

LINEAR AND NONLINEAR OPTIMIZATIONS FOR THE ESRF UPGRADE LATTICE

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Abstract

The ESRF storage ring will be replaced in 2020 by a new hybrid multi bend achromat lattice with 134 pm · rad equilibrium horizontal emittance. To determine the best working point, large scans of tunes and chromaticities have been performed, computing Touschek lifetime and dynamic aperture. From different working points, the multi-objective genetic algorithm NSGA-II has been used to optimize the nonlinear magnets values and some linear optics parameters. The analysis have been carried out on lattices with errors and corrections. The optimizations have produced lattices with longer lifetime and larger dynamic aperture for different working points with positive chromaticities.

INTRODUCTION

The ESRF upgrade storage ring will provide x-rays with a 40 times higher brilliance than the present machine, with 5 % coherence at 1 keV [1]. The optics functions of the hybrid multi bend achromat lattice cell are shown in figure 1. The 32-fold symmetry of the lattice is broken at the

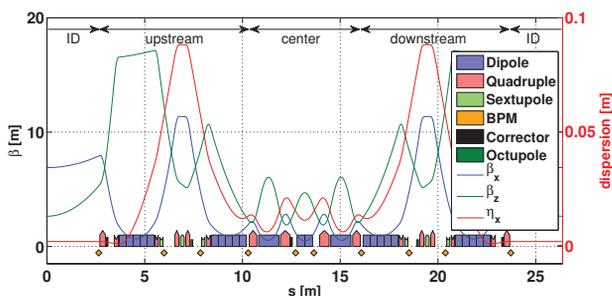


Figure 1: Twiss functions of the ESRF upgrade lattice.

injection straight section, where the horizontal β function is increased to 18 m, to allow off-axis injection. Touschek lifetime and dynamic aperture are two crucial parameters for lattice design: the first for beam stability and limited losses around the ring [2], the second to increase injection efficiency. The reduced beam size of the upgrade lattice is detrimental for the Touschek lifetime: the scattering rate increases due to the higher bunch density. The dynamic aperture, even if larger in terms of beam size compared to the current machine, is only 10 mm with errors at the injection (8 mm is the minimum required).

This paper reports the various methods used to optimize the linear and non-linear optics in order to improve the Touschek lifetime and the dynamic aperture. A deterministic technique to partially cancel the effect of the injection cell symmetry breaking will also be addressed.

Simulations

Beam dynamics simulations are done with the Matlab Accelerator Toolbox (AT) [3] [4] [5] and they are designed to exploit the ESRF computer cluster (768, 2GHz cores).

The Touschek lifetime is computed with the Piwinski formula [6], assuming a current per bunch of 0.23 mA. The momentum acceptance computation is limited to four lattice cells, with a loss of only 5% in the accuracy compared to the computation with 32 cells.

Linear optics matching

The linear optics of the cell is obtained putting constraints on the following parameters: the β functions and the dispersion at the focusing sextupoles, in the straight sections and in the middle of the cell, the phase advances between the sextupoles and the total tune of the cell. The target values of this parameters are optimized to improve the properties of the lattice. Nevertheless these modifications have impact on the non-linear optics, demanding for an iterative process of optimization.

LATTICE OPTIMIZATIONS

Working point scan

To determine the optimal tune working point we vary the horizontal and vertical tune over various units and compute the Touschek lifetime and the dynamic aperture, as shown in figure 2.

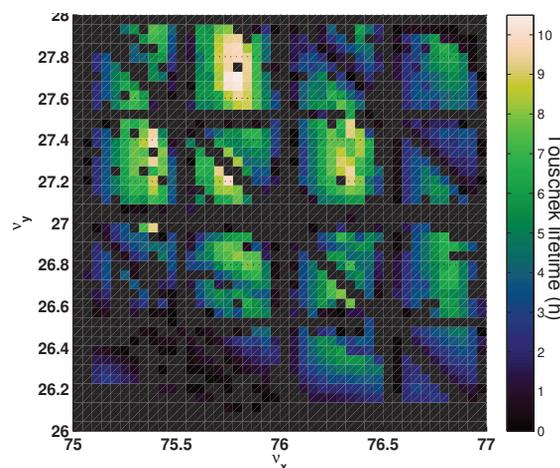


Figure 2: Touschek lifetime for different tunes values.

Keeping the same error seed for the whole scan, at each working point a complete commissioning-like procedure is performed: search for the closed orbit, corrections of orbit, linear optics and coupling [7]. The sextupoles are not

optimized at each point but they are adjusted to keep the chromaticity fixed. The maximum lifetime is obtained for the working points: $(\nu_x, \nu_y) = (75.60, 27.60)$, for which the sextupoles had been specifically tuned, and the region about $(\nu_x, \nu_y) = (76.20, 27.30)$. This second point is on a different integer tune and has a smaller emittance compared to the nominal working point. The scan also individuates major resonances (integer, half integer, coupling). This conclusions have however to be tested against various seeds of errors: figure 3 shows how two different error seeds could lead to completely different solutions.

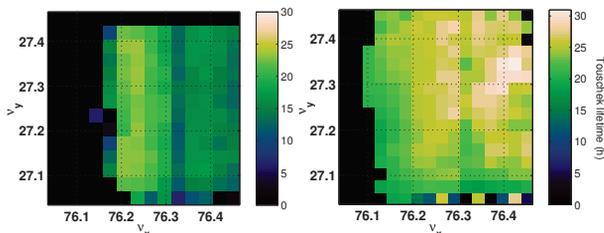


Figure 3: Touschek lifetime versus tunes for two different seeds of errors.

Chromaticity scan

Similarly to the working point, also the chromaticity impacts on the Touschek lifetime and needs to be optimized (see figure 4).

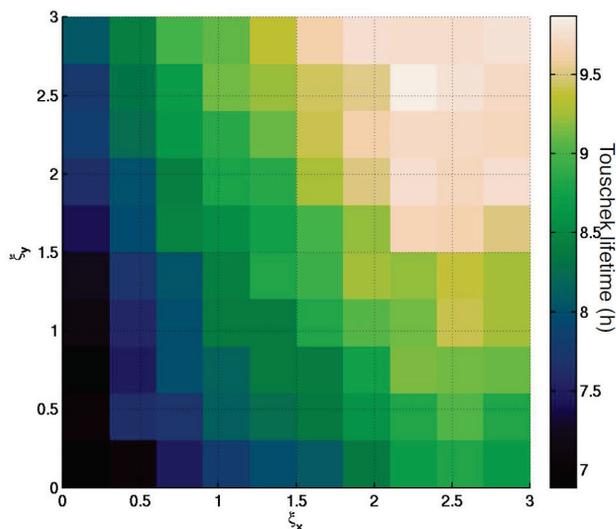


Figure 4: Touschek lifetime for different chromaticity values.

High chromaticities are beneficial. This is mainly due to an overcompensation of the path lengthening with amplitude at small amplitudes, that enhances the dynamic aperture and the momentum acceptance.

Multi-objective genetic optimization

Although the scans of working point and chromaticity gave very interesting insight, they do not allow to determine

definitive values, as a more complete process of optimization would be required at each point of the scans. For this reason the optimal values found are not assumed as definitive parameters, but are used as initial values to a global multi-objective minimizer.

The chosen optimizer is the multi-objective genetic algorithm NSGA-II [8], implemented in Matlab as NGPM [9]. The variables used for the optimizations of Touschek Lifetime and dynamic aperture are the linear matching parameters and the sextupoles and the octupoles strengths. In order to find robust solutions in the presence of errors, the objectives of the optimizations are the average of lifetime and dynamic aperture over 10 different seeds of errors (this is a compromise between cpu time and accuracy). Figure 5 shows an example of optimisation: the solutions obtained during the process are displayed, evidencing the large region of solutions explored and the Pareto front of best sets.

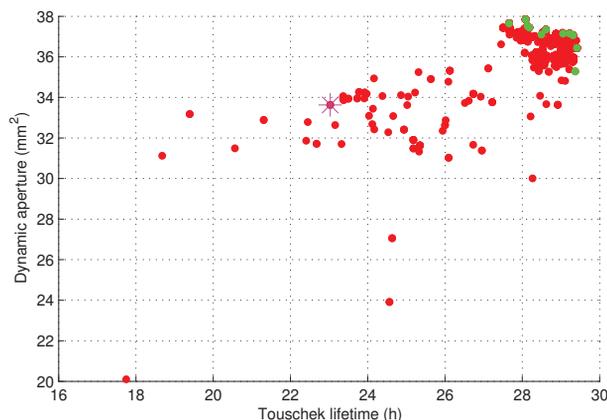


Figure 5: Optimization of Touschek lifetime and dynamic aperture with the NGPM program. The magenta star is the initial setting, the green points are the of the optimum settings found by the optimizer.

After several different runs of NSGA-II, an optimal set of linear parameters and the best associated non linear optics parameters could be determined. The most relevant changes in linear optics include the tunes, that have been moved to $(76.21, 27.34)$, and the horizontal β function in the straight sections, that has been increased from 5.2 m to 6.9 m, without affecting the properties of the photon beam source. The final lifetime is improved by more than 30%. The dynamic aperture increase is partially driven by the higher beta functions in the straight section.

The variables used for the nonlinear optimizations are the chromaticities, the sextupoles (six families) and the octupoles (two families). The change in corrections induced by the variation of the main sextupole fields are neglected in the optimization, but the final results have been verified performing a new correction using the optimal sextupoles. The optimization confirmed that positive chromaticities increase the Touschek lifetime and the dynamic aperture. The optimum values are $\xi_x = 6$ and $\xi_y = 4$. Settings with higher chromaticities ($\xi_x = 10, \xi_y = 10$) have also been found, and

are going to be considered for the high current per bunch filling modes.

The optimization also showed that the gain of using a large number of sextupole and octupole families is negligible. The number of sextupole families has been reduced from six to three (one focusing and two defocusing) keeping the mirror symmetry inside the cell, and the octupoles have been grouped in a single family.

The reduction of the sextupole families reduced also the maximum integrated strengths, therefore the length of the defocusing sextupoles could be shortened by 4 cm, with an important gain in space for additional equipments.

The final non-linear setting has non-zero horizontal detuning with amplitude. Increasing the octupole strengths to have a zero tune shift with amplitude is possible, but the Touschek lifetime would be shorter.

The optimizations described in this paper need a very large computing power and they would not have been possible without the dedicated cluster of the Accelerator and Source division of the ESRF. A typical NSGA-II optimization computes Touschek lifetime and dynamic aperture for 10 seeds of errors for a few hundreds settings. This would take about 10000 h on a single core, while only 20 h are required using 500 cores.

INJECTION CELL TUNING

In order to increase the injection efficiency, the two cells adjacent to the injection straight section have a higher horizontal β functions (see figure 6).

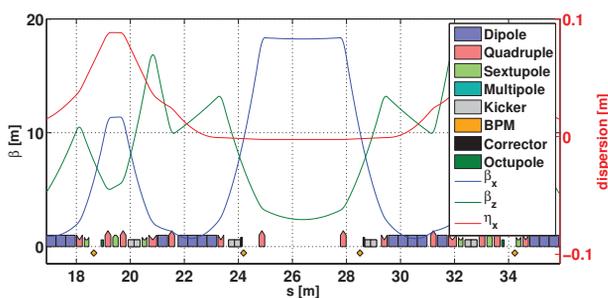


Figure 6: Twiss functions of injection cells.

The two injection cells break the symmetry of the lattice and decrease the momentum acceptance. This can be seen by the chromatic hamiltonian driving terms [10], which are no longer periodic. The sextupole values of the injection cells can be computed in order to restore the periodicity of the chromatic terms. The variation of the chromatic hamiltonian terms determined by each sextupole is inverted using SVD to find the optimal set of the injection cells sextupoles.

The chromatic hamiltonian terms before and after changing the injection cell sextupoles are shown in figure 7.

The Touschek lifetime of the periodic lattice without errors is 55 h, when the injection cell is included this value drops down to 22 h, and after the restoration of the chromatic hamiltonian terms periodicity using all the sextupoles in the injection cells, the lifetime is back to 42 h.

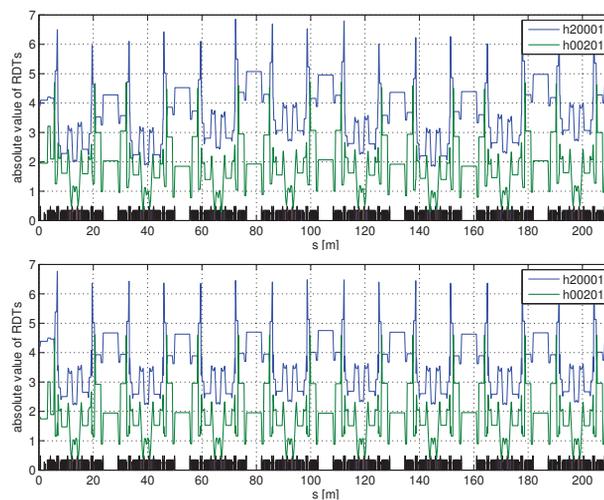


Figure 7: Chromatic hamiltonian driving terms h20001 and h00201 in the first 8 cells, without changing the sextupoles of the injection cells and with the optimum values.

CONCLUSION

The lifetime and dynamic aperture optimization of the ESRF upgrade lattice cell is performed iterating between tune scans, chromaticity scans and multi-objective genetic algorithm optimizations. The latest give the most complete results and allow to tune the parameters of the lattice cell in presence of errors, increasing substantially lifetime and dynamic aperture. The process also allowed to free space in the cell and reduce the number of non-linear magnets families. This optimizations evidenced that positive chromaticities are beneficial for the lattice lifetime.

The symmetry breaking introduced by the injection cells is recovered computing new sextupole values for this cells that restore the periodicity of the chromatic hamiltonian driving terms and consequently increase the Touschek lifetime.

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