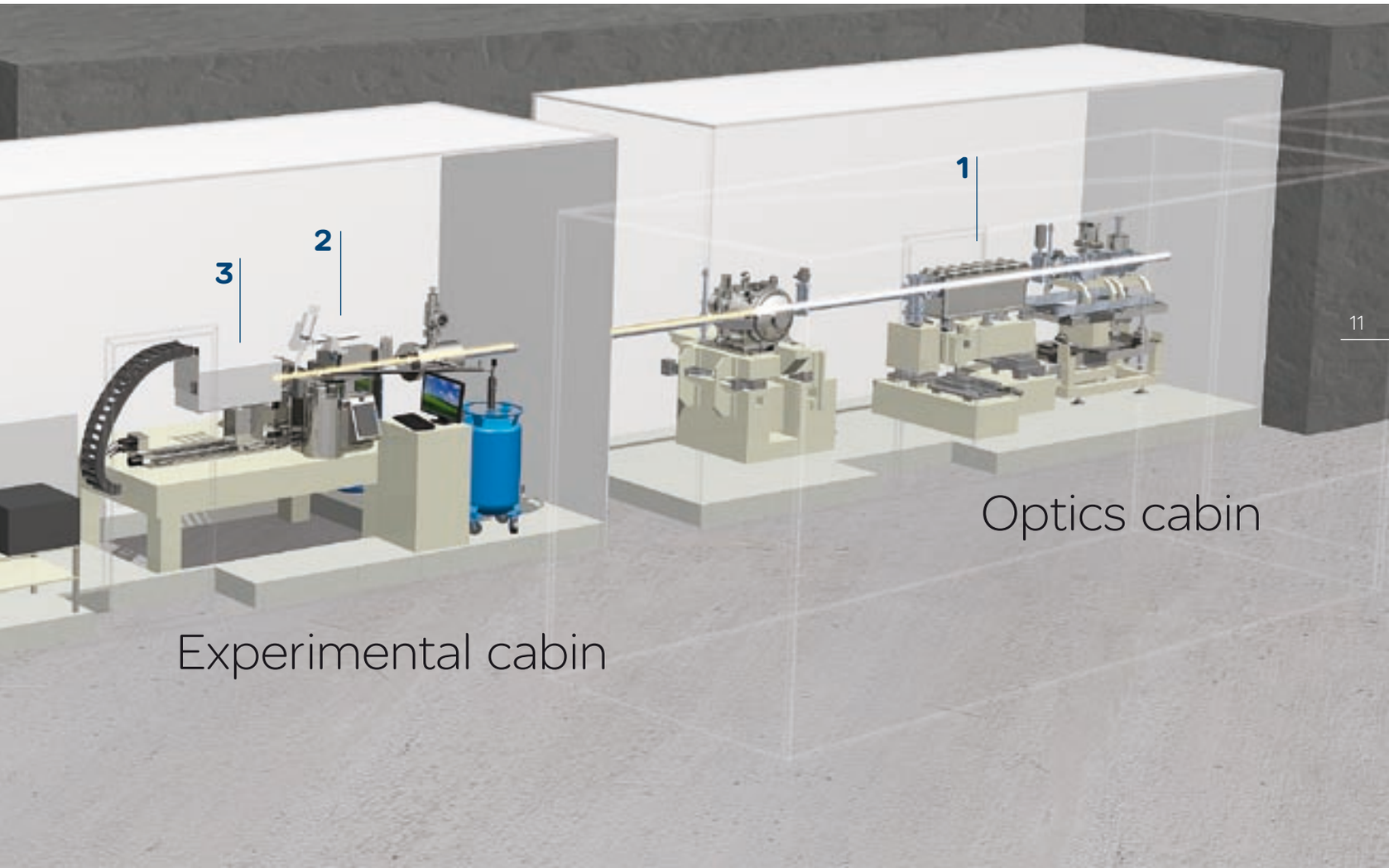
ESRF possesses a large variety of detectors, using different technologies, for a range of experiments. Image plates, first developed for medical imaging, have been progressively replaced by sophisticated image intensifiers, making use of CCD cameras. Today, a detector relies heavily on electronics to collect data with efficiency, resolution, sensitivity and speed. But all these criteria are not usually found in one detector. Dedicated detectors, tailored for a specific experiment, give the best results.

4 Beamline control

Operation of the beamline is obtained through beamline control software. This combines the functionality of each beamline component with the overall process of the experiment. The software must also be able to handle a large number of experimental scenarios autonomously. Remote control, by users in their home laboratories, has also become possible.

5 Data analysis

Data is usually taken at ESRF and analysed later by the users on their return home. However, online analysis is highly desirable as it improves the final quality of the experimental data. It can provide feedback on the quality of the data and give a first look at results in real or quasi-real time. Today, data is being produced at a faster rate and in ever greater quantities than before, so powerful computing technology is needed for online data analysis.



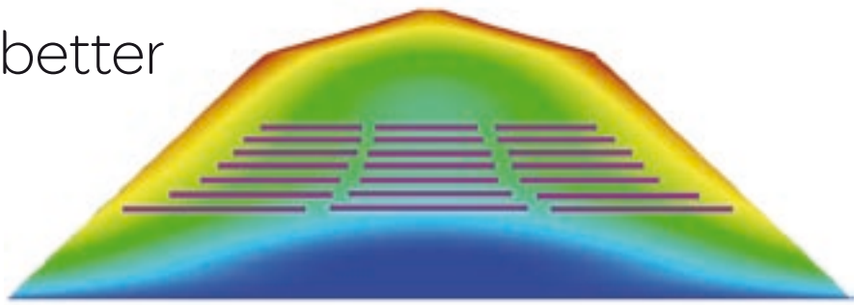
New challenges

The exceptional brightness of synchrotron light allows scientists to go further, towards increasingly complex experiments, with greater speed, higher resolution and more sophisticated sample environments.

The smaller the better

At the atomic scale

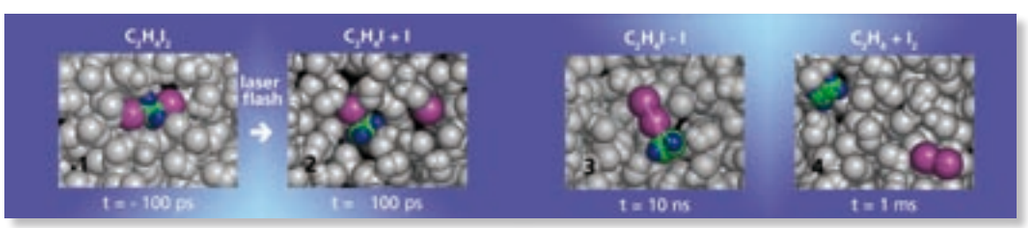
Science at the nanoscale addresses important questions across a broad range of disciplines. It can identify the driving phenomena behind pollution processes involving nanoparticles, such as global dimming, ash particles and colloid transport. It can also clarify the role of trace metals in neurodegenerative diseases and examine how extremophile bacteria adapt their metabolic processes to their hostile environments. It can even research how nanoscopic crystals, called quantum dots, behave under stress.



Looking inside a quantum dot with X-ray vision.

Nanobeams

Nanobeams are a unique way of probing the electronic and magnetic properties on the atomic scale. Also, with imaging techniques using nanobeams, quantities such as density, chemical content and state, structure and crystallographic perfection can be mapped into two or three dimensions. Coherent diffraction imaging and phase-contrast imaging, which exploit the properties of coherence of the ESRF X-ray beams, can open up new fields of investigation at the nanoscale.



Studying the dissociation and re-association of a molecule within a solvent on a 100 ps timescale.

Filming reactions

Higher time resolution

A new experimental challenge involves studying chemical and biological reactions. This requires atomic resolution on timescales fast enough to follow the evolution of molecules through their initial, intermediate and final structures. Since reactions unfold on timescales ranging from seconds to femtoseconds (1 fs = 10^{-15} s), the experimental probe has to be equally fast. The reactions also have to be activated quickly and uniformly by an external trigger (the pump). These experiments are called "pump-and-probe".

Down to the picosecond

X-ray beams from undulators are so intense that only one flash of light is needed to record diffraction patterns from proteins. This allows protein motions to be filmed to a time resolution of 100 picoseconds (1 ps = 10^{-12} s). The protein is typically activated by femtosecond laser pulses and the evolving structure is probed by delayed X-ray flashes. A series of time delays are combined, and the correlated motions of all the atoms in the molecule are filmed in real time and in three dimensions.

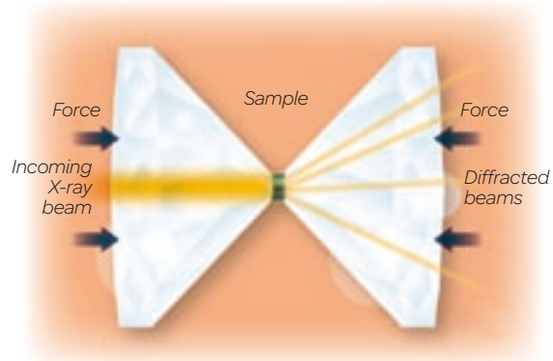
Under pressure

Extreme conditions

On ESRF beamlines the most demanding experiments need complex sample environments involving different temperatures, magnetic fields, mechanical constraints, chemical reactions and pressure. Pressure is central to fundamental studies of matter but can also be applied to real systems such as geophysical phenomena and the synthesis of new materials.

Using diamond-anvil cells

In order to reach extreme pressures of millions of atmospheres, scientists have developed the diamond-anvil cell technology: tiny samples, some 50 micrometres across, are squeezed between two diamond tips. The samples can be viewed through the diamonds and probed using X-ray diffraction or spectroscopy to explore changes in structure and properties.



Pressures of millions of atmospheres can be obtained in a diamond-anvil cell.

Visualisation of the progression of a crack in an aluminium alloy.

Superscanner

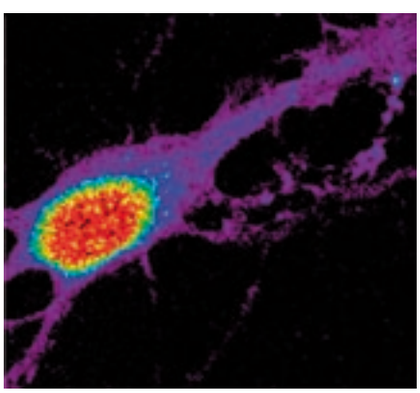
X-ray imaging

Although known and used for more than a hundred years, X-ray imaging remains one of science's most versatile and powerful techniques. Third-generation synchrotrons, with their coherent beams of X-rays, offer new opportunities of research in many fields. These include:

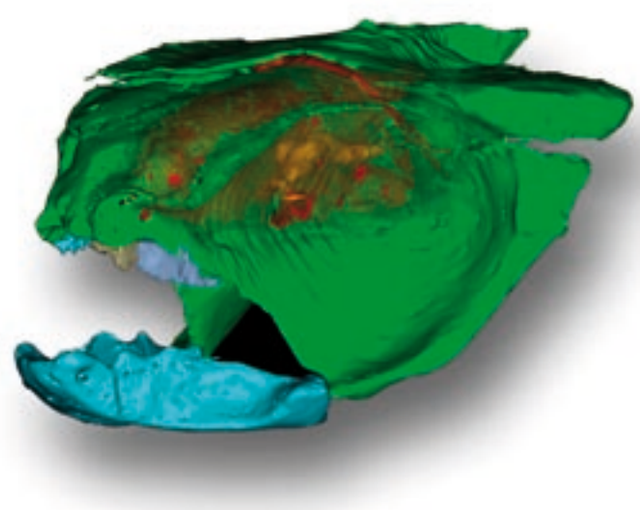
- Biomedical applications in both diagnostic imaging and radiotherapy.
- Materials science, such as the investigation of cracking in an alloy vital for air transport.
- Cultural heritage, where synchrotron techniques revealed the unexpected presence of oil in ancient paintings in the Bamiyan Buddhist caves in Afghanistan.
- Environmental sciences with, for example, the investigation of cometary grains collected during the NASA Stardust mission.
- Palaeontology, such as the exploration of 100 million-year-old opaque amber pieces containing insect fossils.

Investigating fossils

ESRF is a world leader for the non-destructive investigation of fossils. It not only provides high quality data, but also helps preserve fossils by being non-invasive. Many fossils are mineralised and propagation phase-contrast imaging (making use of the coherence of ESRF X-rays) produces a clear contrast, revealing structures that are invisible in the absorption mode. This new technique, called holotomography, allows the high-resolution reconstruction of virtual fossils. The virtual image can then be used by palaeontologists without having to transport and manipulate sensitive specimens.



Zinc distribution within a neuron, viewed by X-ray fluorescence.



A unique specimen: the brain (in orange) of a 300-million-year-old fish fossilised under exceptional conditions.

A European vision

A successful collaboration

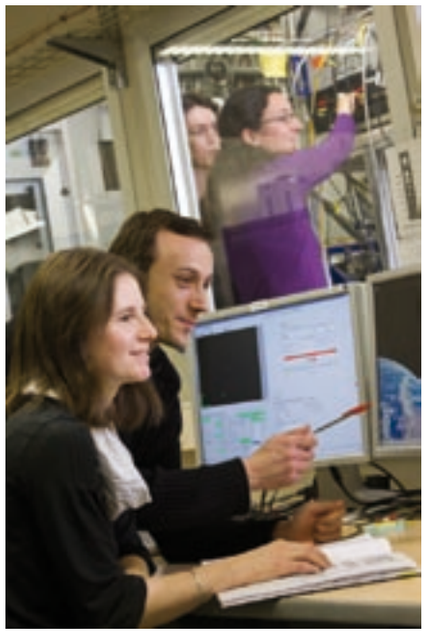
In 1988, twelve European countries joined forces to build the largest synchrotron in the world. It was a bold plan filled with scientific vision and has put European science on an overwhelmingly successful path. The initial objectives, in terms of accelerator performance and beamline production, have been more than exceeded – in the case of the brilliance of the X-ray beam, by several orders of magnitude.

Today, more than twenty years later, the success of ESRF is without doubt. Some of its beamlines and instrumentation are viewed as scientific role models and remain unsurpassed. Seven more countries have joined the facility and it has a diverse community of thousands of users, far beyond the traditional fields of research.

World-class staff and users

ESRF is at the forefront of X-ray science and the number of publications in peer-reviewed journals is increasing steadily, to reach more than 1,500 annually. ESRF is clearly ahead in the race to excellence and, since 2008, has started developing an outstanding upgrade programme to maintain its world-leading position for the next decades.

One of the reasons for this achievement is ESRF's staff. They come from thirty-five countries and the mixture of cultures and different scientific and technical backgrounds is an invaluable asset. While these men and women guarantee that the installations operate at their best, they are also actively participating in the development of innovative techniques. They are in permanent contact with the wide community of users, who bring a continuous flow of expertise and fresh ideas to the facility.



Total annual budget: About 90 million Euros

Members' shares in contribution to the annual budget

France	27.5%
Germany	25.5%
Italy	15%
United Kingdom	14%
Spain	4%
Switzerland	4%
Benesync (Belgium, The Netherlands)	6%
Nordsync (Denmark, Finland, Norway, Sweden)	4%

Additional contributions*

Austria	1%
Israel	1%
Poland	1%
Portugal	1%
Centralsync (Czech Republic, Hungary, Slovakia)	1.05%

*Percentages refer to members' contribution.

For a bright future

In addition, ESRF takes care of young scientists. A large number of PhD students and post-docs are taking their first steps as scientific researchers in one of the most acclaimed synchrotrons in the world. This flow of new scientists is essential to maintain the vitality of European research and ensure its future.

ESRF also organises international conferences, seminars and workshops, which benefit the whole scientific community. Although often targeted at specialists in one field, more and more they are addressing cross-disciplinary topics, following the general trend of scientific research today.

Fruitful partnerships

In a similar spirit, scientific partnerships permit new collaborations resulting in new discoveries. ESRF (synchrotron light) and its neighbouring facility ILL (neutrons) naturally complement each other and this relationship is exploited in many ways.

The PSB (Partnership for Structural Biology) is a collaboration between ESRF, ILL, EMBL Grenoble (European Molecular Biology Laboratory) and IBS (Institute for Structural Biology). With its neighbour UVHCI (Unit of Virus Host Cell Interactions), it provides an integrated platform of dedicated state-of-the-art techniques, unique in Europe.

On a wider scale, ESRF plays a crucial role in the development of the European Research Area, particularly in close partnership with other European research organisations under the banner of EIROforum.

As an international leader, ESRF is collaborating with synchrotrons, universities and research organisations from all around the world for a wide range of technical and scientific developments.

The PSB, looking towards the future.

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