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USSR HMBA STORAGE RING LATTICE OPTIONS*†

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Abstract

Several new accelerator facilities will be built in Russia in few years from now. One of those facilities is a 6 GeV storage ring (SR) light source (USSR – Ultimate Source of Synchrotron Radiation) to be build in Protvino, near Moscow. The Cremlin+ project [1, 2] aims to incorporate in this activity the best experience of European Accelerator Laboratories. The design of the optics for this SR is presented here in two declinations leading to ~70 pm rad equilibrium horizontal emittance. The first is a 40 cells lattice, the second is the same but includes high field Short Bending magnet sources in each cell. Optics and high order multipole optimizations are performed to obtain sufficient lifetime and dynamic aperture for a conservative off-axis injection.

INTRODUCTION

The HMBA (Hybrid Multi Bend Achromat) lattice was initially diffused in 2012 has an option for the ESRF-EBS upgrade [3]. Since then the HMBA based ESRF-EBS upgrade project has been approved and successfully commissioned in 2020 [4]. At least three light sources are planned to be built in Russia in the near future. One is a 6 GeV Storage Ring (SR) light source (USSR – Ultimate Source of Synchrotron Radiation) to be built in Protvino (Moscow region) [5]. Similarly to the MAXIV design [6], a full energy linac [7] will be used for injection in the SR and provide beam in parallel to a Free Electron Laser (FEL) facility. This introduces additional complication in the design of injection systems. The design of the optics for the USSR SR is presented here in two versions leading to ~70 pm rad natural horizontal emittance. The first version is a 40-fold symmetry HMBA lattice, the second adds a high-field (0.86 T) Short Bending (SB) magnet source in the center of each cell. Optics and high order multipoles optimizations are performed to obtain sufficient lifetime and dynamic aperture for a conservative off-axis injection.

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STORAGE RING LATTICE

The starting point of the design study is a periodic HMBA lattice including an injection straight section with a large horizontal β function ($\beta_{h,inj}$ =25 m) to provide larger injection efficiency for off-axis injection schemes. Providing the USSR operates at the same energy as the ESRF-EBS ring and uses the same unit cell we can use the following scaling law to determine the number of unit cells N_c required to achieve the designed horizontal emittance ~70 pm rad [8]: $\epsilon_h \propto \frac{E^2}{N_c^3}$ where E is the beam energy. Using this scaling law we find that 70 pm rad horizontal emittance can be achieved with $39 > N_c > 40$. A natural way to achieve the design goal without deviating too much from the well optimized ESRF-EBS standard cell is therefore to increase the number of cells to 40 with respect to the initial 32.

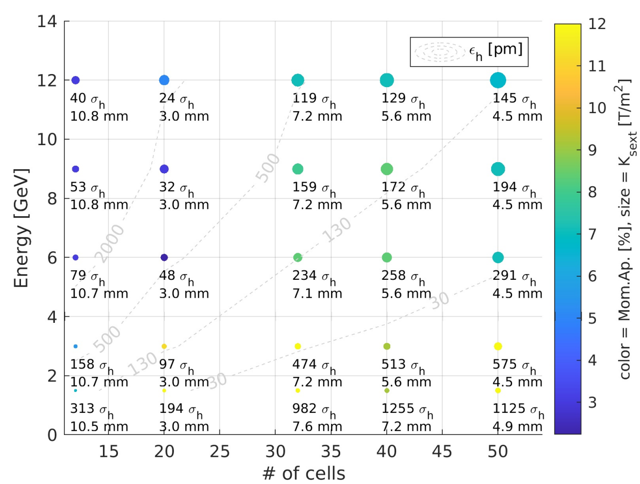

Figure 1: Scaling of an HMBA lattice cell (no injection cell) to different energies and number of cells. Fixed tunes, chromaticities and cell length.

Figure 1 shows the evolution of the SR parameters as a function of the number of cells and of the electron beam energy. The numbers represent the dynamic aperture at injection (in mm or in units of horizontal beam size), the grey lines are the horizontal emittance, the size of the dots are the strength of the sextupoles and their color is the momentum acceptance at the injection point. The dynamic aperture is representative of the injection efficiency while the momentum acceptance will constrain the achievable lifetime [9]. We can see that at 6 GeV the 40 cells lattice will provide the desired emittance with performances consistent with the

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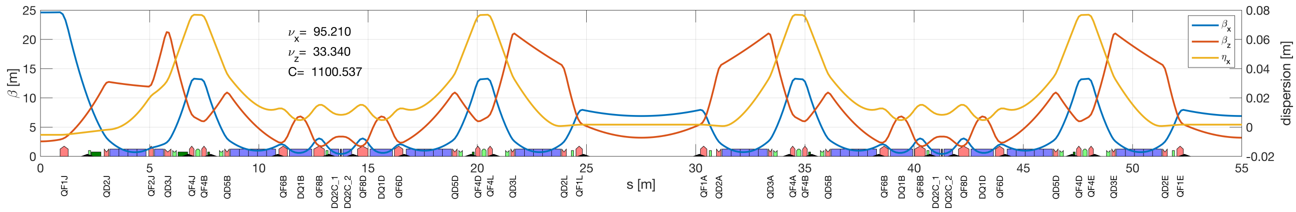

Figure 2: Twiss functions and dispersion for the first (injection) and second (standard) cell out of 40 cells (2 injection and 38 standard cells) composing the HMBA lattice of USSR.

Table 1: Main Parameters for the USSR SR Lattice

6 GeV USSR	HMBA	HMBA +SB
Circumference	1055 m	1100 m
cells	40	40
beamlines	34 ID	34 ID + 40 BM
nat. hor. emittance	68 pm.rad	70 pm.rad
vertical emittance	5 pm.rad	5 pm.rad
energy spread	$0.85\ 10^{-3}$	$0.86\ 10^{-3}$
mom. comp. factor	$5\ 10^{-5}$	$6\ 10^{-5}$
bunch length (I=0)	2.7 mm	2.9 mm
tune	95.21, 33.34	95.21, 33.34
chromaticity	12,7.5	7,6
Energy loss / turn	2.1 MV	2.0 MV
RF voltage	5.0 MV	5.0 MV
RF frequency	352 MHz	352 MHz
harmonic number	1240[1]	1296[2]
Max. total current	200 mA	200 mA

original 32 cells ESRF-EBS lattice. The strength of the sextupoles is increased but remains within the design range of the ESRF-EBS sextupole magnets. This layout will therefore be assumed in all the following sections.

The proposed 40 cells lattice layout is presented in Fig. 2 (first two cells out of 40). All magnet gradients are compatible those realized for the ESRF EBS upgrade, therefore minimizing the magnet design effort. Key parameters of USSR SR are summarized in Table 1. Two lattice options are considered for USSR: one of the same length of the EBS cell (~26.3 m) and one with SB inserted in every cell and slightly longer (~27.5 m) to recover similar horizontal equilibrium emittance. This second option has one extra magnet to design (DQ2C, see Fig. 2) but provides more than twice the number of beamlines. Six straight sections are kept for accelerator operation: 1 for injection, 1 for injection improvements [10], 3 for RF cavities, 1 for diagnostics. The RF frequency was chosen to be the same as the ESRF-EBS in order to be able to use also for USSR the ESRF HOM damped cavities design and existing 352 MHz power sources [11, 12]. The final arrangement and configuration of the straight sections should be decided in view of the beamlines requirements for this machine. In addition to the increased flexibility in terms of beamlines arrangement, the version including short bends meets all design requirements.

Beam position monitors, correctors and the space for vacuum pumping ports, absorbers, and flanges are considered in the lattice models for both options.

Short Bend Lattice Cells

Compared to the the standard HMBA cell the Short Bend lattice option, has longer longitudinal gradient dipoles and a 0.86 T bending magnet source added in the center of the cell [13]. A completely new design for the DQ2C+SB magnets may be envisaged as done, for example, for the Brazilian light source [14], with larger field in the central part. This will have potentially some impact on the equilibrium horizontal emittance of the SR.

The total cell angle is 9°, giving an angular separation between Insertion Device and Short Bend sources of 4.5°. Five degrees separation between SB and ID sources in each cell may be achieved with a 36 cells option ($\epsilon_{h,0}$ =94 pm rad), that has been studied and optimized but is not included in this paper.

BEAM DYNAMICS SIMULATIONS

Transverse dynamic aperture at injection and Touschek lifetime are optimized empirically and using NSGA-II multi objective genetic algorithms following [15].

For Touschek lifetime estimates the impedance is assumed to be $|\frac{Z}{n}| = |\frac{Z}{f/f_{rev}}|$ =0.67 Ω and the vertical emittance is set to 5 pm rad. Bunch lengthening is considered for a uniform filling of 7/8 of the bunches in the SR (7/8 uniform). The momentum acceptance (MA) is computed along the cell at all elements as in Fig. 3. An optimum is found for operation with an RF Voltage of 5 MV.

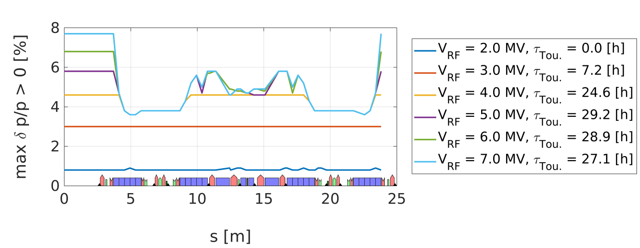

Figure 3: Momentum acceptance along a standard cell vs total RF voltage. Without injection cell.

Figure 4 shows the dynamic aperture and Touschek lifetime for the USSR lattice cell after an optimization process

[1] for simulations the harmonic numbers used is 1241
[2] for simulations the harmonic numbers used is 1294

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that included the tuning of: all standard cell optics parameters (β functions and dispersion at sextupoles and insertion devices, $-\mathcal{I}$ condition, etc.), tunes, chromaticities and injection sextupoles and octupoles.

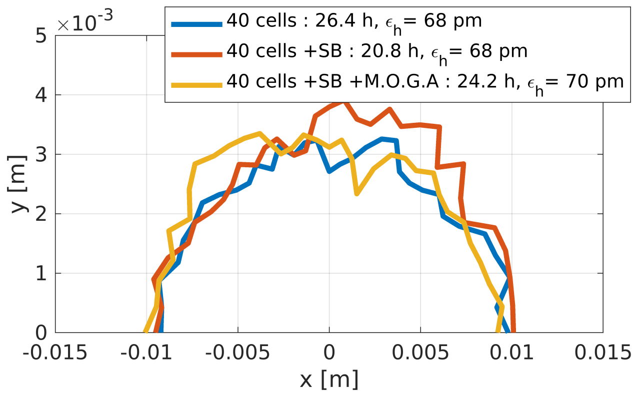

Figure 4: Dynamic aperture, lifetime and natural horizontal emittance for USSR lattice with 40 cells, 40 cells + SB, and optimizing the cell key optics functions using MOGA. Including injection cell.

An horizontal dynamic aperture of 10 mm is achieved together with beam Touschek lifetimes without errors above 20 h. Traditional off-axis injection with a four kickers bump is foreseen for USSR [16, 17]. This choice prevents the more complicated swap-out injection schemes, as adopted by several upgrade projects [18]. For the injection efficiency simulations the assumptions are: a 3 mm thick septum blade, 2 σ injected beam cut off, an injected beam with about 1 nm horizontal emittance and matched optics at the injection point [19]. These conditions guarantee 100% injection efficiency without errors. Further studies with errors and comparison of several injection schemes are presented in [20]. A particular interest to users community is the USSR SR lattice option that includes special cells (up to 8) with long enough straight sections (~10 m). Preliminary studies of such lattice option shows high impact on DA and MA. Further investigations should be carried out in order to achieve design parameters of the light source.

USER OPERATION EMITTANCE

The equilibrium horizontal emittance of the storage ring will be reduced when Insertion Device (ID) gaps are closed. Such a reduction is difficult to predict and will vary in time according to the users defined ID gap set points. Figure 5 shows the expected reduction of horizontal natural emittance as a function of the total radiated ID power. This curve assumes negligible dispersion is generated by the ID and zero dispersion at the straight sections. Future refined simulations will include the real ID installed. Furthermore, Fig. 5 shows the potential achievable horizontal emittance in real operation conditions (excluding Intra Beam Scattering).

The natural horizontal emittance presented in Table 1 corresponds to the zero current approximation. In normal operation, and in particular in the high current per bunch

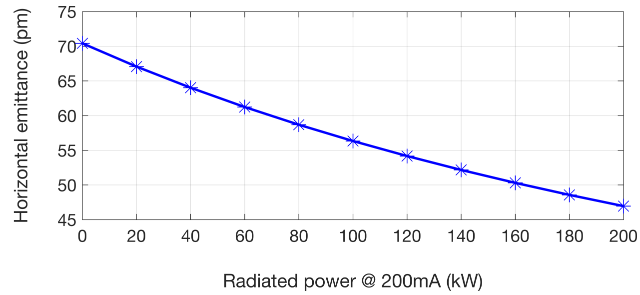

Figure 5: Theoretical emittance reduction versus IDs radiated power (assuming zero dispersion). Expected variation of natural horizontal emittance as a function of ID power at 200mA.

modes, the intra beam scattering (IBS) can significantly increase the transverse beam size. In Fig. 6, the horizontal and vertical emittance growths due to IBS effect are shown as a function of the bunch current, for different zero current vertical emittance values.

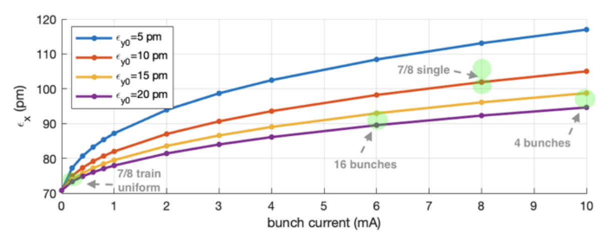

Figure 6: Horizontal emittance growth as a function of the bunch current for the intrabeam scattering effect for 5, 10, 15 and 20 pm rad zero current vertical emittance. No ID gaps (0 radiated power). In green, the horizontal emittance for the different operation modes.

For the most common operation filling modes (at ESRF) 7/8 uniform the emittance is only mildly affected. The camshaft bunch (7/8 single) and the high current per bunch modes (16 and 4 bunches) are more visibly impacted. Operation with an artificially increased vertical emittance may be beneficial both in terms of final lifetime and in terms of delivered horizontal emittance.

CONCLUSIONS

A lattice is proposed for the USSR 6 GeV SR, adapting and scaling the ESRF-EBS lattice optics. The main differences are in the different bending angle and in the introduction of a Short Bending magnet of 0.86T at the center of the cell. The lattice beam dynamics are detailed in [20] and show that (without errors) injection efficiency of 100% and lifetimes above 20 h can be obtained.

REFERENCES

[1] Cremlin+, https://www.cremlinplus.eu/work_programme/wp4_ussr_collaboration_with_ussr/.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB049

[2] T. Kulevoy *et al.*, "USSR - the Project of the Ultimate Synchrotron Radiation Source in Russia", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper TUPAB055, this conference.

[3] G. Admans, P. Berkvens, A. Kaprolat, and J.-L. Revol, "ESRF Upgrade Programme Phase II", ESRF, Grenoble, France, Dec. 2014.

[4] S. White *et al.*, "Commissioning and restart of ESRF-EBS", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper MOXA01, this conference.

[5] I. Ashanin *et al.*, "Conceptual Design of a Dedicated Fourth-Generation Specialized Synchrotron Radiation Source (SSRS-4) at the Kurchatov Institute", *Phys. At. Nucl.*, vol. 81, p. 1646-1651, Dec. 2018. doi:10.1134/S1063778818110030

[6] P. F. Tavares *et al.*, "The MAXIV storage ring project", *J. of Synchrotron Radiat.*, vol. 21, p. 862–877, Sep. 2014. doi:10.1107/S1600577514011503

[7] I. Ashanin *et al.*, "Beam dynamics simulation in the linear accelerator used as an injector for the 4th generation Specialized Synchrotron Radiation Source SSRS-4", *Vestnik Sankt-Peterburgskogo Universiteta*, vol. 15, pp. 126–139, 2019. doi:10.21638/11702/spbu10.2019.110

[8] D. Einfeld *et al.*, "First multi-bend achromat lattice consideration", *J. of Synchrotron Radiat.*, vol. 21, no. 5, pp. 856–861, Sep. 2014. doi:10.1107/S160057751401193X

[9] E. B. Levichev, "Low emittance electron storage rings", *Physics-Uspekhi*, vol. 61, no. 1, p. 29, 2018. doi:10.3367/ufne.2016.12.038014

[10] S. White *et al.*, "A flexible injection scheme for the ESRF-EBS", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper MOPAB116, this conference.

[11] V. Serriere *et al.*, "352.2 MHz HOM Damped Normal Conducting ESRF Cavity: Design and Fabrication", in *Proc. 2nd Int. Particle Accelerator Conf. (IPAC'11)*, San Sebastian, Spain, Sep. 2011, paper MOPC004, pp. 68-70.

[12] A. D'Elia *et al.*, "ESRF-EBS 352 MHz HOM Damped RF Cavities", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper MOPAB333, this conference.

[13] S. Liuzzo *et al.*, "Optics Adaptations for Bending Magnet Beam Lines at ESRF: Short Bend, 2-Pole Wiggler, 3-Pole Wiggler", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 666-669. doi:10.18429/JACoW-IPAC2017-MOPIK062

[14] L. Lin *et al.*, "The Sirius project", *J. of Synchrotron Rradiat.*, vol. 21, pp. 904–911, Sep. 2014. doi:10.1107/S1600577514011928

[15] N. Carmignani *et al.*, "Linear and Nonlinear Optimizations for the ESRF Upgrade Lattice", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 1422-1425. 10.18429/JACoW-IPAC2015-TUPWA013

[16] S. Takano *et al.*, "Renovation of Off-Axis Beam Injection Scheme for Next-Generation Photon Sources", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 2318-2321. doi:10.18429/JACoW-IPAC2019-WEPMP009

[17] M. Aiba, "Review of Top-up Injection Schemes for Electron Storage Rings", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 1745-1750. doi:10.18429/JACoW-IPAC2018-WEXGBE1

[18] T. E. Fornek, "Advanced photon source upgrade project preliminary design report", ANL, IL, USA, Rep. APSU-2.01-RPT-002, Sep. 2017.

[19] A. Streun, "SLS booster-to-ring transferline optics for optimum injection efficiency", SLS, Switzerland, Rep. SLS-TME-TA-2002-0193, May 2015.

[20] L. Hoummi *et al.*, "Error studies and optimizations for the USSR 6GeV storage ring", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper MOPAB224, this conference.