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STUDY OF HIGHER-ORDER ACHROMAT LATTICE AS AN ALTERNATIVE OPTION FOR THE SOLEIL STORAGE RING UPGRADE

R. Nagaoka, A. Loulergue, A. Bence, P. Brunelle, A. Gamelin, L. Hoummi, A. Nadji, L. Nadolski, M.-A. Tordeux, A. Vivoli
Synchrotron SOLEIL, Saint-Aubin, France

Abstract

A ring composed of 20 identical 7BA cells, where a pair of chromaticity correcting sextupoles is placed in each cell around the horizontal dispersion bumps *à la* ESRF-EBS was developed as a baseline lattice for the SOLEIL storage ring upgrade [1]. The strict betatron phase relation between the two dispersion bumps provides an efficient way of optimizing the (on-momentum) nonlinear optics with both a limited number and strength of sextupoles. As an alternative, a scheme known as Higher-Order Achromat (HOA) develops a MBA (Multi-Bend Achromat) lattice where chromaticity correcting sextupoles are distributed in each *M* unit cell with strict phase advances over the cell such as to cancel basic geometric and chromatic resonance driving terms. The beam dynamics in a 20-fold 7BA HOA ring is optimized and compared with those of the baseline lattice, with focus on off-momentum properties, which are important for medium energy rings such as SOLEIL. Robustness against errors, feasibility of reducing the ring symmetry by introducing 4 longer straight sections, as well as integrating a horizontal dispersion bump to cope with longitudinal on-axis injection scheme are also explored.

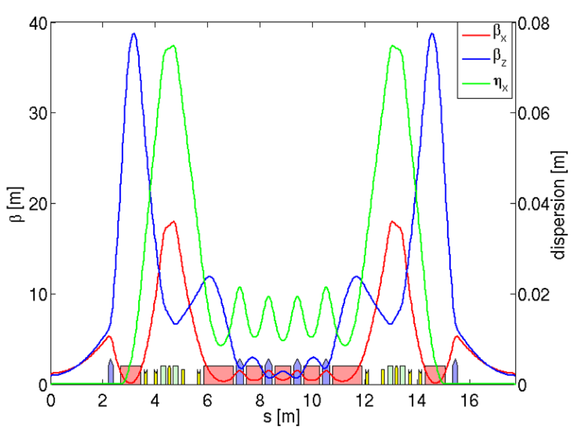

Figure 1: Baseline lattice: 20 × (ESRF hybrid type 7BA) presented in Ref. 1.

INTRODUCTION

For the upgrade of the 2.75 GeV SOLEIL storage ring to an ultra-low emittance ring (< 100 pm.rad), a 20×7BA lattice was designed as a baseline (Fig. 1) [1], employing the "hybrid" scheme developed at the ESRF. While the scheme employs the (-I) relation for pairs of chromaticity correcting sextupoles, an alternative known as the "Higher-Order Achromat (HOA)", composes M unit cells per a MBA cell, correcting the chromaticity locally in each unit cell with optimized betatron phase advances that suppress low-order sextupolar resonances. Inspired by the work made by S.C. Leemann et al. for ALS-U [2], the latter scheme is applied to SOLEIL to compare its performance and lattice properties with the former. The motivation of the present work comes to a large part from the observation of a significant reduction in the on-momentum dynamic aperture of the baseline lattice when the synchrotron motion is taken into account, arising from path lengthening of large-amplitude betatron motions.

LATTICE AND LINEAR OPTICS

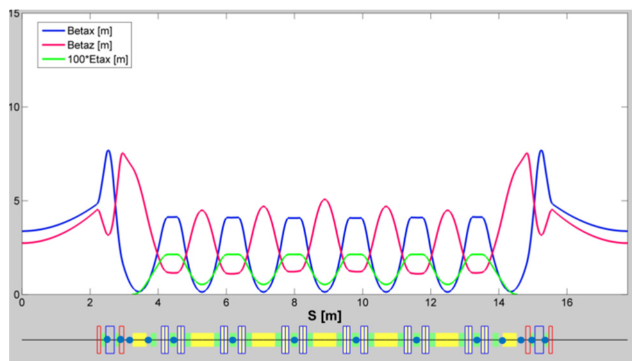

Figure 2: 20 × (7BA HOA lattice) studied in this contribution. Yellow - bends; Vertical rectangles - quads (red QD, blue QF); green - sextupoles; blue circles – octupoles.

In aiming at a horizontal emittance of below 100 pm·rad, the horizontal and vertical phase advances chosen in Ref. 2 of $2\pi \times$ (3/7, 1/7) across the basic unit HOA cell are found optimal for our lattice as well. Keeping the same boundary conditions as the baseline lattice, namely a ring composed of 20 identical 7BA cells with 4.4 m straight sections in between, the length available for the magnet section comes to be 13.31 m. Composing a HOA cell of 1.79 m with a combined function dipole in the center and two focusing quadrupoles (QFs) on each side and introducing five of which in a 7BA cell, 2.19 m is available for each matching section, where a *Q*-triplet, a dispersion suppressing dipole and a QF are introduced. The HOA cell in Fig. 2 has a dipole of 0.719 T with its gradient of 31.6 T.m^{-1}. The two QFs have 61.5 T.m^{-1} and a small reversed bend angle of 0.05°. Anticipating the need of strong chromaticity correcting sextupoles, QFs are split into two and the space in between them and between a QF and a dipole are reserved respectively for focusing and defocusing sextupoles whose lengths are of the order of 0.2 m. Dipoles in the matching sections are slightly shorter with field and gradient respectively of 0.638 T and 13.67 T.m^{-1}. The matching of the optics to the straight

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section is handled by a Q-triplet, where β_x and β_z at the center of a straight are adjusted to 2~3 m to have good matching of the phase space distribution of electrons with that of photons up to the photon energy of a few keV.

Table 1: Comparison of Basic Parameters

	Hybrid 20 cells	HOA 20 cells
Emittance (@2.75 GeV)	72 [pm.rad]	76.5 [pm.rad]
Circumference	353.1 [m]	354.2 [m]
Straight section	4.4 [m]	4.4 [m]
Straight Ratio	25%	25%
Working Point	(54.3, 18.3)	(64.2, 23.2)
Natural Chromaticity (H,V)	(-134, -125)	(-143, -62)
Mom. Comp. Factor α	1.5 10^{-4}	1.1 10^{-4}
Natural Energy Spread	8.6 10^{-4}	7.8 10^{-4}
Energy Loss/turn	310 [keV]	394 [keV]
Damping Times (H,V,S)	10/21/24 [ms]	10/17/12 [ms]

Two families of harmonic sextupoles are introduced in between the quads of a Q-triplet. While the original HOA-based 7BA cell described above have tunes of (3.240, 1.155), a slight retuning is made to (3.210, 1.160) with the Q-triplet to adjust the ring tunes to (64.20, 23.20). The major machine and beam parameters are listed in Table 1 in comparison with those of the baseline lattice. While most of them are comparable to those of the hybrid solution, the vertical natural chromaticity is nearly half of the former, and the horizontal damping partition factor J_x of 1.58 is notably smaller than 2.13 of the hybrid solution.

NONLINEAR OPTIMIZATION

As already stated, our interest in pursuing a HOA-based MBA lattice lies in exploring if the degradation of off-momentum dynamics present in the hybrid lattice along with its path lengthening that effectively spoils the on-momentum dynamics as well is better controlled in the latter thanks to the distributed correction of chromaticity. As good off-momentum performance is vital for a medium-energy ring such as SOLEIL, this is an important point of clarification as argued in Ref. 3. In fact, as to the path lengthening, the HOA lattice studied here exhibits a much smaller effect as shown in a companion paper [4]. On the other hand, since the smallness of dispersion in a HOA lattice renders sextupoles to be strong, whether the required strengths remain in the feasible range is another important point of investigation.

A simple configuration consisting respectively of 2 chromatic and 2 harmonic sextupole families generates sufficiently large on and off-momentum dynamic apertures (DAs) giving a Touschek lifetime of 15 hours as compared to 3 of the baseline lattice (for a 500 mA multi-bunch current). Upon a closer look, however, the tune shifts with momentum are unacceptably large crossing integer resonances which would not be tolerated with errors. A comparison of the robustness against errors between the baseline lattice and a HOA 20-cell lattice is made in a companion paper [5].

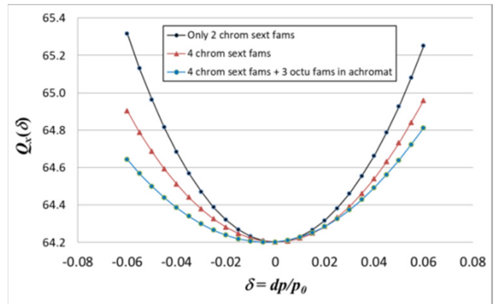

Figure 3: Horizontal momentum-dependent tune shifts for different sextupole and octupole settings.

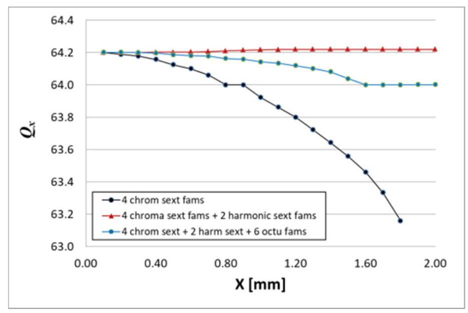

Figure 4: Horizontal amplitude-dependent tune shifts (ADTS) for different sextupole and octupole settings.

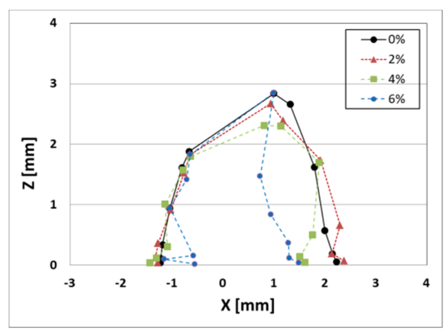

Figure 5: Dynamic aperture with 6D tracking with only a single pair of chromatic sextupoles.

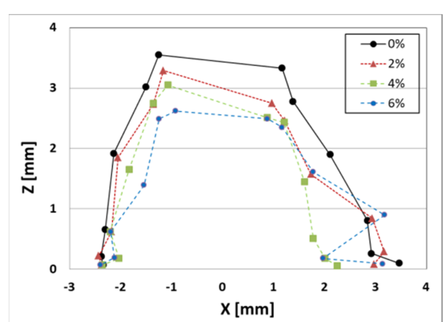

Figure 6: Dynamic aperture with 6D tracking with respectively 6 families of sextupoles and octupoles.

The above observations led us to develop a nonlinear optimization routine on the basis of "CATS-

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RACETRACK" platform [6-8], which is used in parallel with MOGA-BMAD developed by M. Ehrlichman [9]. Inspired by its use in MOGA-BMAD, the developed routine employs the so-called *QR-decomposition* that allows varing chromatic sextupoles under the constraint of keeping the chromaticities to imposed values. This feature is particularly useful in HOA lattices where there are many chromatic sextupoles without strict symmetry among them, and furthermore in treating a ring with reduced symmetry as shown later. Two functions were prepared involving sextupoles and octupoles: 1) Scan with imposed strength boundaries to find N (e.g. 10) best combinations that maximize (or minimize) a physical quantity (e.g. transverse DA). 2) Least-Square fit of selected physical quantities (e.g. nonlinear chromaticity, RDTs, ADTS, DA, …), which can well be momentum dependent and be defined in the 6D phase space (e.g. DA via 6D-tracking).

With the developed routine, outer chromatic sextupoles in the achromat were differentiated from the inner ones to create 4 families, by which the tune shift with momentum was improved to the extent as shown in Fig. 3 (black to red) with less than 20% of variation in strength. Though the above did not improve the large ADTS (Fig. 4, black), the two families of harmonic sextupoles managed to flatten the ADTS (Fig. 4, red). Adding 3 families of octupoles in the achromat, the tune shift with momentum could further be improved (Fig. 3, blue), at the cost of degrading ADTS. Finally, three additional octupole families were added in the non-dispersive section to improve on-momentum DA and ADTS. Improvement on 6D DA is seen in Figs. 5 and 6 between the initial (i.e. with 2 families of chromatic sextupoles alone) and the final (i.e. with respectively 6 families of sextupoles and octupoles) settings. The maximum strength required for sextupoles is $B''l/(2B\rho)$ = 155 m^{-2} (122 m^{-2}) and $B''/2$ = 7100 T.m^{-2} (6229 T.m^{-2}) (numbers in parentheses are averages). For octupoles, they are respectively $B^{(3)}l/(6B\rho)$ = 1364 m^{-3} (503 m^{-3}) and $B^{(3)}/6$ = 125000 T.m^{-3} (46000 T.m^{-3}). As expected, significantly higher strengths are required for this lattice especially for sextupoles as compared to the baseline lattice (in which $B''/2$ = 2000 T.m^{-2}) [1].

REDUCED SYMMETRY RINGS

Even though a high symmetry ring such as 20×7BA is most preferred from the beam dynamics point of view, it is not compatible with the existing requirement and present beamline geometry at SOLEIL. Continued efforts to explore lattices better fulfilling the demand and geometric constraints must be made. One such towards this direction is a symmetry 4 20-cell 7BA-HOA ring accommodating 4 longer straight sections of 6 m and reducing slightly the rest of 16 straight sections to 4 m. To integrate the longitudinal on-axis injection scheme originally developed in-house at SOLEIL [10], a dispersion bump of 8 cm in amplitude is introduced in one long straight section (Fig. 7). Nonlinear optimization of this reduced symmetry lattice is in process. Another set of solutions which appears highly attractive for the upgrade of SOLEIL is a symmetry 4 20-cell HOA ring composed of alternating MBA-NBA cells (e.g. M = 9 and N = 5), in which MBA cell deflects the trajectory by 22.5 and NBA cell by 11.25 degrees, in accordance to the present ring. This allows a much better matching of the present beamlines and preserves all the ratchet walls.

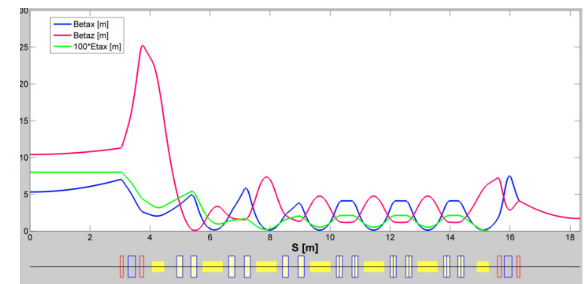

Figure 7: Symmetry 4 7BA HOA lattice with 8 cm of horizontal dispersion in the long straight to accommodate longitudinal injection [10].

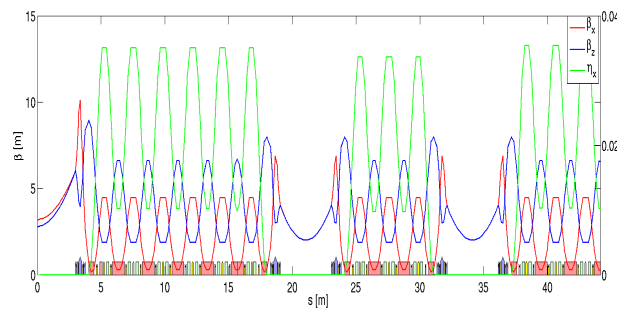

Figure 8: Symmetry 4 7BA-4BA HOA lattice (representing 1/8 of the ring).

Besides the fact that a large number of magnets is required for a HOA lattice, a 9BA-5BA lattice requires even stronger sextupoles than the 7BA shown earlier exceeding the limit of electromagnets. Since a scheme alternating 7BA and 4BA, Fig. 8, would relax this aspect, it is currently under study and seems promising in terms of beam dynamics. The initial horizontal emittance of 125 pm.rad is reduced down to 80 pm.rad by means of reversed-bends all along the unit HOA cells.

CONCLUSION

A 20-fold 7BA HOA lattice was studied as an alternative for the SOLEIL upgrade and compared to the baseline 20-fold 7BA hybrid lattice. Though nonlinear optimizations are more involved, HOA lattices appear capable of providing good beam dynamic properties for both on- and off-momentum, in contrast with the hybrid lattice. Being composed of HOA unit cells, there is more flexibility in fitting a ring into the existing geometric constraint by adjusting the number of HOA cells (such as the 7BA-4BA solution shown), even though some further elaboration on nonlinear optimization may be needed due to reduced symmetry. As a trade-off, however, sextupoles tend to be much stronger due to smaller dispersion and more magnets are needed as compared to hybrid (quadrupoles: 360 versus 200, sextupoles: 440 versus 160 for the two 20-cell 7BA solutions compared here).

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