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PETRA III STORAGE RING PERFORMANCE IMPROVEMENT BASED ON MULTI-OBJECTIVES GENETIC ALGORITHMS (MOGA)

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Abstract

This paper reports the first application of Multi-Objective Genetic Algorithms (MOGA) to optimize the non-linear beam dynamics of PETRA III storage ring. New settings of quadrupoles and sextupoles magnets are found by MOGA to improve the dynamic aperture and the momentume acceptance, enlarging as a consequence the injection effiency and the beam lifetime, respectively. Those new solutions show an improvement of a factor 2 in beam lifetime maintaining the current dynamic acceptance of PETRA III.

LATTICE DESCRIPTION

PETRA III is a 3rd generation light source operating since 2009. It is composed by five octants based on a 72° FODO structure and 20 damping wigglers to achieve the design emittance of 1.3 nm mrad, one octant (von Laue Hall) with nine 23 m double bend achromat (DBA) cells with dispersion free straight sections to accommodate a total of fourteen beam lines and two octants to accommodate 10 additional beamlines in the North and East halls (see Fig. 1). The arcs are connected by straight sections of 64.8 m and 108 m long. The main parameters of PETRA III are listed in Table 1.

PETRA III operates in two modes: a timing mode of 40 bunches with 2.5 mA of bunch current and a 960 normal mode, both with a total current of 100 mA. The beam lifetime during operation is 1.2 h for the timing mode and 15 h for the normal mode.

Table 1: Main Parameters of PETRA III

Parameter	Value
Energy [GeV]	6
Circumference [m]	2303.95
Current [mA]	100
Emittance hor./ver. [nm mrad]	1.3/0.013
Number of bunches	960/40
Harmonic number	3840

GENETIC ALGORITHMS

The performance of the 3rd generation light sources relies on the beam lifetime and the injection efficiency, both related with the beam dynamic properties of the storage ring as momentum acceptance (MA) and dynamic aperture (DA), respectively. The strong focusing necessary to increases the brilliance has to be compensated and corrected with strong sextupole magnetic fields that in turn introduce large non-linear effects that dramatically affects the performance during operation. High values of beam lifetime and injection efficiency are desirable to reduce the storage ring perturbations during injection, the radiation losses to protect specially the insertion devices with permanent magnets and the energy consumption of the facility. Then, an improvement of the beam lifetime is extremely beneficial to increase the availability during operation, and by extension to the users.

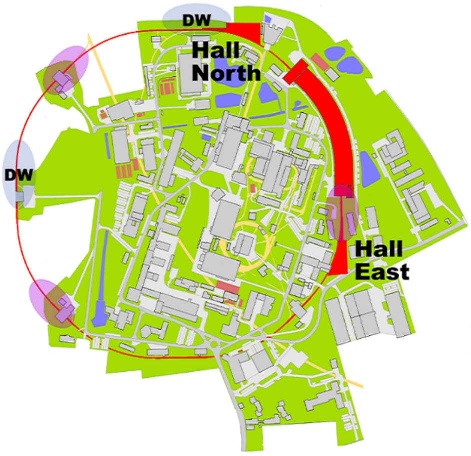

Figure 1: Layout of PETRA III with the location of damping wigglers (DW) and halls with a total of 24 beam lines.

Different approaches and analitycal methods has been developed until now to optimize the non-linear beam dynamics of light sources due to the impact in the performance of such machines [1]. Althought all of these approaches have succeed, for lattices with a high level of complexity, these methods can be tedius and very time consuming because oftenly rely on the experience of the accelerator phycisist.

A new approach based on Genetic Algorithms (GA) [2] arises during the last 20 years due to the development of the performance of high-level computer clusters. GA are a heuristic search that mimics the Darwinian concept of natural evolution to optimize problems of high level of complexity. This method globally explores the multi-parameter space defined by the optimization variables and iteratevely finds the best configuration of the optimization objectives, the so-called Pareto front.

The type of MOGA used in this study was developed at APS, it is based on NSGA-II algorithm [3] and it is based on Elegant [4] as tracking code.

SIMULATIONS

The model of PETRA III storage ring used during simulations includes the quadrupoles families QD and QF to vary

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the fractional part of the tune in a range between 0.1 and 0.4 to avoid indesirable effects of integer and half-integer resonaces, the four sextupoles families with individual power supplies fitting the chromaticity to 1 in both planes and with strenghts limited up to the limit of power supplies (5.6 m^{-3}), the dimensions of the vacuum chamber and random multipole field errors in quadrupoles and sextupoles generated by *elegant* based on analytical formulas [6]. The undulators are not included in the simulations.

Both dynamic and momentum apertures are tracked including the synchrotron oscillation with the operation voltage of 20 MV and frequency of 500 MHz. The Touschek lifetime is computed taken into account 14.7 mm of bunch length at zero current, 2.5 mA of bunch current and 0.25 % of coupling. The single-bunch mode is selected to enlarge the contribution of the Touschek lifetime instead of the gas lifetime (16 h).

A list of approximations is assumed to speed up the tracking computation:

- The total summatory of the Resonance Driving Terms (RDT) is included as optimization objective. As it is shown in reference [5], small values of RDT are necessary but not a suficient condition for large values of DA.
- The number of turns considered for tracking is 100. However several results of the Pareto front are refined with 1000 turns to check their completeness.
- The local momentum acceptance (LMA) is tracked at the location of the quadrupoles of the first 16 part of the ring starting from the middle of the South-West short straight section with a betatron function of 9.35 m. The LMA of the complete ring is reconstructed from this previous result.

Figure 2 shows the optimization results obtained by MOGA for the Touschek lifetime as a function of the area of the DA of the PETRA III storage ring. 4 generation of solutions were obtained after 3 days of computation using 300 CPUs of the BIRD cluster [7]. The red point marks the current dynamic properties of PETRA III storage ring (starting point) and the blue points are the solutions of the Pareto front. The rest of black points are all the solutions found by MOGA. Among all of those solutions with better compromise between objectives, three solutions with ID number #162 (green dot), #366 (magenta dot) and #1004 (orange dot) are selected to study their completeness.

Figure 3 shows the DA of the starting point and the selected solutions computed at the injection point (South-East straight section) with a beta function of 9.49 m and 1000 turns. The negative side of the DA of the selected solutions is increased in 2 mm respect to the starting point. However, the effect of the random multipole errors is overestimated in the model.

Table 2 shows the values of Touschek lifetime and area of the DA of those selected optimized solutions shown at Fig. 3. The DA computed at the injection point are similars to the values obtained at the short straight section as expected due to the similar values of horizontal betatron functions. In addition, the improvement of objectives obtained in Fig. 2 is confirmed with 1000 turns.

Figure 4 compares the MA of the current machine of PETRAIII with and without random multipoles and the solutions selected mentioned above taken into account 1000 turns. The contribution of the multipoles field errors is also overestimated in terms of momentum aperture and it explains the discrepancy between the 0.6 h of Touschek lifetime obtained in Table 2 and the 1.2 h deduced from operation beam lifetime.

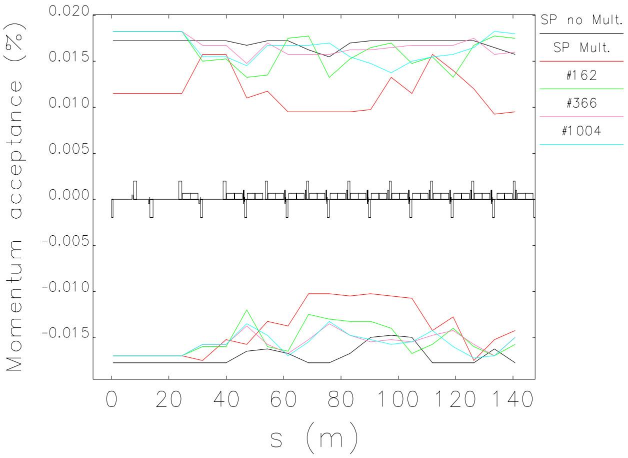

Figure 2: Dynamic properties of the PETRA III storage ring optimized by MOGA obtained at the middle of the South-West straight section with 100 turns.

Table 2: Area of the DA and Touschek lifetime of the Optimized Solutions Computed with 1000 Turns at the Injection Point

Solution	DA Area (mm^2)	T. Lifetime (h)
PETRA III	70.1	0.6
#162	97.4	1.2
#366	100.1	1.3
#1004	102.3	1.3

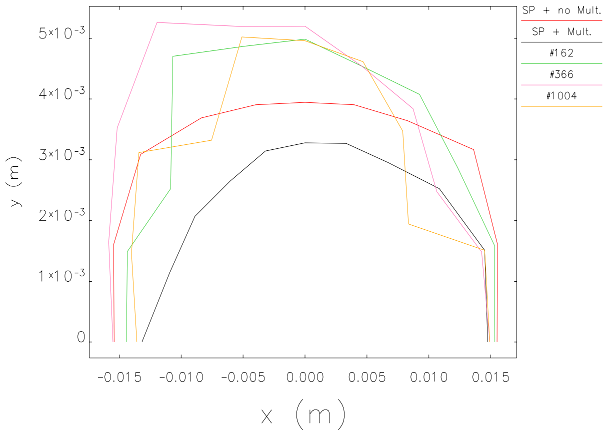

Figure 3: Dynamic apertures of the current PETRA III lattice and optimized solutions at the injection point with 1000.

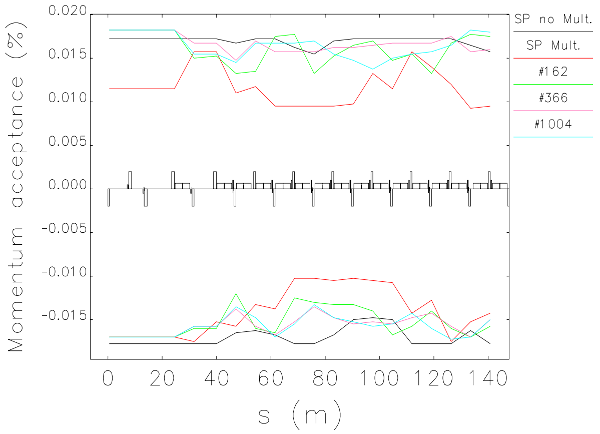

Figure 4: Momentum aperture of the PETRA III storage ring and the optimized solutions obtained by MOGA at injection point with 1000 turns.

A second postprocessing step is done computing the Frequency Map Analysis (FMA) of the selected solutions to estimate the injection efficiency according to the diffusion rate [8, 9], which give information about the stability of particles in the transverse plane and allows to identify the resonance lines. It is coded with a color scale from magenta color for small tune variations to red color for large amplitude oscillation induced by resonance perturbations. Resulting of this analysis, the solution #162 (Fig. 5) is highlighted because it shows an acceptable diffusion rate at the injection point (−13 mm) and consequently it will present an acceptable injection eficicency during operation. Therefore, the solution #162 is identified as a good candidate to test in the control room with beam-based experiments.

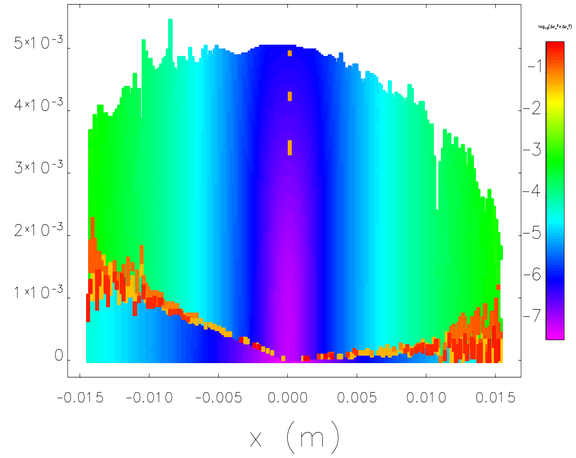

Figure 5: FMA of the solution #162 including synchrotron oscillations and 1000 turns.

CONCLUSIONS

MOGA has been applied to optimize the dynamic propeties of the PETRA III storage ring. The model used includes the dimension of the vacuum chamber and random multipole field errors. The Touschek lifetime is improved by a factor 2 maintaining the current dynamic aperture. However, the effect of the multipole field errors is overestimated and the model is not as accurate as expected.

Beam basic experiments are planned during summer of 2018 to experimentally check the improvement obtained by simulations.

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