

STUDY OF LOWER HORIZONTAL EMITTANCE OPTICS IN THE PRESENT SOLEIL STORAGE RING

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Abstract

With the aim of delivering a lower horizontal emittance beam to the users of the present SOLEIL ring, a systematic lattice study is carried out. The goal is to discover feasible optics solutions having the horizontal emittance notably lower than the present value of 3.9 nm rad, while fulfilling all the physical requirements and without changing the current magnet structure in the lattice. The strategy adopted is a cell-wise optimization of the linear lattices in the two types of double-bend cells that constitute the SOLEIL ring. In the second step they are concatenated via finer matching. A global scan of the 5 quadrupole families for the search of stable solutions is performed. The statistical properties are given. One can easily select possible solutions without matching. For the second type of cell having 10 quadrupole families, another scan of quadrupoles and a matching using a quadrupole triplet are applied for linear optics characteristics. Finally, the nonlinear optimization is performed with modern nonlinear optimization algorithms.

INTRODUCTION

The current magnet structure of SOLEIL light source consists of 16 double-bend structures with 3 types of straight sections. There are 4 long straight sections (SDLs), 12 medium straight sections (SDMs) and 8 short sections (SDCs).

There are two types of cells. The SDL-SDM cell is the double-bend structure which contains the drift space from half of the SDL section along with a quadrupole triplet, followed by 2 dipoles with 4 quadrupoles in between, and ends with another quadrupole triplet and the drift from half of SDM section.

The other unit cell is the SDM-SDC-SDM cell. The first half is the SDM-SDC structure and the second half is its mirror symmetry. The SDM-SDC structure begins with the drift from half of SDM section and a set of three quadrupoles, followed by an identical dipole, a quadrupole doublet and ends with the drift from half of the SDC section. The schematic of the two cells is shown in Fig. 1.

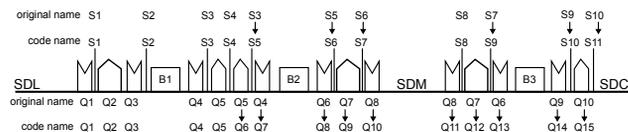


Figure 1: Magnet schematics and the naming conventions.

In 2012, the Nanoscopium structure was installed in a long straight section, which broke the original four-fold symmetry [1]. Some of the current parameters of SOLEIL are listed in Table 1. This study targets a smaller emittance lattice than

the current one. The ultimate goal is an applicable solution to all physical constraints. In this paper, we focus only on the cases without the Nanoscopium structure.

Table 1: SOLEIL Storage Ring Parameters

Parameters	Values
Energy	2.739 GeV
Circumference	354.097 m
Natural emittance (ϵ_0)	3.90 nm rad
Natural chromaticities (C_x/C_z)	-47.6/-20.0
Betatron tunes (ν_x/ν_z)	18.157/10.228

LINEAR LATTICE

It is difficult to optimize the lattice by varying all quadrupoles at once because the degree of freedom is large. But one can reduce the complexity of the problem by dividing the lattice into smaller pieces by symmetry. Furthermore, an easier way is to deal with the lattice piecewise. Our strategy is as follows: The first step is to find a small emittance solution with reasonable optics in SDM-SDC-SDM section. Secondly, the optics from the previous step are propagated from SDM to SDL. The optics are concatenated by matching zero slopes of β -functions and dispersion D_x in the center of SDL section.

Finally, a minor matching preserving the main optical structure is needed for adjusting the betatron tunes. During the procedure only the solutions fulfilling all kinds of local optics criteria along with the small emittance are picked up.

We break the group of magnet families and define the code naming convention of quadrupoles from Q1 to Q15 in sequence from upstream to downstream. Similarly the sextupoles are named from S1 to S11. The naming conventions compared to the original ones are depicted in Fig. 1.

SDM-SDC Cell

An efficient way is to begin with those pieces which are simple and repeat most frequently. The first step is to focus on SDM-SDC cell. There are 5 quadrupoles of which maximal strengths are fixed. Therefore we are able to carry out a systematic scan through all quadrupole strengths to find the periodical solutions. With the resolution of integrated quadrupole strength $\Delta K1L = 0.01$ [1/m], there are totally about 3 billion cases in which only about 7 % of them are periodical solutions. With the quadrupole strength constraints, the smallest emittance found in this section is 2.7 nm rad, which is 50 % higher than the theoretical minimal emittance. However this case is not applicable because its β_z -function is very large.

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The whole data is huge, but there are many infeasible solutions which can be dropped. For example, large emittance lattices are of no interest. Solutions with $\epsilon_0 > 5$ nm rad are abandoned. Filtering out ill-behaved solutions, there are about 0.8 million records finally saved.

They are stored in a big matrix, including the information of natural emittance, energy spread, β -functions and dispersion functions in the center of SDM and SDC, and the maximum β -functions along this cell. With this data, one can extract the useful information by mining the data with filters and carry out some post data processing.

For instance, one can easily make the contour maps of low emittance lattice. Figures 2 (a) and (b) show the low emittance contours in $(\beta_{x,SDM}, \beta_{x,SDC})$ and $(D_{x,SDM}, D_{x,SDC})$ planes respectively. These maps give good references for the linear optics matching. For example, the achromat condition is not possible with the emittance less than 5 nm rad.

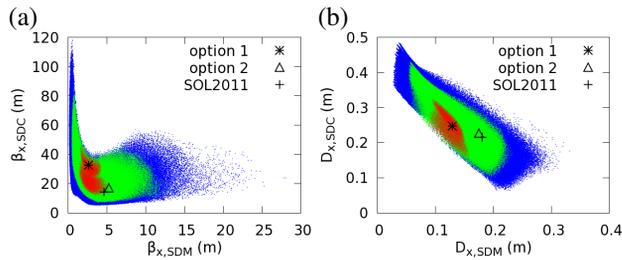


Figure 2: Emittance (ϵ_0) contours. Red: $\epsilon_0 < 3$ nm rad, Green: $\epsilon_0 < 4$ nm rad, Blue: $\epsilon_0 < 5$ nm rad. (a): in $(\beta_{x,SDM}, \beta_{x,SDC})$ plane. (b): in $(D_{x,SDM}, D_{x,SDC})$ plane. Different symbols represent different options.

As another data mining example, we chose the cases in which maximum β -functions are less than 20 m and see the statistics. The parallel axis plot of the β -functions, shown in Fig. 3 (a), shows the distribution of the emittance versus the β -functions. As expected, there is less dependency of β_z than β_x .

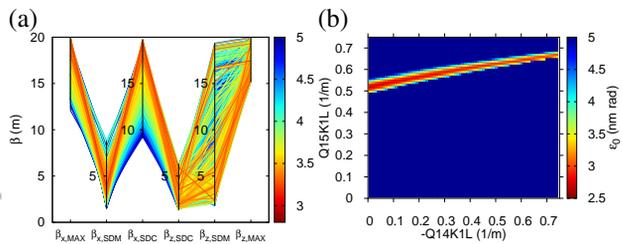


Figure 3: (a) Parallel axis plot of the β -functions with emittance. (b) A valley in Q14-Q15 plane. The color scale shows the emittance in unit of nm rad.

An interesting relation between Q14 and Q15 for extra low emittance lattice was discovered. Figure. 3 (b) shows the minimum emittance of each Q11-Q12-Q13 cubic in Q14-Q15 plane. A narrow valley of low emittance is revealed. Their dependency can be approximated by a fitting curve. With this relation the degree of freedom for small emittance lattice is reduced by one.

The tomography in the remaining 4 dimensions is shown in Fig. 4. This helps locating the domain of small emittance lattice. One can see that stronger Q12 and weaker Q13 are suggested for small emittance lattices.

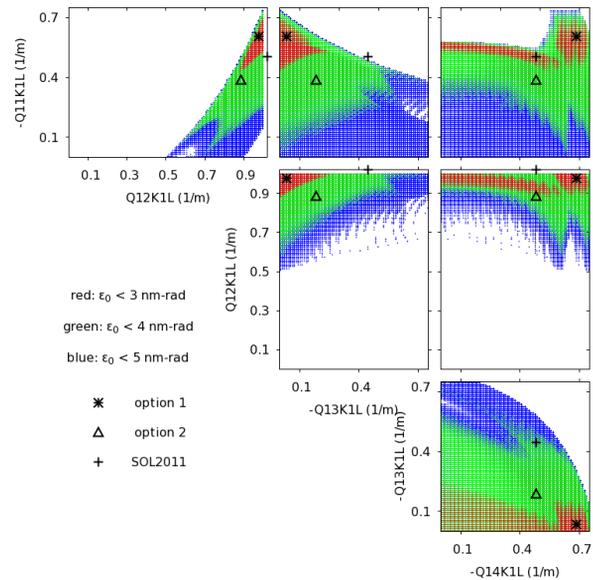


Figure 4: Tomography of SDM-SDC cell. Different colors stand for different emittance range. Different options are indicated by different symbols.

SDL-SDM Cell

Based on the solutions found in SDM-SDC cell, the optics are propagated from SDM center till the center of SDL. Their slopes in the end have to be zero to guarantee a periodical solution in a superperiod. In this cell there are 10 quadrupoles as variables. The degree of freedom is too big to carry out a systematic scan. An efficient strategy is to further divide this step into three substeps.

First of all, we could impose the symmetry condition of the optics in the SDM section. This condition is not necessary but it helps reduce the complexity of the problem. Therefore, the quadrupole triplets on both sides of the SDM will be mirrored symmetrically of each other. The H-function inside the dipole B2 will be identical to those in SDM-SDC cells.

Then the optics are propagated through the 4 quadrupoles before entering the dipole B1. At the end zero slopes are matched $(\alpha_x, \alpha_z, D'_x)$ with the second quadrupole triplet.

In the second step, we perform a four-quadrupole scan with the resolution of $\Delta K1L = 0.01$ [1/m], associated with a zero-slope optics matching for each case. The objective of the matching is defined as $\alpha_x^2 + \alpha_z^2 + 100D_x'^2$. However, due to the limitations of the quadrupole strengths, not all objectives can converge well to zero. Results with reasonable optics are kept and non-zero slopes are discarded. Among all candidate solutions we have to pick up the ones with objectives nearly zero and with as small emittance as possible.

Results

Finally, once the two pieces of optics are concatenated, we can have a rough idea about the working tunes. A minor matching with $\pm 5\%$ quadrupole strength variation is performed in order to adjusting the betatron tunes to be away from the integer, half-integer, and systematic resonances.

Following this strategy and different selection criteria, here comes some options. Option 1 targets to get the smallest emittance without considering the natural chromaticities. Its natural chromaticities are too high to find a good dynamic aperture. The option 2 is a solution with much more relaxed natural chromaticities, but the emittance is higher. For comparison, we add a case SOL2011 [1], which is the last lattice before the installation of the Nanoscopium structure. These options are summarized in Table 2. The Twiss optics of the option 1 is shown in Fig. 5. The 100-turn dynamic aperture of the option 2 is shown in Fig. 6.

Table 2: Linear Lattice Options.

Parameters	option 1	option 2	SOL2011
ν_x	20.155	18.180	18.202
ν_z	11.229	6.320	10.317
C_x/C_z	-82.2/-22.7	-51.6/-20.9	-47.2/-22.0
ϵ_0 (nm rad)	2.9	3.5	3.9

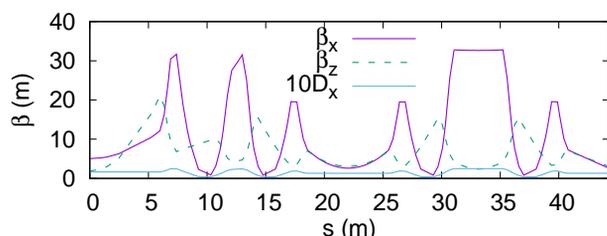


Figure 5: Optics of the option 1.

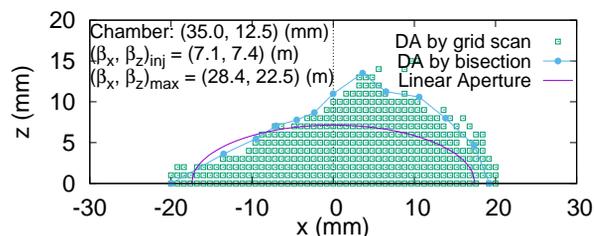


Figure 6: On-momentum dynamic aperture of the option 2.

NONLINEAR OPTIMIZATION

Genetic Algorithms (GA) are modern tools for problem optimizations. In the last decade, it has been intensely used in the storage ring design community. It is successful in some design simulations and experiments [2,3]. Here we use GALib [4] to implement the GA algorithm and SimTrack [5] as an engine to calculate the beam dynamic quantities.

To keep the chromaticities to the desired values, the technique [6] utilizing the chromaticity response matrix and its pseudo-inverse is used. Two degrees of freedom are sacrificed. In our problem there are 11 families of sextupoles. Therefore there are 9 variables to operate with. The genome

is defined as a 9-dimensional array with 2^{15} equal grids in each dimension. The objective is set to be the on-momentum dynamic aperture area, for now.

Different from the conventional GA, the additional pre-selection procedures are added when initializing the population and before evaluating the objective. Constraints can be put into the preselection steps. Some properties that are analytical and fast to estimate (e.g. the sextupole strengths, the driving terms, etc.) can be checked before performing the computationally expensive operations (e.g. tracking). The intention is to speed up the process by bypassing evaluating the wrong solutions. The flow chart of the algorithm is depicted in Fig. 7.

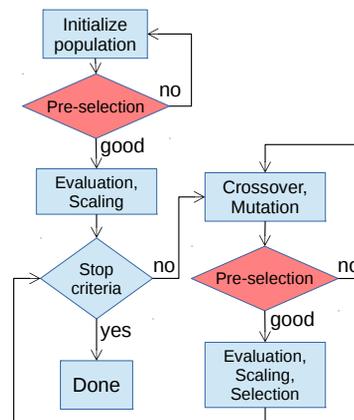


Figure 7: Genetic Algorithm flow chart.

CONCLUSION

Keeping the current magnet structures of SOLEIL, a database was built with all stable linear lattice solutions for the SDM-SDC cell. Data mining gives a global vision of its potential: the lowest reachable emittance is 2.7 nm rad where the family Q12 hits its maximum. The workable solution allowing injection and to host in-vacuum undulators is close to the nominal optics which is already almost an optimum. In this case the emittance could be reduced from 3.9 to 3.5 nm rad. This work helps us understand the limitations of the current machine in terms of emittance minimization. A multi-step strategy to make a low emittance lattice was proposed. A custom-made GA optimizer for dynamic aperture is being developed. First results are encouraging and obtained after just a few days of computation. Further efforts are needed to find a better feasible solution and extent the algorithm to deal with off-momentum dynamics.

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