ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOMS002

STATUS OF SIRIUS OPERATION

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Abstract

SIRIUS is a Synchrotron Light Source Facility based on a 3 GeV electron storage ring with 518 m circumference and 250 pm.rad emittance. The facility was built and is operated by the Brazilian Synchrotron Light Laboratory (LNLS), located in the CNPEM campus, in Campinas, Brazil. The accelerator commissioning and operation has been split into 2 phases: Phase0, corresponding to the initial accelerator commissioning with 6 beamlines, has been completed, and the project is now in preparation for Phase1, with full accelerator design performance and 14 beamlines in operation. We report on the status of SIRIUS last year operation and ongoing activities towards achieving completion of Phase1.

INTRODUCTION

SIRIUS is the new Brazilian synchrotron light source based on a 3 GeV electron storage ring, comprising a 20-cell 5BA magnetic lattice with 250 pm.rad emittance. It is one of the three 4th generation storage-ring-based light sources in operation worldwide. The new facility can house up to 40 beamlines based on insertion devices or low field (0.6 T) and high-field (3.2 T) bending magnets of the lattice, covering an energy range from infrared to hard x-rays.

The project commissioning is planned to take place in 2 Phases: Phase0 with 100 mA and 6 beamlines, and Phase1 with full accelerator performance at 350 mA in top-up mode, conclusion of 14 beamlines, high performance insertion devices, support labs, and computing infrastructure. Phase0 has been completed by the end of 2021 and the project is now preparing to complete Phase1 by mid 2024. All facility instruments were optimized for cutting-edge experiments in agriculture, environmental science, health, and energy experiments, spanning diverse scientific programs strategic for Latin American science and technology.

In this report, we present the SIRIUS current operation status, and the preparation for achieving Phase1 parameters.

PRESENT PERFORMANCE

Presently, the SIRIUS storage ring is operating regularly, delivering beam for users shifts, for machine studies and subsystem tests. In 2022, 3408 hours are scheduled for user's shifts, 1272 hours for machine studies and subsystem tests with beam, and 1944 hours for installations and maintenance with access to the accelerators tunnel. The remaining hours are shared between machine recovery from longer stops, special tests and shutdown period.

There are presently six beamlines in operation in science commissioning mode. Five beamlines are based on adjustable phase (APU) commissioning undulators, and one beamline is from a dipole source.

For user's shifts, the SIRIUS storage ring is running with 100 mA in current decay mode with 2 injections per day, in uniform filling pattern mode with 864 bunches.

The stored current is presently limited by the RF system, consisting of a 500 MHz room temperature Petra 7-cell RF cavity, without HOM dampers, driven by 2x65 kW solid state amplifier towers. This cavity is temporarily being used while the final system is not available. The stored current was achieved after a careful work of temperature tunning of the Petra7 cavity. The final RF system will comprise 2 superconducting 500 MHz cavities driven by total power of 8x65 kW, and a superconducting passive third harmonic cavity.

Figure 1 shows the machine reliability, defined as the delivered beam time to the experiments within programmed time, over the last 13 months. The overall reliability in this period is 94.7%. During this period, the mean time between failures (MTBF) was 38 hours and the mean time duration of each failure was about 2 hours. There were 23 beam interruptions, with a concentration in the beginning of 2021.

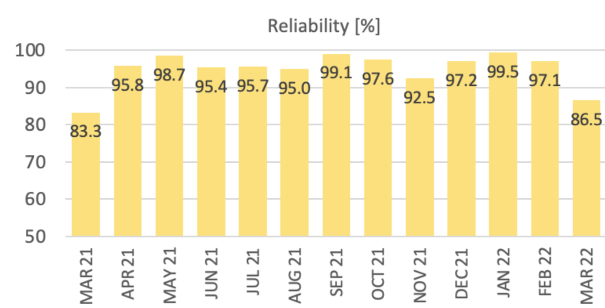

Figure 1: Machine reliability from March 2021 to March 2022.

The storage ring linear optics is close to design after correction using the LOCO algorithm applied to the machine with orbit corrected after calibration of BPM offsets with BBA. Presently, BBA and LOCO calibrations are routinely performed to check for machine conditions after maintenance periods. Optics symmetry is restored using both quadrupole family strength adjustments and individual quadrupole trim coil adjustments, as can be seen in Figure 2, where the measured betatron function at BPMs using the principal component analysis (PCA) in shown. The beta-beat at BPMs is corrected to 2.2% rms and 1.8% rms respectively, in the horizontal and vertical planes.

The measured beam lifetime at 100 mA is 17 h for 3% emittance ratio and for uniform filling. It is limited by the Touschek scattering effect. An experiment to measure the contribution of each effect to the total lifetime using 2

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single bunches in the machine, one with high and the other with low current, is described in Ref. [1].

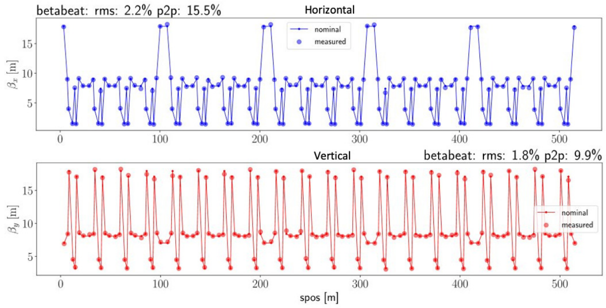

Figure 2: Measured betatron functions at BPMs after calibration of the linear optics with LOCO and of BPM offsets with BBA. Dots are measured values and lines are values from the nominal model.

Orbit Stability

The requirements for beam orbit stability for SIRIUS has been initially set as better than 10% of the rms beam size in all three coordinates. It is expected that tighter beam stability requirements will be possible to be met in the future, as perturbation sources are identified, and feedback systems are implemented and perfected.

Presently, orbit stability is provided by the slow orbit feedback system, with crossover frequency at 1 Hz. Other key stabilizing mechanisms, the fast orbit feedback system with 1 kHz crossover frequency, the local correction based on feedforward tables to compensate for reproduceable ID perturbations, and the top-up operation mode, that will guarantee an almost constant heat load at the beamlines, are being planned to be implemented during this year.

The orbit spectrum has been measured using BPM data acquired at 25 kHz sampling rate at 2 BPMs, one in a non-dispersive and the other in a dispersive region. The measurements show a higher perturbation peak at the mains frequency of 60 Hz for all cases. For BPMs in dispersive regions, there is an additional perturbation peak in the horizontal orbit around 1.5 kHz (synchrotron frequency) as shown in Figure 3. This peak is related to horizontal oscillations induced by energy oscillations excited by RF noise (around harmonics of 64 Hz).

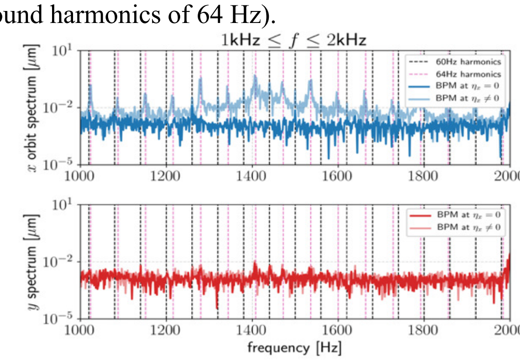

Figure 3: Horizontal (top) and vertical (bottom) orbit spectrum measured at 2 BPMs, one in a non-dispersive region (dark curve) and other in a dispersive region (light curve).

Figure 4 shows the integrated orbit spectrum measured at a non-dispersive location in the ring, where the contribution of the 60 Hz perturbation is evident. The source of this perturbation is being investigated, as reported in Ref. [2]. The measured values are compared to the requirement of 10% of the beam size.

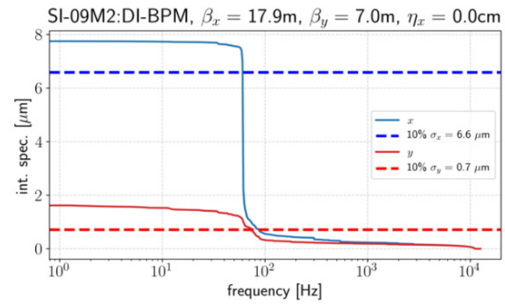

Figure 4: Integrated spectrum from BPM data acquired at 25 kHz sampling rate. The dashed lines represent the requirement of 10% of beam size.

Other main sources of perturbation under investigation are: (i) 24-hour period drifts measured at the most sensitive beamlines, correlated to daily temperature variation, (ii) 2 Hz perturbations associated with the booster ramping rate, and (iii) short term perturbations from the pulsed magnets, such as the septa leak field and nonlinear kicker residual field at the stored beam position (see Figure 5).

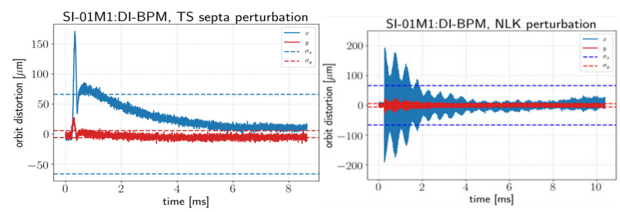

Figure 5: Stored beam orbit transient perturbation due to septa leak field (left) and nonlinear kicker (right). Dashed lines indicate one rms beam size.

Injector Optimization

The SIRIUS injector consists of a 150 MeV Linac and a 3 GeV full energy synchrotron booster installed in the same tunnel as the storage ring. The booster lattice has been optimized for low emittance (3.5 nm.rad @ 3 GeV) and resulted in a small value for the momentum compaction factor (α_c=7.2x10^{-4}). At design stage, we have overlooked the contribution of the change in revolution frequency during acceleration, a known effect in the acceleration of heavier particles, that is generally negligible in electron synchrotrons with large momentum compaction factor. As the RF frequency is fixed, locked to the storage ring's frequency, the effect appears as an energy offset, and consequently, orbit offset along the ramp, more important at low energy. In our case, the energy mismatch at injection energy was about 1.5%. A major booster realignment was performed in January 2022 to match its revolution period at injection energy to the RF frequency. The frequency mismatch has thus been transferred to the high energy part of the ramp, where the beam is more robust. The efficiency of the booster ramp increased from about 15% to about 70%, with losses still occurring at low energy. See detailed report in Ref. [3].

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An emittance exchange in the booster has also been implemented to improve the booster-to-storage ring injection efficiency, as reported in Ref. [4].

Collective Effects

The storage ring currently operates in decay-mode with maximum current of 100 mA. Beam stability at this intensity in terms of collective effects is granted by temperature tunning of the Petra7-cell RF cavity and the closed loop operation of three bunch-by-bunch feedback systems, one for each plane.

The systematic characterization of the storage ring in terms of impedance and collective effects has started recently and the first results are reported in Ref. [5].

RF System

SIRIUS storage ring current RF system is operating a 7-cell room temperature PETRA cavity driven by a 130 kW RF plant comprised of two 65 kW solid state amplifiers (SSA) controlled by a digital LLRF. In its final design configuration, the RF system will employ two CESR-B type superconducting cavities, driven by eight 65 kW SSAs operating at 500 MHz. The installation of the two SC cavities is expected to take place in the second half of 2023, after the installation of SIRIUS cryogenic plant. The final RF design also contemplates the installation of a SC passive third harmonic cavity.

The RF system has been in continuous operation for over two years. During this period, the two SSAs have operated for about 15 thousand hours with a reliability close to 100%. See details in Ref. [6].

Vacuum System

The SIRIUS storage ring is based on fully NEG-coated vacuum chambers. Considering the complexity of the system, the installation went well and was performed in a short time. The expected static pressures were achieved right after the vacuum installation. Despite few problems that have been faced during the commissioning, the vacuum has been performing well, and pressures have decreased as expected with beam conditioning. A fast conditioning has been observed for the NEG-coated chambers, and the design dynamic pressure of $3\text{x}10^{-12}$ mbar/mA was achieved with a beam dose of about 60 A·h. Figure 6 shows the normalized average dynamic pressure rise as a function of beam dose. Also, we have been successfully using the Neon venting process for vacuum interventions, and until now, none of the vacuum chambers of the SIRIUS arc sectors had to be reactivated.

SIRIUS PHASE1 PROJECT PLAN

Recently the Brazilian Federal Government has approved funding that will allow for the completion of Phase1 of the SIRIUS project by mid 2024. This funding will allow for the conclusion of 14 beamlines and their associated experimental stations, implementation of the final RF system required for operation at the nominal current of 350 mA, completion of the orbit monitoring and correction systems required to achieve the high stability of the electron beam, acquisition and development of undulators required for the beamlines, completion of sample preparation and pre-characterization laboratories, completion of computing infrastructure for data storage and processing.

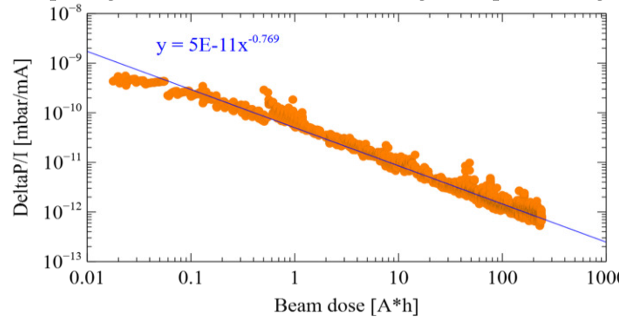

Figure 6: Normalized average dynamic pressure rise (ΔP/I) as a function of the beam dose.

Table 1 compares the presently achieved key performance parameters with the target parameters for Phase1.

For several beamlines, the acquisition of undulators is in the critical path. The in-house development of Delta undulators has been delayed, and a new undulator baseline plan has been established including commercial undulator options. A study to define the best alternatives for each beamline is in progress, and the in-house development of Delta undulators continues in parallel.

Table 1: SIRIUS Key Performance Parameters

Parameter	**May 2022**	**Phase1**
Beam energy [GeV]	3.0	3.0
Current [mA]	100	350
Injection mode	decay	top-up
Emittance [pm.rad]	250*	250
Orbit stability	> 40% σ	< 10% σ
Beamlines	6	14

*not measured yet

NEXT STEPS

The SIRIUS project has completed the initial Phase0 commissioning phase by end of 2021 and is now focused on completing Phase1 in about two years from now, by mid 2024, an ambitious goal in terms of schedule. The priorities for this year regarding the accelerators include placing the order for commercial IDs for the critical beamlines, placing the order for the superconducting passive third harmonic cavity, completing the fast orbit feedback (FOFB) system, implementing the top-up mode at 100 mA, and commissioning the emittance measurement beamline. For the next year, the priorities are related to the installation and commissioning of the final RF system with superconducting main cavities and higher harmonic cavity that will allow reaching the nominal current of 350 mA.

ACKNOWLEDGEMENTS

The authors are reporting this work on behalf of the whole SIRIUS team.

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