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# STATUS OF SIRIUS OPERATION WITH USERS

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*Abstract*

SIRIUS is a green-field 4th generation Synchrotron Light Source Facility based on a 3 GeV electron storage ring with 518 m circumference and 250 pm.rad emittance. It was designed, built, and is operated by the Brazilian Synchrotron Light Laboratory (LNLS/CNPEM). After completion of Phase-0 commissioning of the accelerators and first beamlines, SIRIUS is now open for external users, with 6 fully operational beamlines, 4 close to start scientific commissioning, and 4 in different stages of installation. We report on the status of SIRIUS operation with users in the recently implemented top-up mode, with important upgrades in the orbit feedback systems and in the reduction of transient perturbations to the stored beam during injection process.

## INTRODUCTION

SIRIUS is the Brazilian synchrotron light facility recently commissioned and opened to external users. The design and construction of this green-field fourth generation light source was initiated in 2012, about 11 years ago, and, since March 2023, the machine is open to external users, with 6 beamlines in operation executing experiments from the first regular user's call, after about a year of scientific commissioning. Of these, 5 beamlines are based on commissioning APU undulators, and one is from a low-field dipole (IR beamline). Four additional beamlines have already been illuminated with synchrotron light and are almost ready to start scientific commissioning: one is based on a superbend dipole, one on low field dipole, and two are based on temporary refurbished IDs from the first synchrotron source at LNLS, UVX, that was decommissioned in 2019. There are 4 additional beamlines in installation and construction phases, completing the 14 beamlines for SIRIUS Phase-I, to be delivered by the end of 2024. Among the Phase-I beamlines are the 6 extra-long ones that extend outside the main building experimental hall. A map with the Phase-I beamlines is shown in Figure 1. Phase-II beamlines are now being defined and designed.

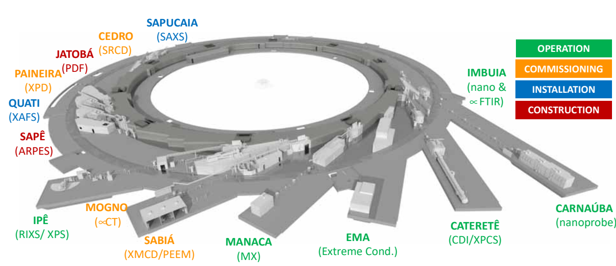


Figure 1: SIRIUS Phase-I beamlines.

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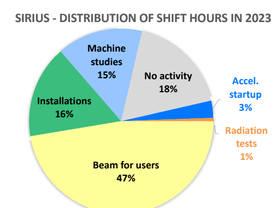
In the first regular SIRIUS user's call for the first semester of 2023, 325 research proposals were submitted, with 125 being selected in a double-blind peer-review evaluation process. The number of user's shifts allocation was 84% to researchers from Brazil and 16% from abroad.

The distribution of machine shift hours for this year reflects the increase in beam time for users as compared to the previous year, as shown in Figure 2. The allocated time for installations and machine studies was kept almost the same, as the activities for new beamline installations and studies to further improve the beam performance and reliability are still demanding. SIRIUS is operating in a regime of 24/6, resulting in a large fraction for no-activity shifts.




| Shift hours | 2023 | 2022 |
|---|---|---|
| Beam for users | 4152 | 3360 |
| Installations | 1416 | 1968 |
| Machine studies | 1320 | 1296 |
| No activity | 1560 | 1608 |
| Accel. startup | 264 | 480 |
| Radiation tests | 48 | 48 |

Figure 2: Distribution of machine shift hours.

Figure 3 shows the machine reliability for the last 12 months, from April 2022 to March 2023. The overall reliability in this period is 97.4%.

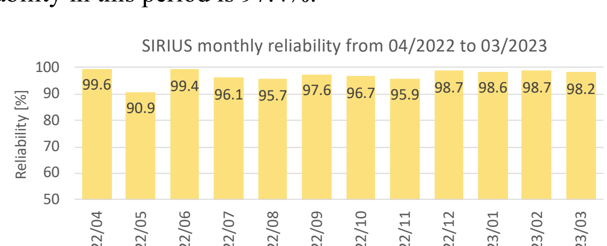



Figure 3: SIRIUS monthly reliability for last 12 months.

In user's shifts, the SIRIUS storage ring is running in top-up mode with 100 mA in uniform filling pattern since end of March this year. The stored current is still limited by the presently installed RF system. The final system, consisting of two superconducting RF cavities with 480 kW SSA transmitter power, is expected to be installed in the first semester of 2024.

The SIRIUS fast orbit feedback system (FOFB) has been operational during user's shifts since November 1st, 2022, running initially at 25 kHz update rate, and recently upgraded to 48 kHz. With the upgrades, the present orbit stability is better than 1% and 4% of the RMS beam size in the horizontal and vertical planes, respectively. Additional upgrades are ongoing.

In this paper, we describe the main achievements for SIRIUS operation with users.

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## SIRIUS STORAGE RING

The SIRIUS storage ring main parameters are described in more detail in [1-3]. The 3 GeV electron storage ring has 518 m in circumference and reaches 250 pm.rad bare lattice emittance. Twenty 5BA achromatic cells make up the storage ring, that can accommodate about 40 beamlines in total: 18 from 6.5 m long straight sections available for insertion devices, 20 from superbends with a narrow peak magnetic field of 3.2 T in the center, and up to 10 from low field (0.6 T) dipole sources, covering a photon energy range from infrared to hard X-rays. The lattice optics is 5-fold symmetric, providing two different types of straight sections, 15 low-beta and 5 high-beta sections. The low-beta sections have the betatron functions matched to ~1.5 m in the center, a condition that optimizes effective brightness by matching the phase-spaces of the electron and the photon beams for undulators. The small values also allow for small horizontal and vertical gap IDs. Another benefit is that ID perturbations to the machine optics are very small, making their daily operation much simpler. Simulation of ID effects are presented in [2].

The SIRIUS project completed an initial phase with 100 mA current in decay mode in November 2021, with the linear optics calibrated, and slow orbit feedback (SOFB) and bunch-by-bunch feedback loops closed. Since then, various developments resulted in higher stability of the beam and reliability of the facility. Recently, project milestones such as top-up operation and FOFB loop have been deployed. Studies to improve the machine performance are also on-going, such as the online optimization of the dynamic aperture with higher fractional tunes to reduce orbit amplification factors. As a result, the fractional tunes increased from (0.08, 0.14) to (0.16, 0.22) and the new tunes are now used as reference configuration for users since a week. Results are reported in [3].

### *Orbit Stability with SOFB and FOFB*

The implementation of the FOFB and SOFB is a major project milestone. The SOFB system comprises 160 BPMs, 120/160 horizontal/vertical slow correctors and the FOFB system comprises a subset of 80 BPMs and 80 additional dedicated fast correctors per plane, with 2 BPMs and 2 correctors per plane for each of the ID and superbend based beamlines, ensuring beam position and angle stability at these source points. Beam based experiments have been performed to have both systems working simultaneously. The implementations are: (i) to have the RF frequency as a parameter to correct for changes in circumference or energy variations in both loops but to apply the correction only in the SOFB loop, and (ii) to avoid saturation of the fast correctors with a partial download (~4%) of their kicks to the slow correctors at each SOFB loop iteration at 10 Hz. The FOFB system currently runs at 48 kHz update rate.

Figure 4 illustrates the FOFB loop performance presently achieved. The system is capable of effectively attenuating orbit perturbations caused by the booster ramping at 2 Hz, the power grid frequency at 60 Hz and disturbances induced by the IDs motion. The achieved disturbance rejection crossover frequency is approximately 400 Hz, with peak amplification below 5 dB in both planes. The performance goal of 1 kHz crossover frequency is still not met, despite the measured overall loop delay of 51 µs allowing it theoretically.

System identification tools will be deployed to provide a detailed characterization of the subsystems dynamics and allow the equalization of their responses. This procedure will enable the multivariable control loop dynamics to be modelled as multiple mode-by-mode single-input-single-output control loops. In this way, the expected performance of 1 kHz crossover frequency in closed loop is expected to be achieved. A similar methodology has been carried out in the LNLS UVX ring with successful results [4].

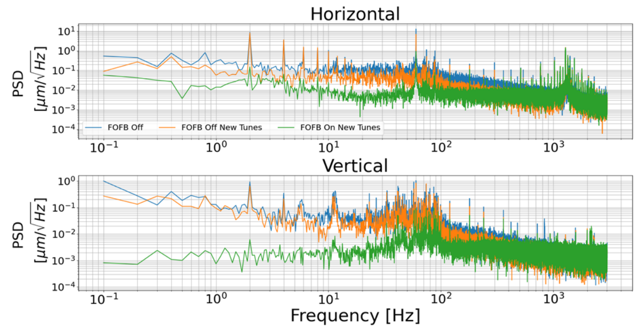


Figure 4: Square root of the PSD from BPM data acquired at 6 kHz sampling rate, showing the performance of the FOFB system.

Yet the present FOFB implementation is rendering the overall orbit stability better than 1% and 4% of the RMS beam sizes in the horizontal and vertical planes, respectively, as shown in Figure 5. The beneficial effect of the new tunes on orbit variations can also be seen in Figure 5.

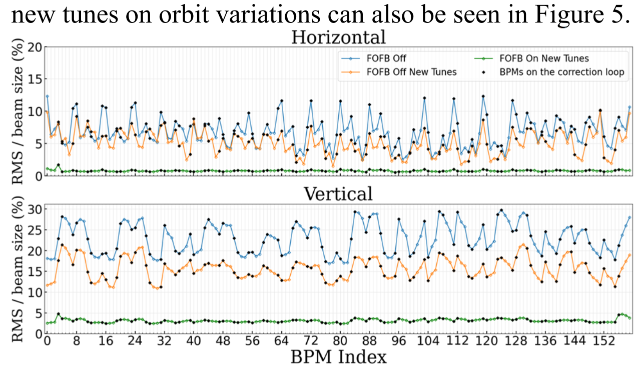


Figure 5: Effect of the FOFB loop in attenuating orbit RMS variations. Results are shown relative to the beam size at each BPM. Black dots indicate the subset of BPMs included in the FOFB loop. Integration from 0.1 Hz to 1 kHz.

### *Top-up Operation*

Another project milestone is the operation in top-up mode, implemented as the regular operation mode for user's shifts since March this year, after a series of developments, such as the completion of the interlock system to allow for injection with the beamline shutters open, and the optimization of the injector parameters and its reliability.

The present top-up parameters are set to a single pulse from the injector every 3 minutes. With just one pulse, the

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transient perturbation is restricted to a few milliseconds per injection shot, and the current intensity is kept within the limiting values of 100 ± 0.3 mA. The needed charge per pulse from the Linac is calculated a few seconds before each pulse, and the thermionic e-gun bias voltage is set accordingly as a charge control parameter.

### *Transparent Injection*

The injection scheme into the SIRIUS storage ring is based on off-axis injection in the horizontal plane using a single pulsed nonlinear kicker (NLK) [5]. The NLK design is based on the implementation at BESSY-II [6]. Both the NLK and pulsed septa magnets cause transient orbit perturbations to the stored beam at injection. Initially, the amplitude of these perturbations was about 2-3 times the RMS beam size in both transverse planes.

Top-up tests in combination with the beamlines were carried out in February this year and showed that most experiments could accept the transients of the injection process, but a few more demanding ones would need to discard data acquired during few tens of milliseconds after the injection shot. To make the injection process more transparent to users, the developments described below are in progress. The results so far show a big improvement to the injection transparency, enabling even the most demanding experiments to use data taken during injection.

#### Compensation of Injection Septa Leak Field

The perturbations to the SIRIUS stored beam from the injection septa leak field were measured to have a peak larger than 2 times the beam size and to last for a few milliseconds. Attempts to increase shielding resulted in marginal improvement and motivated the development of an orbit feedforward compensation scheme, making use of four fast orbit correctors (two horizontal and two vertical) already available on both sides of the injection straight section. These magnets were initially designed to be used with FOFB and have a large overall bandwidth (magnet core plus vacuum chamber) of approximately 15 kHz. Online optimizations are ongoing and showed a significant reduction of the perturbation, as can be seen in Figure 6. The amplitude of the perturbations from the septa leak field have been reduced to ~7% $\sigma_x$ and ~20% $\sigma_y$.

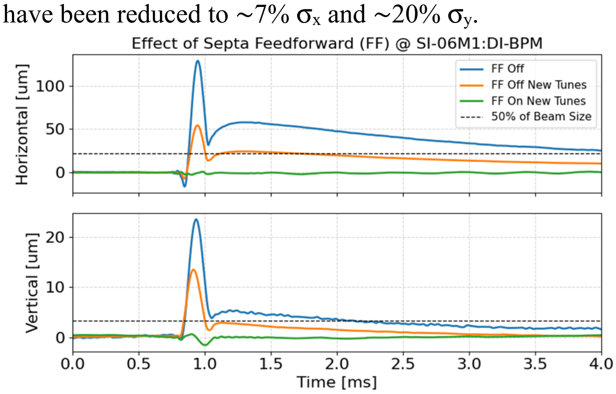


Figure 6: Orbit perturbation on stored beam at the low-beta ID BPM induced by the septa leak field with and without feedforward compensation, for the old and new tunes.

#### Compensation of Residual Field on NLK Axis

The pulsed field of the SIRIUS NLK is produced by 8 current-carrying wires assembled on grooves machined on a single piece ceramic tube. A layer of titanium with ~8 µm thickness coats the inner surface for impedance reduction. The design magnetic field should be zero at the stored beam position. However, in practice, there was a residual magnetic field on-axis that perturbed the stored beam position with amplitudes larger than 3 times the beam size for a few milliseconds. A perturbation beyond tolerance was expected as the required accuracy for the wires positioning is difficult to be achieved. Thus, since early design, a compensation for the residual field was planned, but only recently implemented. The idea is based on the installation of two additional pairs of pulsed current-carrying wires that create a dipolar field to cancel the residual field on-axis. These additional pair of wires are pulsed with independently adjustable current amplitudes with the same half-sine shape with 2.4 µs duration. During the assembly of the new setup, it was noticed that the cable connecting the NLK wires to the high-power power supply was not suitably shielded. The cable was replaced, and it turned out it had a big impact on the orbit disturbance during injection. Figure 7 shows the effect of the new cable and the new upgraded NLK with compensating wires. The overall effect is a reduction of the NLK perturbation amplitude to ~3% $\sigma_x$ and ~20% $\sigma_y$. The effect of eddy current induced fields on the beam due to the titanium coating in the ceramic tube are being studied.

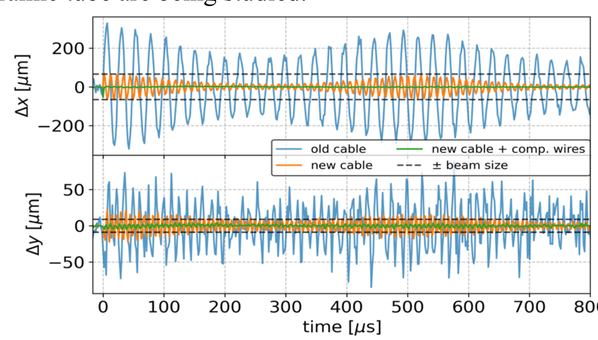


Figure 7: Orbit perturbation on stored beam at an injection straight BPM induced by the NLK residual field with and without compensation. Effect of new cable is also shown.

## CONCLUSIONS

The SIRIUS project has recently been opened for regular external users with 6 beamlines in operation and 100 mA in top-up mode with uniform filling pattern. Recent improvements in orbit stability with the new working point with higher fractional tunes, deployment of FOFB loop, and reduction of injection transients, allow for a better beam quality delivered to the beamlines. Further developments to reach better orbit stability are underway. The nominal current of 350 mA still depends on the final RF system. SIRIUS is presently operating with commissioning undulators and the titular ones are either being purchased or developed internally.

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