ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB113

A LOW-EMITTANCE BOOSTER LATTICE DESIGN FOR THE SOLEIL UPGRADE

M.-A. Tordeux, A. Loulergue, R. Nagaoka
Synchrotron SOLEIL, L'Orme des Merisiers, 91 191 Gif-sur-Yvette, France
Z. H. Bai, T. Zhang, G. Liu
National Synchrotron Radiation Laboratory, USTC, Hefei 230029, China

Abstract

The SOLEIL storage ring upgrade will require an injected beam with small transverse and longitudinal sizes. To meet this requirement, the present booster also needs to be upgraded, aiming to reduce the emittance below 10 nm·rad. A multi-bend achromat lattice is designed in this context for the booster upgrade, which consists of two superperiods to respect the present race-track configuration. The lattice is a 16BA HOA (Higher-Order Achromat) type lattice, composed of 14 unit cells, 2 matching cells and a long straight section, and combined-function bending magnets are used in the unit cells to both save space and reduce the emittance. The natural emittance of the designed booster is 5.2 nm·rad at the final energy of 2.75 GeV. This paper presents the general constraints, linear lattice design and nonlinear dynamics optimization for the booster upgrade.

INTRODUCTION

SOLEIL is the French third generation light source routinely operated for users since 2007 with a low emittance electron beam of 4 nm·rad at an energy of 2.75 GeV. It provides a high intensity beam current, up to 500 mA, in multibunch and temporal structure (e.g. single and 8 bunches) modes. After nearly 14 years of successful operation, a series of feasibility studies are underway for a possible future upgrade of the storage ring lattice that would significantly reduce the emittance to 50 pm·rad in the full coupling mode [1, 2]. In parallel, injection studies into the new storage ring show the need to drastically reduce the transverse and longitudinal emittances of the booster injector [3]. A study of a new lattice design for the SOLEIL booster upgrade is therefore being undertaken in the frame of collaboration between SOLEIL and NSRL (Hefei).

SPECIFIC CONSTRAINTS

Two injection schemes into the storage ring upgrade are being studied [3], and both need typically a reduction of the natural emittance of the booster from the current value of 140 nm·rad [4] to less than 10 nm·rad, together with a reduction of the RMS bunch length from 50 ps to the range 25-35 ps at the extraction energy. The cycling frequency should remain the same as presently (3 Hz) to fulfil a flexible top-up injection, and the time structure modes of operation of the storage ring should be preserved. The betatron tunes working point should possibly be set on the coupling resonance, to allow an equal distribution of the emittance in the two transverse planes (see Table 1).

Table 1: Booster Upgrade Main Specifications

Parameter	Unit	Present booster	Upgraded booster
Circumference	m	156.6	156.46
Natural emittance	nm.rad	140	5-10
RMS bunch length	ps	50	25-35
Min.- max. energy	GeV	0.1-2.75	0.15-2.75
Betatron tunes	-	6.65, 4.58	Coupling res.
Max. RF voltage	MV	3.6	3.6
Max. cycling freq.	Hz	3	3
Mom. comp. factor	-	$2.8 \cdot 10^{-2}$	$> 3 \cdot 10^{-3}$

The new booster should locate in the same tunnel as the present one, respecting the current race-track configuration. The main difficulty will come from the reuse of the 2 current RF systems consisting of 2 copper units, each comprising 5 cells @ 352 MHz (LEP type) and occupying a significant space in a constrained location.

The rest of the injector complex will remain at the same position: the Linac and the first transfer line TL1 on one side and the second transfer line TL2 from booster to storage ring on the other side. As far as possible, the pulsed magnets at injection and extraction will be reused. The Linac will make hardware optimisations, essentially regarding the maximum beam energy available at the booster entrance (from 100 to 150 MeV), and the stability of this energy.

Care is taken with the value of the momentum compaction factor α. It should limit the excursion of the extracted beam energy each time the RF frequency of SOLEIL is modified. As a typical variation of ±1.5 kHz is observed every year on our present storage ring for thermal and operating reasons, and as the extracted beam energy relative variation should be preferably limited to $\pm 10^{-3}$, we propose to set an α value greater than $3 \cdot 10^{-3}$. The future storage ring will in fact be composed mainly of permanent magnets, which should decrease the RF frequency variation amplitude, but on the other hand the thermal drift of the booster itself will become an important issue compared to today. This latter will be considered after a thermal measurement campaign has been carried out on the present booster.

NEW BOOSTER LATTICE DESIGN

To reach the low emittance goal within the limited tunnel of the present booster, multi-bend achromat (MBA)

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB113

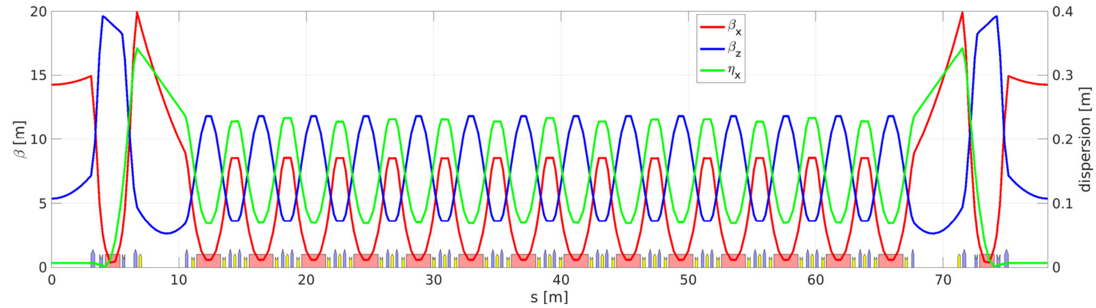

Figure 1: Optical functions and magnet layout of half of the designed lattice (red for dipole, blue for quadrupole, yellow for sextupole).

lattice was used. To both save space and further reduce the emittance, combined-function bending magnets were employed in the lattice design. The new booster has two superperiods to respect the present race-track configuration.

To achieve good nonlinear dynamics performance, the MBA lattice was designed with the higher-order-achromat (HOA) concept. It is a 16BA lattice based on a combination of three HOA type 5BA cells, in which the horizontal and vertical phase advances of each unit HOA cell of the 5BA are (0.3965, 0.1044)·2π. The early version of SLS-2 lattice [5] as well as a recent 6BA lattice developed in [6] had also been designed based on repetitive unit cells with the same phase advances. The HOA property was broken to some extent due to the constraint of inserting the two existing RF systems and thus leaving two short straight sections of at least 3 m length. In addition, their location is constrained by the current RF power source which will be preserved.

The designed lattice is shown in Fig. 1, which was optimized using a multi-objective particle swarm optimization (MOPSO) algorithm. It has 14 unit cells, two matching cells, a 6.2-m long straight section and two 3.44-m short straight sections. It is somewhat similar to the CDR-version design of the Diamond-II booster [7]. Figure 2 shows the enlarged view of the matching cell and unit cell. In the optics optimization, the maximum beta functions and dispersion were restrained as low as possible, and a special effort was made to fit the geometry of the designed booster to the present one. It was found that the bending angle of the matching bending magnet and the lengths of the two kinds of straight sections had a significant effect on the geometry fitting. There is no transverse gradient in the matching bending magnets, while the rest of the bending magnets are combined-function dipoles.

The main parameters of the designed booster are listed in Table 2. The natural emittance is 5.2 nm·rad, with a horizontal damping partition number of 1.58. Due to the low emittance, the momentum compaction factor is also relatively low, nearly one order of magnitude lower than the present value. The fractional parts of betatron tunes are the same to produce a fully-coupled beam. The horizontal tune is close to an odd number so that the nonlinear dynamics effects can be further cancelled over the two superperiods.

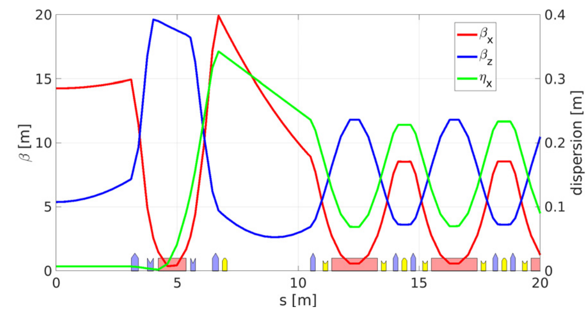

Figure 2: Enlarged view of the matching cell, the cell dedicated to the RF systems and the unit cells of the designed lattice.

Table 2: Main Parameters of the Designed Booster at 2.75 GeV

Parameter	Unit	Designed booster
Circumference	m	156.46
Natural emittance	nm.rad	5.2
Betatron tunes	-	13.19, 4.19
Natural chromaticities	-	-27, -12
Mom. comp. factor	-	$3.3 \cdot 10^{-3}$
Damping partitions	-	1.58, 1.0, 1.42
Natural damping times	ms	3.3, 5.2, 3.7
Energy loss per turn	keV	554
Natural energy spread	-	$0.93 \cdot 10^{-3}$
RMS bunch length	ps	25 @ 3 MV

The nonlinear dynamics was also optimized using the MOPSO algorithm. In the optimization, the objectives are to enlarge the dynamic aperture (DA) and to minimize the momentum dependent tune shifts. Four families of sextupoles are used, two near the short straight sections and two in the unit cells. The horizontal and vertical chromaticities were corrected to (1, 1). The DA and its frequency map analysis (FMA) are shown in Fig. 3. It is 40~50 mm in the horizontal plane. The tune shifts with momentum are shown in Fig. 4, and Fig. 5 shows the horizontal DAs for the relative momentum deviation range of -4%~4%. The off-momentum nonlinear dynamics is reasonable. In Fig. 5, the horizontal DA becomes smaller as momentum deviation decreases. This is mainly due to the dependence of beta function on momentum.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB113

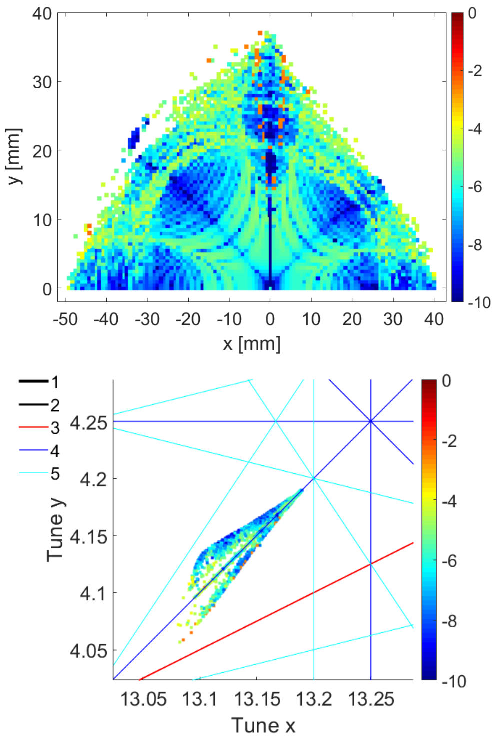

Figure 3: FMA of on-momentum DA. Upper: *x-y* space, lower: tune space. The color bar represents the tune diffusion rate.

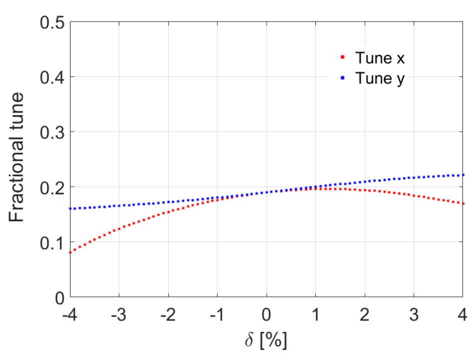

Figure 4: Momentum-dependent tune footprints with chromaticities corrected to (1, 1).

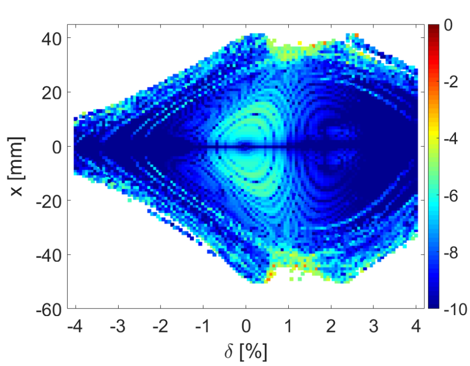

Figure 5: Horizontal DAs vs. momentum deviations.

Figure 6 shows the geometry fitting. The geometry of the designed booster is very close to that of the present one. The maximum transverse deviation is less than 10 cm in the short straight section, and about 0.1 cm elsewhere. The parameters of all magnets used in the lattice are moderate. At the maximum energy, the dipole field of the matching bending magnet is 1.29 T, and the dipole field and defocusing gradient of the combined-function bending magnet are 0.97 T and 3.79 T/m, respectively. The maximum gradient of the quadrupoles is about 28 T/m, and the maximum sextupole gradient (B″/2) is about 270 T/m2.

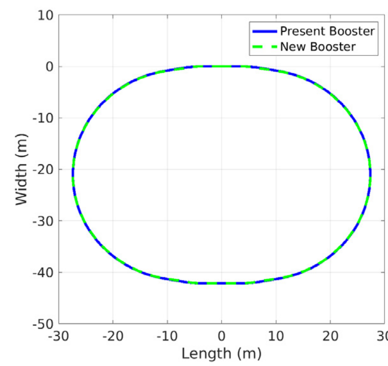

Figure 6: Geometry fitting of the new booster to the present one.

CONCLUSION

Upgrading the SOLEIL storage ring implies that the SOLEIL booster is also to be upgraded to provide a low-emittance beam. The new booster will be located in the same tunnel as the present one. To reduce the emittance, a 16BA lattice has been designed, based on the HOA concept for achieving good nonlinear dynamics. The designed lattice can well satisfy both the parameter requirements and the geometrical constraints for the new booster. The lattice has a natural emittance of 5.2 nm·rad and a large DA. The geometry fitting of the new booster to the present one is also very good. A further advanced design of the new booster is ongoing, considering now in detail the realistic space needed for the vacuum system, dipolar corrector system and diagnostics.

ACKNOWLEDGEMENTS

The authors thank Amor Nadji (SOLEIL) and Guangyao Feng (NSRL) for their support and encouragement of this ongoing collaboration.

REFERENCES

[1] Conceptual Design Report: Synchrotron SOLEIL Upgrade, 2021, in press.

[2] A. Loulergue *et al.*, "CDR Baseline Lattice for the Upgrade of SOLEIL", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper TUPAB054, this conference.

[3] M.-A. Tordeux *et al.*, "Injection Schemes for the SOLEIL Upgrade", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper MOPAB248, this conference.

[4] A. Loulergue *et al.*, "The New Booster Synchrotron for SOLEIL", in *Proc. 8th European Particle Accelerator Conf.*

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB113

(EPAC'02), Paris, France, Jun. 2002, paper TUPRI096, pp. 593-595.

[5] A. Streun *et al.*, "Proposed Upgrade of the SLS Storage Ring", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, paper WEPOW038, pp. 2922-2925.

[6] P. Yang, W. Li, Z. Ren, Z. Bai, and L. Wang, "Design of a diffraction-limited storage ring lattice using longitudinal gradient bends and reverse bends", *Nuclear Inst. and Methods in Physics Research, A*, vol. 990, p. 164968, Feb. 2021. doi:10.1016/j.nima.2020.164968

[7] L. C. Chapon *et al.*, "Diamond-II: Conceptual Design Report", Diamond Light Source, Oxfordshire, UK, 2019.