STUDY OF A LOWER EMITTANCE LATTICE AT SOLEIL

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Abstract

With the aim of lowering further the horizontal emittance of the SOLEIL ring, a study is made on the magnet lattice and linear optics by introducing superbends that associate longitudinal dipole field variations, under the constraint of leaving the circumference of the ring as well as the existing straight sections unchanged. A solution giving a sub-nanometer emittance and achieving more than a factor of 5 of reduction on the effective emittance is found with a QBA (Quadrupole Bend Achromat) lattice.

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 6 years of successful operation, a first feasibility study is launched towards a possible future upgrade of the lattice with a lower emittance.

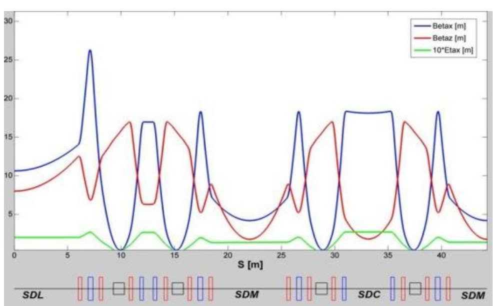

Figure 1: Original SOLEIL optics and the DB (Double Bend) lattice over 1/8th of the ring showing long (SDL), medium (SDM) and short (SDC) straight sections.

The approach taken is to make use of whatever methods effective in lowering the emittance, such as the genetic algorithm based scan in the tune space or introduction of a multiple bend achromat lattice and longitudinally varying dipole fields [2], but to fully respect the geometric constraints on the circumference of the ring as well as the available straight sections, in order not to impact the existing insertion device beamlines.

Table 1: Current Standard SOLEIL Parameters

Energy	2.75 GeV
Circumference	354.097 m
Nominal current	400 mA (multibunch), 8×12 mA (8-bunch mode)
Horizontal emittance	3.91 nm·rad
Controlled emittance ratio	1%
Betatron tunes	(18.18, 10.23)
RF frequency	352.2 MHz

As a first such study, the use of longitudinal field variation of superbends is attempted inspired by an earlier work of A. Streun [3], since at SOLEIL there are growing interests in the dipole beamlines for such dipoles as means to raise the photon energy.

EMITTANCE MINIMISATION WITH LONGITUDINALLY VARYING DIPOLES

Let us start from recalling the expression for the horizontal emittance familiarly given by,

$$\varepsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\oint H(s)/\rho(s)^3 ds}{\oint ds/\rho(s)^2} = C_q \frac{\gamma^2}{J_x}\frac{I_5}{I_2}, \quad (1)$$

where $C_q = 3.832\times10^{-13}$ m, γ is the relativistic factor, J_x is the horizontal damping factor, H is the so called H-function, I_2 and I_5 are the radiation integrals. It can be shown that if the bending radius ρ varies in a specific manner with the longitudinal position s, the theoretical minimum emittance (TME) can be decreased beyond that of a constant field dipole having the same bending angle [2]. Such benefit however associates an increase in the energy spread of a beam as inferred from the expression

$$\sigma_{\Delta p/p} = \left[\frac{C_q\gamma^2}{J_\varepsilon}\frac{I_3}{I_2}\right]^{1/2}. \quad (2)$$

Given a dipole profile $\rho(s)$, the expressions for TME are derived for both with and without the achromat condition in Ref. 2. In the former case, TME is given by

$$(\varepsilon_x)_{min} = C_q \frac{\gamma^2}{J_x}\frac{2\sqrt{S_1S_3 - S_2^3}}{I_2} \quad (3)$$

where S_i (i=1, 2 and 3) are integrals defined as

$$S_i = \oint \frac{F_i(s)}{\rho^3} ds \quad (4)$$

with $F_i(s)$'s given respectively by $F_1 = D'^2$, $F_2 = D'\cdot(D - sD')$ and $F_3 = (D - sD')^2$ with $D(s)$ the dispersion function satisfying $D(0) = D'(0) = 0$. TME in the latter case reads

$$(\varepsilon_x)_{min} = C_q \frac{\gamma^2}{J_x}\frac{2\sqrt{S_{01}(S_{03} - S_5^2/I_3)}}{I_2}, \quad (5)$$

where S_{0i}'s are respectively S_i's with a (pseudo) dispersion function $D_1(s)$ fulfilling $D_1 = D_1' = 0$ at the

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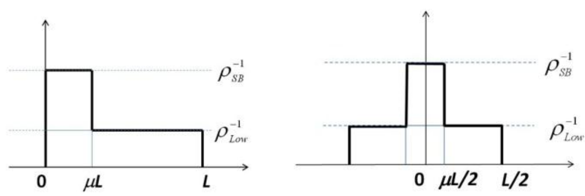
centre of a dipole, and F_5 for S_5 is given by $F_5 = D_1(s) - sD_1'(s)$ [2].

Following the work of A. Streun [3], a superbend is modelled with the hard-edged model, consisting of high (ρ_{SB}^{-1}) and low curvature (ρ_{Low}^{-1}) parts. Two types are considered here: One with its peak field at one end, which is optimal under the achromat condition, while another peaked at the centre, optimal under the non-achromat condition (Figs. 2).

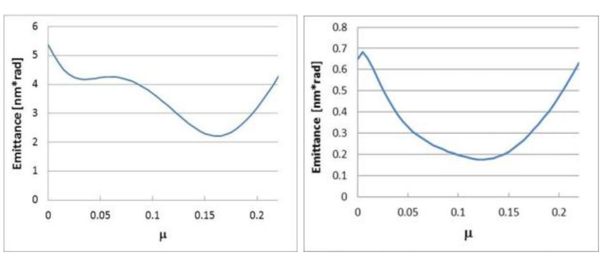


Figures 2: Asymmetric and symmetric profiles of the superbends field $\rho(s)^{-1}$ in the hard-edged model.

Given the total length L and bending angle Θ of a superbend, its high curvature ρ_{SB}^{-1} is assumed to extend over the length μL ($0 \leq \mu \leq \rho_{SB}\Theta/L$). The low curvature ρ_{Low}^{-1} is then constrained to be

$$\rho_{Low}^{-1} = \frac{1}{1-\mu}\left(\frac{\Theta}{L} - \rho_{SB}^{-1}\cdot\mu\right). \qquad (6)$$

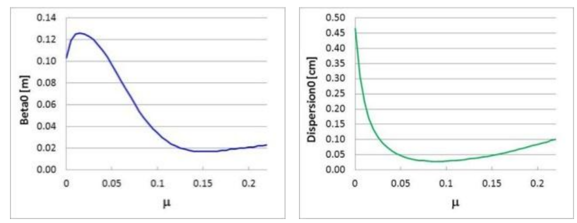
In the present study, ρ_{SB}^{-1} = 0.785 m^{-1} was assumed, corresponding to a peak field of 7.2 T employed in Ref. 3.



Figures 3: Left: TME of an asymmetric dipole under the achromat condition (Θ = 11.25°, B_{SB} = 7.2 T). Right: TME of a symmetric dipole without the achromat condition (Θ = 8°, B_{SB} = 7.2 T).

For a given set of L and Θ, the parameter μ was then swept to follow the attainable TME value, as well as the feasibility of optics matching (Figs. 3 and 4).

The strategy adopted in the lattice search was to have zero dispersion in the straight sections except for SDCs which are in the achromat (see Fig. 1), to avoid the effective emittance degradation due to the energy spread. It turned out that with an asymmetric superbend having the SOLEIL bending angle of 11.25°, TME does not go below 2 (Figs. 3 left), which led us to employ symmetric superbends along with dispersion suppressing dipoles, indicating the need of at least three dipoles per cell.



Figures 4: Beta and dispersion functions at the centre of a symmetric dipole of TME solutions without the achromatic boundary condition (Θ = 8°, B_{SB} = 7.2 T).

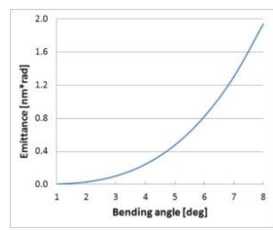
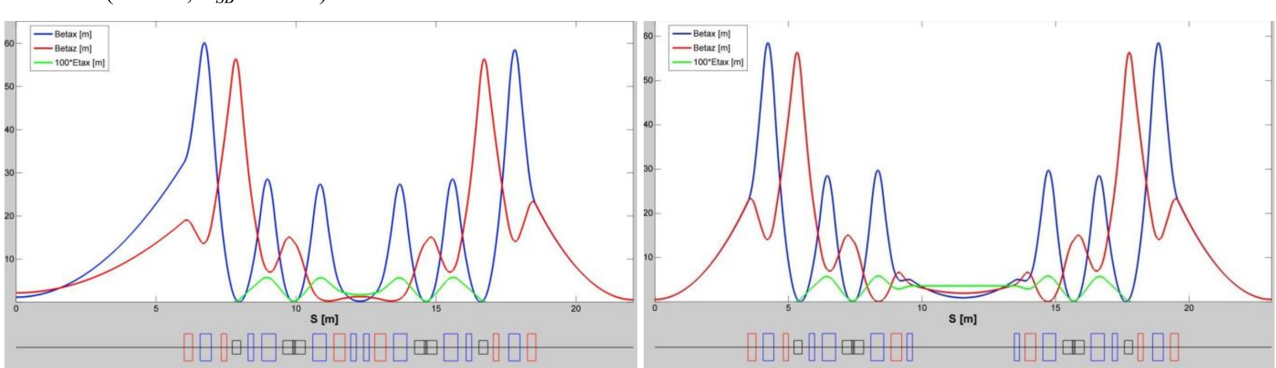


Figure 5: TME of a dispersion suppressing dipole as a function of its bending angle.

The bending angles of superbends and dispersion suppressors were partitioned in such a way that the emittance contribution stays equivalent between the two parties (Fig. 5).

OBTAINED RESULTS

The last finding actually implies the use of (at least) 2 superbends and 2 dispersion suppressors in the cell having SDC. A QBA (Quadruple Bend Achromat) lattice



Figures 6: Lattice and envelop functions for the SDL-SDM (left) and SDM-SDC-SDM (right) cells, altogether representing 1/8$^{\text{th}}$ of the ring.

Table 2: Summary of the Bending Magnets used (the Employed Field Gradients are not Shown).

	Θ [deg]	L [m]	High field			Low field		
			B_{SB} [T]	ρ_{BS} [m]	L_{BS} [m]	B_{Low} [T]	ρ_{Low} [m]	L_{Low} [m]
Superbend	8	0.8	7.2	1.273	0.1	0.8	11.460	0.7
Dispersion suppressor	3.25	0.304	1.71	5.36	0.304			

Table 3: Obtained Major Machine Parameters in Comparison with those of the Original SOLEIL Optics (in Squared Brackets). The values are calculated per cell.

	Cell SDL-SDM	Cell SDM-SDC-SDM
Horizontal emittance [nm·rad]	0.98 [3.85]	0.97 [2.67]
Energy spread	1.94×10^{-3} [1.02×10^{-3}]	1.94×10^{-3} [1.02×10^{-3}]
Momentum compaction factor	0.983×10^{-4} [4.836×10^{-4}]	0.941×10^{-4} [4.154×10^{-4}]
Betatron tunes	(2.805, 1.368) [1.110, 0.477]	(2.811, 1.717) [1.165, 0.811]
Natural chromaticities	(-29.36, -9.63) [-3.22, -1.15]	(-29.68, -12.25) [-3.34, -1.69]

was therefore pursued, finding a solution with an emittance of 0.97 nm (Figs. 6 right). Due to the strong horizontal focusing required and to the tight spatial constraint, introduction of transverse field gradient turned out to be vital in all dipoles.

For the SDL-SDM cell, a TBA (Triple Bend Achromat) structure was initially studied, which has a clear advantage of relaxing the spatial limitation. Although well behaving optics were found for emittances around 2 nm, the same was not true as 1 nm is approached, the origin of which was suspected to be the dispersion suppressors with a larger bending angle as compared to the previous QBA case. It was therefore decided to adopt the QBA structure used for the former cell, by squeezing the SDC. This choice is also beneficial in enhancing the consistency between the two cells. The optics solution found for the latter cell has the emittance of 0.98 nm, with the envelop functions behaving sufficiently similarly to the former ones (Figs. 6 left).

Table 4: The effective emittance [nm·rad] as defined by $[\varepsilon_x(s)]_{eff} \equiv \sqrt{\varepsilon_x^2 + H(s)\cdot\varepsilon_x\cdot\sigma_{\Delta p/p}^2}$ in the straight sections, in comparison with those of the original optics.

	SDL	SDM	SDC
SOLEIL original optics	5.34	5.55	5.58
SB-QBA	0.98	0.98	2.48
Ratio	5.5	5.7	2.3

Table 2 summarises the characteristics of the dipoles used. Major optics and beam parameters for the obtained solutions are listed in Table 3. Although there is a factor of nearly 4 of reduction in the emittance, the energy spread increases by roughly a factor of 2. Reflecting the strong horizontal focusing at four dipoles, the betatron tunes increase by more than double in both planes, resulting in a significant increase in the natural chromaticities as well. Combined with the small horizontal dispersion, the nonlinear aspect of the optics is expected to be quite severe with the chromaticity correction. Since the original SOLEIL optics has non-zero dispersion in the straight sections, the effective emittance is compared in Table 4, where a factor of more than 5 of reduction is found for SDL and SDM.

SUMMARY

In view of the growing interest of some dipole beamlines for superbends at SOLEIL, the use of these dipoles was attempted in lowering further the emittance of the SOLEIL ring, under the constraint of keeping the circumference and the existing straight sections (lengths and locations) fixed.

With a QBA (Quadruple Bend Achromat) lattice consisting of 2 superbends and 2 dispersion suppressors, a solution reaching a sub-nanometer emittance was found. The study should therefore be continued in this direction, along with other schemes such as a multiple bend lattice and their combinations. The obtained solution clearly exhibits a number of non-trivial issues (linear and nonlinear dynamics, beam injection, magnet technology, beam lifetime, instability, …), which must be pursued in parallel.

ACKNOWLEDGEMENT

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