OPTIMIZATION OF NONLINEAR DYNAMICS FOR SIRIUS

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Abstract

In this work we describe the optimization of the nonlinear dynamics for the Sirius storage ring. The strong sextupoles of the lattice, necessary to correct the linear chromaticities, generate higher order terms in the tune-shifts with amplitude and energy, which may result in a large tune footprint for the machine. The configuration of sextupole families found that wraps this tune footprint and thus avoids dangerous resonances was achieved with minimization of Hamiltonian driving terms and tracking-based multi-objective algorithms that include realistic values of misalignment and excitation errors of the magnets, orbit correction, insertion devices fields and real vacuum chamber apertures.

INTRODUCTION

Sirius is a 4th generation storage ring based on a 5BA magnetic lattice presently under construction at LNLS in Campinas, Brazil. Although construction is already in advanced phase [1], the optics is being continuously upgraded, as reported in various conferences [2-4].

Every upgrade of the linear optics creates the necessity of re-optimization of the nonlinear dynamics, which we had been doing successfully following a method that iterates between an initial optimization of Hamiltonian driving terms, tune-shifts with amplitude and momentum deviation, and a more detailed optimization using genetic algorithms based on direct evaluation of the desired parameters via tracking of the particles in a machine with realistic errors.

Some upgrades, such as the most recent one where the symmetry of the lattice was changed from 10-fold to 5-fold [5], impose challenges to the nonlinear optimization and demand a review of some of the tools and parameters employed in this process.

SIRIUS NONLINEAR LATTICE

Figure 1 shows one arc of the Sirius lattice with the linear optics together with the chromaticity driving terms. It is worth noting a few properties of the lattice regarding the nonlinear dynamics. Each arc contains 10 sextupoles, which is the minimum number of elements necessary to correct the chromaticity without exceeding the strength limit (2400 T/m^2). Early versions of the lattice had 12 sextupoles in the arc, with an extra one between Q4 quadrupoles and BC dipoles. However, due to the low value of the optical functions at this position, its strength often surpassed the limit.

There is a strong cross talk among sextupoles in the chromaticity correction scheme because they are placed at positions where the separation between the horizontal and vertical betatron functions is relatively low. See Fig. 1. Even though the focusing sextupoles are placed at the positions of highest horizontal betatron functions in the arc, it is not possible to decrease the value of the vertical betatron function at this location because all the defocusing quadrupole strength of the arc is located in the dipoles and they were used in the emittance optimization process. Besides that, the defocusing sextupoles are not located at the best places to correct chromaticity, close to B1 and B2 dipoles, because simulations have shown that better results in terms of dynamic aperture and beam lifetime can be achieved with them in the current position. This can be explained by the higher horizontal betatron function at this position which increases the effect of these sextupoles on the control of the horizontal nonlinear dynamics which requires better performance than the vertical, due to large excursions during injection and after a Touschek scattering event.

Overall, this cross talk increases the strengths of the sextupoles which would already be high due to the small value of the dispersion function and the large natural chromaticities, -120 in the horizontal and -80 in the vertical plane. Consequently, strong nonlinearities are introduced by these elements, which are evidenced by large nonlinear tune-shifts with amplitude and momentum deviation.

The linear optics in the arc has mirror symmetry around the BC magnet, but to control nonlinear effects on sextupole strength, this symmetry was broken for the nonlinear optics. Thus, each sextupole in the arc belongs to a different family. In the current version of the lattice, with a 5-fold symmetric optics, Sirius has 21 sextupole families. Octupoles could be used to correct the second order chromaticities and linear tune-shifts linearly [6], instead of the additional sextupole families, but we have not observed improvements in the performance of the dynamics when we tried to use them in early versions of the lattice.

Together with the large number of sextupole families, another tool employed in the nonlinear optimization process is the large tune flexibility of the lattice, which allows us to study several different integers without changing significantly the global parameters of the lattice.

BARE LATTICE OPTIMIZATION

The Sirius optics has already gone through many versions since the 5BA lattice was adopted in 2012. For a long time, the bare lattice optimization was performed using OPA [7]. In the first design, the lattice was 20-fold symmetric with 9 sextupole families. For this lattice configuration the sextupole optimization module of OPA worked very well, because the Sirius dynamics was dominated by second order effects in sextupole strength, such as second order chromaticities and linear tune-shifts

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with amplitude, quantities calculated and used in the optimization by this module.

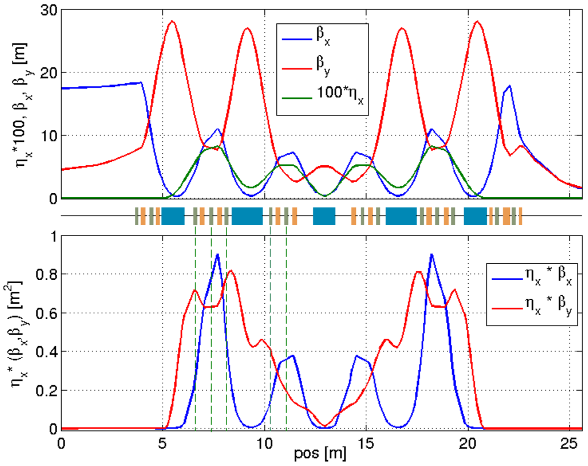

Figure 1: Optical functions (above) and sextupolar chromaticity driving terms (bellow) for one arc of the lattice. The matching sections consist of quadrupole doublets in the high straight β_x sections and quadrupole triplets in low β_x sections. The lattice is 5-fold symmetric, a high β_x section is followed by three low β_x sections, adding up to 5 high and 15 low β_x sections in total.

When the lattice changed to a 10-fold symmetric optics, the dynamics was still dominated by second order chromaticities but the tune-shift with amplitude had a strong non-linear contribution, which is not considered in the OPA module. When a new mode with low horizontal betatron functions ($\beta_x \sim \beta_y \sim 1.5$ m) at the odd straight sections was implemented, we split the sextupoles into more families by breaking the symmetry around the BC dipole. This was necessary to control the second order chromaticity in the horizontal plane and the linear tune-shifts. With the large number of sextupole families, optimization with OPA became more difficult, the calculation of the optimization matrix was slower and the application often crashed. However it was still possible to get good initial configurations for the multi-objective genetic algorithm MOGA.

However, further lattice changes to a 5-fold symmetric optics, with one high beta followed by three low beta sections, motivated us to implement an optimization code in Matlab®, using AT [8], based on analytic expressions for the Hamiltonian first order driving terms and tracking based parameters, such as tune-shifts, beta-beating with energy and maximum horizontal dynamic aperture. With this code we were able to generate initial configurations for MOGA optimizations with large negative horizontal dynamic apertures, close to -10 mm.

OPTIMIZATION WITH MOGA

For more than two years we have been using MOGA [9] to optimize the dynamic aperture and lifetime of Sirius. MOGA is an implementation of a multi-objective genetic algorithm which uses Elegant [10] to perform lattice computations and to calculate the objective functions, in this case, Touschek lifetime and dynamic aperture area.

The initial algorithm used the following procedure to evaluate the objective function: for a given setting of sextupoles and tunes, the linear optics was adjusted to the desired tune, obeying a series of predefined constraints, and the chromaticity was corrected to the desired value using the two sextupole families that were not used as knobs on the optimization. After this matching phase, the tune shifts with momentum deviation were calculated to identify integer and semi-integer resonance crossings to set the maximum momentum acceptance for the machine. Then a set of tiny errors was used to simulate the residual orbit of a corrected machine and the dynamic aperture at the injection point and the momentum acceptance along the machine were calculated with 6D tracking. Finally, the area of the dynamic aperture and lifetime were calculated and both results returned to the optimizer as two different objectives.

After few hundreds of configurations were generated and tested by the algorithm, the best results were validated with a more detailed calculation, based on tracking codes, of the momentum acceptance and dynamic aperture for a set of 20 machines with real random alignment, excitation, and multipole errors, with orbit, tune and coupling correction. For all the computations it was very important to consider the small gap ID vacuum chambers.

Even though a perfect agreement between the values of the dynamic aperture and lifetime calculated by MOGA and the validation through the ensemble is not expected, a good objective function should keep the rank order invariant in both calculations, i.e., if configuration 1 has better lifetime and worse dynamic aperture than configuration 2 according to the objective function calculation, then this should be also true for the results of the ensemble validation, otherwise the optimizer will not improve the performance of the ring.

This was not the case for the objective function described above. We noticed that this rank variance was produced because the beta-beating of the machine used in MOGA was much smaller than those from the ensemble validation. This is related to the fact that the orbit and beta-beating amplification factors are different with and without orbit correction, i.e., the orbit correction system changes the weight each element has on the total residue orbit and beta-beating.

So the objective function was changed to consider realistic alignment and excitation errors in the machine, correct the orbit and calculate the figures of merit for three different sets of random errors. Then, the minimum lifetime and dynamic aperture are used to represent that configuration. It is necessary to use three random machines because, with the 14 degrees of freedom available at that time, 12 sextupoles and 2 tunes, MOGA was optimizing the apertures for the specific set of errors used in the calculation. The same argument justifies the use of the minimum instead of the average of the three machines.

Besides these changes in the calculation of the objective functions, other parameters of the genetic algorithm were also changed to gain in performance. The number of parents used in each breeding was set to 2 and the maximum rank used for breeding and mutation, was set to 4. This last parameter value is important because the larger the maximum rank, the slower speciation happens. For example, with maximum rank equals one or two, the algorithm converges to sets of solutions separated in the objective space more rapidly, being trapped in local minima, see Fig. 2.

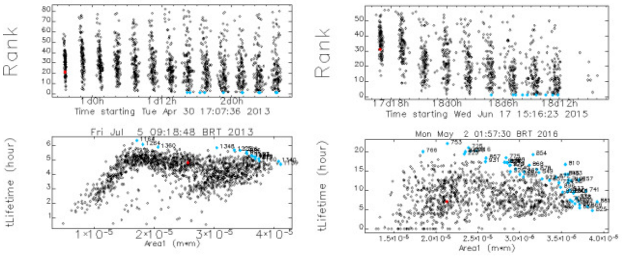

Figure 2: Blue dots are the individuals used in the optimization to generate new configurations. Left: optimization performed with only rank 1 individuals, notice the existence of two different sets of machines. Right: optimization performed with individuals up to rank 4, the whole front of optimization is being explored.

Since we began using MOGA, the Sirius lattice underwent several changes and the method proved itself efficient for all the versions. Fig. 3 and Table 1 shows the evolution of the 10-fold symmetric mode through some versions of the lattice. We notice the Touschek lifetime has doubled from version V03 to V14 and the dynamic aperture increased by 25% and if compared to V10, by 45%.

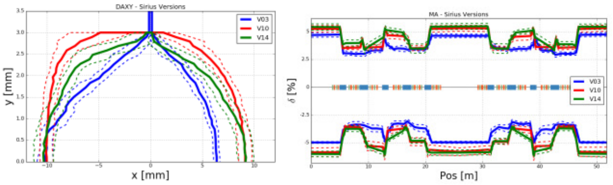

Figure 3: evolution of the dynamic aperture at the center of the injection straight (left) and momentum aperture (right). Simulations include all perturbations and the dashed curves indicate one standard deviation from the average (solid curve) over 20 random machines.

Table 1: Evolution of Sirius Dynamic Aperture and Touschek Lifetime

Version	DA [mm^2]	Touschek LT [h]
V03	32.6 ± 2.4	13.6 ± 1.6
V10	49.4 ± 3.0	23.3 ± 2.6
V14	41.7 ± 3.1	29.0 ± 4.6

We have also successfully used MOGA to optimize the dynamic aperture and lifetime with all the fields of IDs predicted for Sirius. In a specific case, the optics was optimized for the bare lattice and when the field of the IDs were added to the machine model, a fourth order non-systematic resonance was excited and the dynamic aperture and momentum acceptance reduced. After one run of MOGA with the IDs in the machine, both figures of merit were improved significantly, as can be seen in Fig. 4.

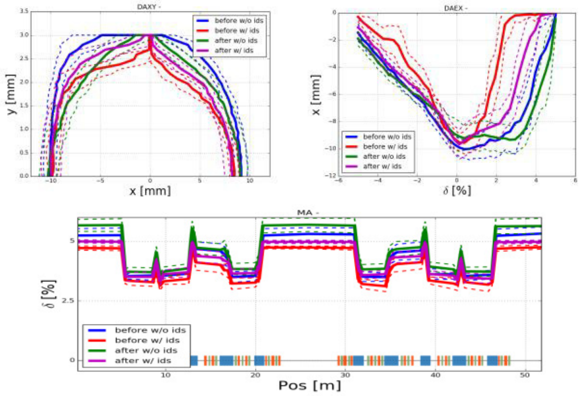

Figure 4: Dynamic aperture (left, up), off-momentum dynamic aperture at y=1 mm (right, up) and momentum aperture (down) for the optics before and after inclusion of IDs on MOGA optimizations. Simulations include all perturbations and the dashed curves indicate one standard deviation from the average (solid curve) over 20 random machines.

Currently we are working on the optimization of the 5-fold symmetry optics and, as shown in Fig. 5, we already have a result with good dynamic aperture but we still wish to improve the momentum aperture, even though the total lifetime achieved of 6.5 h is enough for operating the ring.

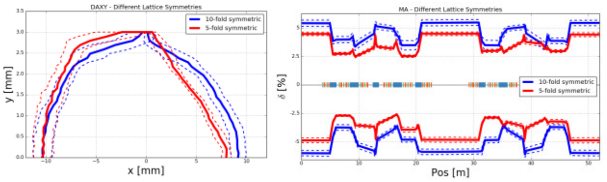

Figure 5: Comparison of dynamic aperture and momentum acceptance for the previous 10-fold (blue) and the new 5-fold (red) symmetric modes. Simulations include all perturbations and the dashed curves indicate one standard deviation from the average (solid curve) over 20 random machines.

CONCLUSIONS

The procedure adopted for the Sirius nonlinear optics optimization has been proved successful for several versions of the lattice. It relies on a large number of sextupole families, careful choice of the working point and iterations between simple and fast algorithms with more complete ones, multi-objective and based on tracking.

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