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PRELIMINARY SIRIUS COMMISSIONING RESULTS

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Abstract

Sirius is a 4th generation 3 GeV low emittance electron storage ring that is in final commissioning phase at the Brazilian Centre for Research in Energy and Materials (CNPEM) campus in Campinas, Brazil. Presently (April 2020) we have accumulated 15 mA of current, limited by vacuum, using a nonlinear kicker for injection. In this paper we report on the Sirius main commissioning results and main subsystems issues during installation and commissioning.

INTRODUCTION

Sirius is a new light source in Brazil based on a low emittance 3 GeV electron storage ring with 518 m circumference. The storage ring natural emittance of 0.25 nm.rad is reached with twenty 5BA lattice cells and it can be further reduced to 0.15 nm.rad as insertion devices are added. Sirius will be an international multiuser research facility with up to 37 beamlines: 20 from permanent magnet superbends reaching peak magnetic field of 3.2 T (and therefore 19 keV critical photon energy); 4 from insertion devices at high beta sections and 13 at low beta sections. The low beta sections are optimized to maximize brightness from insertion devices by matching the electron beam and undulator radiation phase spaces. In these low beta sections, where the horizontal and vertical beta functions are simultaneously reduced to 1.5 m in the centre, small horizontal gap devices such as Delta undulators can be installed. Sirius main parameters are shown in Table 1 and the optical functions in Figure 1.

Table 1: Main Sirius Storage Ring Parameters

Parameter	Value	Unit
e-beam energy	3.0	GeV
Circumference	518.4	m
Lattice	20 x 5BA	
Hor. emittance (bare lattice)	0.25	nm.rad
Betatron tunes (H/V)	49.11 / 14.17	
Natural chrom. (H/V)	-119.0 / -81.2	
Energy spread	0.85e-3	
Energy loss/turn (dipoles)	473	keV
Damping times (H/V/L)	16.9/22.0/12.9	ms
Nominal current	350	mA

The injection into the storage ring will be based on conventional off-axis accumulation in the horizontal plane using a non-linear kicker (NLK). The injection system is composed of a 150 MeV Linac and a full-energy synchrotron booster with 497m circumference, built in the same tunnel and concentric with the storage ring. The booster has a very small emittance of 3.5 nm.rad at 3 GeV that is essential for a high injection efficiency using the NLK.

Commissioning activities were interrupted on last March 23rd due to the Covid-19 pandemic, when most of the staff switched to teleworking. We have reached 15 mA of accumulated current with off-axis injection in the horizontal plane using the NLK. This current is presently limited by vacuum. We are now slowly returning to work to continue with beam commissioning and proceed with installation of the first undulator for the protein crystallography beamline MANACÁ.

The Sirius project has effectively started in July 2012 when the decision to change to a low emittance 5BA lattice was taken, implying completely new components design. Installation of the accelerator subsystems in the machine tunnel started on May 2018 and the first turn in the storage ring with on-axis injection was achieved on Nov. 22nd, 2019. The first stored beam was obtained 3 weeks later, on Dec. 14th. Two days later, first light from a superbend was observed at the MOGNO beamline and first X-ray microtomography results were taken (see Figure 2). First beam accumulation with the NLK was obtained on Feb. 20th, 2020. Figure 3 shows a picture of the main accelerator tunnel.

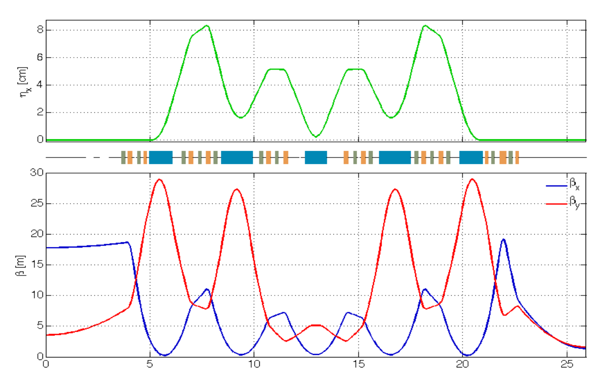

Figure 1: Sirius optical functions with a high-beta section on the left and a low-beta section on the right. The optics is 5-fold symmetric with 5 high-beta and 15 low-beta sectors. The centre dipole is a permanent magnet superbend.

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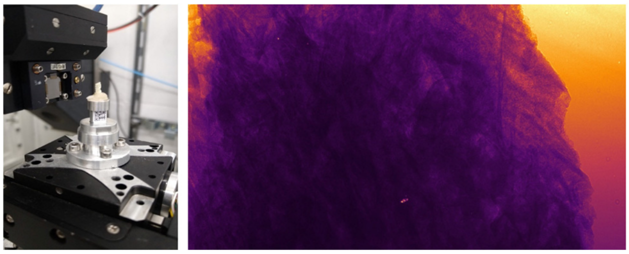

Figure 2: First X-ray microtomography of a carbonate rock sample obtained on Dec.16th 2019 at beamline MOGNO, using white X-ray beam from 8 keV to 200 keV from the 3.2 T superbend permanent magnet dipole source. The image was obtained two days after storing the first beam with on-axis injection.

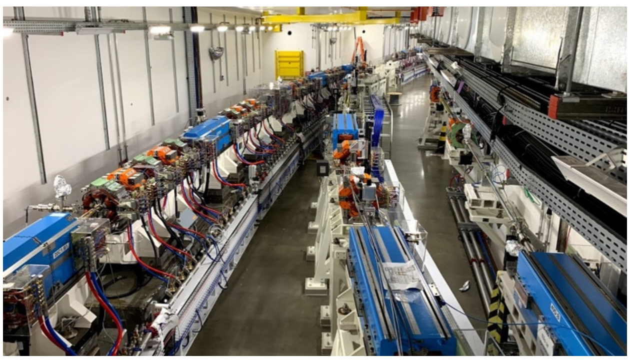

Figure 3: View of Sirius accelerators tunnel with storage ring on the left, booster on the right and BTS transfer line.

ACCELERATOR PHYSICS ISSUES

The main issues related to accelerator physics during booster commissioning were: (i) an unexpected gradient field in the booster pulsed injection septum had to be introduced in the LTB model to improve optics matching and thus injection efficiency at 150 MeV. This is a very strong septum, with a deflection of ~22 deg. (ii) the very small booster momentum compaction factor α_c causes a non-negligible effect of beam velocity variation on orbit period during the ramp (as compared to the energy contribution) that was not anticipated. As the revolution time is fixed by the RF frequency, this causes a variation of beam energy deviation δ during the ramp, requiring extra horizontal aperture (~2 mm in our case). The main accelerator physics issues related to the storage ring commissioning were: (i) a systematic error from building shrinking resulted in different RF frequencies for the booster and SR. The measured difference between the rings (~800 Hz) is larger than expected. This caused some difficulty in searching for the correct SR frequency in the beginning because a change in RF frequency requires a re-optimization of the injector. (ii) a large calibration error of electromagnet dipoles B1 and B2 with respect to permanent magnet dipole BC (2.5%) was noticed during initial optics measurements with the on-axis injected beam. After correction, measured optics functions are closer to the model and accumulation with the NLK was successful. Figure 4 shows the measured dispersion function as compared to the nominal. Further optimization work is on-going to improve the optics and injection efficiency, presently at about 60%.

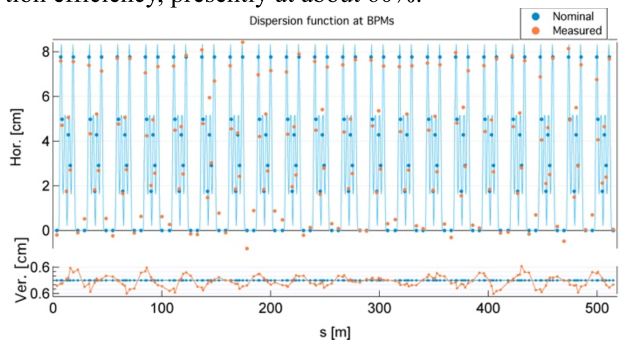

Figure 4: Measured dispersion function along the storage ring as compared to the nominal after correction of dipole calibration error.

DC AND PULSED MAGNETS

All Sirius DC electromagnets were fabricated using stacked laminations by a Brazilian company, and are aligned by mechanical design on the girders, using reference surfaces, with no adjustment flexibility, to improved stiffness and stability. The 20 permanent magnet superbends BC (reaching 3.2 T peak field) in the centre of the achromatic arc have been produced in-house. Figure 5 shows a picture of storage ring magnets in one 5BA arc.

The main issue related to DC magnets was the magnetic field calibration of electromagnet dipoles with respect to the permanent magnet dipole. The cause of the problem is being investigated but is probably related to the large range of measured field intensities. Another issue is the storage ring pulsed injection septa leakage field. Additional shielding is being planned to mitigate this effect.

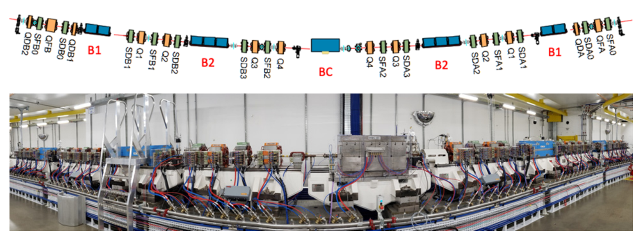

Figure 5: View of Sirius magnets in one 5BA arc.

VACUUM SYSTEM

The Sirius vacuum system for the storage ring is based on fully in-house NEG-coated copper chambers. The NEG activation process was carried out by in-situ bake-out with the magnets in place, and by using a custom developed heating system [1]. During installation, a few issues occurred and were all easily solved: one sector vented after NEG activation, few RF shielded bellows stuck during bake-out and a few components presented leak. During operation, the main issues were a leak in a septum chamber due to arcing that required substituting the chamber, two ion-pumps short-circuited, and a photon beam induced hot-spot that was mitigated by realignment of the chamber. Figure 6 shows some of the described problems.

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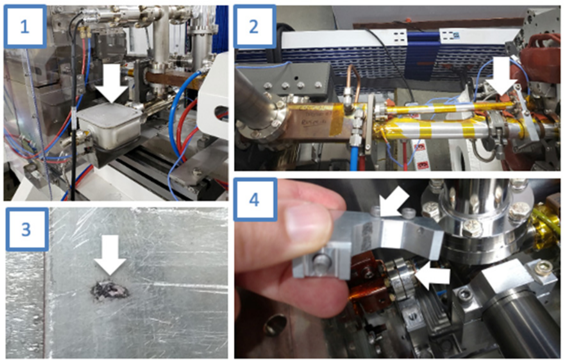

Figure 6: Some problems related to vacuum system during operation: (1) storage ring ion pump short-circuit; (2) photon beam induced hot-spot; (3) septum chamber leak; (4) booster extraction septum arc on the chamber.

The pressure in the storage ring is evolving smoothly, as can be seen in Figure 7.

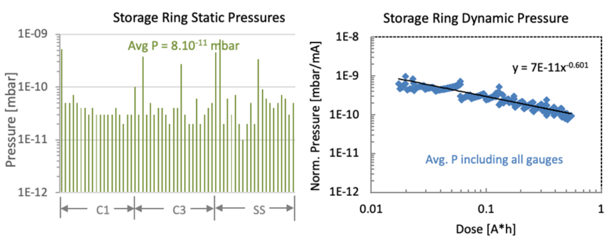

Figure 7: Storage ring static pressure and evolution of dynamic pressure as a function of accumulated dose.

BEAM DIAGNOSTICS

Here we present two beam diagnostic systems that have most interesting results up to now.

Beam Position Monitors

The storage ring 160 BPMs had all parts contracted to Brazilian industry. The buttons were assembled and brazed in-house and welded to the BPM body in-house as well. All BPMs have bellows on both sides and are referenced to the girders by design. BPM electronics were developed in-house and produced by a local Brazilian company.

Figure 8 shows the results of measured BPM electrical offset calibration and Beam Based Alignment (BBA) offset calibration using normal and skew quadrupole trim coils.

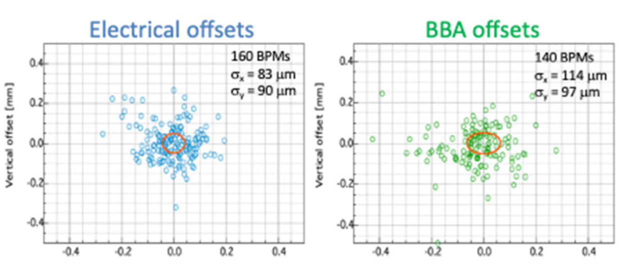

Figure 8: Measured BPM electrical and BBA offsets.

The main issue related to BPMs was a strong electromagnetic interference induced by the injection kicker on the BPM next to it. The problem has been mitigated by the implementation of a digital filter, as can be seen in Figure 9.

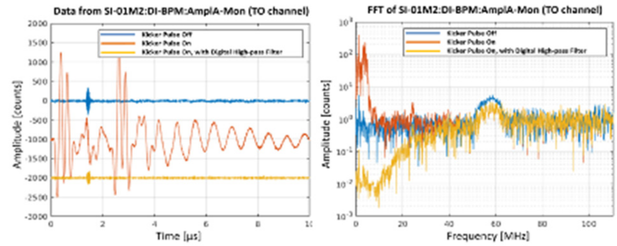

Figure 9: Effect of injection kicker electromagnetic interference on the closest BPM signal was mitigated by means of a digital filter.

Beam Scrapers

Special scrapers have been designed for Sirius to minimize beam coupling impedance effects. The design uses a special round blade geometry with angular motion, driven by a linear-to-angular motion transmission. See picture in Figure 10. The main difficulties in this design were the indirect blade position feedback, that required 3D measurements. After installation and baking, the linear stages of the horizontal scraper were found to be offset, not allowing one blade to fully open, and the opposite blade stuck after first 2 days of testing. The horizontal scraper has been removed for inspection and will be reinstalled in the next opportunity. The vertical scraper had no problems up to now.

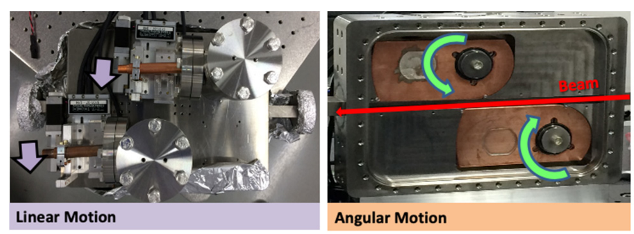

Figure 10: Sirius scraper design minimizes beam coupling impedance. It is based on a special round blade geometry with angular motion driven by a linear-to-angular transmission.

RF SYSTEM

Sirius is being commissioned with a reduced RF system. A single RF plant delivering up to 120 kW of power at 500 MHz drives one 7-cell Petra cavity. The final system consists of 2 superconducting cavities and is expected to be installed within 2 years. The 50 kW, one 5-cell cavity booster RF system is fully operational. The conditioning of the 7-cell cavity for high power is still under way, progressing at a much slower pace than expected. Planned operation voltage is 1.8 MV (70 kW in the cavity). A new version of ALBA LLRF was developed for Sirius and is fully operational for commissioning. The amplifiers have been tested during cavity conditioning up to 100 kW in pulsed mode, 80 kW in CW mode. The main storage ring RF parameters during commissioning and final design are shown in Table 2.

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Table 2: Main Storage Ring RF Parameters

	Commissioning	Design
RF Cavities	1 x 7-cell	2 x SC CESR
Power/cavity	120 kW	240 kW
Acc Voltage	1.6-1.8 MV	3 MV
Max beam current	50 mA	350 mA

NON-LINEAR KICKER

The Sirius NLK is based on the Bessy design [2] using 8 wires. Figure 11 shows the position of the wires and the NLK being assembled. The resulting magnetic field shape is close to zero at the center and has maximum intensity at -8 mm from the beam axis, were the injected beam from the booster is deflected into the storage ring acceptance. A vertical full gap of 9 mm at the ceramic chamber center is set to allow positioning of the wires. The single piece NLK ceramic chamber was produced by a Brazilian company and precise channels were machined to position the wires. The coating with titanium was performed in-house. The main challenges during chamber manufacturing were achieving the internal profile tolerances and producing a homogeneous Ti coating. A new split ceramic design is expected to reduce the profile tolerance from present 0.4 mm to 0.05 mm. The Ti coating was successful after replacing DC by RF magnetron sputtering as can be seen in Figure 12.

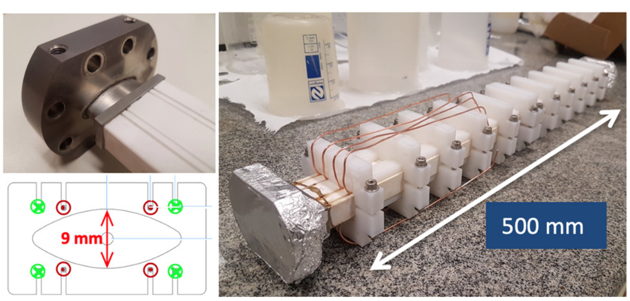

Figure 11: Sirius non-linear kicker being assembled.

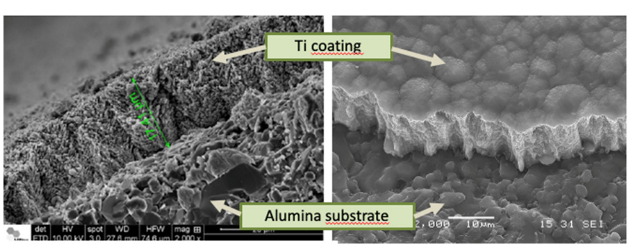

Figure 12: Ti coating on NLK ceramic chamber with DC (left) and RF (right) magnetron sputtering. The Ti layer thickness is 17.4 µm and 8 µm respectively.

CONTROL SYSTEM

The Sirius control system is based on EPICS framework and the main applications and IOCs are running on Control Servers. The nodes are based on open source and low-cost Single Board Computers (BeagleBone Black). Hardware and software are developed in-house. Presently there are approximately 110 k connected EPICS PVs, 60 GB of data per day with 2.5 Gbps of data traffic on core switch.

For the High-Level system, the main development language is Python and Soft IOC servers are based on PCASpy and PyEpics. Currently there are 222 Soft IOCs running with 2 to 10 Hz update rates. HLAs are mainly based on PyQt and PyDM.

POWER SUPPLIES

The Sirius power supplies (PS) were designed in-house and contracted to a Brazilian company for fabrication. Regarding the injection system PS, the measured tracking error for booster magnets were initially above specification when tested in the real machine and required more time than expected to be adjusted. The main issues related to the storage ring PS are: (i) overheating of dipole power supplies that caused capacitor explosion in 3 units, as can be seen in Figure 13. The manufacturer sent new capacitors and the problem did not happen again after all capacitors were substituted. This problem caused a big inconvenience in commissioning because it required turning the storage ring off for one hour after one-hour operation, until all capacitors were substituted. (ii) a cross-talk between quadrupole trim coils appeared in the final installation and took longer than expected to be solved.

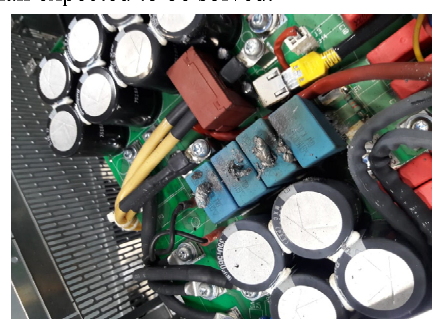

Figure 13: Damaged capacitors of storage ring dipole power supply.

FINAL COMMENTS

Many problems only appear during real operating conditions. A well prepared team capable of investigating the problems is fundamental. Beam commissioning could have been briefer if the subsystems were thoroughly tested beforehand. Precise and accurate beam diagnostics tools (hardware and software) are fundamental for commissioning. In particular, precise BPM turn-by-turn capabilities and flexible analysis and simulation software tools are very helpful. The booster commissioning while the storage ring was being installed in the same tunnel led to an intermittent booster commissioning schedule that was not very effective. The booster might have been commissioned close to the end of storage ring installation. Provision for on-axis injection in the storage ring was essential for initial optics adjustments based on beam measurements. The control system with remote control capability proved to be very useful, especially in the present Covid-19 pandemic case.

ACKNOWLEDGEMENTS

The work presented here is the result of a collective effort from all Sirius team.

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