ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB260

OPTICS CORRECTIONS WITH LOCO ON SIRIUS STORAGE RING

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Abstract

Sirius is a 4th generation 3 GeV synchrotron light source at the Brazilian Center for Research in Energy and Materials (CNPEM). In this work, we report the results of linear optics and coupling corrections during the commissioning of Sirius storage ring, using the Linear Optics from Closed Orbits (LOCO) algorithm. Beam-based measurements were performed to verify independently the impact of corrections on storage ring parameters.

INTRODUCTION

Sirius is a 3 GeV synchrotron light source in Campinas, Brazil, that has just finalized the first commissioning stage. With a 4th generation storage ring which uses a 5BA magnetic lattice, the design emittance is 250 pm rad. The 518 m circumference with twenty 5BA arcs provide an optics with 15 low-β_x and 5 high-β_x straight sections [1, 2]. The linear optics functions for one superperiod of the Sirius magnetic lattice are shown in Fig. 1.

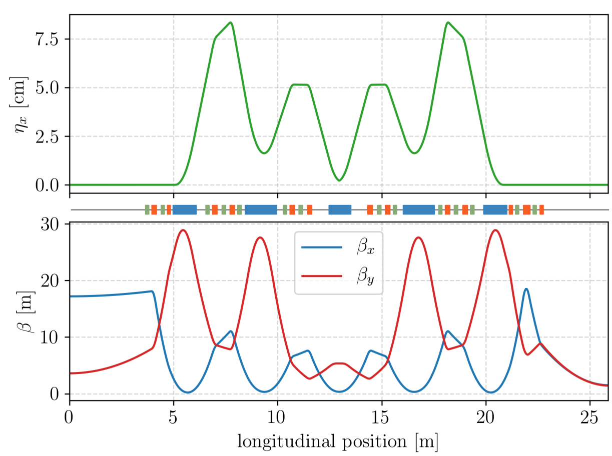

Figure 1: Lattice functions for one 5BA cell for the Sirius storage ring with a high-β_x straight section on the left and a high-β_x on the right.

LOCO is a model-dependent algorithm that fits the Orbit Response Matrix (ORM) measured in the machine to obtain a calibrated accelerator model [3]. LOCO has been applied to several synchrotrons over the years and has been proven to be an efficient tool to accomplish the task of optics correction [3–13]. The focus of this work is, based on the Sirius calibrated model with LOCO, obtain the corrections that push the machine optics parameters closer to the nominal.

In this work we report the first applications of LOCO algorithm during Sirius commissioning. The results presented in this paper are discussed in more detail in [14].

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SIRIUS LATTICE AND LOCO ALGORITHM

A schematic view of the 5BA magnetic lattice used in the Sirius storage ring can be viewed in [1, 2]. The total number of quadrupoles in the ring is 270. The quadrupoles magnets are divided in 12 families whose main coils are fed by grouped power supplies. In addition, each quadrupole has trim coils that allow for individual gradient settings.

The slow orbit correction system has 160 BPMs, 120 horizontal and 160 vertical correctors. The RF frequency is also used in the correction loop to correct beam energy variations through orbit length. With 320 orbit readings in BPMs (horizontal and vertical) and $(120 + 160 + 1) = 281$ orbit correct knobs, the Sirius ORM dimension is 320×281. The coupling control system has 80 skew quadrupoles.

The LOCO cost function is the difference between the ORM calculated with the model and the measured ORM:

$$\chi^2 = \sum_{i,j} \left(\frac{M_{ij}^{\text{measured}} - M_{ij}^{\text{model}}}{\sigma_i} \right)^2 =: \sum_{k=(i,j)} V_k^2, \quad (1)$$

where σ_i is the measurement noise for the i-th BPM. The problem can be numerically solved by applying least-squares methods. For example, with the Levenberg-Marquardt (LM) method [15, 16], the parameters variations that minimize the 2-norm of the residue vector $\vec{V}$ are calculated by solving

$$\left(\mathbf{J}^\mathsf{T}\mathbf{J} + \lambda \operatorname{diag}\left(\mathbf{J}^\mathsf{T}\mathbf{J}\right)\right) \Delta\vec{P} = -\mathbf{J}^\mathsf{T}\vec{V}, \quad (2)$$

where $\mathbf{J}$ is the jacobian matrix. If $\lambda = 0$, Eq. (2) reduces to the Gauss-Newton (GN) method.

A Matlab based version of LOCO compatible with Accelerator Toolbox (AT) is available [17]. However, the predominant programming language used in Sirius machine control system and high level applications is *Python* [18]. Moreover, the LNLS Accelerator Physics Group has been developing accelerator modeling and simulation codes in *Python* over the last years. Therefore, implementing an in-house *Python* version of LOCO for Sirius was an idea that came quite naturally to facilitate the integration with the control system. Currently this LOCO implementation is a *Python* package (the source code is open to access in [19]) and the fitting results are analyzed via *Jupyter Notebook*. The tests performed to validate the implemented code are reported in [14].

Constraints in Quadrupoles Variations

For compact magnetic lattices, adjacent quadrupoles might have similar signatures in the ORM, then becoming quasi-degenerated fit parameters for LOCO. In this case, the fitting may provide a solution with unrealistic large variations for the quadrupoles. Singular values selection might

12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB260

be a strategy to circumvent the degeneracy problem. However, finding the best set of selected singular values may be a very heuristic and time consuming process [4]. A more effective approach is including the quadrupole variations in the minimization problem as a constraint [15, 16]. The constraints can be included in the minimization problem by:

$$\chi_c^2 = \chi^2 + \frac{1}{\sigma_{\Delta K}^2} \sum_q \left(w_q \Delta K_q\right)^2 \tag{3}$$

where $\sigma_{\Delta K}$ is a normalization constant, w_q are individual weight factors and χ^2 is defined in Eq. (1).

To demonstrate the importance of applying constraints in quadrupole variations for LOCO on Sirius, two ORM fits were performed. In the first fit, LOCO ran with GN minimization method and without constraints. In the second fit, the LM method was used setting $\lambda = 1 \times 10^{-3}$ initially and the constraints were applied in the quadrupoles. The residue vector versus the accumulated relative quadrupole variations over the iterations is shown in Fig. 2. The final quadrupole variations around the storage ring for each fit are plotted in Fig. 3. Based on the results shown in Fig. 2 and

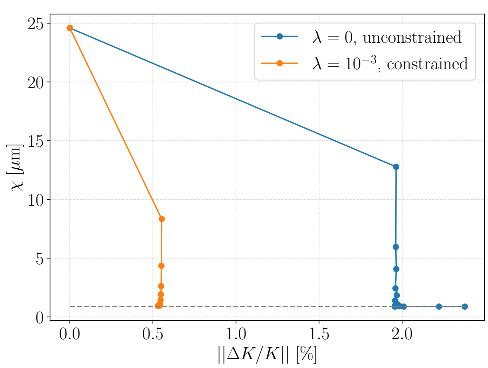

Figure 2: χ versus $||\Delta K/K||$ throughout 10 fitting iterations. The gray dashed horizontal line corresponds to $\chi = 0.9$ µm, the value used as reference for convergence.

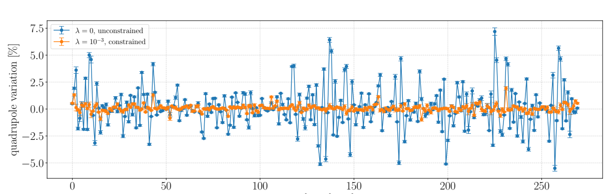

Figure 3: Comparison of quadrupole variations obtained from LOCO with two calculation methods.

Fig. 3 it is clear that the same level of ORM fitting can be achieved in both cases, with the advantage of much lower (and more realistic) variations on the quadrupoles for the fitting with constraints.

OPTICS CORRECTIONS

Considering that the constraints in quadrupoles must be applied in the LOCO algorithm for Sirius, the fitting setup discussed in the previous section (LM method and constraints in quadrupoles) was chosen as default for the optics corrections. The ORM measurement time for the storage ring is 25 minutes.

Since the Sirius ORM is a 320 × 281 matrix, the number of data points to be fitted with LOCO is 89920. The fit parameters used were quadrupoles and skew quadrupoles gradients, BPMs and correctors gains and BPMs roll angle errors. These parameters add up to 1100 knobs. The LOCO fitting was iterated three times in the machine until convergence and the results are shown in Table 1.

Table 1: LOCO fitting progress: ORM residue and knobs variations

Iteration	χ [µm]	Quad. [%]	Skew Quad. [km^{-1}]
# 1	24.6	0.33	2.7
# 2	2.7	0.21	0.5
# 3	2.1	0.07	0.4

The measured BPM noise was 0.25 µm. The differences between the ORMs obtained with the calibrated model and the measured ORM were 0.9 µm, indicating that there are systematic errors in the ORM measurements that still demand investigation to be mitigated [3]. The BPMs and correctors gains fitted were not a major concern at the time, since the fitting provided reasonable results. Applying constraints in the BPMs gains fitting is being considered to obtain more reliable gains that can be used in the control system, for example.

The dispersion function was included in LOCO by fitting the orbit response due to RF frequency variation. Furthermore, an appropriated weight factor was necessary to fit and correct the measured dispersion. When this factor was not used, the solution reproduced the correctors part of the measured ORM but not the dispersion. Applying this solution to the machine actually increased the dispersion errors. When the dispersion weight factor was large, the measured dispersion was better reproduced with the model by the cost of degrading the fitting of the ORM columns related to the correctors. Consequently, applying this solution to the machine increased the betabeatings.

BEAM-BASED MEASUREMENTS

A set of beam-based measurements were performed before and after the optics corrections to check independently the effects of pushing the measured ORM close to the nominal with LOCO.

The comparison for the dispersion (horizontal and vertical) is shown in Fig. 4. It can be seen that the η_y error could not be reduced with the same effectiveness as η_x. This is a consequence of the poor fitting of the measured η_y with LOCO that still needs investigation.

The betatron function was measured with the individual quadrupole variation method and the betabeating was calculated. The results are shown in Fig. 5. The beta func-

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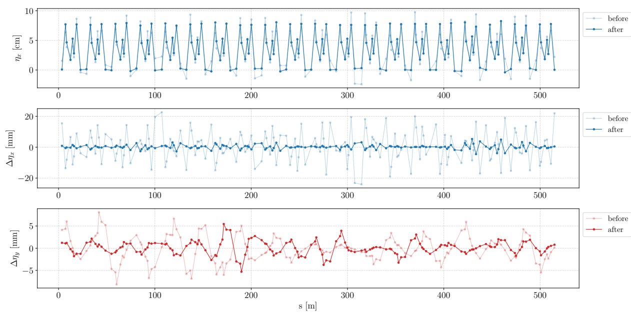


Figure 4: Dispersion functions measured at BPMs before and after LOCO.

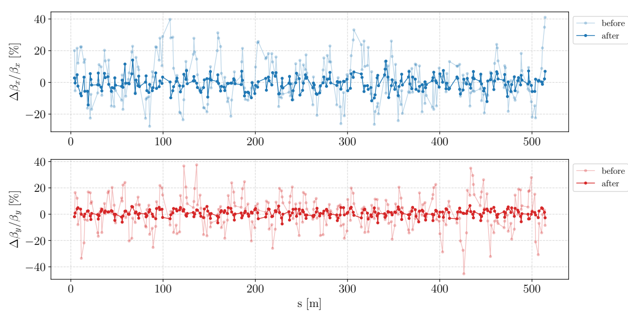
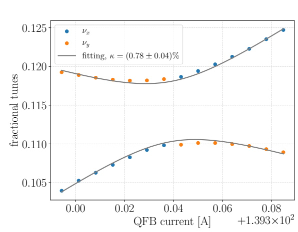


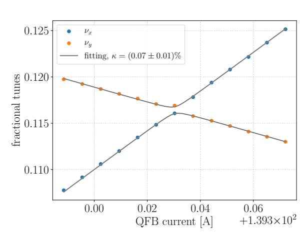
Figure 5: Betabeating measured at quadrupoles before and after LOCO.

tions at BPMs were also obtained with turn-by-turn measurements [20] and the improvement in the betabeatings was comparable with the values obtained for the quadrupoles.

The global betatron coupling was measured by the closest tune approach, where the strength of a quadrupole family (QFB) was varied to approximate the betatron tunes. The results are shown in Fig. 6. The measurements showed that minimizing the ORM off-diagonal blocks implies in an expressive reduction of global coupling.



(a) Before.



(b) After.

Figure 6: Global betatron coupling before and after LOCO.

Finally, the horizontal dynamic aperture (DA) was measured by exciting the electron beam with a horizontal pinger. The relation between beam survival rate and the minimum x position (using the BPMs turn-by-turn data) was registered for increasing values of kick amplitude applied by the pinger. The result of this measurement is presented in Fig. 7. Beam accumulation in Sirius storage ring occurs by injecting off-axis at $x = -8$ mm with a NLK. As expected, the

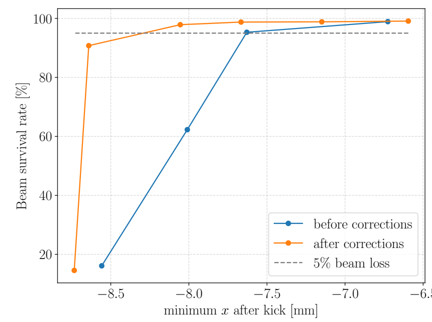


Figure 7: Horizontal DA before and after LOCO. The gray dashed horizontal line corresponds to 95 % of beam survival rate used to define the DA border.

improvement in the horizontal DA obtained with the optics corrections had a positive effect on the injection efficiency. This and other beneficial effects of the coupling and optics corrections are summarized in Table 2.

Table 2: Summary of LOCO corrections effects on storage ring parameters

Parameter	**Before Corr.**	**After Corr.**
$\Delta\beta_x/\beta_x$ (std)	13.8(8) %	4.5(8) %
$\Delta\beta_y/\beta_y$ (std)	13.0(5) %	2.8(5) %
$\Delta\eta_x$ (std)	10.5(2) mm	1.5(2) mm
$\Delta\eta_y$ (std)	2.9(3) mm	1.6(3) mm
H. Dynamic Aperture	−7.6 mm	−8.3 mm
Inj. Efficiency (mean)	20 %	78 %

CONCLUSIONS AND PERSPECTIVES

The implemented LOCO algorithm in *Python* was tested and applied to the Sirius storage ring during the commissioning. The corrections improved the optics symmetry, reduced the betatron coupling and increased the dynamic aperture and injection efficiency. The implemented code have been used over the last year to analyze and correct the Sirius linear optics and LOCO will be applied regularly during Sirius machine studies and operations. Nevertheless, the correspondence between the predicted parameters with the calibrated model and the measured parameters still requires further investigation to be improved. This study is planned to be extended to cover Sirius non-linear optics using a LOCO-like approach to analyze off-energy ORM measurements.

ACKNOWLEDGEMENTS

The author would like to thank the LNLS Accelerator Physics Group members for all the fruitful discussions and support during the machine studies that resulted in this work.

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ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB260

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