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OPERATIONAL STATUS OF SYNCHROTRON SOLEIL

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Abstract

The synchrotron SOLEIL is the French third-generation 2.75 GeV synchrotron light source, a research laboratory at the forefront of experimental techniques for the analysis of matter down to the atomic level, and a service platform open to all scientific and industrial communities. A major upgrade was financed at the end of 2023, the progress of which is presented in the second part of the article. We present the performance of the accelerators, which deliver extremely stable photon beams to 29 beamlines. We report on last year's overall performance figures and the operation of the new cooling station. As the optimization of the energy and carbon footprint becomes more and more important in France and Europe, measures for a more sustainable operation are presented. Major ongoing activities and the progress report of the intensive R&D of the SOLEIL II project follow.

SOLEIL ACCELERATOR PERFORMANCE

SOLEIL is the French third-generation light synchrotron source that has been providing highly stable brilliant photon beams to external users since 2008 (see main parameters in Table 1, [1, 2]). Its injector complex is based on a 110 MeV LINAC and a full-energy 3 Hz booster ring. The year 2023 was marked by several measures to reduce the overall power consumption of the facility in response to the excessive increase in the electricity cost resulting from a difficult international context. Only 4 of the 5 usual RUNs were scheduled to the beamlines (BLs) for 4257 hours. The accelerators' performance remains at the highest level, despite a major incident during RUN3, as reported below. The beam availability and the mean time between failures were 97.32% and 146 hours (best year), respectively (Fig. 1). The beam availability was above 99% during the 3 other RUNs, with 19 weeks above 99% and 10 weeks at 100% during the year. The record for the longest time between two beam failures was set at 639h55.

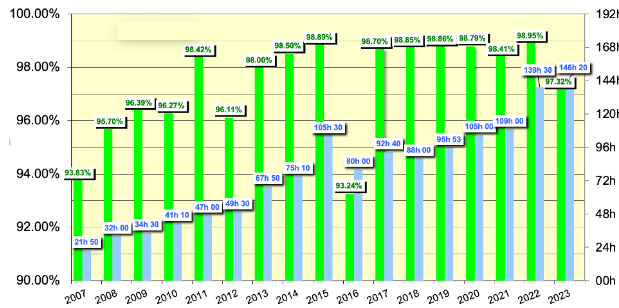

Figure 1: Beam availability (green) and mean time between failures (blue) over the years.

Table 1: Basic Parameters of the SOLEIL Storage Ring

Parameter	Value	Unit
Circumference	354.097	m
Energy	2.75	GeV
Nominal Tunes (H/V)	18.155 / 10.229	-
Natural Chromaticities (H/V)	-53 / -19	-
Momentum Compaction	4.18×10^{-4}	-
RF Voltage	2.6	MV
RF Frequency	352.197	MHz
Harmonic Number	416	-

Cost Saving Measures

As a first consequence of the sharp rise in electricity prices in 2023, the first RUN1 was canceled and replaced by a "deep" technical shutdown for part of January 2023 (shutdown of all accelerator equipment, beamline equipment, and cooling towers). Since the beginning of RUN3, the maximum current was reduced to 450 mA instead of 500 mA. This allowed us to reduce the number of RF cavities from 4 to 3, saving about 15% of the electrical power required by the RF system. Monday machine sessions were limited to the 7 a.m. to 4 p.m. time slot. No beam in the machine from 4 p.m. to 5 a.m., with equipment in "standby" mode. The August 2023 technical shutdown has been reorganized to include a three-week "deep" shutdown phase. All these efforts resulted in savings of 4.88 GWh, which were required by our funding agency and allowed us to deliver high-quality photon beams for the rest of the year.

Major Incidents

The operation was interrupted by two major incidents. The first involved the dipole coils of the linac-to-booster transfer line, which, due to human error, remained energized even though the coils were no longer water-cooled. Tests at low and then high currents in the coils showed that they remained operational to restart the accelerators while waiting for new coils to be manufactured as soon as possible. The beam was delivered to the beamlines 72 hours after the event. During the technical shutdown in August 2023, the coils were replaced with new ones manufactured on an urgent basis by the French company SEF. The second in-

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cident occurred in July when a fault in the cooling station led to a 17-hour beam interruption. The root cause was the weathering of cables that had been exposed to the elements since 2006. Another stressful incident occurred at the very beginning of RUN4, and hopefully remained transparent to users: nitrogen contamination of helium was detected in the helium refrigerator of the RF cryogenic system of the SR. The source of the contamination was a leak between the different helium circuits and the liquid nitrogen (LN2) circuit. Since then, the cryogenic system has been re-qualified to operate safely without its LN2 stage after a series of heavy maintenance activities.

Major Developments and Achievements

The year 2024 began with the successful connection of the new chilled water production station to the accelerator complex and BLs. It replaces the water-cooling station in operation since the synchrotron went into operation 2006, and supplies the various water networks that cool the accelerator and the beamline equipment, as well as air conditioning of the various buildings. The station's equipment and materials comply with current standards and regulations. An environmental approach was taken for the project. The construction schedule was tight. In 2020, SOLEIL received a grant of 12.67 M€ from the French government's 'France Relance' plan [3]. Operational performance was improved and optimized by eliminating 90% of the operation and maintenance constraints identified with the old station. 80 % water savings, 2 MWh per year electricity savings Free cooling with high flexibility and upgrade compatibility. The fatal heat will be connected to the 5th generation heat and cold exchange network to heat 1,000 homes on the urban campus and the aquatic center of Gif-sur-Yvette.

The new fast orbit feedback (FOFB) architecture was put into operation. It replaced the previous system embedded in the BPM electronics modules and is based on a new flexible stand-alone platform to follow the future upgrades of the surrounding equipment and to allow the integration of future correction schemes. Its performance corresponds to the previous system and offers fast response matrix measurement capability. As a next step, a future BPM electronic is expected in 2026 [4].

SOLEIL II PROJECT

SOLEIL II is our upgrade project [5–7] to build the science of tomorrow with synchrotron light radiation. Providing the highest brilliance in its class while maintaining the photon energy range from IR to hard X-rays, the project is an ambitious triple upgrade of the SOLEIL facility: 1) accelerators (new booster and storage ring), 2) 29 beamlines and 3 laboratories, and 3) an information technology transformation plan. High-order Achromat based on multi-bend achromat lattices will be used to replace both the storage (SR) and booster rings. The achieved equilibrium emittance of the SR is about 50 times smaller than that of the existing storage ring. An intensive R&D phase based on extensive numerical simulations, prototyping, and measurements has been carried out to ensure the technical feasibility.

Funding and Timeline

In December 2023, the SOLEIL II project received the first part of its funding. The project is divided into 2 phases of 5 years each: a "construction phase" (accelerator upgrade and upgrade of the first 10 BLs) starting in 2025 followed by a "Towards full performance" phase (upgrade of the remaining 19 BLs). The 12-month dark period is expected to precede the commissioning of the new storage ring in January 2030 with a photon beam distributed to the 29 BLs in October 2030. During the second year Technical Design Report (TDR), significant progress has been made in many technical areas, where potential bottlenecks and technical challenges continue to be thoroughly identified and addressed with appropriate R&D resources. The end of the TDR phase should result in mechanically integrable accelerators with detailed specifications ready for tender.

Towards New Injectors

To achieve high injection efficiency, a new 5 nm rad low-emittance full-energy booster is required along with an early upgrade of the LINAC energy (110 to 150 MeV for this later, schedule in 2026). The booster lattice uses a compact and unique 16BA HOA structure embedded in the same 157 m tunnel as today. Mechanical integration with all the necessary technical systems such as vacuum components and magnets has already started. The first collective effect simulations including the ion effects and the resistive wall during the energy ramp of the booster and advanced robustness studies are ongoing, and equipment specifications are being finalized [8–12].

Ultra-Low Emittance Storage Ring

The storage ring has an ultra-low emittance of 85 pm rad, compared to the current 4000 pm rad. The magnet arrangement for the new storage ring is based on an interleaving of 7BA and 4BA cells, providing 22 straight sections, 19 of which house beamline insertion devices (IDs). The critical phase of mechanical integration of all elements of the storage ring is underway. Minor modifications are being made based on the results of the magnet prototype, the available space for necessary equipment (such as vacuum equipment, bellows, and diagnostics), and the potential for magnetic crosstalk due to the proximity of the magnets (50 mm). Additionally, photon extraction is being improved with a focus on the dipole crotch absorber and reducing low energy ID radiation power in the straight sections, which require changes to the geometry of certain magnets. The storage ring performance is maintained at each step by continuously adapting and re-optimizing the lattice using a multi-objective genetic algorithm [13–16].

Progress Report: Selected Highlights

Vacuum Chambers and Additive Manufacturing The storage ring will use vacuum chambers with a low diameter

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of 12 mm made of CuCrZr material in the arcs, which will be 16 m long in a 7BA arc. The chambers will have an extending 0.5 µm NEG (Non-Evaporable Getter) coating to ensure efficient distributed pumping and an antechamber to extract the photon beams. To demonstrate the technical feasibility and pumping performance, two "Innovative contracts" have been signed with SAES Group and FMB Berlin to validate the proof-of-concept of the high-stake arc chamber. Additive manufacturing is also being tested for elements with complex geometry, such as dipole photon absorbers (Fig. 2). Their site acceptance testing is ongoing.

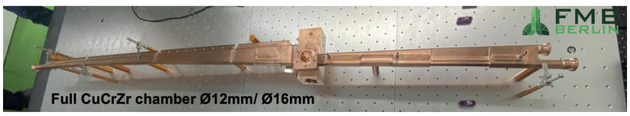

Figure 2: Prototype of a segment of the arc vessel (electron beam welded, diameter 12 and 16 mm) manufactured by FMB Berlin with its NEG coating TiZrV 0.5 µm.

Permanent Magnets and Electromagnets The storage ring contains a high density of magnets with 67 magnets along a single 7BA arc. Due to their strong fields and the need for low higher order magnetic content, experimental validation of their design is necessary. The SigmaPhi company manufactured a sextupole prototype of 8200 T m^{-2} (Fig. 3), which will be integrated into the lattice along with more than 412 sextupoles, each with extra coils for dedicated orbit correction. Additionally, a second prototype of the permanent magnet-based quadrupole (110 T m^{-1}) was produced by the Precis-Fil at the end of 2023. These magnets will be magnetically characterized in-house. A prototype for a short and a long permanent magnet dipole has been launched, while the mechanical design of an octupole is in progress [17].

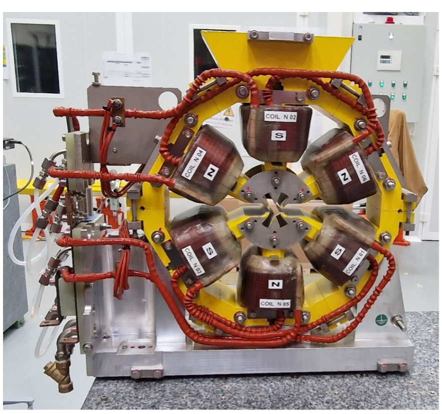

Figure 3: Prototype of a sextupole for the SOLEIL II storage ring produced by the French company SigmaPhi. The six main poles are marked with North and South polarities. Additional coils power horizontal and vertical correctors primarily used for the closed orbit correction.

Power supplies The number of precision power supplies for the SR exceeds 1,500 requiring high reliability (1.7 Mh of mean time between failures). For most of them, the FGC control and regulation platform from CERN was selected [18, 19]. The performance of the dedicated in-house developed electronic power board, which provides 20 A for bipolar power supplies and air-conditioning racks, is currently being evaluated [20].

Diagnostics A call for tender for the beam position monitor electronic will be issued in 2024. Its goal is to replace the current obsolete electronic with a new one that is fully compatible with the new storage ring and provides stability close to 50 nm RMS. Prototypes of the new conical capacity BPM button are being manufactured by SOLCERA and PMB [21]. Metrology and testing were performed in-house before the final beam testing in the storage ring. In addition, a new global synchronization for both the SOLEIL and SOLEIL II facilities is being studied. Finally, new imaging systems (pinhole type, polarization-based) are being designed to pre-test the tiny beam sizes of the upgrade in the current ring [22].

RF Systems The main RF system of the storage ring will be based on four Cu-cavity ESRF-EBS type 352 MHz normal conducting cavities [23]. A tender will be launched in 2024 and the validation performance and beam conditioning of two cavities will be performed in the storage ring before the dark period. A harmonic bunch-lengthening RF system will also be mandatory to ensure design transverse emittance and a long enough electron beam lifetime in all operation modes. The design and testing of the fourth harmonic system will be part of a close collaboration with ESRF. A new 352 MHz digital LLRF using a microTCA platform has been tested on one of SOLEIL cavities with stored beam demonstrating in close loop, an accuracy of 3×10^{-4} in amplitude and 0.024 deg RMS in phase. The SSPA amplifier upgrade continues at a rate of a tower per shutdown [24] (transistor power to 315 W, LDMOS LR301 from POLYFET).

Photon Sources Significant progress has been made on the photon sources, in particular with the first portfolio of insertion devices for the 19 ID-based beamlines for phases 1 and 2 of SOLEIL II. The unique spectrum of SOLEIL covers an energy range from IR, UV, and soft to hard X-rays. Innovative solutions are being developed to exploit the small emittance and coherence rate provided by the electron beam. For beamlines that use two-photon sources, a dual technology is under test to allow lateral switching between IDs. Another solution is the use of the innovative bi-period undulator whose prototype (50/150 mm) was installed under the beam in early 2024 to validate both the electron and photon performance [25, 26]. For the spectral range 5-40 eV a new 5-meter long APU250, under mechanical design, will be installed from day one.

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