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MULTI-OBJECTIVE OPTIMIZATION OF THE NON-LINEAR BEAM DYNAMICS OF SYNCHROTRON SOLEIL

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Abstract

The optimization of a storage ring lattice is a multi-objective problem that involves a high number of constraints and a multi-dimensional parameter space. In this paper the Multi-Objective Genetic Algorithm (MOGA) [1] and the tracking code ELEGANT [2] are used to optimize the non-linear beam dynamics of the SOLEIL synchrotron light source storage ring. This paper will discuss the application of this tool using the SOLEIL computer cluster. The first results will also be presented and will discuss possible improvements.

INTRODUCTION

SOLEIL is the 2.75 GeV French third generation light source routinely operated for users since 2007 with a low emittance electron beam of 3.91 nm·rad (cf. Table 1).

Table 1: Current Standard SOLEIL Parameters

Energy	2.75 GeV
Circumference	354.097 m
Horizontal Emittance	3.91 nm·rad
Betatron tunes	(18.18, 10.23)
Nominal current	430 mA

Present lattice settings have being obtained using minimization of driving terms, control of tuneshifts with energy and amplitude coupled to frequency map analysis using symplectic tracking for on and off-momentum particles. This man-made optimization gives good performance of the storage ring but may not lead to a thorough exploration of all optics settings to reach the best performance ever. Highly parallel and computer demanding tools such as genetic algorithms may help answering this question. In this paper we report results from computation tool MOGA of APS applied to optimize the dynamical aperture (DA) and the momentum aperture (MA). Both concepts are strongly related to the injection efficiency and the Touschek lifetime (TL), respectively.

ALGORITHM DESCRIPTION

Genetic Algorithms (GAs) [3] are inspired by the Darwinian evolution processes, where the search of a set of variables that optimizes a fitness function, e.g., the dynamical aperture, is performed over populations rather than on single individuals. For this reason, the optimization process can be considered as an evolutionary process on successive generations. The fitness of every generation is evaluated at every step and the merit solutions are chosen as the “parents” of the next generation. A generation can evolve through three main processes: mutation, selection and crossover. GAs have been used in the accelerator field as early as 2010 to accomplish beam dynamics optimization studies for potential upgrades of different light sources around the world.

In particular, a multi-objective version of a GA ranks the best solutions from an initial random population based on the comparison of the objective values among all of them. Thereafter, it chooses two parents from this group of best solutions, called Pareto front, to generate two children. Finally, the algorithm mutates the children and randomly selects the parents for the next generation of solutions. The process is iterative and stops when the maximum number of generations is achieved. Different to the standard GAs, there is no special convergence criterion for MOGAs approaches.

In a MOGA approach, a multi-dimensional problem is optimized under a set of constraints. In this study case, the multi-parameter space is defined by the settings of quadrupole and sextupole magnet strengths. The constraints are related to the optical parameters of the storage ring, such as the betatron functions, the chromaticities, and the betatron tunes.

The calculations reported here, were performed on the high-performance computational resources of SOLEIL, i.e., on a computer cluster of 1072 cores reaching a peak performance of 11.4 Tflops. The current implementation of the APS MOGA package assigns one individual task per core, thus requiring a number of cores equal to the size of the population. The results presented below where obtained using up to 160 cores.

OPTIMIZATION PARAMETERS

The constraints taken into account in the optimization process cover the betatron tunes and chromaticities. The betatron tunes are allowed close to the nominal value with variation confined between the integer and half-integer resonance lines. The desired chromaticities values are fixed at 2 and 3.5 for the horizontal and vertical planes, respectively.

The tracking calculation performed by ELEGANT to obtain the DA and Touschek lifetime uses 400 turns. This

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is a compromise between accuracy and computation speed: the experience shows us this number is enough for our purpose. The DA is calculated at the injection location where the values of the horizontal and vertical betatron functions are respectively 11.6 m and 7.9 m. On the other hand, to compute the beam lifetime, the tracking process does not consider the RF cavities for now (4D tracking) and the calculation is located at the sextupole position to save computation time.

RESULTS

The optimization results of an ideal model without coupling or multipole errors, using 2 quadrupole families to correct the tunes and 11 sextupole families to optimize non-linearities will be presented. Then, these results are checked and compared against TRACY-III code [4] to examine their completeness adding the vacuum chamber, the multipole errors and both parameters at the same time.

The Ideal Storage Ring Model

The preliminary results using the ideal model described before are shown in Fig. 1. These results have been obtained during 6 days of computation using 80 cores. The Pareto's solutions (blue points) and the currently SOLEIL lattice (red point) are plotted with respect to the value of DA area and the Touschek lifetime. These preliminary results show an increase of 12 mm in the negative side of the DA and a reduction of 5 mm in the positive side (Fig. 2). The Touschek lifetime is increased by 100 hours from the 22.7 hours of the starting point.

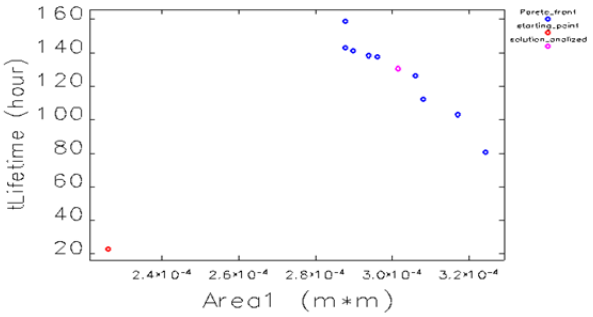

Figure 1: Optimization results of the DA area vs. the Touscheck lifetime of the ideal SOLEIL storage ring model.

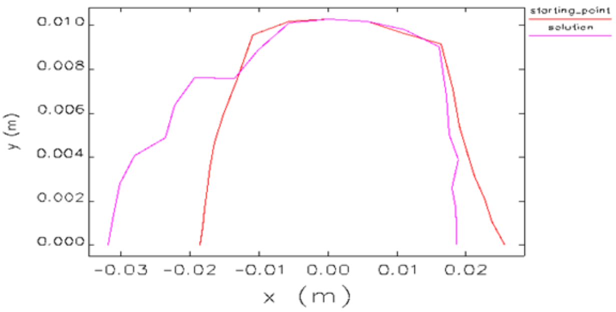

Figure 2: DA Comparison between the SOLEIL nominal lattice and one solution from the Pareto front of Fig. 1.

The corresponding variation of sextupole strengths shows a change below 10% for all the sextupole families and a maximum of 20% in the eleventh family.

TRACY-III Comparison

Using one optimized solution of MOGA, a list of results is presented using TRACY-III code for different cases: the ideal storage ring model (I), adding vacuum chamber (II), adding multipole errors [5] (III) and adding both vacuum chamber and multipole errors (IV). Table 2 presents the negative DA and Touschek lifetime values for each case. The values in brackets correspond to the values of the current SOLEIL storage ring.

Table 2: TRACY-III results: the ideal storage ring model (I), adding vacuum chamber (II), adding multipole errors (III) and adding both at the same time (IV).

	I	II	III	IV
DA (mm)	-27(-21)	-19(-19)	-22(-19)	-19(-19)
TL (h)	160(92)	60(51)	94(72)	45(53)

I. The Ideal Storage Ring Model

The frequency maps analysis (FMA) and the DA are shown on Fig. 3. The improvement observed is 6 mm in the DA and 68 hours with respect to the 92 hours of the starting point. These results show a general improvement of both objectives but looking more

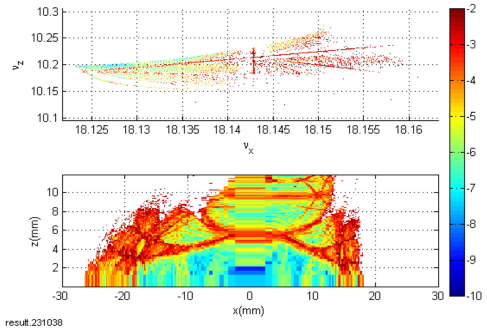

Figure 3: FMA and DA of a particular solution of the Pareto front found by MOGA of Fig. 1 obtained using TRACY-III.

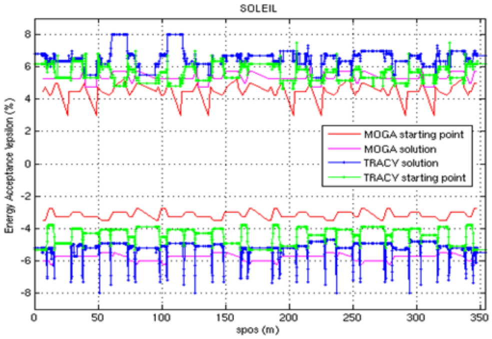

Figure 4: Comparison of the MA between the SOLEIL nominal lattice and one optimized solution.

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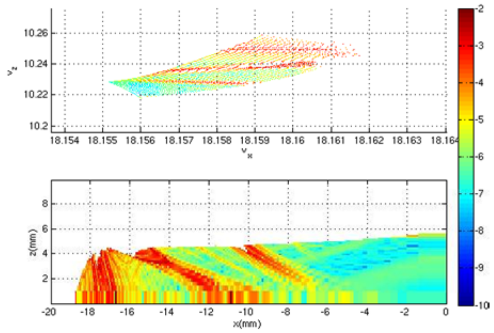

Figure 5: FMA and negative side of the DA of a particular solution of Fig. 1 adding the multipole magnetic errors using TRACY-III.

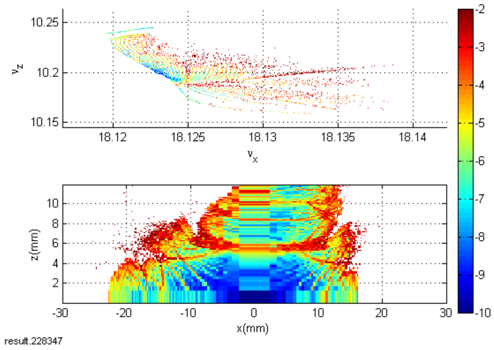

Figure 6: FMA and DA of a particular solution of Fig. 1 adding the multipole magnetic errors using TRACY-III.

carefully do not completely agree with the optimized results. The negative side of the DA, where the injection system is located, is affected by resonances and is not consistent to inject the beam. The initial optimization constraints must be more restrictive to take into account the non-linear effects. In addition, the MA computed by ELEGANT and TRACY-III disagree due to a mistake in the parameters used in ELEGANT (Fig. 4). This is under investigation.

II. Adding Vacuum Chamber Limitations

The results obtained in Fig. 5 are different to respect to the results obtained in the first case. The improvement of the beam lifetime is 9 hours but the DA is fully different. The particles are lost mainly in the vertical wall of the vacuum chamber and in a lower contribution in the septum of the injection system.

III. Adding Multipole Errors

The DA improvement is reduced down to 3 mm at the negative side and is decreased 10 mm in the positive side (Fig. 6). The beam lifetime is increased by 24 hours. The DA is not affected by the same resonances lines as the previous cases due to the new tuneshift with amplitudes induced by multiole errors.

IV. Adding Vacuum Chamber and Multipole Errors

The negative side of the DA remains unchanged and the beam lifetime value is worse with respect to the starting point (Fig. 7). In addition to the effect of the vacuum chamber explained before, the multipole errors reduce the

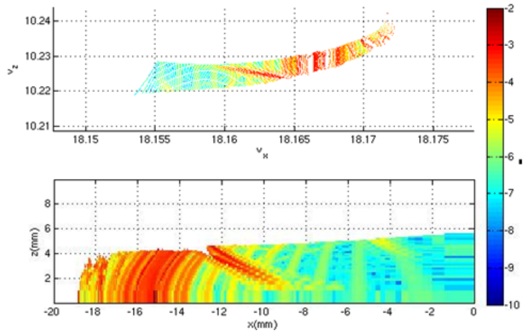

Figure 7: FMA and negative side of the DA of a particular solution of Fig. 1 adding the multipole magnetic errors and vacuum chamber using TRACY-III.

DA and the beam lifetime of the second case.

CONCLUSION

A preliminary study of the non-linear beam dynamics of SOLEIL was performed. One optimized solution of the ideal storage ring model has been treated and compared with TRACY-III code to examine their completeness. The improvement of dynamical aperture and Touschek lifetime by MOGA is confirmed by TRACY-III for the ideal case only. Therefore, the optimization constraints must be more restrictive to explore more efficiently the non-linear beam dynamics effects of a given lattice.

In order to be closer to the reality, this study will be completed adding in the ideal storage ring model used by MOGA the dimensions of the vacuum chamber, the magnetic multipolar errors, the radiofrequency cavities in the tracking computation and all the quadrupole families to optimize the linear beam dynamics. The introduction of these parameters will increase the computation effort.

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