ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOTK004

STATUS OF THE SOLEIL UPGRADE LATTICE ROBUSTNESS STUDIES

O.R. Blanco-Garcia*, D. Amorim†, M. Deniaud‡, A. Loulergue, L. S. Nadolski, R. Nagaoka
Synchrotron SOLEIL, L'Orme des Merisiers Saint-Aubin, BP 48 91192 Gif-sur-Yvette Cedex, France

Abstract

The SOLEIL synchrotron has entered its Technical Design Report (TDR) phase for the upgrade of its storage ring to a fourth generation synchrotron light source. Verification of the equipment specifications (alignment, magnets, power supplies, BPMs), and the methodology for optics corrections are critical in order to ensure the feasibility of rapid commissioning restoring full performance for daily operations. The end-to-end simulation, from beam threading in the first turns to beam storage and stacking, should be handled with a comprehensive model close to the actual commissioning procedure, taking into account all practical steps. During 2021 and 2022, the CDR lattice has undergone significant modifications in response to additional constraints. In this paper, we present an update of the robustness studies for the TDR baseline lattice.

INTRODUCTION

The SOLEIL Upgrade project aims to design and build a 2.75 GeV diffraction-limited synchrotron light source preserving the actual infrastructure, 29 beamlines (far-IR to hard X-rays) and the 500 mA uniform filling pattern. The lattice of the new storage ring presented in CDR report [1] is built over a non-standard combination of twelve 7BA cells and eight 4BA cells compliant with strong geometric constraints to produce a 80 pm rad natural emittance. The lattice can accommodate 20 straight sections (18 devoted for insertions devices) where the betatron functions at their centers are minimized to be closed to the matching value [1]. The compact injection uses a Multipole Injection Kicker (MIK) to inject the beam off-axis in the horizontal plane in a quasi-transparent way [2]. During the TDR phase significant modifications have been introduced leading to a new reference lattice [3]. The short straight sections were extended in order to allow the use of the existing in-vacuum insertion device, the tunability of the lattice has been improved, first mechanical integrations were considered, two double-waist mini-beta sections were introduced with addition of a quadrupole triplet at their centers and a magnetic chicane for one of them to host canted in-vacuum undulators. Table 1 shows the main parameters of the new TDR lattice (see [3]).

As a part of the study program for the new storage ring, the robustness studies have been refined from the work already presented in the CDR phase [4]. The present study should analyze the impact of assumed errors on the ring performance. In particular: a) ensure the possibility of on-axis (first day) and then off-axis injection (standard operation) b) guarantee the feasibility of the storage ring commissioning [orbit correction, Beam Based Alignment (BBA), correction of beta-beating, restoration of lifetime, emittance, coupling, etc.] to achieve full performance for daily operation, c) validate the selected correction schemes and corrector maximum strengths via end-to-end simulations, d) verify that the equipment tolerance specifications are consistent with commissioning and future operation, e) identify possible showstoppers and additional equipment constraints. We present in this article preliminary results on the best performance achievable under the current assumptions.

Table 1: Parameters of the SOLEIL TDR lattice

Parameter, Unity	**Value**
Lattice	TDR V0356 7BA/4BA
Energy, GeV	2.75
Circumference, m	353.92
Symmetry/Cell Number	2/96
H. Natural Emittance, pm rad	84.4
V. Emit. (30 %H. Emit), pm rad	25.3
Tunes (H/V/L)	54.2/18.3/0.00210
Energy Spread, %	0.091
Bunch Length, ps	8.5
Harmonic Number	416
Main RF Frequency, MHz	352.382
Energy Loss per turn, keV	458.5
Main RF Voltage, MV	1.8
Natural Chromaticities H/V	-118.1/-56.2
Operation Chromaticities H/V	+1.6/+1.6
Momentum Compaction Factor	1.05×10^{-4}
Damping Time H/V/L, ms	7.7/14.4/12.2
Touschek Lifetime (500 mA), h	2.5

LATTICE LAYOUT

The studied lattice is a composition of twelve 7BA, eight 4BA arc sections and two mini-beta sections with chicanes, where all dipoles and reversed bends are permanent magnets. Quadrupole magnets are either permanent or electromagnetic. The maximum current is 500 mA in a uniform filling pattern. An initial (first day) on-axis injection, with no possibility of beam accumulation, can achieve maximum 1 to 3 mA in the ring on 104 consecutive bunches. After the initial steps in the ring commissioning, the Multipole Injection Kicker (MIK) is expected to be used for off-axis as principal injection and to allow accumulation.

For this study we consider 214 girders, 180 BPMs, 180(180) dipolar horizontal(vertical) correctors, and 412(412) normal(skew) quadrupolar correctors (Fig. 1).

* oscar-roberto.blanco-garcia@synchrotron-soleil.fr
† now at CERN
‡ now at Royal Holloway, University of London

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOTK004

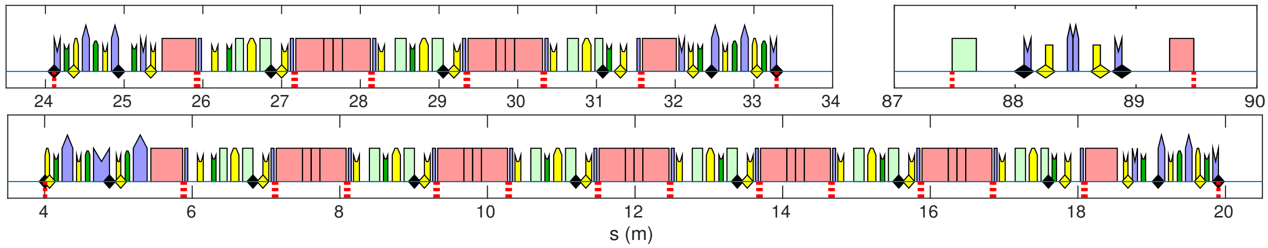

Figure 1: Layout of the SOLEIL Upgrade TDR lattice with (TOP-LEFT) 4BA, (BOTTOM) 7BA arc cells and (TOP-RIGHT) mini-beta sections with chicane. Permanent dipoles and reverse bends are shown in light-red and in light green, respectively. Sextupoles are in yellow, where 180 of them have a dipolar corrector and are marked with a diamond at their feet. Quadrupoles are shown in light-blue and octupoles in dark green; all 216 octupoles and 196 electro-magnetic quadrupoles (412 in total), each one aside of a sextupole, are used for linear optics corrections, while a subset of 180 near a dipolar corrector is used for BBA. BPMs are shown as black diamonds. Girder limits are shown as negative red marks.

The physical aperture of the machine has been modeled as circular apertures having 12 mm in diameter in the 7BA and 4BA arc cells. Open insertions in straights, are 8 mm in diameter except in the long straight sections which are 12 mm. The injection section aperture adapts to the optics; in it, the MIK, has smallest vertical aperture, it is rectangular and measures 14 and 7 mm in the horizontal and vertical plane, respectively. In the horizontal plane, the thin septum has the smallest horizontal aperture of −5 mm towards the inner side of the ring. In-vacuum undulators are open, while, photon absorbers, scrappers and collimators are not yet considered.

SET OF ERRORS

The error budget is shown in Table 2. The random distribution has been truncated at 2-sigma gaussians, except for the girder distribution which is truncated a 1-sigma gaussians. The BPM reading errors are specified for a minimum current of 0.1 to 1 mA, and their calibration will be corrected in later stages of the commissioning when the optics correction (LOCO) is performed. The injection errors have a systematic component (Stat.) that is preserved over the entire on-axis injection simulation, while a jitter component (Jit.) is assigned to each injection pulse. The injected beam size, σ_{inj}, corresponds to a horizontal and vertical emittance of 5 and 0.5 nm rad, respectively, matched to the optics parameters at the injection point (see [3, 5]).

Table 2: RMS error budget for alignment, BPM, injection.

Magnet, Girder, RF	**RMS**	**BPM**	**RMS**
Girder H/V	50 µm	Offset	500 µm
Magnet H/V	30 µm	Roll	100 µm
Girder Roll	60 µrad	Noise (TbT)	500 µm
Magnet Roll	50 µrad	Noise (CO)	1 µm
CM calibration	5%	Calibration	10%
Magnet Cal.	0.1%		
RF Voltage	5 kV		
RF phase	60°		
RF frequency	100 Hz		

Inj. Axis	**Stat.(Jit.)**	σ_{inj}	**Inj. Axis**	**Stat.(Jit.)**	σ_{inj}
x, µm	500	253	$\Delta E/E$, %	0.5 (0.01)	0.09
x', µrad	100 (25)	20	ϕ, °	10 (0.1)	3.2
y, µm	500	37			
y', µrad	100	14			

CORRECTION STRATEGY

In the simulation the initial lattice is modified to include girders, BPMs, correctors and their errors using Simulated Commissioning (SC) [6, 7]. The beam dynamics is simulated with AT [8, 9], while the LOCO routine is part of MML [10]. These studies require parallel computation resources, therefore, an internal server has been configured with SLURM [11] as a job sequencer, and parallel functionalities in Matlab [12], as well as Jupyter [13], Pandas [14], Seaborn [15], Matlab and pyAT [16] for data analysis.

In order to study the probability of the beam dynamics restoration, we simulated 30 machines with a random set of errors using the values previously described. We have included the effect of radiation damping and the 6D tracking to estimate the Dynamic Aperture (DA), and the Momentum Aperture (MA). We set two simulation approaches: the first considers a set of realistic BPM errors for the first stages of the commissioning, while, the second considers ideal BPMs in order to analyze the best possible performance of the BBA and LOCO procedures.

The dipole corrector force is limited to 0.5 and 0.3 mrad in the horizontal and vertical planes, respectively, while the quadrupolar corrector force is not bounded. In addition, corrections have been simplified in simulations: first, the dipolar correctors are foreseen to be constructed as extra coils in 180 sextupole magnets (See Fig. 1), however, they are simulated as perfectly aligned and calibrated additional elements next to sextupole magnets; second, the 412 quadrupolar correctors foreseen to be realized in all octupoles and in the quadrupoles next to sextupoles are in simulations located inside the 412 sextupoles of the machine; at last, the simulation model contains only the main RF cavity and does not include the Harmonic cavity.

For these studies we keep sextupoles on. Every ring in the simulation will follow a step-by-step based procedure in or-

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der to restore the beam parameters: A) *On-axis* injection and trajectory correction up to first-turn correction, second-turn correction, and convergence, B) Tuning of the main RF system to store the beam which gives the first closed orbit (CO), C) closed orbit BBA and orbit correction, D) LOCO, E) Iterations of BBA, LOCO and orbit correction to improve the DA, thus, increasing injection efficiency F) Final performance evaluation.

From first turns to closed orbit There is less than 7% probability to achieve a first turn around the machine without trajectory corrections, and zero probability for a second turn, however, there is a high probability to perform a successful trajectory orbit correction and to find a closed orbit with reduced beam losses. Figure 2 shows the Beam Loss Cumulative Distribution Function (CDF) during the early commissioning steps and the expected D.A. when beam is stored. The closed-orbit correction improves the D.A. due the reduction of the BPM noise w.r.t. to the Turn-by-Turn (TbT) operation mode (see Table 2).

BBA results A closed orbit BBA procedure with 180 BPMs has been conceived to reduce the orbit deviation w.r.t. a set of 180 chosen magnet centers, close to each BPM. A preliminary analysis of the optics-beat due to defects in the lattice showed that sextupoles in the cell degrade the optics by the largest amount (beta-beat larger than 6% rms), therefore, a subset of 180 sextupoles was selected for the BBA procedure in the simulations; see Fig. 1. Table 3 show the median results of the BBA procedure with perfectly calibrated BPMs.

The number of BPMs is not enough to correct the beam trajectory in all magnets, leaving a residual orbit close to 50 µm rms in both planes. Furthermore, the limited dipole corrector force deteriorates the BBA result in 50% of the simulations. The induced optics errors need to be compensated by LOCO.

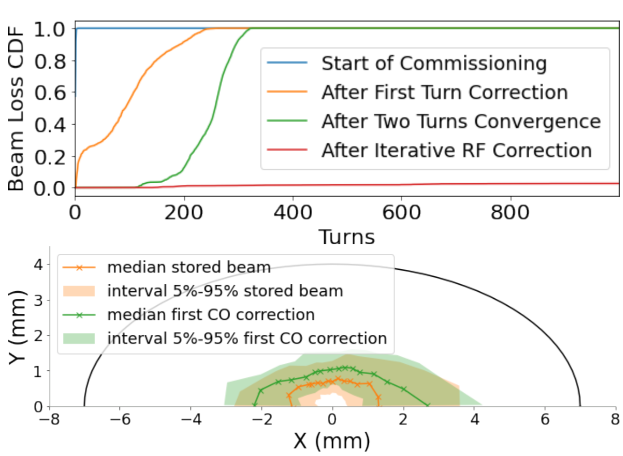

Figure 2: (TOP) Beam loss cumulative distribution as a function of the number of turns for 30 rings. (BOTTOM) Dynamic aperture during *on-axis* injection before BBA. Physical aperture is shown in black.

Table 3: RMS BBA residual closed orbit in μm.

Residual Closed Orbit	**Hor**	**Ver**
BPM readings wrt Golden	1.3	1.2
BBA magnet list	5.8	5.7
All elements	48.2	43.5

Final Performance Figure 3 shows the restoration of the DA and lifetime of the rings. The median of the machines achieve −4 mm of DA in the horizontal plane, which indicated a 50% likelihood to get 100% off-axis injection efficiency. The recovered momentum aperture is able to restore the Touschek lifetime up to 2.1 h for the median of the machines. The normal and skew quadrupole corrector force is in 95% of cases below 0.15 T, and in rare cases it reaches 0.8 T max.

CONCLUSION

Specific schemes of closed orbit, BBA and optics correction have been applied to the SOLEIL Upgrade TDR lattice design, and no major issues were identified for the first turns corrections. The DA after optics corrections does not give much margin to enable 100% injection efficiency. In spite of that, the restoration of the −4 mm horizontal DA is reached for 50% of the machines. The low BPM number induced significant residual closed orbit in between BPMs of approx. 50 µm rms, and results show that the limit in the dipolar corrector force deteriorates the orbit correction performance in 50% of the cases. The quadrupole corrector force used to restore the optics remains within the limits for 95% of cases.

Simulations will be improved with real positions of correctors, validation of the number of BPMs and correctors strength for a more realistic model to perform BBA, LOCO and orbit correction with error settings before and after stacking. Also, the inclusion of ID roll-off, multipoles and crosstalk between magnets is foreseen for next studies. Furthermore, increased statistics will be necessary to improve the model certainty.

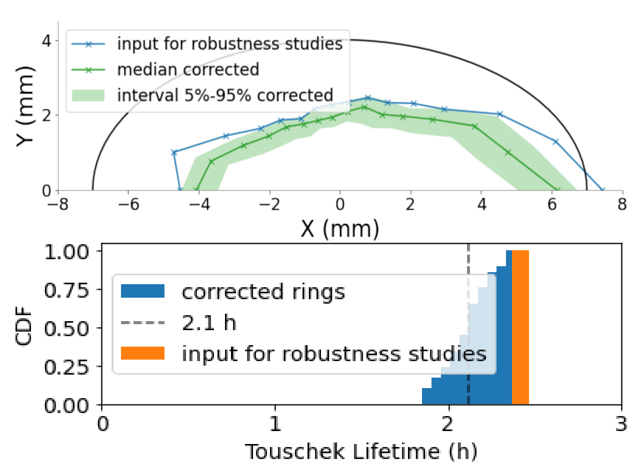

Figure 3: (TOP) DA and (BOTTOM) lifetime of the simulated machines, and the TDR as input for robustness studies.

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