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SOLEIL MACHINE STATUS AND UPGRADE

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Abstract

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. We report on the commissioning of a superbend magnet replacing a standard 1.71 T dipole with a 2.84 T narrow peak permanent magnet-based dipole. It required local modification of the lattice to compensate linear and nonlinear optics distortions introduced by the new magnet field. The latest measurements made with a Multipole Injection Kicker are also reported. Work on the NEG test bench and its dedicated front-end for a 10 mm inner diameter vacuum pipe and other major R&D areas are also addressed in the frame of the SOLEIL upgrade.

ACCELERATOR PERFORMANCE

Since January 2008, the synchrotron SOLEIL [1, 2] has been providing external users with high stability, high flux and high brightness photon beams. Among the 29 beamlines (BLs), 20 are on insertion devices (IDs), 9 on bending magnets including 2 IR beamlines: 27 diverse IDs are daily operated (gap/phase) by the users (2 in-vacuum in-vacuum cryogenic permanent magnet undulators (CPMUs), 6 in-vacuum undulators (IVUs), 13 Apple-II type undulators, 4 electromagnetics IDs, and 2 wigglers). The overall facility has been performing at a high level during the year 2021: 4935 hours (including 32 h of radiation safety tests) with a beam availability of 98.4 % and a record meantime between failure (MTBF) of 109 hours. All five operation modes were delivered in top-up mode of injection (availability: 99.7 %; MTBF: 25h) keeping the current within ±0.5% of its nominal value for the uniform and hybrid mode with a distribution given by Fig. 1. The year 2021 showed a significant increase of machine dedicated time (1431 h) to commission several innovative systems as described in the following section.

MAIN ACHIEVEMENTS

Lattice Modification for the ROCK BL Superbend

The storage ring (SR) lattice features a one-fold symmetry based on a modified double-bend achromat structure [3] allowing the space for 24 straight sections (see Table 1). One of the long straight sections, SDL13, hosts two canted

Table 1: Storage Ring Main Parameters

Parameters	Values
Energy	2.75 GeV
Circumference	354.097 m
Natural chromaticities (H/V)	-53/-19
Natural Emittance	4.0 nm · rad
Number of Cells/Symmetry	16/1
Tunes (H/V)	18.155 / 10.229
RF frequency (harmonic number)	352.197 MHz (416)
Total RF Voltage	2.8 MV

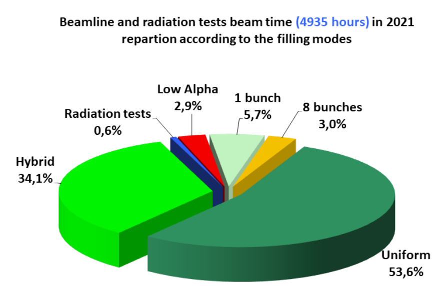

Figure 1: Filling pattern distribution during the year 2021.

BLs accommodating a double beta waist in the vertical plane for the simultaneous closure of the two 2 m long CPMUs at 5.5 mm minimum gap [4, 5].

Since August 2021, another major modification of the lattice has been introduced: the nominal 1.71 T dipole source of the ROCK beamline was replaced with a superbend, an permanent magnet 2.84 T dipole developed in-house (Fig. 2). A full week was necessary to complete its commissioning and the campaign of radiation safety test in order to qualify the storage ring and all beamlines with the superbend. The first photon beam was recorded by the ROCK beamline on August 27, 2021; two days later a flux increase by a factor 7.4 was measured at a photon energy of 40 keV as predicted. The additional focusing of the superbend was locally compensated using LOCO [6] and the strong chromatic contribution of the high field sextupolar component was first corrected globally before further MOGA-based [7] sextupole optimization enabling to recover most of the dynamic aperture and then a better injection rate. The latest performance results in an average total beam lifetime of 12 hours at 500 mA with an injection efficiency closed to 86 % for the bare lattice.

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Additional losses are produced at the location of the ROCK squeezed vacuum chamber aperture and scrapers have been slightly further closed to concentrate the residual losses in the over-shielded injection area.

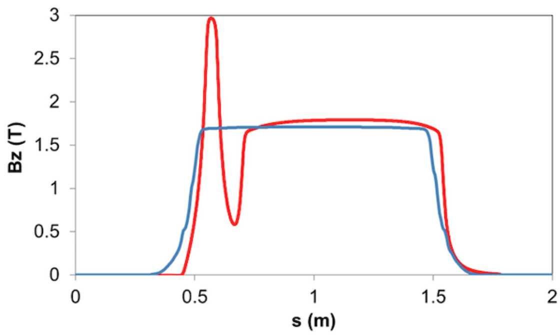

Figure 2: Longitudinal magnetic field profile of the superbend (red) and nominal dipole (blue).

Towards Transparent Injection

Since January 2021, a new R&D pulsed magnet is installed in the storage ring: the Multipole Injection Kicker (MIK) is the key element both for compact injection and for reducing the residual closed orbit oscillations observed by some beamlines each time the electron beam is injected during top-up (typically every 2 to 3 min in uniform filling pattern). Its commissioning is described in [8] and the latest results to quasi-transparent injection in [9]. The MIK device kicks the injected beam by 2.2 mrad at an amplitude of 10.3 mm from the stored beam in the horizontal plane without producing any magnetic field on the trajectory of the latter. Fine beam-based alignment resulted in a reduction of the stored beam disturbances from 30 % less than 2 % of the horizontal beam size. The residual magnetic field defect in the vertical plane was thoroughly analyzed and an active correction was designed using a single-turn pulsed corrector located in the injection section. The experimental measurement of disturbance of the stored beam is reduced from 250 % of the vertical beamsize with the nominal four-kicker injection to the limit of detection using new turn-by-turn high performance diagnostics [10]. The injection with the MIK device makes the injection almost completely transparent with improved injection efficiency due to the lower requirement in term of dynamic aperture. Heating-up observations of the MIK device and comparisons with simulations are presented in [11].

Utility Upgrade

The main PLC controlling the aging cooling station supplying the fluids for the accelerators and beamlines was replaced during last October shutdown, pending the construction of a new cooling station. This latter is funded by the French economic recovery plan: all call-for-tenders were issued in December 2021 and the civil engineering work of the new T7 host building started early 2022 and will continue until the end of this year before the installation of the cooling pipes and its machinery the next year. The new station will be fully compatible with the upgrade project of the accelerators and beamlines. Its environmentally friendly design will save 50 % of the electricity consumption and 80 % of the tap water consumption. Connection to the synchrotron building is planned for mid-2024, during a dedicated shutdown. The construction work activity is carefully monitored in term of induced mechanical vibrations and potential impact on the photon beam stability.

Other Improvements

The MRSV (Visible Synchrotron Light Monitor) beamline was upgraded in January 2021 with a new extraction slit mirror equipment and a more efficient cooling system: the collected photon flux is increased by more than a factor of 2. This diagnostic beamline is now being used to commission innovative equipment like the turn-by-turn Kalypso Camera [10] and high resolution beamsize measurement using polarization in preparation for the SOLEIL Upgrade. Efforts are also being made to reduce the facility energy footprint. Following the upgrade of 3000 modules of the RF system solid state amplifiers (SSA), which increased efficiency from 48 % to 55 %, the multi-year renewal of SSA power supplies has begun: an expected efficiency increase will lead to an annual reduction in consumption of up to 1.75 GW h. Faced with the obsolescence of the Libera-Electron BPM electronis, the chosen strategy [12] consists first of all in modernizing the fast orbit feedback system (FOFB) presently embedded in the BPM electronics. The selected platform is based on micro-TCA technology which will comply with the SOLEIL Upgrade requirements with lower latency time aiming at a DC–1 kHz correction bandwidth. Its commissioning is expected late spring 2023. The BPM electronics will then be upgraded in a time frame of two years before the upgrade dark period.

UPGRADE PROGRESS REPORT

The SOLEIL Upgrade project is currently in the Technical Design Report Phase (TDR). The project [13–15] is divided into 2 phases of 5 years each for accelerators, beamlines and related infrastructure, 20 years after the facility was open to users, keeping SOLEIL competitive and complementary with the ESRF-EBS. The new reference lattice features a 84 pm · rad natural emittance with 30% coupling using white noise excitation. The lattice provides 100 times brighter beams, and adapted beamlines keeping the broad energy range of the present SOLEIL, from THz to hard X-rays. In phase 1, priority is given to 6 beamlines needed to be relocated (2 IR, 1 UV, 2 soft X-ray BLs, 1 tender X-ray BL) and flagship BLs benefiting fully from the small emittance. The other BLs will get upgraded in the second phase only. If funding were received early 2024, the dark period could begin in August 2027 for 18 months. After a commissioning period of 6 months, high brightness and coherent photon beams will be available for all 29 beamlines by summer 2029.

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TDR Lattice

As described in [16], the unique 7BA-4BA lattice has been modified to fit the present IVUs by increasing the short straight sections to 3 meters while keeping the ring geometry compatible with the present shielding walls. All dipoles, reverse bends and quadrupoles are permanent magnets; lattice tunability was improved, first mechanical integration was achieved. The 20-cell ring presents a 2-fold symmetry. The MIK-based injection is housed in a single long straight section. The opposite section will host a 5-meter long undulator dedicated to produce low energy-photons. The other two long straight sections are equipped with a quadrupole triplet at their centers to generate a double vertical low-beta waist. One of them will accommodate two canted CMPUs of the present long high stability nano-beamlines. The combined long dipoles of the 7BA cells are divided in 3 parts to allow the central part to be replaced by a superbend for a limited number of BLs. The overall performance of the TDR lattice is reported in [16], robustness studies in [17].

Injection

The Top-up injection uses, as a key component, a miniaturized MIK device, where the beam is injected at 3.5 mm from the axis in the horizontal plane [18]. To achieve high injection efficiency a new full energy booster ring is required [19] (5.2 nm · rad, 25 ps RMS bunch for 3 MV, 14BA lattice). Injection efficiency of 100 % is not yet fully reached in the presence of all injection and multipole errors. Building the thick extraction injection septa in permanent magnet is being considered to drastically reduce the time jitter in the horizontal plane.

Operation Modes

500 mA in uniform filling pattern is considered as the primary mode of operation. Time resolved experiments will benefit from single bunch, and 8 symmetrically spaced bunches (possibly 16 or 32 under study). The hybrid mode was discarded since the transient beam loading in the harmonic cavities strongly degrades the beam performance. The short beam lifetime (2-3 hours) and the IBS (Intra Beam Scattering) effect make the use of a harmonic cavity mandatory. The main RF system is based on four ESRF-EBS normal conducting cavities. The harmonic RF-technology is being evaluated among passive superconducting, passive and active normal conducting systems. The stability limits of superconducting system is given in [20].

Magnets

A very large variety of magnets must be built: 41 types, 7 superbends with 3 T or 1.7 T magnetic field for a total number of 1296 magnets. Their design and prototyping are actively progressing. The final design of the 3-part dipole prototype will be launched as well as the second quadrupole prototype without correction coils. A 8200 T m^{-2} sextupole integrating dipolar correctors and a 100 000 T m^{-3} octupole with normal and skew quadrupole corrector capacity will be launched. The cross-talk between magnets (yoke-to-yoke distance 50 mm) and the photon beam extraction require careful evaluation due to the high compactness of the lattice.

Vacuum System

The minimum magnetic bore diameter of 16 mm allows a generic chamber to be defined with a 12 mm of inner diameter. Dipole vacuum vessels are critical to design with 1.945 kW to dissipate and a high power density (60 W mm^{-2}): the simple round tube with soldered/brazed cooling pipe version had to be discarded. For every achromat a generic chamber was designed based on copper alloy (Cu-OFS or CuCrZr) made of 3 parts: keyhole shape with antechamber (with a 3 mm gap between the 12 mm e-beam and the 16 mm photon-beam pipes), crotch absorber with standard pumping in direct copper. Additional thermo-mechanical simulations are underway to ensure that the temperature never exceed 40 °C for compatibility with the magnet thermo-shims. Impedance issues were considered at an early stage of the conception. Design of a specific RF-Gate Valve with VAT company which integrates a MO flange adapter [21] with a modified RF mechanism reduced to a 16 mm bore diameter. Wake fields and wake loss factors are simulated to choose the best mechanical candidate and optimized the NEG type and coating thickness. The proof-of-concept phase for high-stakes chambers has begun to evaluate any technical showstoppers with potential technical partners for vacuum chambers and absorbers. Consideration of resistive wake field and gas scattering lifetime led to the choice of a full distributed Ti-Zr-V NEG coating with an average thickness from 0.5 to 1 μm targeting an average pressure lower than 1×10^{-9} mbar at 500 mA to be reached for an integrated dose of 100 A h. In the framework of a collaboration with SAES Getter, Photon Stimulated Desorption (PSD) yields for 3 different 1 meter long-chambers with 63, 20, 10 mm diameters were studied and the yields were compared before and after activation of a standard NEG. No down-scaling issues were identified with standard 1 μm NEG coating. The sorption capacity in small diameter chambers is comparable to published data of standard chambers.

Undulators

As regards the IDs, most of them will be re-used at the restart of SOLEIL with minor technical changes for the existing IVUs. For the soft X-rays polarized photon beamlines, the choice between the 2 APPLE-II of the straight section or DUAL undulator is being considered. Construction of DESIRS undulator is considered as a priority since SOLEIL Upgrade cannot house the previous 10 m long ID HU640. A candidate could be a 5 meter long permanent magnet DELTA AP250 device providing photons from 5 to 40 eV with at least 95 % of linearly and circularly polarized photons. The other existing insertion devices will be gradually replaced by a new generation of CPMUs. Photon extraction for low-energy photon remains a challenge since the small diameter vacuum chambers intercept most of them.

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