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SOLEIL MACHINE STATUS: OPERATION AND UPGRADE PROJECT

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Abstract

The synchrotron SOLEIL is both a 2.75 GeV third-generation synchrotron light source and a research laboratory at the forefront of experimental techniques dedicated to matter analysis down to the atomic scale, as well as a service platform open to all scientific and industrial communities. We present the performance of the accelerators delivering extremely stable photon beams to 29 beamlines. The beam delivery schedule and operation have been affected by the energy crisis. Shortages of cryogenic fluids and electronic components, coupled with high inflation, are impacting the operation budget and related projects. The update on the construction of the new low-energy footprint cooling station is presented. Finally, new developments and testing of prototype equipment related to the upgrade of the injector complex and the main storage ring are discussed.

SOLEIL PERFORMANCE

SOLEIL is the French 3rd generation light synchrotron source that has been providing highly stable brilliant photon beams to external users since 2008 (Table 1, [1]). Its injector complex relies on a 110 MeV linac and a full energy 3 Hz booster ring. In 2022, 5001 photon beam hours were scheduled for the users of the 29 beamlines (BLs). The beam performance was a record with a beam availability of 98.95% and a mean time between failures of 139 hours (Fig. 1). Four filling patterns were delivered: uniform (500 mA), hybrid (445 + 5 mA), 8 bunch (100 mA) and single bunch (16 mA) with a FWHM bunch length of (98 ps) doubled for the two timing modes. The facility performed very well with 27 out of 34 weeks showing a beam availability above 99% and 13 reaching 100%. As an example, only 2h23 of the losses originated from the power supplies.

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	2.8	MV
RF Frequency	352.197	MHz
Harmonic Number	416	-

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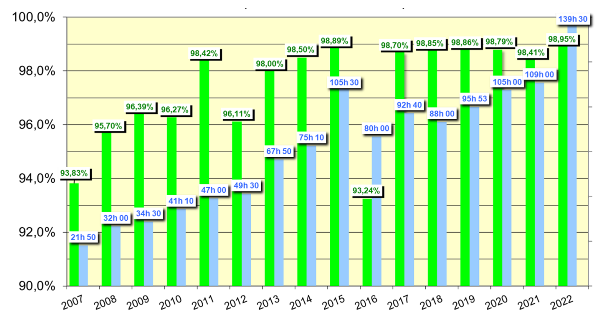

Figure 1: Beam availability (green) and mean time between failures (blue) over the years. In 2022, 4970 hours of high stability beam were delivered to the beamlines with a record beam availability of 98.95% and an MTBF of 139h30.

ENERGY SOBRIETY

In order to cope with the multiple crises affecting our various supply chains, in-depth work has been undertaken to make the SOLEIL facility more resilient to raw materials and energy supply tensions in a complex geopolitical context. The rationalization of the operation cost of the RF systems and of the injection complex is under progress with the aim of increasing the energy efficiency of the accelerators. For example, the RF power supply upgrade consists of replacing the existing Bruker's power supplies and DC/DC converters to address the obsolescence of this equipment and to achieve much higher efficiencies. Together with the ability to optimize the RF operating point by controlling the voltage, a reduction in power consumption of 22% (450 mA) and 25% (450 mA) can be achieved. Equipped with a 30% redundancy, these power supplies have high reliability (MTBF > 350 000 h) and are more robust against electric power drops. The first newly refurbished SSPA (Solid State Power Amplifier) tower was put into operation in the booster in March 2023. A second example is the Helium Gas (GHe) recovery system for the beamlines where a complete refurbishment (piping, intermediate storage, sensors, quality control, supervision) allowed to increase the recovery rate from 32% to 89% by the end of 2022 and to return a high purity GHe to the CEA for liquefaction (70% operation budget savings).

A new cooling station is under construction at SOLEIL. It should allow better reliability, greater flexibility in the management of technical stops, an expected gain in electrical energy of about 2 GWhs (20%), and a reduction of about 80% in the consumption of cooling water. The new T7 building, which will house the station, was handed over

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at the end of November 2022, according to the project schedule, despite a very tight execution schedule. With regard to the installation of the utilities and cabling, the cooling equipment such as adiabatic air coolers, chillers, and pumps are now fully installed. The High Voltage (HV) parts and the connection to the 20 kV loop are done. The underground gallery that will connect the T7 to our existing networks is 75% complete. A digital twin is being used to pre-validate the supervision of the technical machinery. The commissioning and testing periods are scheduled for September and October of this year, with the final connection to the synchrotron building expected in early 2024.

MAIN DEVELOPMENTS

An important step towards a transparent injection into the storage ring using a Multipole Injection Kicker (MIK) has been achieved as reported in Refs. [2, 3] with orbit disturbance less than 2 % of the RMS beam sizes. Better control of the radiation during beam losses when the beam is interlocked has been achieved: a versatile electronic board allows the beam to be dumped in a single turn in the injection overshielded straight section. A new diagnostic slit mirror for the visible light monitor beamline has been installed with a more efficient cooling system: the collected photon flux is increased by more than a factor of 2. It is now being used to commission innovative equipment such as the turn-by-turn Kalypso camera and a high-resolution beam size measurement using the vertical polarization in preparation for the SOLEIL II [4].

The fast-orbit feedback architecture will move from the present Electron Libera electronics to a dedicated flexible microTCA/CACTUS RTM board platform fully compliant with SOLEIL II [5]. A star topology with a central node and 4 cell nodes running on a 10 GbE fiber will be commissioned in the fall of 2023.

The LINAC accelerator is undergoing a multi-stage upgrade to address obsolescence issues and prepare for the SOLEIL II project. A spare buncher manufactured by THALES AVS will be installed at the beginning of 2024. A new Labview-based control was put into operation, with better communication with the TANGO control system. JEMA Energy will deliver next year the first SSPA-based modulator; this new redundant modulator will allow us to maintain the nominal beam energy instead of today's 66 MeV downgraded in case of a klystron failure. Then we aim to increase the LINAC energy and its transfer line to 150 MeV in late 2025 to facilitate the injection in the new low-emittance booster of SOLEIL II.

SOLEIL II PROGRESS

Introduction

The SOLEIL II project [6, 7] is currently in the second year of the Technical Design Report (TDR) phase and is awaiting the project budget from the funding national agencies. The project will be divided into two 5-year phases. The “Construction Phase” includes the realization of a major upgrade of the storage ring and the booster ring, the modification, and the adaptation of a group of beamlines and the related infrastructure. The "Towards Full Performance Phase” will allow the beamlines to take full advantage of the coherence and the low emittance electron beam thanks to the availability of the latest generations of insertion devices (IDs) and state-of-the-art new beamline components. The overall timeline has been shifted by one year with an 18-month dark period commencing in August 2028 and a storage ring commissioning around early 2030.

In 2022, a new reference TDR lattice was validated that guarantees the same performance in terms of photon brilliance but preserves the positions of the current source points of all the ID-based BLs [8, 9]. Due to the severe constraints of the ring geometry, the lattice is based on 20 cells using a combination of 7BA and 4BA Higher-Order Achromats (HOA). The achieved horizontal natural emittance is 84 pm rad at 2.75 GeV energy with 30% coupling as the baseline and round beam as the ultimate goal. The horizontal and vertical beta functions are as low as 1.5 m at the center of short and medium ID straight sections to enhance the matching between the electron and photon emittances. A uniform filling pattern with a 1 to 2-bunch gap symmetrically distributed between the 4 quarters to combat ions [10] will become the main mode of operation. A 32-bunch filling pattern is currently under consideration to meet the requirements of the experiments using the timing modes. The fundamental radiofrequency (RF) system uses 4 ESRF-type 352 MHz warm cavities. A harmonic bunch lengthening RF system will be also required; the choice of the harmonic system (passive/active/warm/cold) is still under intense consideration as it should allow compatibility with the different filling patterns and cope with the transient loading and the collective effect induced instabilities [11, 12]. Robustness studies have been progressing taking into account an updated error budget [13] and the latest lattice version. The tracking simulation incorporates refined magnetic models and the results of the first cross-talk simulations. Collimation studies have been initiated in collaboration with CEA/IRFU/DACM in order to define the number of collimators to safely collimate 80% of the particle losses during Touschek scattering and gas scattering without compromising the injection efficiency. A strategy for dumping the beam during a machine interlock or voluntarily will also be investigated shortly.

Injection Components

The injection system into the storage ring occupies a full 7.9 m straight section and is kept compatible with an off-axis betatron injection scheme [14]. A new generation in-vacuum MIK magnet will be the key component of the injection system generating a one-turn kick in the horizontal plane with a flat-top deflection maximized at −3.5 mm. The first prototype in D-topology showed good agreement between field measurements and three numerical calculation methods. A second version in MACOR allowed the obtention of the required voltage (16-18 mT for 6.5 kV/2 kA) and did not show any arcing. Initial thermal simulations give encouraging

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results and will be followed by tests in a real accelerator environment [14, 15]. To achieve high injection efficiency, a new low-emittance 5 nm rad full energy booster is required. Its lattice uses a 16BA HOA structure embedded in the same 157 m dedicated tunnel as today [16, 17]. Mechanical integration has started together with all technical systems (vacuum, magnet). First collective effect simulations including the ion effects and the resistive wall during the energy-ramp of the booster are presented in [18]. Advanced robustness studies have started together with the final specifications of the various equipment.

Storage Ring Subsystems

An intensive prototyping phase has been initiated in most technical areas to reduce any major risks to the project. The FGC controler [19] should be adopted as a standard for most of the SOLEIL II power supplies. Tests for powering the current correctors of the storage ring are underway and have already shown enhanced performance in terms of stability and synchronization. The performance of the dedicated electronics power board 20 A for bipolar power supplies [20] and air-conditioning racks are under evaluation.

Magnet design has advanced significantly: prototypes of a long permanent magnet-based dipole, a sextupole ($8200\,\mathrm{T\,m^{-2}}$), and a second permanent magnet-based quadrupole ($110\,\mathrm{T\,m^{-1}}$) are expected in 2023. Magnetic cross-talks between neighboring magnets are carefully evaluated and integrated into beam dynamics models. The budget of the correctors has been revised according to the latest lattice robustness results.

The very small diameter of the vacuum chambers (12 mm) in the arcs, the choice of ex-situ backing-out, the use of 0.5 µm NEG (Non-Evaporable Getter) in most of the circumference and the choice of a 16 m long arc vacuum vessel represent several challenges for the SOLEIL II vacuum system. Photon Stimulated Desorption (PSD) yield measurements from a bending magnet were performed on a dedicated front-end of the current storage ring using NEG-coated vacuum chambers with diameters ranging from 63 to 10 mm to evaluate the balance between pumping and photodesorption with a NEG-coated chamber of a small diameter. No downscaling problem was observed for chamber sizes down to 10 mm in diameter with standard 1 µm TiZrV NEG coating. Two innovative markets have been signed with SAES Group and FMB Berlin to validate the proof-of-concept of the high-stake arc chamber with an antechamber to evaluate any showstoppers for vessel fabrication and NEG deposition in complex geometry. Photon extraction is also in progress with special attention to the dipole crotch absorber and the low energy ID radiation in the straight sections. This work includes the position interlock with typical 500 µm thresholds.

The ID portfolio has been identified for most beamlines. In order to cover UV-soft X-ray polarized photon energy requirements, an R&D program is focused on two new types of undulator systems. One solution consists of a dual undulator equipped with a mechanical system allowing the users to switch from one undulator to the other by means of lateral displacement; a mobile platform for the dual ID has been built consisting of a test bench using an existing carriage; the first mechanical and metrology measurements have started. Another solution is based on an innovative bi-periodic undulator (patent pending) that operates with two different periods on the same mechanical chassis. A prototype undulator has been constructed, the magnetic measurements are in progress, and the ID should be tested in 2024 in the storage ring in terms of electron beam dynamic effect and photon spectrum [21]. An Apple-X undulator is also being considered for very specific BLs. Moreover, ongoing efforts are being made to automate the permanent magnet measurements and the undulator assembly. The use of robotics to carry out measurements and magnetic and mechanical corrections of the magnet modules of a magnetic insertion is underway: a Staubli robot is used for the automation of the magnetic test bench for the permanent magnets of the undulators: it includes laser sensors, precise mechanical control, adjustment with a screwdriver of the magnetic field measured with a Hall probe.

The number of storage ring girders has been reduced from 284 to 86 and a prototype is being built. Experimental measurement of the main vibration mode (first theoretical eigenmode: 49 Hz and the transfer function of the girder equipped with decoy magnets will be performed by the end of 2023.

The high sensitivity of the very compact SOLEIL II lattice led us to evaluate new techniques for magnet alignment. A combination of magnetic measurements using the vibrating wire and the pulsed wire is being considered. In addition, to increase the correlation of the alignment of the magnetic centers of the strong sextupoles and the adjacent permanent magnets, the alignment of a block of magnets within ±10 µm is being experimentally evaluated.

In terms of logistics and storage space, a large amount of space (at least $8500\,\mathrm{m^2}$) is required to store, assemble and test components for the accelerators and beamlines. Some of this will be provided on-site, but there is not enough space for all of the requirements, so, some off-site storage will be needed (girder storage). A considerable amount of space is required for the dismantled components of the SOLEIL storage ring and booster. They have to be stored and measured on-site in accordance with French radiation safety regulations. In order to keep the SOLEIL II dark time as short as possible, the pre-assemblies of the new storage ring and booster must be available before the dark time.

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