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SOLEIL II PROJECT: ENTRANCE IN THE CONSTRUCTION PHASE

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Abstract

SOLEIL II is the French upgrade project to build the science of tomorrow with synchrotron light radiation. Providing the highest brightness in its class while maintaining the radiation range from IR to hard X-rays, the project is an ambitious triple upgrade of the SOLEIL facility: accelerators (new Booster and Storage Ring), 29 beamlines (BLs) and 3 laboratories, and an information technology transformation plan. Higher-Order Achromat based on multi-bend achromat lattices will be used to replace both the Storage Ring (SR) and the Booster Ring (BR) of the Synchrotron SOLEIL. The achieved equilibrium emittance of the SR (below 100 pm rad, 354 m, 2.75 GeV) is about 50 times smaller than that of the existing Storage Ring (4000 pm rad). To ensure technical feasibility, an intensive R&D phase based on extensive numerical simulations, prototyping, and measurements has been carried out. This paper presents the latest status of the project, the updated timeline, and describes the main results obtained so far in terms of performance and the prototypes launched in many technical domains (lattice, magnets, insertion device, vacuum, alignment, etc.).

SOLEIL II PROJECT

Synchrotron SOLEIL [1], in operation since 2006, is undergoing a major transformation into a fourth-generation light source through the SOLEIL II upgrade project [2–4]. This upgrade will reduce the emittance by a factor of 50, resulting in a 100-fold increase in both coherent flux and brightness. The upgrade will enable experiments at the diffraction limit in the soft X-ray regime, while preserving SOLEIL broad spectral coverage from the infrared (IR) to hard X-rays. In parallel, the project involves a comprehensive modernization of beamlines, laboratories, and the digital infrastructure [5], positioning SOLEIL to meet national and European scientific priorities and contribute to long-term sustainability goals.

To mark the transition into the construction phase of the SOLEIL II project, an event titled "A Step Forward Toward SOLEIL II" was held on March 14, 2025, at the SOLEIL facility. The event was attended by the Minister of "Enseignement Supérieur et de la Recherche", the President and CEO of the CNRS, and the High Commissioner of the CEA.

The SOLEIL II Project is structured into 4 programs: (1) Accelerators construction, (2) Relocation and adaptation of beamlines, (3) Overhaul of the information system, (4) Infrastructures and logistics; and divided into two main phases:

- **Phase 1 (2025–2030)**: Shutdown and dismantling of the existing SR and BR, commissioning of the new AR and BR, restart of 7-10 modernized BLs + 19 current BLs, IT infrastructure, modernization of support laboratories, R&D program on instrumentation.
- **Phase 2 (2031–2035)**: Accelerators performance optimization, complete modernization of 19 beamlines and support laboratories including IT infrastructure, Instrumentation R&D program.

The dark period, restart phase, and expert user commissioning period must be completed within 24 months to ensure a full restart of user operations by October 2030.

INJECTOR UPGRADE

To achieve high injection efficiency into the SOLEIL II storage ring, a new low-emittance Booster (5 nm rad) will be built. The Booster adopts a 16BA higher-order achromat lattice, reducing the emittance to 5 nm rad at 2.75 GeV. Emittance exchange using a pulsed skew quadrupole is also included in the project [6]. Substantial progress has been achieved on the Booster lattice, with realistic machine modeling accounting for alignment errors, multipole content, hard-edge field representations, eddy current effects, and power supply tracking errors [7]. The lattice demonstrates robustness to installation errors, and no showstoppers have been identified with respect to collective effects [8, 9]. In parallel, the impedance budget is being consolidated using finalized components, particularly within the straight sections. The first calls for tenders for the Booster are expected to start at the end of 2026. The TL2 transfer line beam dynamics study and mechanical integration are also nearing completion. Moreover a upgrade of the LINAC from 110 MeV to 150 MeV is required (see details in [10]) for a high injection efficiency into the BR.

LATEST STORAGE RING DEVELOPMENT

Stabilized V3631 Lattice

The new 354 m circumference Storage Ring is based on a hybrid MBA lattice: 12 seven-bend achromats (7BA) and 8 four-bend achromats (4BA). It delivers a natural horizontal emittance of 84 pm rad, and 53 pm rad with full coupling [11, 12]. The lattice was stabilized in March 2025 and emphasizes compactness, energy efficiency, and alignment practicability (see Table 1). Straight sections of varying lengths (3.2 m to 8.1 m) with low-beta functions of 1.4 m (1.7 m for both planes) in short (medium) straight sections supporting advanced insertion devices and canted layouts.

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A realistic model of the physical aperture has been implemented for both arcs and straight sections, incorporating updated photon absorber geometries. The lattice redesign has also led to the relocation of 20 beam position monitors (BPMs) and a reduction in the total number of quadrupole correctors. Mechanical integration has progressed significantly, particularly in evaluating the feasibility of photon extraction paths. In parallel, practical source point configurations have been comprehensively studied for the DESIRS and MARS beamlines. The stabilized V3631 lattice presents similar performance in terms of beam dynamics and collective effects [13–17] compared to the previous version, while ensuring compatibility with the initial commissioning scenario (first beam, stored beam, and stacked beam). Robustness has been confirmed through dedicated performance and error studies [18]. Additionally, the lattice offers sufficient tunability to support both early commissioning phases and long-term operational flexibility.

Table 1: Present and SOLEIL II V3631 Lattice Parameters

Parameter [unit]	Present	V3631
H-Emittance [nm rad]	3.9	0.085
Circumference [m]	354.10	353.98
Straight sections [–]	24	20
Long straight length [m]	12.00	8.05 / 2×3.9
Medium straight length [m]	7.00	3.79 / 4.26
Short straight length [m]	3.80	3.19
Straight length ratio [%]	46	25
Betatron tunes H/V [–]	18.16 / 10.2	54.2 / 18.3
Momentum comp. factor [–]	4.18e-4	1.07e-4
RMS energy spread [%]	0.102	0.089
Energy loss/turn (no IDs) [keV]	917	462
Damping times s/x/z [ms]	3.3 / 3.3 / 6.6	7.9 / 14.0 / 11.8
RMS bunch length [ps]	15.2	8.7
RF voltage [MV]	2.8	1.7

Complementary simulation studies were conducted to assess collimation [19] and radiation protection aspects in the context of the V3631 lattice. All major categories of beam losses were evaluated using conservative assumptions regarding injection efficiency, vacuum quality, and operational conditions. No significant differences were observed compared to previous lattice versions, confirming the current strategy: No lattice redesign or arc collimators are required.

From a radiation protection perspective, the target of maintaining an average dose rate below 0.5 μSv h^{-1}—previously validated with the V3588 lattice—remains achievable with V3631, even under pessimistic loss scenarios. This is expected to improve further with the enhanced beam lifetime provided by the harmonic cavities. Additional margin can also be obtained through localized shielding at key positions. These elements support compliance with ASNR [20] requirements for the beam operation license.

With regard to magnet exposure, FLUKA simulations under pessimistic beam loss conditions indicate that the neutron fluence remains at least one order of magnitude below the damage threshold for Sm_2Co_{17} permanent magnets. Experimental irradiation tests performed at the CHARM facility of CERN [21] confirm the absence of measurable degradation in magnetic field strength at such fluence levels.

ACCELERATORS SYSTEMS

Magnetic Systems

The magnet design for the V3631 lattice is nearing completion [22]. Key features include new three-part and monoblock dipoles, a reduced number of permanent magnet quadrupole families, low-saturated sextupoles, and the use of magnet doublets (octupole/quad. corrector-sextupole). All technical aspects have been addressed. A fast corrector magnet was ordered from Sigmaphi on January 25, based on a SOLEIL pre-design. The system is specified for a deflection of 30 μrad, with a 15 kHz bandwidth and a phase error below 3.6° at 1 kHz.

Vacuum and Mechanical Engineering Systems

Standard 7BA and 4BA achromat chambers are nearing final geometry, with a new curved chamber—without a keyhole and using a simple bent sector (see Fig. 1). A second prototyping with FMB company serves as a pilot run: chamber profiles are finalized, including an integrated BPM block and fabrication is ongoing, with delivery expected by end of 2025. Pressure profiles have been simulated for a full 7BA achromat; The influence of undulators on pressure will be assessed next. Tendering for standard vacuum components is progressing: RF-shielded sector valves are underway, pumps and gauges are scheduled for June 2025, and achromat chambers and BPM/bellows blocks may follow by year-end. To address front-end high-power constraints, absorbers and shutters will be upgraded to meet increased power and power density demands.

Over the last year, several technical developments have progressed significantly. Although 3D-printed crotch absorbers have been abandoned for the main arc vacuum chamber, the technology remains promising for applications involving high-density heat loads in constrained spaces. Collaboration between the Vacuum and Mechanical Engineering groups has improved, leading to a streamlined design workflow: CAD → SynRad+ → ANSYS simulation → validation. The design of the short dipole curved vessel is nearing completion, with no major technical obstacles encountered during the implementation of the stabilized lattice.

Diagnostics Systems

The orbit feedback architecture for SOLEIL II is designed around a centralized platform capable of processing high-rate data streams—from 10 kHz to 100 kHz—with low latency (<50 μs) [23] from all BPMs and XBPMs. This unified system is now engineered to control both fast correctors in the straight sections and the slower correctors embedded in sextupoles. Communication with fast corrector controllers (PandaBox) is validated through dedicated point-to-point 1 Gbit s^{-1} Ethernet links, achieving a frame propagation time

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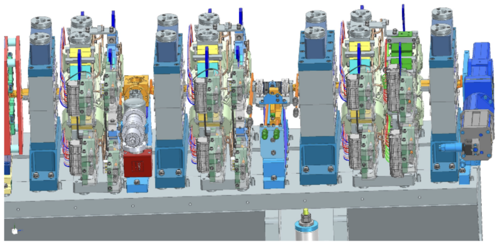

Figure 1: Mechanical integration: Downstream Matching Cell-18 equipment with sector CCRF valve at the entrance of the straight section. Magnet density is high and reach typically 113 magnet functions and 11 BPMs for a 7BA cell.

of 3.5 µs for 100 correctors, and a combined controller and DAC latency of 4.16 µs for a 0.7 % full-scale step.

Development and production of the BPM electronics are progressing on schedule, supported by extensive machine validation tests on BPM buttons [24], XBPM prototypes, pinhole assemblies, and the communication interface with the orbit feedback system. A new procurement contract has been signed for the supply of 220 Libera Brilliance Plus BPM modules from Instrumentation Technologies. As part of the installation phase, a BPM test vacuum chamber was installed on the Storage Ring in January 2025.

In parallel, a novel XBPM prototype using metallized diamond blades operating in photo-conduction mode is under development to improve performance in planar insertion devices. This design includes a front blade filter that attenuates low-energy radiation from upstream bending magnets. While traditional XBPMs with W/Cu blades have proven reliable in bending magnets and planar undulators, they remain ineffective for helical undulators due to their non-Gaussian and variable transverse beam profiles. An alternative solution based on SiC blades, developed in collaboration with SensiC (Switzerland), is also under investigation. SiC offers similar filtering properties and functions as a semiconductor, making it suitable for photo-conductive applications. A first batch of SiC blades was delivered to SOLEIL in April 2025, with initial testing scheduled on a laboratory X-ray source during summer 2025.

RF Systems

A contract was signed with the company RI at the end of 2024 for the manufacturing of five 352 MHz HOM-damped cavities, along with two spare sets of HOM dampers. Delivery is planned in two phases: the first two cavities are expected by June 2026 and will be conditioned in the upgraded RF test bunker before the end of that year. They will subsequently be installed on the current SOLEIL Storage Ring in 2027, where they will operate until the start of the dark period, providing valuable operational feedback and helping to reduce commissioning time for SOLEIL II.

In parallel, a collaboration agreement with CERN is under review for the fabrication of 300 kW continuous-wave fundamental power couplers, based on the APS design. Power testing at APS is scheduled for July 2025. Starting in mid-2026, SOLEIL's RF test infrastructure will be used to condition key components for SOLEIL II, including five 352 MHz HOM-damped cavities, seven corresponding power couplers, one 352 MHz five-cell LEP-type cavity for the booster, and three 1.41 GHz harmonic cavities [25].

The digital low-level RF front-end is under development, and a fast interlock system prototype is under test. Full system validation on the booster RF plants is planned before the end of 2026. The 4th harmonic cavity design, developed in close collaboration with ESRF, has been finalized, with the call for tenders scheduled for June 2025.

Source Points

In the context of IR photon extraction for the AILES and SMIS beamlines, a slotted, retractable mirror is positioned 40 mm–50 mm before the dipole exit, optimized for 10 µm, 100 µm, and 1000 µm wavelengths. The mirror is horizontally retractable (X-axis) and fully adjustable, with its edge placed approximately 4.5 mm from the electron beam axis. It is tilted outward by 18° to facilitate IR photon extraction. The collected solid angle is approximately 40 mrad (H) × 30 mrad (V). The upstream dipole emits photons with a cutoff frequency around 1 THz, due to the 12 mm vacuum chamber diameter. To refine the flux estimation, SRW simulations are underway using a near-field approach that incorporates chamber geometry.

The ID portfolio has been revised to reflect updated priorities. High priority is given to the APU250 undulator for the DESIRS BL, scheduled for 2028; a new DUAL undulator for the CASSIOPEE BL in 2030; and a phase-2 APPLE-X undulator for the SEXTANTS BL, expected in early 2031. In parallel, Phase 1 includes a complete refurbishment of all in-vacuum undulators. Additionally, up to four beamlines will be upgraded using existing EPU devices in DUAL configurations, with implementation planned by 2030.

CONCLUSION

The SOLEIL II project has now officially entered the construction phase, a major milestone in the upgrade of the facility into a fourth-generation synchrotron light source. The injector design and the Storage Ring are being finalized, and key technical systems are undergoing detailed engineering reviews. The upcoming period will be characterized by an intense phase of procurement, including calls for tender for major components such as magnets, girders, vacuum chambers, and power supplies. This stage is crucial for maintaining the project timeline and enabling a full restart of user operations by October 2030, as planned. The project continues to build on the expertise developed over nearly two decades of operation, with the ambition to position SOLEIL II at the forefront of synchrotron science in Europe.

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