ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS105

SIMULATION OF SIRIUS BOOSTER COMMISSIONING

M. B. Alves *, L. Liu, F. H. de Sá
Brazilian Synchrotron Light Laboratory (LNLS), Campinas, Brazil

Abstract

Sirius is the new 3 GeV fourth-generation low emittance light source under construction at the Brazilian Synchrotron Light Laboratory. In order to study strategies for the commissioning, different scenarios were studied by tracking simulations on lattice models with realistic alignment and magnet excitation errors, taking into account the finite precision of the beam diagnostic devices. We developed a commissioning algorithm that provides an efficient adjustment of the on-axis injection parameters, trajectory and closed orbit corrections and tuning of the RF parameters. With this algorithm it was possible to obtain a stable beam for thousands of turns in all the random machines simulated. The algorithms allows for partially automated commissioning procedures.

INTRODUCTION

The Sirius Booster function is to receive a beam with 150 MeV coming from the linear accelerator and to execute the energy ramp that increases the beam energy to 3 GeV. After that, the beam is injected into the storage ring [1, 2].

Since modern machines are expected to have a challenging commissioning, there is a trend in simulating start-to-end commissioning procedures before dealing with the real machine [3–5]. The LNLS accelerator physics group used Matlab Accelerator Toolbox (AT) [6] to simulate the booster commissioning.

The implemented simulation steps were:

- Generate machines with random errors following a Gaussian distribution with the standard deviation given in Table 1 and higher-order multipole errors [1].
- Simulate on-axis injection scenarios with errors according to Table 2 and adjust injection parameters with the available diagnostics.
- Apply trajectory correction methods to obtain sufficient turns to estimate the closed orbit.
- Perform closed orbit correction without RF cavity.
- Tune the RF parameters.
- Correct the closed orbit with RF cavity.

Table 1: Machine Errors (rms) used in the Simulation

Magnets offset (x and y)	160 µm
Magnets roll	0.80 mrad
Quadrupoles and sextupoles strength	0.30 %
Dipole strength	0.05 %
Quadrupolar strength in dipoles	0.30 %

We developed several functions in AT to test and to validate the proposed algorithms for commissioning. We applied

* murilo.alves@lnls.br

Table 2: Injected Beam Errors (rms) Considered in the Simulation

	Static	**Jitter**
Δx and Δy	2 mm	500 µm
$\Delta x'$ and $\Delta y'$	3 mrad	30 µrad
$\Delta\theta_{\text{kicker}}$	1 mrad	30 µrad
$\Delta E/E$	1 %	0.3 %

these functions over 20 random machines (seeds) generated from its lattice model including random errors in magnets - Table 1. We also have considered the finite resolution of diagnostic devices and their misalignment according to Table 3.

It was assumed that the diagnostic devices resolution depends linearly on the beam intensity. If only a fraction N_{diag} of the total number of generated particles N_{total} reaches the diagnostic device, its resolution will follow a Gaussian distribution with standard deviation error indicated in Table 3 increased by the factor $N_{\text{total}}/N_{\text{diag}}$. The resolutions in Table 3 are given for a 1 nC beam. The total number of particles simulated was always a macro-particle representation of 1 nC.

Table 3: Beam Diagnostic Devices Errors (rms)

BPMs offset (x and y)	500 µm
BPMs resolution (single-pass)	2 mm
BPMs resolution (turn-by-turn)	3 mm
Screens offset (x and y)	1 mm
Screens resolution	500 µm

ON-AXIS INJECTION ADJUSTMENTS

The on-axis injection layout into the booster is represented in Fig. 1.

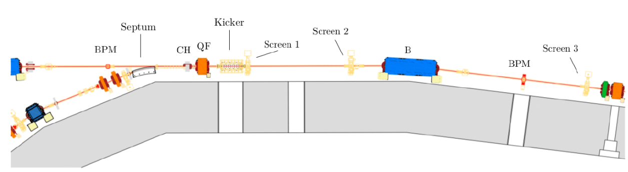


Figure 1: Booster injection layout.

There are three fluorescent screens installed in the injection region. The first screen is used to adjust the beam position and angle at the end of the injection septum. These changes can be done with a combination of correctors kicks in the transport line and the septum field. Between screens

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS105

1 and 2 there is no magnet element therefore both, beam position and angle, can be adjusted after the kicker.

The third screen is placed after the first booster dipole so that it can be used as a spectrometer. With the dispersion function given by the model lattice the energy deviation can be estimated based on screen 3 horizontal position measurements. Therefore, with these three screens it is possible to determine independently the optimum septum and kicker deflection angles and also to do a first correction of booster dipoles energy.

We simulated injection scenarios in the booster generating 5000 macro-particles with the following parameters: emittance $\epsilon_x = \epsilon_y = 170\,\mathrm{nm\,rad}$, energy spread $\sigma_E = 0.5\,\%$ and bunch length $\sigma_z = 3\,\mathrm{mm}$, following a Gaussian distribution with 3σ cutoff. A macro-particle is considered lost if its transverse position is greater than the vacuum chamber aperture along the ring. We also introduced errors in the injected beam after the septum, according to Table 2 and considered 100 injection pulses to obtain average position measurements.

This procedure was applied to 20 random machines and in all the cases the beam reaches the third screen with 100 % intensity.

TRAJECTORY CORRECTION

The simulation showed that with the magnet errors considered in Table 1 it is not possible to obtain first turn transmission with correctors set to zero, so the application of some correction algorithm is needed.

Three correction algorithms were tested:

- The first one considers only first turn BPMs measurements to calculate the correctors kicks until first turn transmission is obtained. After that, corrections are applied until the rms of both horizontal and vertical BPMs position measurements is as small as possible. We will refer to this method by FT, a short for First Turn.
- After obtaining first turn transmission, the second method also takes into account the position measurements of the following turns to calculate the corrector kicks, in which we deal with $n-$turns of the beam as a trajectory correction in a transport line n times the ring size. The abbreviation for the Multiple Turns method will be MT.
- The last one applies the same idea of considering multiple turns measurements, the major difference to the second method is that it sets the first turn trajectory as a reference orbit to calculate the corrector kicks in a extended ring. The goal is to force a periodic condition in the beam trajectory in order to get a closed orbit. We will refer to this method by CO, a short for Closing the Orbit.

The three methods uses the Singular Value Decomposition (SVD) method to calculate the kicks. Based on the betatron tune fractional part, we expect that a sufficient number of turns to obtain a fairly good closed orbit estimative is $n = 5$.

The booster orbit correction scheme contains 50 BPMs, 25 horizontal and 25 vertical correctors. The maximum correction kick is 6 mrad at 150 MeV energy. We implemented the trajectory correction algorithms with 1000 macro-particles. If less than 50 % of the injected particles reaches a particular BPM, then this BPM and also the downstream BPMs are neglected in the correction. The criteria that we used to count the turns was to check how many times the last BPM was reached by more than 50 % of the particles.

In the first simulation step it was noticed that averaging over 100 injection pulses is sufficient to suppress the injection jitter error, so for the sake of computational time we carried out the following steps with only one injection pulse and, on the other hand, we reduced the jitter error by a factor of 10. Beginning with very few singular values and increasing it slowly after each correction application was the approach that performed best in the simulations for all the three algorithms. The rms correction kicks for each method is represented in Fig. 2.

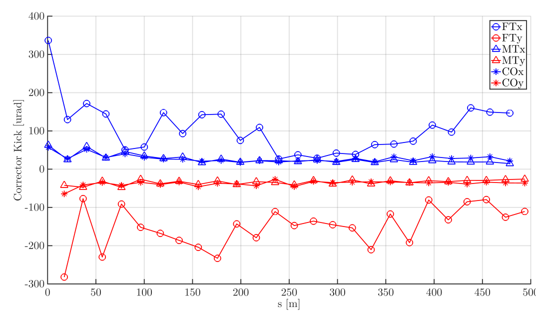


Figure 2: Booster corrector kicks rms (20 seeds) for the three trajectory correction methods. The blue data is the absolute of rms horizontal kicks and the red data is the absolute of rms vertical kicks with a minus sign.

Rms kick values for horizontal and vertical are organized in Table 4.

Table 4: Booster Correctors Kicks (rms) for Each Trajectory Correction Method

Method	**Hor. (µrad)**	**Ver. (µrad)**
First Turn (FT)	106	151
Multiple Turn (MT)	27	34
Closing the Orbit (CO)	28	38

The kicks found with FT method are four times larger than the ones found with the other two methods. Moreover, the performance in turns after correcting with FT method is: in 45 % of the cases the beam is lost in the second turn, 20 % in the third turn, 15 % in the fourth turn and only in 10 % the beam completes 5 turns. Both for MT and CO methods, in 100 % of the cases the beam reaches 5 turns.

Our interpretation for the bad results of FT method is the following: correcting only the first turn induces the correctors to reduce the residual on-axis injection errors (related

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS105

mainly to the screen offsets). One can notice that the first horizontal and vertical correctors (the closest to the injection region) have the largest kicks, therefore when the beam passes through this region in the following turns it will be wrongly deflected. A practical solution to this problem could be to readjust the injection parameters in order to reduce the first correctors strength without compromising the beam transmission.

ORBIT CORRECTION

Since it was possible to obtain at least 5 turns after the trajectory correction, we used the 20 random machines with correctors settings given by CO method to correct the orbit. The macro-particles tracking gets computationally expensive as the number of turns increases, so for this stage we set 100 as the maximum number of turns.

The closed orbit was estimated averaging BPMs position measurements over turns and we calculate the corrector kicks with the ideal response matrix initially with few singular values. The number of singular values was gradually increased during the process.

In all the 20 machines the beam completed 100 turns with efficiency greater than 90 %. The results for the rms reduction of closed orbit are in Table 5.

Table 5: Closed Orbit Distortion rms Before and After the Orbit Correction Without RF Cavity

	Horizontal	Vertical
Before Correction	1.20 mm	1.97 mm
After Correction	0.19 mm	0.34 mm

After the orbit correction, the final corrector kicks obtained (rms) was 48 µrad in the horizontal plane and 77 µrad in the vertical.

RF CAVITY TUNING

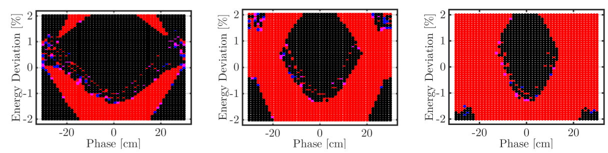
After 4D closed orbit correction the RF cavity was turned on. The nominal RF frequency is $f_{rf} = 499.654$ MHz and RF wavelength is $\lambda_{rf} = 60$ cm. The nominal RF voltage at 150 MeV is $V_{rf} = 150$ kV [1].

We expect the ring length error on the order of a few millimeters, then $\delta L/L \propto 10^{-6}$. Since the momentum compaction factor for the booster is $\alpha = 7.19 \times 10^{-4}$, the RF frequency error is estimated to be a few kHz. Based on this assumption we turned on the simulated RF cavity with a frequency error of $\pm$ 1 kHz and a phase sorted by a uniform random distribution between 0 and 60 cm.

This step consists in a 2-dimensional search algorithm to obtain the optimum pair of RF frequency and phase. There are some misleading points (for the simulation) in longitudinal phase space where the beam completes thousands of turns even if it is not inside the RF bucket. The longitudinal dynamics is much slower than transverse dynamics and, as already mentioned, tracking particles for thousands of turns is computationally expensive. Therefore, since we were limited to simulate only few hundreds of turns in a reasonable time, using the number of turns as a figure of merit to the search algorithm is unappropriated.

A solution for this simulation issue, which can also be applied to the real machine to improve the time dedicated to RF tuning, is to increase the RF voltage while scanning the RF phase. With a higher voltage the longitudinal stable region becomes smaller in phase and bigger in energy deviation, therefore the particles outside the RF bucket will be lost faster and the longitudinal fixed point neighborhood is more apparent.

With one macro-particle we simulated variations of the RF parameters and checked the number of turns this particle completed in each RF setting for 3 different RF voltages, setting the maximum number of turns as ten thousand. The results are shown in Fig. 3.



(a) $V_{rf} = 150$ kV (b) $V_{rf} = 300$ kV (c) $V_{rf} = 450$ kV

Figure 3: Longitudinal phase space for different RF cavity voltages. Let n be the number of turns completed by the beam. Black dots represents $n > 7500$ turns. Blue dots $5000 < n < 7500$. Magenta dots $2500 < n < 5000$ and finally red dots $n < 2500$.

Figure 3 confirms the argument above and the misleading points are considerably eliminated, which favors the search algorithm to converge.

In 100 % of the cases after the RF tuning the 6D closed orbit solution was found and the orbit correction including the RF resulted in a closed orbit distortion with rms of 0.15 mm in the horizontal and 0.30 mm in the vertical.

CONCLUSION

A commissioning procedure for the Sirius booster was simulated and confirmed as reliable. However, the case where optical parameters (mainly betatron tunes) are considerably away from their nominal values was not covered in the simulation and this might lead to the failure of the reported procedure. To fill this gap, we intend to simulate this scenario and to develop some method to estimate and correct the betatron tunes in the early commissioning. Since particle tracking may easily become computationally expensive, we are considering the use of faster simulation methods in later studies. The next step for this work, which is in progress, consists in simulating the storage ring commissioning.

REFERENCES

[1] Sirius Official Documentation, https://wiki-sirius.lnls.br

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS105

[2] A. R. D. Rodrigues, *et al*, ”Sirius Status Update”, presented at the 10th International Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May. 2019, paper TUPGW003, this conference.

[3] V. Sajaev and M. Borland, “Commissioning Simulations for the APS Upgrade Lattice”, in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 553–555, doi:10.18429/JACoW-IPAC2015-MOPMA010

[4] M. Eriksson *et al.*, “Commissioning of the MAX IV Light Source”, in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, paper MOYAA01, pp. 11–15, doi:10.18429/JACoW-IPAC2016-MOYAA01, 2016.

[5] T. Hellert *et al.*, “Simulation of Trajectory Correction in Early Commissioning of the Advanced Light Source Upgrade”, in *Proc. IPAC'18*, Vancouver, BC, Canada, Apr. 4,, pp. 4256–4258, doi:10.18429/JACoW-IPAC2018-THPMF078

[6] A. Terebilo, “Accelerator toolbox for MATLAB”, presented at the Workshop on Performance Issues at Synchrotron Light, Sources Berkeley, California, October 2-4, 2000