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STUDY OF OPTIMAL MBA LATTICE STRUCTURES FOR THE SOLEIL UPGRADE

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Abstract

Within the context of a future upgrade of SOLEIL, the present paper reports on the low emittance lattice design studies made using 7BA and 6BA cells in the SOLEIL ring. With this combination of the MBA lattices, it is found that the horizontal emittance in the range below 200 pm·rad can be achieved by basically keeping the optical functions in the straight sections unchanged as in the previous 5BA-4BA solutions. In particular, a solution giving the horizontal emittance of 145 pm·rad with the use of longitudinal gradient bends (LGBs) is shown. On the other hand, the required transverse gradients in quadrupoles and combined dipoles as well as the chromaticities increase significantly as anticipated. Future directions including the ways to improve the encountered difficulties are considered.

INTRODUCTION

SOLEIL is the French third generation light source routinely operated for users since 2007 with a low emittance electron beam of 3.91 nm·rad in high intensity multibunch and temporal structure (e.g. 8 bunches) modes (cf. Table 1) [1]. After nearly 9 years of successful operation, a series of feasibility study is launched towards a possible future upgrade of the lattice with a significantly lower emittance. The approach taken is to employ whatever useful methods in lowering the emittance by fully respecting the geometric constraints such as the circumference of the ring and the available straight sections, so not to impact the existing insertion device based beamlines.

Table 1: Main SOLEIL Parameters as of Today

Energy	2.75 GeV
Circumference	354.097 m
Nominal current	430 mA (multibunch mode), 8×12 mA (8-bunch mode)
Horizontal emittance ε_x	3.91 nm rad
Adjusted emittance ratio	1%
Betatron tunes (ν_x, ν_z)	(18.174, 10.232)
RF frequency f_{RF}	352.2 MHz

As a first of such studies, the use of longitudinal field variations of superbends was attempted in a 4BA cell, finding a zero dispersion solution with the horizontal emittance ε_x of 0.98 nm·rad [2]. A particularity of SOLEIL is the short straight sections (SDCs) inserted between the dipoles of half of the 16 double-bend (DB) cells, to provide 8 additional straight sections for users. The SDCs however tend to limit the number (M) of dipoles introduced in those cells. Here we shall refer to cells with and without SDCs as SDM-SDC-SDM and SDL-SDM, respectively. In the second studies, a combination of 5- and 4BA was followed [3,4], where the use of longitudinal gradient bends (LGBs) allowed the emittance to reach 440 pm·rad [4]. In the framework of developing an optimal MBA lattice for SOLEIL, the axis towards the limit of the achievable lowest emittance must also be pursued. An approximate formula for the theoretical minimum emittance (TME) in a ring composed of alternating M_1BA and M_2BA cells may be given by

$$\varepsilon_x^{TME} = \frac{1}{8\sqrt{15}}\frac{C_q\gamma^2}{J_x}\theta_0^3\cdot\left\{\frac{1}{\left[2+(M_1-2)3^{1/3}\right]^3}+\frac{1}{\left[2+(M_2-2)3^{1/3}\right]^3}\right\}, \quad (1)$$

where θ_0 denotes the total bending angle per cell and other symbols have their usual meanings [5]. The above expression extends the derivation found in Ref. 6 for a MBA cell composed of 2 outer dispersion suppressing dipoles and (M-2) inner dipoles, all having the same field but differing in length between the two groups. The TME condition is imposed on each dipole. The optimal ratio between the inner and outer dipoles lengths to minimize the emittance is found to be $1/3^{1/3} \approx 0.69$ and is applied in the formula. Plotting the emittance for several different values of M_1 and M_2 in proportion to the relation given by Eq. 1, by normalizing the $M_1 = M_2 = 2$ case to the present SOLEIL value, suggests that an emittance lower than 200 pm·rad could be reached if a combination of 7BA and 6BA is considered (Fig. 1).

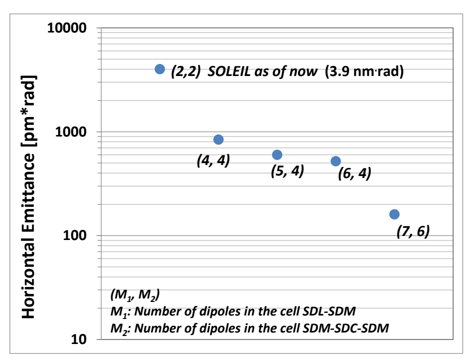

Figure 1: An estimate of attainable emittance in a lattice composed of alternating M_1BA and M_2BA using Eq. 1.

In the following, application of a 7BA-6BA lattice in the SOLEIL ring and obtained solutions are presented.

LATTICE STRUCTURE CONSIDERED

As already said, the SOLEIL ring with its extended DB lattice is optimized to provide as much as 46% of its

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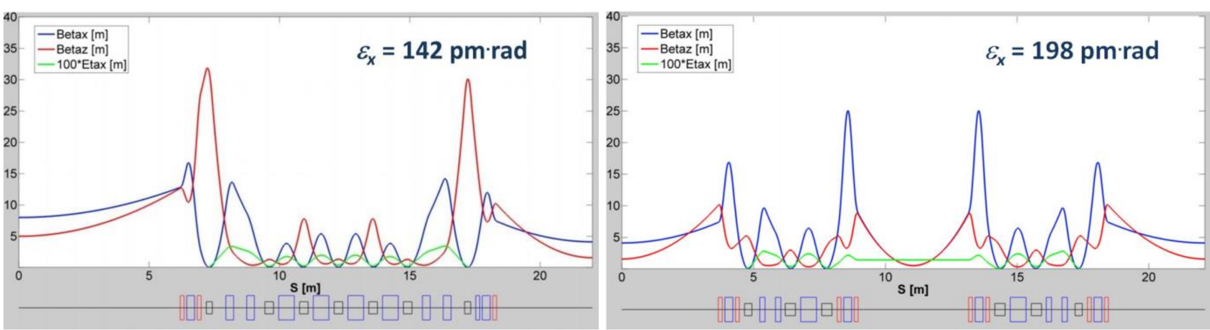
circumference available for free straight sections (SDs). This in turn signifies that the sections dedicated to magnets are relatively short; 12.5 m in SDL-SDM and 2×5.73 m in SDL-SDC-SDM. To keep space for more magnets to introduce, the dipole field in this study was left at the present relatively high value of 1.71 T. Namely, the total dipole length per cell remains to be 2×1.05 m. As in the previous studies, quadrupole triplets were placed at both ends of a magnet section for the flexibility of optics matching at SDs. All dipoles were assumed to integrate transverse gradients (i.e. defocusing quadrupoles). In accordance with the argument leading to Eq. 1, the two outer dipoles in an achromat were reduced in length by 30% with respect to the inner ones. Quadrupole doublets used in the previous 5BA-4BA lattice in between dipoles were replaced by a single focusing quadrupole to gain space. Finally, to let the horizontal dispersion grow in favor of the chromaticity correction, the distance between the outmost dipole and its adjacent one was enlarged and a quadrupole doublet was introduced in between (see the magnet arrangements shown in Figs. 2).

OBTAINED LINEAR SOLUTIONS

On the basis of the magnet arrangement made above, the linear optics matching for the combination of 7BA in the SDL-SDM and 6BA in the SDM-SDC-SDM cells was carried out. In particular, the solutions keeping the same values of betas at the long (SDL) and medium (SDM) straight sections as the previous 5BA-4BA case [4] were searched, finding ones giving 142 pm·rad (7BA) and 198 pm·rad (6BA), in good agreement with the expectation in Fig. 1 (Figs. 2). The imposed matching constraint at SDs implies, however, that the optics may not be fully optimized yet from the viewpoint of minimizing the contribution of each dipole to the emittance. The major lattice parameters and magnet characteristics are listed in Tables 2 and 3, respectively.

Following the exercise made previously on the 5BA-4BA lattice [4], the use of longitudinal gradient bends (LGBs) was attempted in lowering furthermore the emittance. Optimizing the longitudinal profile independently for each dipole allows gaining a significant reduction of typically more than a factor of 2 on the local emittance. It turned out, however, that the apparently small optics distortion generated by the additional focusing in dipoles cannot simply be recuperated by re-matching the optics without spoiling the horizontal emittance. The profile optimization was therefore made over the entire structure simultaneously. In the case of SDM-SDC-SDM, 3 dipoles on one side of the structure were fitted by splitting them into 8 pieces.



Figures 2: Lattice and envelop functions for the SDL-SDM (left: 7BA) and SDM-SDC-SDM (right: 6BA) cells, each giving the emittance of 142 and 198 pm·rad, respectively altogether representing 1/8th of the ring.

Since the natural beam energy spread σ_ε depends inversely on the square root of the radius of curvature and the longitudinal damping partition number J_ε, the use of 1.71 T field along with transverse gradients in dipoles already renders σ_ε to exceed the level of 10^{-3}. The longitudinal field variation was therefore limited to below 30% so as not to increase further σ_ε. For SDL-SDM, all seven dipoles were varied simultaneously by splitting them into 4 pieces. While the emittance of 129 pm·rad was obtained for SDL-SDM practically without affecting the optics, the emittance of 160 pm·rad was achieved for SDM-SDC-SDM, involving some modifications on the optics (Fig. 3). The overall emittance reduction attained is in the 10-20% range. With the last two solutions, the ring emittance reaches 145 pm·rad. The gain in the effective emittance as compared to the original SOLEIL optics is nearly a factor of 40 in SDL and SDM (dispersion-free sections) and 20 in SDC (Table 4). Since the longitudinal field variations introduced as above are in principle only effective in the particular optics chosen, the use of this option would require setting up a thoughtful strategy for the future definitive lattice.

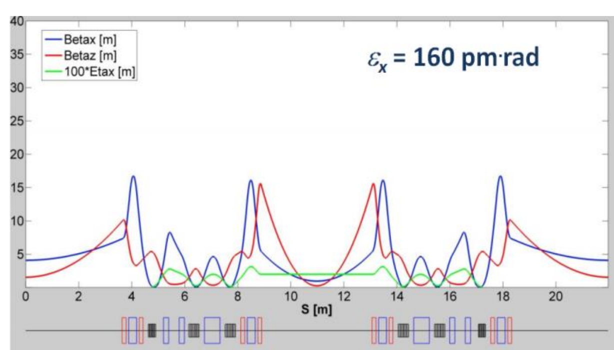


Figure 3: 6BA solution for SDM-SDC-SDM using LGBs, giving the emittance of 160 pm·rad.

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As anticipated, the focusing strengths required in quadrupoles and dipoles increased roughly by a factor of two as compared to the previous 5BA-4BA lattice, due primarily to the reduced lengths for these elements (Table 3). While quadrupoles exceeding 100 T/m could be relaxed by simply rendering them thicker, reducing the field gradient in dipoles reaching as high as 85 T/m would necessitate a more systematic restructuring of the lattice. The use of "anti-bends" as proposed in Ref. 7 to relax the overall focusing, as well as increasing the length of the magnet sections to a certain reasonable level may be explored among different possibilities. Likewise, an unfavorable increase results on the chromaticities. In particular, that in the horizontal plane rises by more than a factor of 2 as compared to the 5BA-4BA lattice, where the focusing quadrupoles in the Q-triplets are found to be responsible in enhancing the increase. While the increased contributions from the central TME-like sections appear less obvious to improve, means to reduce the contributions from Q-triplets must be studied in conjunction with the effort of lowering the overall focusing strengths as described above.

Table 2: Main Lattice Parameters including the Horizontal Emittance for the obtained 7BA and 6BA Solutions

Type of cell	SDL-SDM		SDM-SDC-SDM	
Cell length [m]	22.03		22.23	
ε_x [pm·rad]	142	**129**	198	**160**
Magnetic structure	7BA	7BA + LGBs	6BA	6BA + LGBs
Horizontal tune/cell $(\nu_x)_{cell}$	3.414	3.414	3.511	3.411
Vertical tune/cell $(\nu_z)_{cell}$	1.756	1.757	1.973	1.983
Horizontal chromaticity/cell $(\xi_x)_{cell}$	-13.0	-13.0	-20.9	-16.3
Vertical chromaticity/cell $(\xi_z)_{cell}$	-8.5	-8.5	-5.1	-6.4
Momentum compaction α ($\times 10^{-5}$)	6.0	5.7	6.1	5.8
Energy spread σ_ε ($\times 10^{-3}$)	1.10	1.10	1.08	1.09

Table 3: Main Characteristics of the Dipoles and Quadrupoles used in the obtained 7BA and 6BA Solutions

Type of cell	SDL-SDM		SDM-SDC-SDM	
Magnetic structure	7BA	7BA + LGBs	6BA	6BA + LGBs
(Dipole field $)_{min/max}$ [T]	1.71	1.36/1.96	1.71	1.36/2.17
Dipole length [m]	0.23/0.33		0.27/0.39	
Dipole gradient [T/m]	85	85	75	62/70/26
(Quadrupole field$)_{min/max}$ [T/m]	2.3/75	2.3/75	3.0/124	3.3/135

Table 4: Effective Emittance $[\varepsilon_x(s)]_{eff} \equiv \sqrt{\varepsilon_x^2 + H(s)\cdot\varepsilon_x\cdot\sigma_{\Delta p/p}^2}$ [pm·rad] in the Straight Sections, in Comparison with Those of the Original Optics

	SDL	SDM	SDC
Original optics	5340	5550	5580
7BA-6BA with LGBs	145	145	301
Ratio	37	38	19

SUMMARY

Adopting the combination of 7BA-6BA instead of 5BA-4BA studied earlier [3,4], a linear solution giving the emittance of 145 pm·rad was obtained by keeping the same optics at the straight sections SDLs and SDMs. As anticipated, however, the required focusing strengths in quadrupoles and dipoles, as well as the chromaticities increase significantly. Effective ways to reduce them in a 7BA-6BA lattice must be explored, including the anti-bend scheme proposed by A. Streun [7]. The above investigation is considered to constitute an important criterion for the feasibility of 7BA-6BA for SOLEIL. In parallel, the nonlinear dynamics optimization should be launched to assess whether the dynamic acceptance large enough to guarantee off-axis injection and long enough beam lifetime shall be available for this MBA lattice with reasonable strengths for the nonlinear elements, as preliminary studies have already been made for the 5BA-4BA lattice [4]. Through comprehensive studies and comparisons of the two sets of MBAs above, the most appropriate lattice for the SOLEIL upgrade is to be identified.

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