SOLEIL SYNCHROTRON

SOLEIL II

SCIENCE LIGHTS UP THE FUTURE

SOLEIL II: A LEGACY OF NEARLY 20 YEARS IN THE SERVICE OF SCIENCE

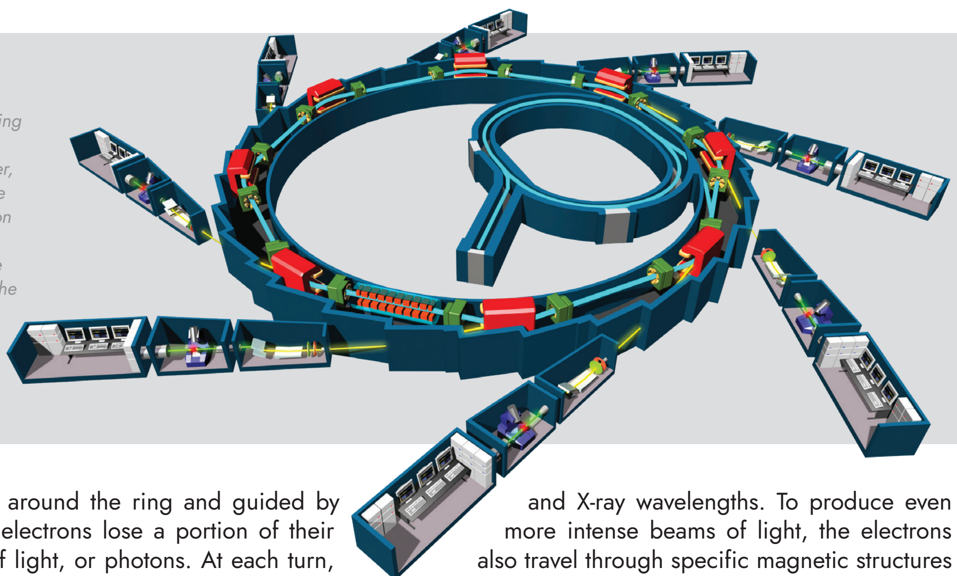
SOLEIL today

Both a "Very Large-Scale National Facility" and a tool serving the scientific and industrial communities, SOLEIL, located within the Paris-Saclay cluster, is a light source with technology that enables scientists to explore the deepest secrets of matter, down to the scale of atoms.

Since 2008, teams at SOLEIL host and assist more than 5,000 researchers, known as «users», every year. The users come from around the world to perform experiments using the synchrotron facility. Some 450 staff at SOLEIL devote their efforts providing them with the optimum conditions for their experiments to succeed.

SOLEIL's teams also develop their own research themes on a variety of topics, either in-house or through partnerships that mobilize the scientific community.

SOLEIL is a source of extremely intense light, called synchrotron radiation, produced by a particle accelerator. Electrons, ripped from a metal tablet the size of a coin, are gradually accelerated to close to the speed of light, raising their energy in two accelerators, the LINAC and the booster ring. They are then injected into the storage ring measuring 354 meters in circumference, where they orbit 24 hours a day, seven days a week.



Schematic diagram illustrating the operating principles of the synchrotron: in the center, electron accelerators enable the production of synchrotron radiation (represented in yellow), which is used in the beamlines located around the large circular storage ring.

During their journey around the ring and guided by magnetic fields, the electrons lose a portion of their energy in the form of light, or photons. At each turn, this extremely bright light is emitted across a spectrum of wavelengths ranging from infrared to visible, ultraviolet and X-ray wavelengths. To produce even more intense beams of light, the electrons also travel through specific magnetic structures that cause their trajectory to bend multiple times ("undulate") over a few meters.

Twenty-nine specialized laboratories called "beamlines"—each equipped with instruments for preparing and analyzing samples and data collection—are built around the electron accelerator.

These unique yet complementary beamlines are designed for specific wavelength ranges, analysis techniques, and sample types. The samples can be solid (e.g., surfaces, materials, cells, or living tissues), liquid, or gas.

As it enters the beamline, the synchrotron radiation travels through several different optical systems that select the wavelength and focus it for the experiment before reaching the sample, object of study. When this incredibly intense light reaches the sample, penetrating the material that comprises it, the sample "responds" by deflecting or absorbing the light, or by liberating photons, ions or electrons. Recorded by equally specialized detectors, this data is then interpreted by researchers, who use it to determine the structure and geometry—surface or volume—or chemical, electrical, or magnetic properties of the sample. All this can be carried out down to the level of the atoms that make up the material.

SOLEIL II

In a commitment to better serving its user communities and taking advantage of recent scientific and technological advances, SOLEIL is now launching a major modernization of its facilities to evolve into SOLEIL II. This ambitious project will benefit from experience and expertise acquired over the last nearly twenty years that the synchrotron has been in operation. The pioneering and innovative spirit of our teams, which came into play during the construction of SOLEIL, makes this update the boldest project among the many underway or planned within the international synchrotron ecosystem.

SOLEIL II will prioritize rational, moderate resource use by keeping existing buildings and offer fundamentally renovated accelerators and beamlines, making France's source of synchrotron radiation more competitive and increasing its lifespan by at least 30 years.

SOLEIL's key figures today

(end 2024)

- **24/7** **operation** with over **98% reliability**
- More than **65,000** **users** since 2008
- **Users** from around **1,200** **laboratories** each year
- More than **9,300** **publications** since 2008
- Used by more than **120** **companies,** from start-ups to major corporations, for **1,600** **industrial experiments** carried out since 2008
- **30,800** **middle schoolers, high schoolers, and university students** have visited SOLEIL since 2010
- More than **1,500** **doctoral theses** include results obtained at SOLEIL since 2008
- Nearly **300** **national and international partnerships** in **46 countries**

SOLEIL II: MEETING THE CHALLENGES OF TOMORROW...

Advanced materials

Big Data and artificial intelligence (AI) require increasing computing performance and storage capacity, which is extremely energy-intensive: computers, data centers, and networks account for nearly 10 percent of the world's electricity consumption. Quantum computing could increase computing power while reducing energy use by a factor of 100 to 1,000.

A key concern in many fields (e.g., aeronautics, transportation, security, energy, communication) is the rapid development of advanced materials, integrating design and synthesis, with pre-determined characteristics and functionalities.

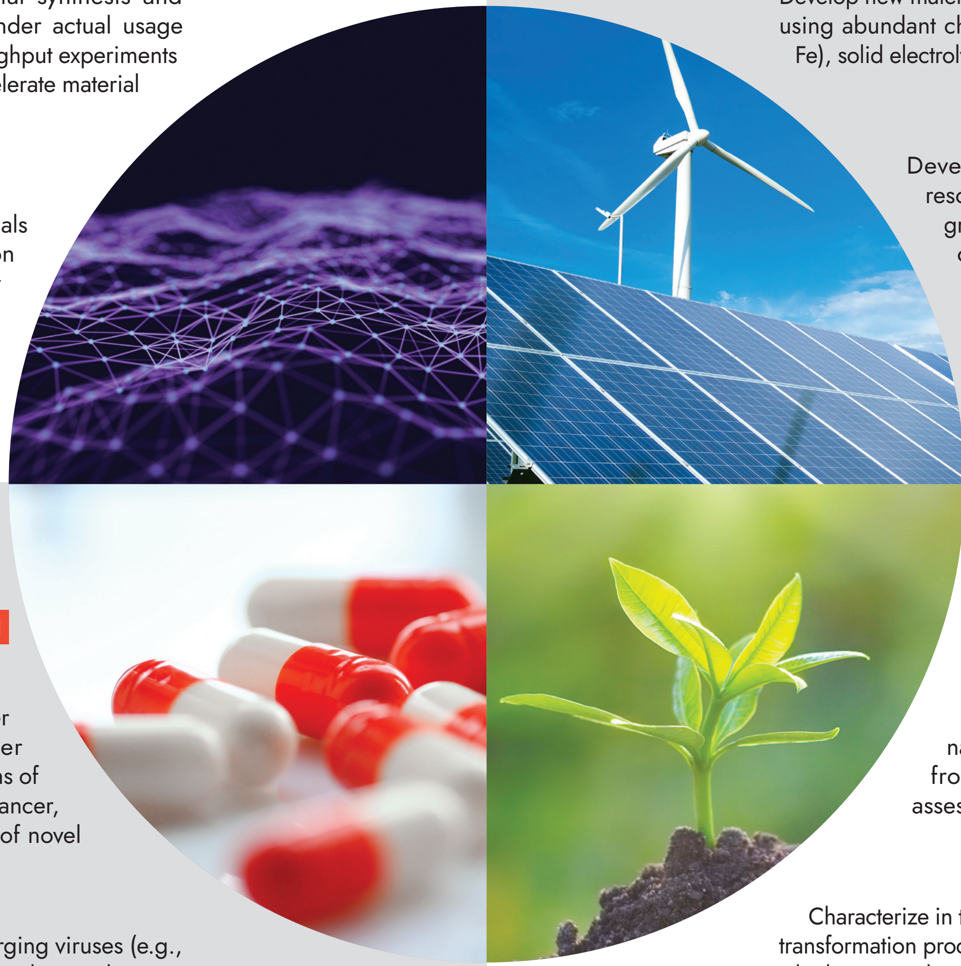
SOLEIL II'S CONTRIBUTION

Materials engineering

Monitor the phases of material synthesis and fully assess their properties under actual usage conditions. Combine high-throughput experiments with AI methods in order to accelerate material development and reduce costs.

Information technologies

To develop new quantum materials and control their properties on demand, even when their composition is heterogeneous down to the nanometer scale (one billionth of a meter).



Energy and sustainable development

Computers, smartphones, tablets, electric vehicles: omnipresent in our daily lives, they operate thanks to electrochemical energy storage in batteries that can be made more compact, safer, faster to recharge, longer-lasting, more durable, and more environmentally friendly.

In industry, 90% of reactions are catalytic and often use scarce resources (noble metals, rare earth elements, etc.). The development of new catalysts and the optimization of reactions could make it possible to reduce global energy consumption by an amount equivalent to Germany's current annual energy consumption by 2050.

SOLEIL II'S CONTRIBUTION

Batteries

Develop new materials for electrodes and electrolytes using abundant chemical elements (e.g., Na, Mg, Fe), solid electrolyte technology; optimize recycling processes.

Towards carbon-free energy

Develop fuels from sustainable resources, like biomass, to reduce greenhouse gas emissions; develop cleaner and more efficient combustion processes for existing fuel stocks; optimise solar energy conversion.

Health

Emerging infectious diseases are caused by pathogens (bacteria, viruses, fungi, parasites, prions) of diverse origins. The treatment of these diseases, which are becoming increasingly numerous and whose impact is amplified by ecosystem changes linked to human activity, presents a major challenge.

The structural and cellular biology techniques developed through SOLEIL II will enable the identification of targets for new therapies and provide a rapid and tailored response to these diseases (vaccines, antibiotics).

SOLEIL II'S CONTRIBUTION

Cancer

Contribute to developing cancer treatments through a better understanding of the mechanisms of cellular dysfunction leading to cancer, as well as the modes of action of novel drugs.

New pathogens

React quickly, especially to emerging viruses (e.g., Ebola, H1N1, SARS-CoV-2) by reducing the time needed to develop new diagnostic methods, drugs, and vaccines.

Environment

By 2030, 50 million tons of plastic could enter aquatic ecosystems. Its degradation leads to the formation of micro- and then nano-plastic particles, which are extremely difficult to detect.

More generally, the transfer of pollutants is expected to increase with the rising frequency and intensity of extreme weather events (storms, floods) linked to climate change. Aerosols from natural sources (volcanoes, massive wildfires) and those resulting from human activity (pollution) have a significant impact on the climate.

SOLEIL II'S CONTRIBUTION

Impact of pollutants

Understand the capacity of nanoplastics to carry contaminants from continents to oceans to assess their toxicological impact on ecosystems.

Climate warming

Characterize in the atmosphere the interaction and transformation processes of gases and nanoparticles, whether natural or linked to human activity, in order to refine models and more accurately predict the consequences of a warming climate.

... THANKS TO A TECHNOLOGICAL LEAP AND AN INTERNATIONALY UNIQUE COMBINATION OF EXPERIMENTAL SET-UPS

- UNIQUE LIGHT SOURCE, FROM INFRARED TO HARD X-RAYS
- EXPERIMENTS UP TO 10,000 TIMES FASTER
- EXPERIMENTS UP TO 1,000 TIMES MORE SENSITIVE
- NANOSCALE RESOLUTION
- STUDY OF SYSTEMS UNDER REAL OPERATING CONDITIONS
- COMPLEMENTARY BEAMLINES AND TECHNIQUES

SOLEIL II : SCIENCE LIGHTS UP THE FUTURE

Designing higher-performing catalysts

More than three-quarters of the manufactured objects around us are produced through catalytic processes. These processes enable selective reactions (the desired substance is produced in larger quantities), efficient reactions (less loss of initial components), and operate under conditions (temperature, pressure, etc.) that are less energy-intensive.

One of the challenges in many industrial sectors is to understand these processes in detail and optimize them to significantly reduce energy consumption.

SOLEIL II

Brighter and more coherent synchrotron radiation =

→ Study of catalytic reactions under operating conditions and in real time.

→ Better understanding of catalyst activation mechanisms.

→ Recommendations for obtaining higher-performing catalysts.

Preserving plants

Our lives depend on plants, for both the air we breathe and the food we eat. Population growth, climate change, and intensive agriculture all make plants more vulnerable to drought and the rapid spread of pathogens.

Optimizing plants' resistance to drought and their adaptation to the emergence of new plant pathogens are the challenges facing tomorrow's agriculture.

SOLEIL II

Increased flux, brightness, and coherence of synchrotron =

Qualitative improvement of X-ray computed tomography and scanning microscopy.

→ Non-invasive techniques that provide morphological and chemical information (detection of trace elements in plants).

Fighting bacterial resistance to antibiotics

Multidrug-resistant bacteria kill about 700,000 people around the world each year.

Understanding the mechanisms of antibiotic uptake and expulsion developed by bacteria are key points in the fight to save lives.

SOLEIL II

Increased photon flux on samples =

Higher-quality measurements.

→ Coupling analytical techniques to elucidate the mechanisms of interaction between antibiotics and bacteria.

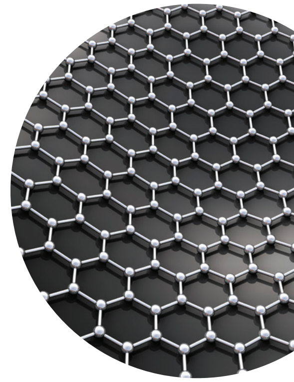
Developing nanoelectronics

On the surface of graphene, referred to as a 2D material due to its extreme thinness (a single layer of carbon atoms), electrons move 150 times faster than in silicon. Can we envision electronics 150 times faster, based on graphene? The main challenge: it is not a semiconductor, a property essential for electronic components. However, modifications of graphene, as well as other 2D materials with similarities to graphene, are being studied to address this challenge.

SOLEIL II

Extreme brightness + increased flux of coherent photons =

→ Identification and optimization of materials for a new generation of ultra-rapid, nanometric transistors.



Preserving and restoring natural and cultural heritage

Over time, degradation processes threaten the appearance of ancient materials, obscure their interpretation, and can lead to their complete destruction. To preserve these materials for future generations, it is essential to understand the deterioration mechanisms at work and develop environmentally sound protocols for conservation and restoration.

SOLEIL II

Brighter and more coherent synchrotron radiation =

→ Detection and characterization of nanometer- to millimeter-sized constituents.

→ Identification of diluted tracers reflective of physical and chemical modifications.

→ Faster analysis, increased number of studied specimens.

Understanding interactions between atoms and molecules

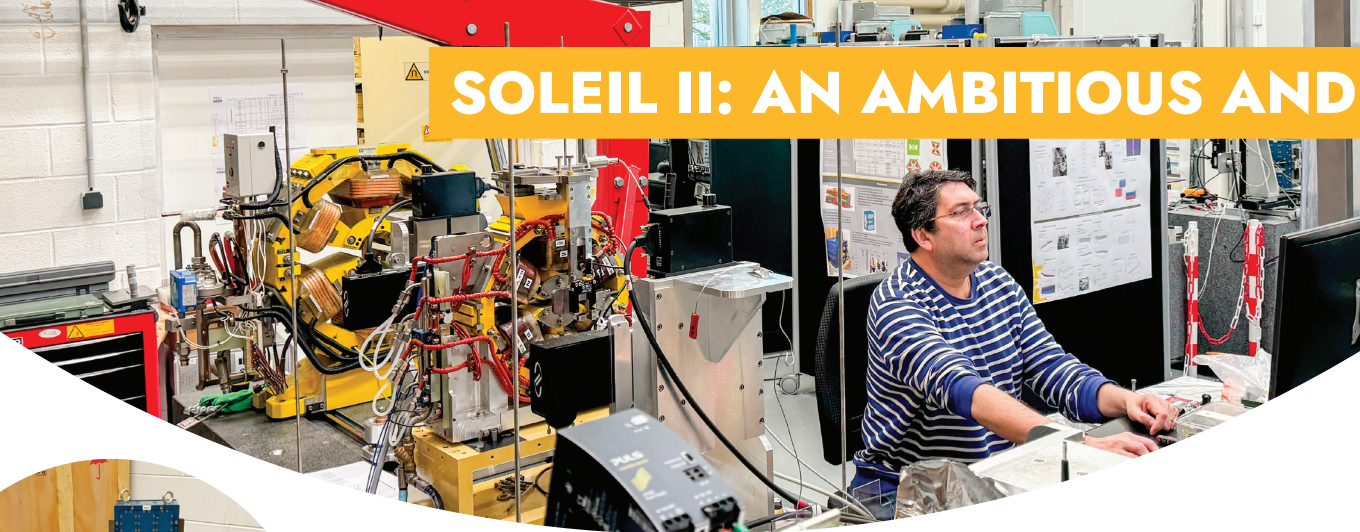
Knowledge of the electronic structure of isolated atoms and molecules is crucial to experimental validation of models based on quantum mechanics. However, in matter, particularly living matter, atoms and molecules are not isolated: they interact with their environment, which impacts their electronic structure. To understand the effect of these interactions, microjets of atomic or molecular ion solutions are generated in vacuum, enabling their study through X-ray spectroscopy.

SOLEIL II

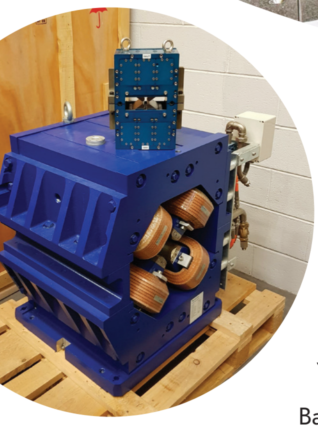
Increased brightness + focus of photon beam =

→ Study of even more diluted samples, nanometric objects in solution, and droplets.

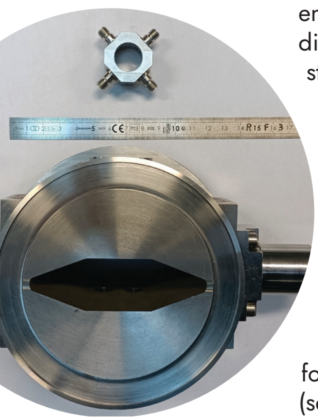
→ Possibility to more easily carry out X-ray absorption spectroscopy.



SOLEIL II: AN AMBITIOUS AND INNOVATIVE PROJECT TO TACKLE MAJOR TECHNOLOGICAL CHALLENGES



Example of a miniaturized magnet used to guide electrons: a SOLEIL II quadrupole on top of a SOLEIL quadrupole.



Beam position monitor: currently in use at SOLEIL (bottom) and a prototype for SOLEIL II (top).

The highest-performance accelerator in the world in its category

Based on a new arrangement of magnetic elements, SOLEIL II's high-performance electron accelerator is designed to produce photon beams of unparalleled quality, which are essential for meeting the scientific challenges ahead.

The new accelerator will be the world's most compact and highest-performance facility in the intermediate energy range (around 3 GeV), in terms of the size and divergence of the electron beams produced. It will strengthen France's strategic position in the production and use of synchrotron radiation.

This innovative and ambitious project aims to replace the current 354-meter circumference accelerator while preserving the existing infrastructure and the beam extraction geometry of the beamlines, thus minimizing total project cost. The energy range of the photons produced covers ten orders of magnitude, from far-infrared to hard X-rays. SOLEIL's area of excellence ("soft" and "tender" X-rays) will remain the focus. A 40 times smaller now circular electron beam (see figure above) will render the photon beams at least 100 times brighter and more coherent in the X-ray range. The enhanced properties will enable experiments that were previously impossible or could only be conducted over very long measurement times, while guaranteeing greater stability of intensity, position, and size.

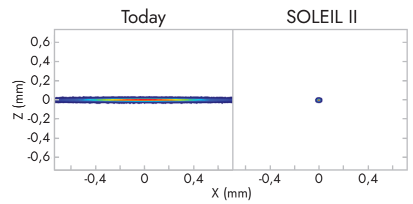


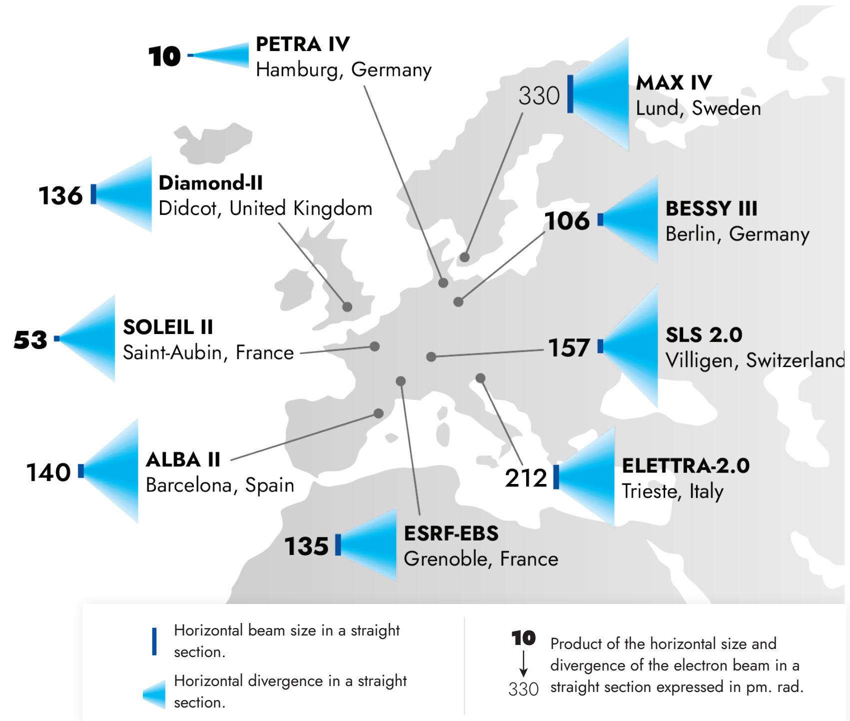
Image of an electron beam at the source of a beamline, currently and with SOLEIL II (simulation).

Upgrading SOLEIL's accelerator is made possible in part by overcoming technological barriers: the vacuum chambers through which the electrons circulate and the magnets that guide them (see photos, left) have undergone extreme miniaturization to achieve a highly compact layout. In addition, major innovations to the accelerator include a redesigned electron injection system, as well as brand new compact magnetic devices that allow for the production and control of increasingly intense photon beams. These innovative concepts are the subject of an intense prototyping phase and have already led to the filing of seven patents.

European ecosystem

SOLEIL II: THE MOST AMBITIOUS PROJECT OF ITS KIND IN A RAPIDLY CHANGING ECOSYSTEM

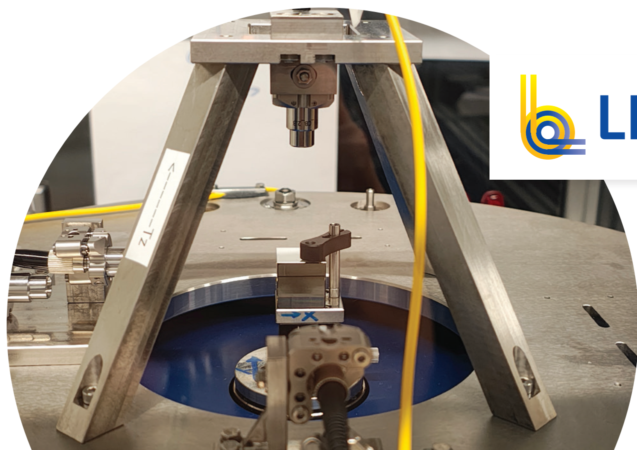
Map of European next-generation synchrotrons.



SOLEIL II operates within a very dynamic European context in which all synchrotrons are engaged in a similar process, initiated by the construction of MAX IV in Sweden, the first of this new-generation synchrotron (map).

The first results obtained at MAX IV and at ESRF—EBS—the European synchrotron in Grenoble, France—demonstrate the remarkable potential of these extremely bright light sources, which are driving the competitiveness of these facilities, and make SOLEIL II indispensable.

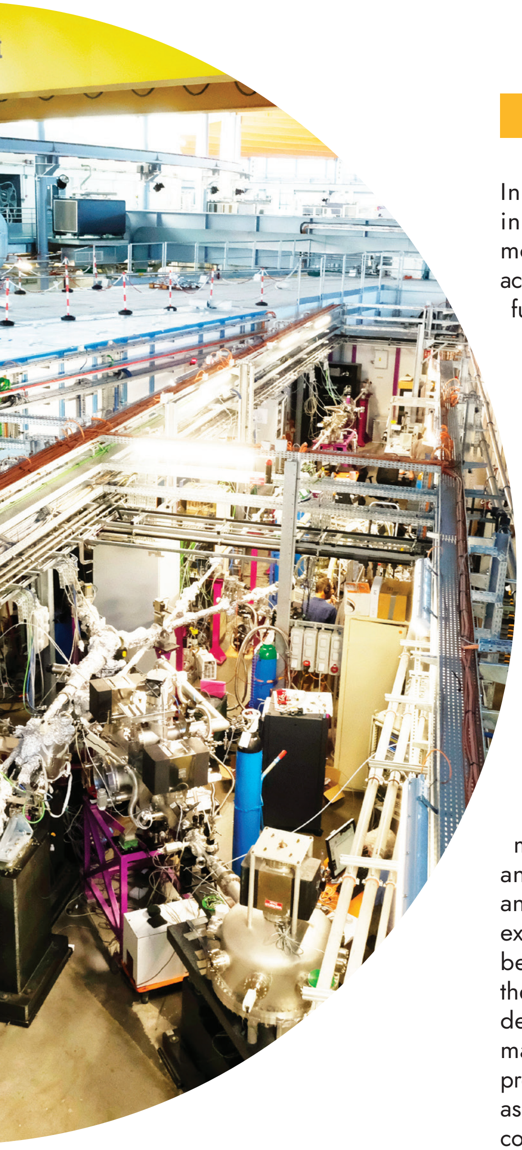
With photon beams ranging from far infrared to X-rays, SOLEIL II will remain the essential complement to ESRF-EBS, which provides higher-energy X-rays. French laboratories and industry will therefore always have access to a full range of techniques that meet all their needs. In 2017, the European synchrotrons formed a community known as LEAPS. Since then, SOLEIL has resolutely committed to this initiative, especially the community's actions around developing innovative instrumentation that will benefit SOLEIL II by accelerating development and sharing costs among members.



LEAPS League of European Accelerator-based Photon Sources

Nanotomography instrument with a magnetic levitation system guided by laser interferometer developed for SOLEIL and LEAPS by Mi-Partners.

BEAMLINES AND EXPERIMENTAL STATIONS AT THE CUTTING EDGE OF INSTRUMENTAL INNOVATION



View of a beamline from the walkway in the experiment hall at SOLEIL.

A comprehensive modernization

Innovative developments in instrumentation and in-depth modernization will be necessary across all beamlines in order to make full use of the unique characteristics (brightness, coherence, and micrometric size) of the photon beams produced by SOLEIL II's accelerators.

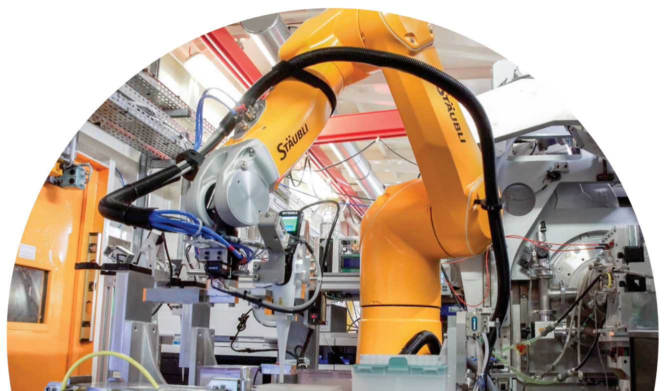
To maintain the quality of the synchrotron radiation produced in the accelerators all the way to the analyzed sample, new optical systems, whose shape will be controlled at the subnanometer level, must be developed, manufactured, and validated. In addition, many engineering challenges must be met, especially to design nano-positioning systems, ensure mechanical and thermal stability, and develop more automation and robotization. The quality of experiments carried out on the beamlines will also depend on the integration of new-generation detectors. Finally, the optimized management of the data flows produced during these experiments, as well as their analysis, is a major concern and calls for new computing strategies.

The synchrotron's equipment will be adapted and modernized to respond to the new expectations of the scientific communities that will use SOLEIL II, for example remote access to the beamlines, analysis and visualization of experiment data in real time, and the ability to carry out experiments under conditions that increasingly resemble actual operating or usage conditions of the objects under study. Combining measurements across multiple beamlines, at different size scales, and thus taking advantage of the wide range of wavelengths of radiation produced by SOLEIL, will be made easier with SOLEIL II.

These ambitious developments are being carried out with the goal of characterizing inert or living matter from a tenth of a nanometer in size to large objects and to study ultra-rapid phenomena in real time, with considerably improved detection sensitivity. They will provide French and international scientific communities with unparalleled tools for exploring the electronic, magnetic, chemical, and structural properties of matter.

These developments will benefit from the creation of strong academic, industrial, national, and international partnerships.

Reliability enhancement, through automation, of micro-pipetting operations on the SWING beamline.



A data-driven project based on a comprehensive digital transformation

New digital services will make full use of the potential offered by the new accelerator and beamlines. Advanced computational techniques such as machine learning will be used to control the characteristics of the electron beam and support experimental projects on the beamlines. Robotics will help to make the best use of available beamtime, including for remote experiments. To manage the barrage of data resulting from the increase in multi-technique experiments, the digital infrastructure will be modernized, supported by national computing and storage centers.

Data center hosting part of SOLEIL's shared computing and storage resources. The space and cooling allocated to the IT equipment has been optimized through an urbanization project.

For beamline users, the added value of SOLEIL II will also lie in the visualization and analysis tools, data preservation, and the associated access and search services. By enabling data sharing and openness, in line with the National Open Science Plan, these services will maximize the impact of experiments conducted at the synchrotron. This transformation will be based on a modular, secure, and interconnected architecture, to facilitate the integration of new services, as well as the evolution of existing ones, ensuring their long-term alignment with technical and scientific needs.

OTHER DIMENSIONS OF SOLEIL II

A heightened impact on research, innovation, and training

IMPACT ON RESEARCH AND INNOVATION

Each year, SOLEIL welcomes more than 5,000 users from 1,200 French and international laboratories and more than 120 industrial companies, who undertake about 650 scientific projects using this unparalleled, multidisciplinary tool. The increased effectiveness of experiments made possible by SOLEIL II will increase these numbers by about 30 percent.

Bibliometric analysis reveals that the projects carried out by SOLEIL users have a higher impact and a stronger innovative character than their non-synchrotron work.

SOLEIL has developed close and fruitful partnerships with many major academic and industrial players in the fields of energy, health, and the environment who, by making SOLEIL II a core component of their strategic approaches, will be able to maximize the impact the synchrotron has on R&D.

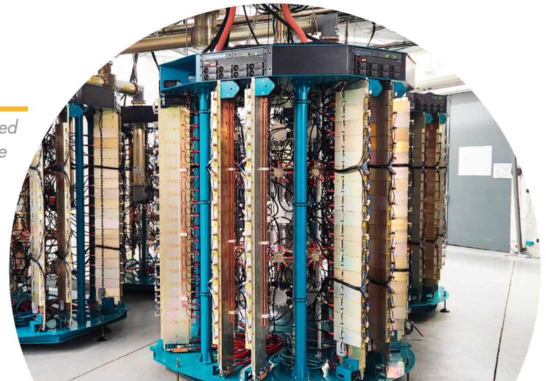
SOCIETAL IMPACT, TRAINING AND OUTREACH

A project as innovative as SOLEIL II already fosters training opportunities on numerous cutting-edge technologies. The project will further strengthen SOLEIL's dynamic learning policy, with its staff traditionally mentoring between 20 and 30 apprentices per year.

SOLEIL also supports the exchange and dissemination of scientific and technological culture, and welcomes all audiences. More than 4,000 people visit the synchrotron annually. Research carried out at SOLEIL II will provide new possibilities for educational and outreach projects, which will continue to be developed with SOLEIL's multiple academic partners.

ECONOMIC IMPACT

A recent socioeconomic impact study shows that one million euros spent by SOLEIL leads to, on the one hand, another million euros of value added to the French economy and, on the other hand, supports more than twelve jobs in France. Beyond these effects, SOLEIL II has a very strong potential for innovation—already eight patents related to the project are in preparation. Going forward French companies and business associations will be involved in our initiative to acquire the necessary know-how in cutting-edge instrumentation and to successfully participate in the many similar projects in Europe and beyond.



Radiofrequency amplification system, designed and developed at SOLEIL, used to accelerate the electron beam on each orbit around the booster or storage ring. SOLEIL was the first synchrotron to use these devices, which have since become essential components in projects to modernize synchrotrons to the fourth generation.

A greener facility

Replacing SOLEIL's aging equipment after two decades of use will considerably reduce the synchrotron's environmental footprint.

A first phase of modernization has already been completed, with the construction and commissioning in 2024 of a new chilled water production station, funded through the France Relance plan. This station supplies the different water networks that cool the electron accelerator and beamline equipment, as well as the air conditioning systems in buildings onsite. It thus contributes to the excellent beam stability on the beamlines, highly valued by our users. This new station also enables an 80% reduction in potable water consumption. Furthermore, it will eventually be connected to the Paris-Saclay district heating and cooling network, helping to heat 1,000 housing units on the urban campus and the aquatic center in the town of Gif-sur-Yvette.

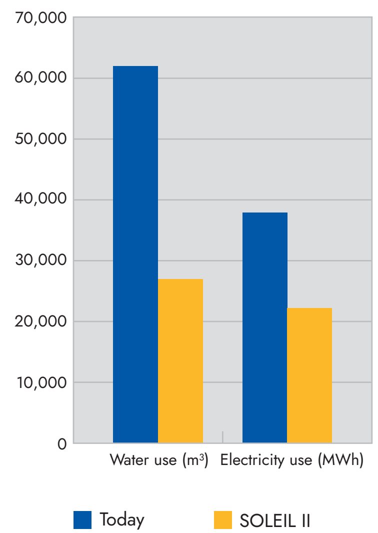
Gradual modernization of equipment used for accelerating electrons (RF amplifiers) has begun and will continue until 2027 to respond to requirements of SOLEIL II. In addition to improved performance and reliability, this upgrade will result in electricity savings of 1.25 GWh/year.

In addition, SOLEIL II's new accelerators will be built with the objective of rational resource use. The use of permanent magnets, recycled, if possible, in place of energy-intensive electromagnets will result in a drastic reduction (up to 50 percent) in electricity consumption. These goals of rationalization and economization will extend to exotic fluids, such as liquid helium, by using closed circuits to minimize losses of these valuable resources.

Finally, tools for conducting experiments remotely will be offered, whenever possible and desirable, on all beamlines, which will contribute to a reduced carbon footprint for user travel.

SOLEIL carried out a greenhouse gas emissions assessment concerning its activities in 2022 and 2023. Effective measures to reduce our carbon footprint will be taken based on regular monitoring of this assessment.

Evolution of electricity and water use.



Cooling circuits in the new, more reliable, and more ecologically sound chilled water production station (funded by France Relance plan).

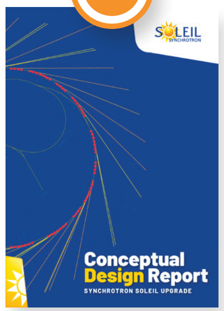
SOLEIL II: PROJECT TIMELINE AND STRUCTURE

→ Synchrotron shutdown + restart + commissioning = 24 months
→ Users return: October 2030

SHUTDOWN (2028–2030)

2020 · 2021 · 2022 · 2023 · 2024 · 2025 · 2026 · 2027 · 2028 · 2029 · 2030 · 2031 · 2032 · 2033 · 2034 · 2035

CDR (CONCEPTUAL DESIGN REPORT)



TDR : (TECHNICAL DESIGN REPORT)

- → Project scope
- → Budget profile
- → Technical specifications of project components
- → Consolidated planning of building works
- → Roadmap for the upgrade of Information Systems
- → Definition and schedule for the modernization of beamlines
- → Project structuring and organization

STAGE 1: CONSTRUCTION

- → Shutdown and dismantling of the booster and storage rings
- → Commissioning of the new booster and storage rings
- → Adaptation and restart of the beamlines
- → Modernization of support laboratories
- → R&D program on instrumentation

STAGE 2: TOWARDS FULL PERFORMANCE

- → Comprehensive beamline modernization
- → Development of support laboratories
- → R&D program on instrumentation
- → Transition towards innovative analysis techniques

Budget of SOLEIL II
~ €309M
(including 15% contingency)

STAGE 1 (6 years) : ~ €186M

STAGE 2 (5 years) : ~ €123M

SOLEIL II: THE WORLD'S TOP PERFORMING SYNCHROTRON OF ITS KIND

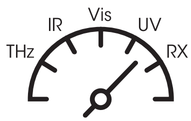
- thanks to an upgrade of the accelerators and beamlines in two stages, over 6 and 5 years
- meeting the challenges of tomorrow to maintain the competitiveness of French research in Europe
- complementing the ESRF—EBS to offer French laboratories an internationally-leading set of unique synchrotron techniques
- resource-efficient with reduced operating costs
- supporting the competitiveness of companies

EXPERIMENTS UP TO **10,000 TIMES FASTER**

NANOSCALE RESOLUTION

EXPERIMENTS UP TO **1,000 TIMES MORE SENSITIVE**

STUDY OF SYSTEMS **IN REAL OPERATING CONDITIONS**



UNIQUE LIGHT SOURCE, **FROM INFRARED TO HARD X-RAYS**

COMPLEMENTARY BEAMLINES AND TECHNIQUES

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