ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB224

OPTIMIZATION AND ERROR STUDIES FOR THE USSR HMBA LATTICE*†

L. Hoummi, S. M. Liuzzo, N. Carmignani, L. R. Carver, T. Perron, S. M. White
ESRF, Grenoble, France
I. A. Ashanin, S. M. Polozov, National Research Nuclear University MEPhI, Moscow, Russia
T. V. Kulevoy[1], ITEP-NRC Kurchatov institute, Moscow, Russia
[1]also at National Research Center “Kurchatov Institute”, Moscow, Russia

Abstract

Several new accelerator facilities will be built in Russia in the next few years. One of those facilities is a 6 GeV storage ring (SR) light source, the Ultimate Source of Synchrotron Radiation (USSR) to be built in Protvino, near Moscow. The Cremlin+ project aims to incorporate in this activity the best experience of European Accelerator Laboratories. The optimization of such optics including realistic errors and a commissioning-like sequence of corrections, using Multi-Objective Genetic Algorithms (NSGA-II) is presented.

INTRODUCTION

The Cremlin+ project aims to build several new accelerator facilities in Russia. One of those is a 6 GeV storage ring (SR) to be built in Protvino, near Moscow. The lattice is an adaptation of ESRF-EBS HMBA (Hybrid Multi-Bend Achromat) lattice [1] and is described in [2]. The ring consists of 40 cells and is available in two versions, with and without a Short Bend (SB) of 0.86 T in each cell. Compared to the ESRF-EBS lattice the horizontal emittance is reduced from 133 pm rad to 70 pm rad and the circumference is increased from 844 m to 1 100 m. The β-functions and dispersion for both the injection and the standard cells are displayed in Fig. 1.

The optimisation of such optics using Multi Objective Genetic Algorithms (NSGA-II) is presented here. Errors and corrections are also included leading to a table of foreseen performances for several injection scenarii.

Both versions of the lattice are tested and compared, including alignment errors and corrections.

ERROR STUDIES

The lattice with errors represents the most realistic model of the future machine. In this section we assume alignment errors similar to the ones used to the ESRF-EBS. In the case of the ESRF-EBS, the errors used for simulations turned out to be pessimistic and better performance was achieved thanks to a better than expected alignment of the storage ring. The values used for the simulations are presented in Table 1. Dynamic apertures, lifetimes and injection efficiencies for several injector options are computed using the ESRF cluster [3] and AT [4]. To obtain realistic values for those quantities, alignment and gradient errors defined in Table 1 are set producing 10 different lattices with imperfections.

Table 1: Standard Deviation of Normal Distribution of Single Element Errors Truncated at 2.5σ

Element	**Δx**	**Δy**	**Δϕ**	**ΔK/K**
Units	**μm**	**μm**	**μrad**	**1e-4**
Dipoles	50	50	90	10
Dipole-Quadrupoles	50	50	90	5
Quadrupoles	50	50	90	5
High grad. Quadrupoles	50	50	90	5
Sextupoles	50	50	90	35
Octupoles	50	50	90	40
Beam Position Monitors	50	50	0	0
Correctors	200	200	0	0

For each of the error produced, a full commissioning-like sequence is simulated, starting from first turns steering up to optics and coupling correction following [5]. The final averaged single particle beam dynamics parameters of the lattice are listed in Table 2 together with the expected correction strengths.

Table 2: Relevant Optics Parameters and Correction Strengths After Correction Averaged Over 10 Error Seeds

	Horizontal	**Vertical**
closed orbit	100 ± 10 μm	80 ± 10 μm
dispersion	0.4 ± 0.1 μm	0.4 ± 0.1 μm
tunes	0.0001	0.0001
β-beating	1.2 ± 0.2 %	1.1 ± 0.2 %
emittance	70 ± 1 pm rad	0.1 ± 0.01 pm rad
chromaticity	7.00 ± 0.01	6.00 ± 0.01
steerers	±300 μrad	±300 μrad
quadrupoles	$\pm 3\,10^{-4}$ m^{-1}	$\pm 3\,10^{-4}$ m^{-1}

The lifetimes obtained after correction are displayed in Table 3 for the two USSR lattice options, including a fixed vertical emittance of 5 pm rad (assuming a vertical emittance blow up is running, as the expected natural vertical emittance is below 1 pm rad), including bunch lengthening according

* This project has received funding from the European Union’s Horizon 2020 research and innovation program under grant #871072
† In accordance with resolution of government of Russian federation no. 287 on approval of the Federal research and engineering programme for development of synchrotron and neutron studies and research infrastructure for 2019-2027

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB224

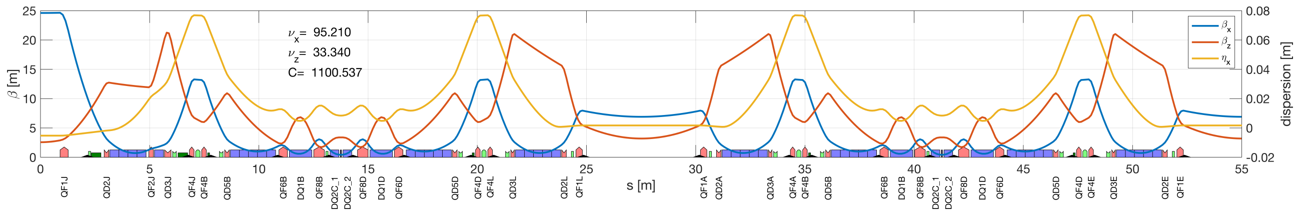

Figure 1: Twiss functions and dispersion for the first (injection) and second (standard) cells out of 40 cells (2 injection plus 38 standard) HMBA lattice including Short Bend of the USSR storage ring.

to the charge per bunch expected in each filling mode and assuming a RF voltage set to 5 MV. The expected lifetime can be estimated to 12.4 h by scaling the lifetime obtained for the ESRF-EBS HMBA storage ring with the natural horizontal emittance for a uniform filling. The lattice version including SB achieves this estimated value. The version without SB may be further optimized to reach the same goal.

Table 3: Touschek lifetime for the 6 GeV USSR SR with errors and correction EBS for several filling modes. ϵ_v = 5 pm.rad, Z = 0.67 ohms. The expected lifetime scaling EBS values: 12.4 h (7/8 uniform).

	HMBA	**HMBA +SB**
7/8 uniform	9.2 ± 1.5 h	12 ± 2 h
16 bunches	1.0 ± 0.2 h	0.9 ± 0.1 h
4 bunches	0.7 ± 0.1 h	0.6 ± 0.1 h

Figure 2 displays the transverse dynamic aperture at injection for the perfect lattice (option including SB) and for the ten lattices with errors and corrections, on-energy and off-energy. The injection is assumed from the inside of the ring, thus the relevant space for off-axis injection is approximately ~6 mm. This space has to host 1 mm stored beam to septum stay clear and a septum blade of 3 mm, leaving about ~ 2 mm space for the off-axis injected beam, depending on the seed of errors.

The injection options considered are: 1) a full energy linac with a photo-gun injector (preferred, first choice); 2) a full energy linac with thermo-ionic gun (available also with option 1 for reliability); 3) a long booster fitting the same tunnel of the main SR as described in [6] ; 4) a booster identical to the existing ESRF booster (FODO design, large emittance, length one third of the main SR) [7].

Table 4: Injected Beam Parameters Considered for the Evaluation of the Injection Efficiency

	$\epsilon_{h,inj}$	$\epsilon_{v,inj}$	$b_{l,inj}$	$\sigma_{E,inj}$
units	**nm**	**nm**	**mm**	**%**
short booster	30	30	20	0.13
long booster	2.9	0.29	5.5	0.07
Linac Thermo. gun	1.5	1.5	8.0	0.2
Linac Photo. gun	0.3	0.3	1.0	0.08

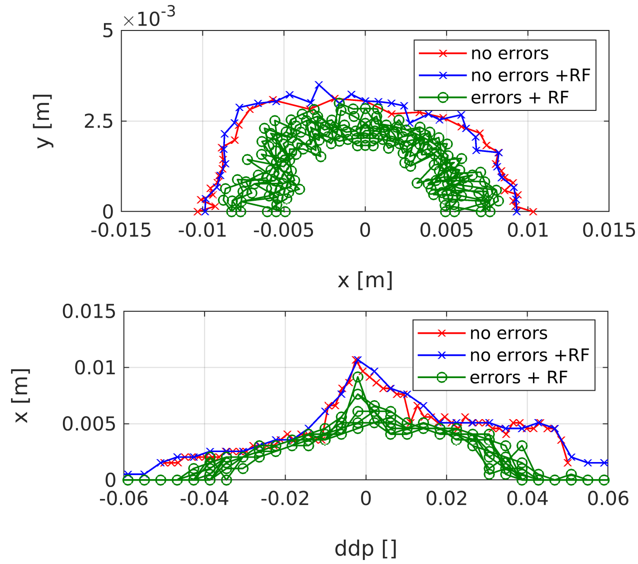

Figure 2: On-energy (top) and off-energy (bottom) dynamic aperture with (green) and without (red, blue) errors for USSR HMBA+SB lattice.

The injection efficiency is evaluated for each of the injector types, with the specific values defined for emittance, bunch length and energy spread provided in Table 4. In all cases the optics at injection are matched to the optimum ones (that depend on the injected beam expected emittance) and assuming that the injected beam center is set at 2σ from the septum blade. Results are displayed in Table 5.

Table 5: Injection efficiency for the 6 GeV USSR SR with errors and corrections. Optimized beta at injection, 3 mm septum blade thickness at injection, 1 mm stored beam stay clear, off-axis injection with four kickers parallel bump, 2σ cut for the injected beam distribution.

	HMBA	**HMBA +SB**
max DA at injection	**8.1 ± 0.4 mm**	**7.5 ± 1.0 mm**
short booster	52 ± 15 %	-
long booster	95 ± 5 %	97 ± 2 %
Linac Thermo. gun	94 ± 7 %	95 ± 4 %
Linac Photo. gun	98 ± 2 %	98 ± 2 %

In all cases, the commissioning-like correction sequence could recover an injection efficiency of almost 100% for all

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB224

injector systems - but the short booster - , for all error sets. The injected beam Gaussian distribution is centred at 2σ from the septum blade, leading to a systematic loss of 1.7% for each case tested.

MOGA OPTIMIZATION

The corrected lattices with errors are then optimised using a Multi-Objective Genetic Algorithm (MOGA) based on Matlab [8]. The optimization evaluates the on-momen-tum dynamic aperture and the Touschek lifetime, while keeping the chromaticities constant. A first approach conserves the symmetry of the sextupoles in the cell, thus uses a total of six sextupole families (three in the standard cells and three in the injection cells) and two octupole families as variables. Additional optimizations could differentiate the defocusing sextupoles and increase the number of knobs.

The insertion of errors and the applied corrections induced strength differences between magnets of the same family in different cells. To conserve this inhomogeneous distribution, the optimization assigns a relative variation of the strengths per family, according to $k^x_{2,3} = k^{nominal}_{2,3} + \Delta k_{2,3}(x)$ with $k_{2,3}$ the sextupole and octupole strengths, x a MOGA individual. Figure 3 shows the evolution of the Touschek lifetime and the on-momentum dynamic aperture area for such an optimization, after 20 generations of 20 individuals each. The optimization recovered the performances of the design lattices with errors and corrections with a maximum 13 h lifetime and a 8 mm^2 on-momentum dynamic aperture area.

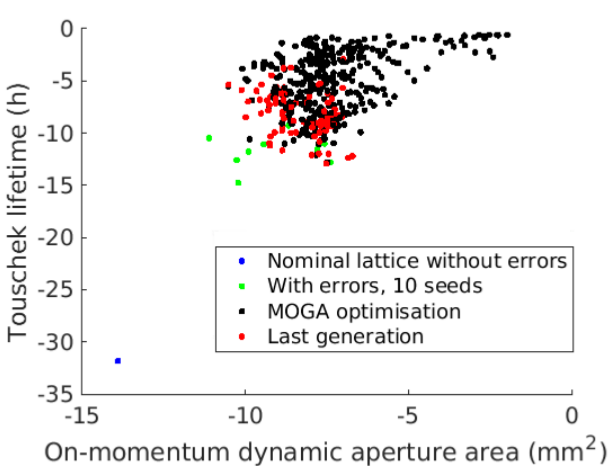

Figure 3: Evolution of the objective functions throughout the MOGA optimization for the lattice with errors and corrected (in black and red), compared to the lattices with errors and corrected over 10 seeds (in green) and the nominal lattice with no errors and no optimization (in blue).

The on-momentum dynamic apertures of the lattice with errors and corrections are compared to their optimised counterparts in Fig. 4. Some settings overtake the performances of the lattice with errors and corrections, but there is still marging to approach the performances of the lattice without errors. Further optimizations shall be conducted to increase the Touschek lifetime while maintaining the current levels of on-momentum dynamic aperture for off-axis injection.

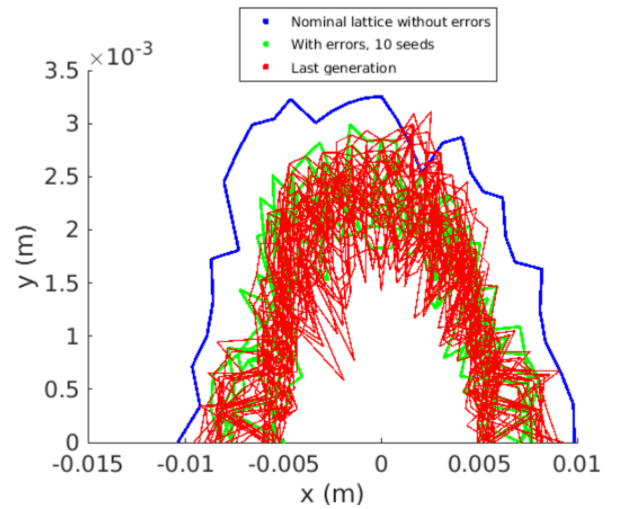

Figure 4: Comparison of the on-momentum dynamic apertures of the design lattice (in blue), the corrected lattice with errors (in green) and all results of the MOGA optimization (in black) with the last generations highlighted (in red).

CONCLUSIONS

The lattices proposed for the USSR 6 GeV storage ring were tested including errors. The errors amplitudes were matched to the ESRF-EBS simulations, as better alignment was achieved during commissioning. Each error was corrected using a commissioning-like sequence. The dynamic apertures were recovered with an averaged 30% decrease in horizontal. The Touschek lifetime for different filling patterns was matched to the expected lifetime, compared to the ESRF-EBS operation. The injection efficiency was simulated for four different injectors, with values compatible with 100% for both linac options and for the long booster.

The stability of the lattice with errors was then optimised using a Multi-Objective Genetic Algorithm, to increase both lifetime and on-momentum dynamic aperture for off-axis injection. The first runs improved the raw lattice with errors, but do not approach the lifetime of the nominal lattice without errors. Future efforts will focus on improving the optimization variables and environment to approach the nominal performances.

REFERENCES

[1] G. Admans, P. Berkvens, A. Kaprolat, and J.-L. Revol, *ESRF Upgrade Programme Phase II*, ESRF, Dec. 2014.

[2] S. Liuzzo *et al.*, “USSR HMBA Storage Ring lattice options”, presented at the 12th Int. Particle Accelerator Conf. (IPAC’21), Brazil, May 2021, paper TUPAB049, this conference.

[3] M. A. Jette, A. B. Yoo, and M. Grondona, “’SLURM’: Simple Linux Utility for Resource Management”, *Lect. Notes Comput. Sci.*, pp. 44-60, 2003. doi:10.1007/10968987_3

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB224

[4] B. Nash *et al.*, "New Functionality for Beam Dynamics in Accelerator Toolbox (AT)", in *Proc. IPAC'15*, Richmond, VA, USA, May. 2015, pp. 113-116. doi:10.18429/JACoW-IPAC2015-MOPWA014

[5] S. Liuzzo *et al.*, "A long booster option for the USSR 6 GeV storage ring", in *Proc. IPAC'16*, Busan, Korea, May. 2016, pp. 2818-2821. doi:10.18429/JACoW-IPAC16-WEPOW005

[6] S. Liuzzo *et al.*, "A long booster option for the USSR 6 GeV storage ring", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Brazil, May 2021, paper TUPAB050, this conference.

[7] J.-M. Filhol, "ESRF booster synchrotron: characteristics and achieved performances", in *Proc. EPAC'92*, Berlin, Germany, 24 - 28 Mar 1992, pp. 471-473. https://accelconf.web.cern.ch/e92/PDF/EPAC1992_0471.PDF

[8] J.M. Herrero, "ev-MOGA Multiobjective Evolutionary Algorithm", MATLAB Central File Exchange. Retrieved April 27, 2021. https://www.mathworks.com/matlabcentral/fileexchange/.