SLS 2.0, THE UPGRADE OF THE SWISS LIGHT SOURCE

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Abstract

The Swiss Light Source (SLS) will be upgraded by replacing the storage ring in the existing hall in 2023–24. The SLS lattice build from 12 triple-bend arcs operating at 2.4 GeV is replaced by a 12×7-BA lattice operating at 2.7 GeV to increase hard X-ray brightness by a factor 60. The layout is constrained by the existing tunnel to 288 m circumference, nevertheless a low emittance of 158 pm is realized using longitudinal gradient and reverse bends. Dynamic aperture is sufficient to start with classical injection based on a 4-kicker bump. An upgrade path for on-axis injection with fast kickers has been implemented. Small beam pipes of 18 mm inner diameter and corresponding reduction of magnet bores, and the use of permanent magnets for all bending magnets enables a densely packed lattice and contributes most to a reduction of total power consumption of the facility by 30%.

INTRODUCTION

The Swiss Light Source (SLS) started user operation in 2001. Today it is fully equipped with a set of 18 beam lines and delivers about 5000 h of user beam time per year at excellent availability (98.5% average 2012-21) and stability (<1 µm) rms at front ends). However, with the advent of modern diffraction limited storage rings (DLSR) of multi-bend achromat (MBA) type it became clear, that the SLS emittance of 5.0 nm at 2.4 GeV would no longer be competitive, and planning for an upgrade started in 2014. Project funding was secured by end of 2020, and the technical design report was published one year later [1]. Between fall 2023 and end of 2024 the existing storage ring will be exchanged by a new one providing much lower emittance of 158 pm at 2.7 GeV, to be installed in the existing tunnel with radial source point shifts limited to ±70 mm. The combination of lower emittance and higher beam energy provides a factor 60 increase of hard X-ray brightness (>10 keV), which will be further enhanced by means of new undulators of shorter period. Long period elliptic undulators on one side, and superbends of up to 5 T peak field on the other side, will support experiments spanning a photon energy range from 6 eV to 80 keV. Routine user operation will resume by mid 2025. In this report we will summarize the upgrade concept and highlight the most challenging issues.

LATTICE

The minimum emittance of a storage ring scales approximately inversely with the third power of circumference, thus the SLS is handicapped by its comparatively small circumference of 288 m. In order to get competitive emittance a new lattice cell was developed. It employs reverse bends (RB), which are realized by slightly shifting the horizontally focusing quadrupoles radially away from the storage ring center, and longitudinal gradient bends (LGB), which are realized in the most simple configuration as a sandwich of a pure dipole between two vertically focusing combined function magnets (VC) of lower field: in the periodic unit cell of an MBA the RB suppresses the dispersion at the LGB center, where the field is highest, in order to minimize quantum excitation, which is the source of emittance [2].

The transverse gradients in the RBs and VCs increase the horizontal damping partition and thus further reduce emittance on expense of higher energy spread. A regular 7-BA arc was found as best compromise between low emittance and feasibility in terms of technology and non-linear dynamics. A summary of the most important lattice parameters for SLS (without the FEMTO insertion for laser beam slicing and without undulators) and for SLS-2.0 is given in Table 1.

Table 1: SLS and SLS 2.0 Lattice Parameters (bare lattice → all undulators closed)

Parameter	**Units**	**SLS**	**SLS-2.0**
Circumference	[m]	288.0	
Beam energy	[GeV]	2.41	2.70
Hor. emittance	[pm]	5030	158 → 131
Vert. emittance	[pm]	5–10	10
Energy spread	$[10^{-3}]$	0.88	1.15 → 1.04
Radiation loss	[keV]	574	689 → 900
Beam current	[mA]	400	
Beam lifetime	[h]	≈ 10	≈ 11

The alternative of a hybrid-MBA [3] as used for other projects, mainly for larger rings at higher energy, was investigated too. However for SLS a regular MBA was found to better fulfill the requirements on emittance reduction, available straight length and beam lifetime while still providing sufficient transverse dynamic aperture for off-axis injection.

In order to follow the footprint of the existing storage ring as close as possible, the 12 arcs are connected by 6 short, 3 medium and 3 long straight sections. Although the footprint thus has 3-fold symmetry and the linear beam optics as shown in Fig. 1 has no periodicity at all due to a high-beta optics in the injection straight, the (on-momentum) non-linear optics is tuned to 12-fold symmetry by adjusting the phase advance of all arcs to the same value irrespective of the type of the adjacent straights.

As a compromise between brightness and beam lifetime, the vertical emittance is set to about 10 pm by means of 22 skew quadrupoles per arc generating closed bumps of vertical dispersion while suppressing betatron coupling in the straight sections.

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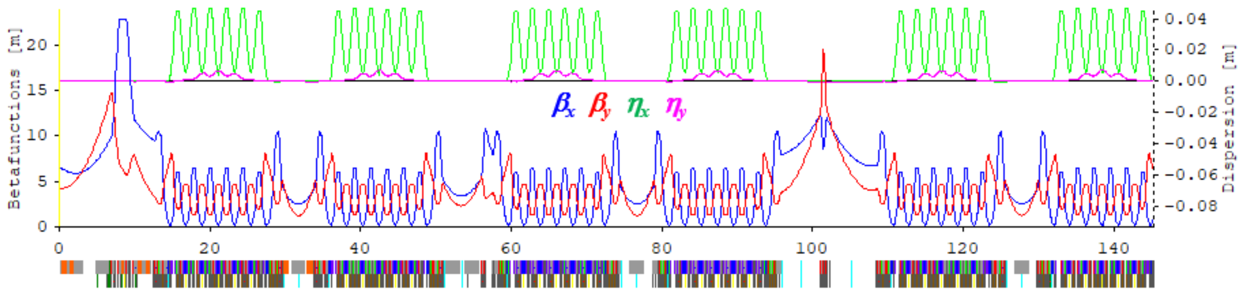

Figure 1: Optical functions for one half of the SLS 2.0 lattice, starting with the injection straight.

VACUUM SYSTEM

Emittance reduction in MBA lattices is based on miniaturization in order to accommodate more cells in a given length. Low dispersion allows the beam pipe dimensions to be reduced while still providing sufficient momentum acceptance to get reasonable Touschek lifetime. Non-evaporable getter (NEG) coating of the vacuum chambers reduces photon stimulated desorption and provides distributed pumping to achieve ultra-high vacuum even in narrow beam pipes. Miniaturization then is limited by the onset of instabilities due to the resistive wall impedance, which scales inversely with the second (longitudinal), resp. third (transverse) power of the beam pipe dimensions.

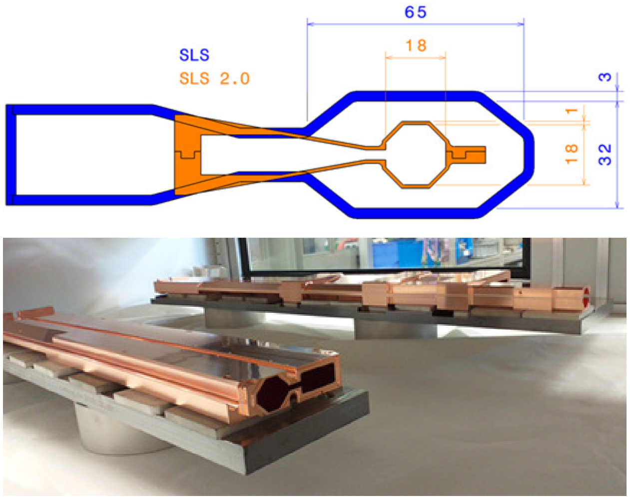

Figure 2: Cross-section of SLS 2.0 dipole chamber in comparison to the SLS chamber [1], and first prototypes.

To minimize the resistive wall impedance, the SLS 2.0 vacuum chamber with 18 mm inner diameter as shown in Fig. 2 is made from copper covered with a thin (500 nm) NEG layer. Together with a careful design of the tapers and other transitions, this results in a typical safety margin of factor 2–3 with respect to single bunch instability thresholds.

The octagon shape has some advantages when manufacturing the chamber from two halves. The flat surfaces are ideal for connection of cooling channels and for inserting BPM buttons in the 45°-planes. Copper as material provides good thermal conductivity. Stainless steel inserts at the corrector magnets reduce eddy currents and increase the frequency range of the orbit feedback to 320 Hz (0 dB point). Arc chambers of 18 m length will be assembled without bellows and baked and NEG-activated in an oven before inserting them into the storage ring by means of a crane with a special support structure. An average pressure below 10^{-9} mbar (CO-equivalent) is expected to be reached after 100 Ah of beam dose.

MAGNETS

The unit cell of the 7BA is only 2165 mm long but includes the LGB-triplet made from a dipole and two combined function bends, two reverse bends, three sextupoles, three octupoles with quadrupole and skew quadrupole functions, two correctors, a beam position monitor (BPM) and an absorber. As a consequence the magnets are close to each other and the fields are rather high in order to provide the strong focusing required for low emittance (cell tunes are 0.429/0.143).

All 348 bending magnets are realized with permanent magnets (PM) in order to save coil spaces and to reduce the magnet power consumption of the new storage ring by 60% compared to the existing one.

Some of the PM-based magnets are rather large in yoke diameter (up to 75 cm) and have high pole-tip fields exceeding 1 T, thus the stray field affects the yoke of neighboring magnets and even saturates it partially, if the magnets are too close. If the neighboring magnet is rather weak like the orbit correctors or the octupoles, its properties change significantly, such that it acquires an offset, i.e., an asymmetric range of operation, or that the axis moves depending on its excitation, which is in particular problematic for the quadrupole function of the octupole to be used for beam based alignment. This cross-talk issue turned out to be a major challenge and required careful optimization of distances, insertion of shielding plates and 3D-simulation of magnet ensembles with multipole fits to field maps and tracking [4].

Depending on their neighborhood magnets have to be tuned individually to obtain the desired optical properties. All PM-based magnets use identical $Nd_2Fe_{14}B$-blocks of $30 \times 47 \times 54\,\mathrm{mm}^3$ size with Ni-Fe shunts to stabilize temperature dependence to 0.01%/°C and moderator plates to allow the magnet to be tuned in a range of a few %.

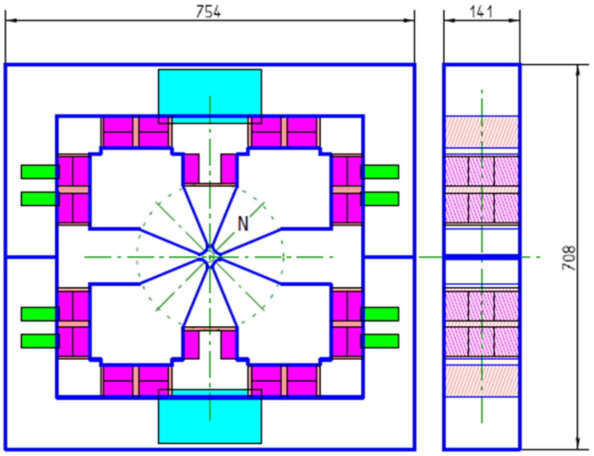

Figure 3: Permanent reverse bending magnet [1].

Figure 3 shows one of the reverse bends. Actually it is a horizontally focusing quadrupole shifted by 3.4 mm radially away from the storage ring center to get a small, negative bending angle.

All non-bending magnets are electric. This includes 108 quadrupoles for matching to the straight sections with gradients up to 98 T/m, 288 sextupoles, 264 octupoles with additional quadrupole and skew quadrupole coils and 2×112 orbit correctors. Octupole and corrector circuits are driven by more than 1000 identical 5A-power supplies.

SLS 2.0 will start with four superbends of 2.1 T peak field which are also based on PM-blocks but with reduced center gap for field enhancement. Two of them will be exchanged later for superconductive dipoles with a peak field variable between 3 and 5 T [5].

INJECTION

The predicted dynamic aperture of the storage ring is sufficiently large and magnified further by local high-beta optics (see Fig. 1) to enable classical off-axis injection reusing the existing set of four kickers of the SLS. However, in the course of miniaturization, the existing 3 mm thick eddy current septum will be replaced by two, a thick in-air septum and a 1 mm thin in-vacuum septum.

In order to reduce the perturbation of the stored beam due to injection and to cope with reduced dynamic aperture in alternative optics modes, a development program towards on-axis injection is under way: two fast kicker modules will be installed in the second straight section.

In a first stage a pulse of 10–20 ns will be applied to perform aperture sharing, i.e., the injected bunch is kicked half-way in towards the reference orbit, while 5–10 bunches of the stored beam are kicked half-way out. Injected and stored bunches then oscillate around the reference orbit and merge due to radiation damping. By reducing the pulse length, the perturbation can be limited to fewer, ideally only one bunch.

In the second stage a super-fast pulse of < 2 ns and double amplitude will be applied and the injected bunch is delayed by about 1 ns in order to kick it onto the reference orbit (i.e., on-axis) and off-phase into the RF bucket, while little affecting the stored bunch in the center of the bucket. Thanks to the large momentum acceptance of the lattice ($> 4\%$) the injected bunch then can perform a synchrotron oscillation and merge into the stored bunch.

The fast kicker is realized in two modules each made from four 100 mm long strip-lines. Between the two modules space is left for a 2 m long undulator. Collimators and a special electrode design are required to protect the kicker blades from synchrotron radiation. In the final stage the kicker will provide 1 mrad deflection for true on-axis injection.

Figure 4 shows a measured pulse and the corresponding deflection by one of eight strip lines.

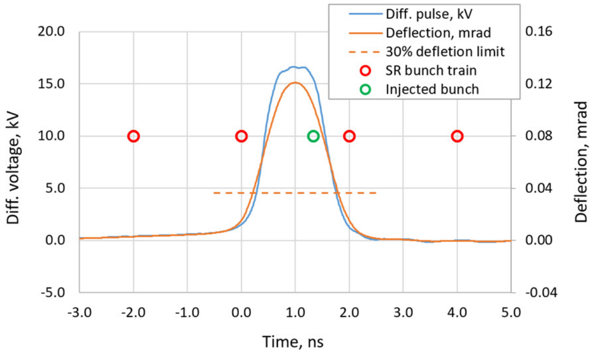

Figure 4: Fast kicker pulse, deflection by one strip-line and positions of stored and injected bunches [1].

Unlike other upgrade projects, SLS 2.0 does not require a major upgrade of the injector, since the existing booster synchrotron has a maximum energy of 2.7 GeV and, thanks to its large circumference of 270 m, delivers a horizontal emittance of only 12 nm [6], which can be reduced further to 1–2 nm through emittance exchange [7]. Only the booster-to-ring transfer line will be modified to adapt it to the new ring layout and enhance its diagnostics capabilities.

CONCLUSION

Despite tight constraints from the existing building, the SLS 2.0 upgrade project will realize competitive performance thanks to a new multi-bend achromat lattice incorporating longitudinal gradient and reverse bends. Extensive use of permanent magnets enables a densely packed lattice while reducing power consumption. Cross-talk issues require careful optimization and simulation. Upgrade paths for on-axis injection and 5 T superbends have been implemented.

This paper allowed only a few interesting or challenging issues to be highlighted, and the interested reader is referred to our technical design report [1] for more details and reports on other systems like undulators, RF, girders, diagnostics, etc.

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REFERENCES

[1] H. Braun, T. Garvey, M. Jörg, *et al.*, "SLS 2.0 storage ring. Technical design report". Paul Scherrer Institut, Villigen, Switzerland, Rep. 21-02, 2021. `https://www.dora.lib4ri.ch/psi/islandora/object/psi:39635`

[2] B. Riemann and A. Streun, "Low emittance lattice design from first principles: Reverse bending and longitudinal gradient bends", *Phys. Rev. Accel. Beams*, vol. 22, p. 021601, 2019. `doi:10.1103/PhysRevAccelBeams.22.021601`

[3] L. Farvacque *et al.*, "A low-emittance lattice for the ESRF", in *Proc. 4th Int. Particle Accelerator Conf. (IPAC'13)*, Shanghai, China, May 2013, paper MOPEA008, pp. 79–81.

[4] B. Riemann and M. Aiba, "Algorithm to Analyze Complex Magnetic Structures Using a Tube Approach", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 1995–1998. `doi:10.18429/JACoW-IPAC2021-TUPAB238`

[5] C. Calzolaio *et al.*, "Longitudinal gradient bend magnets for the upgrade of the Swiss Light Source storage ring", *IEEE Trans. Applied Supercon*, vol. 30, no. 4 p. 4100905, 2020. `doi:10.1109/TASC.2020.2973113`

[6] W. Joho, M. Muñoz, and A. Streun, "The SLS booster synchrotron", *Nucl. Instr. Meth.*, vol. A562, no. 1, pp. 1-11, 2006. `doi:10.1016/j.nima.2006.01.129`

[7] J. Kallestrup and M. Aiba, "Emittance exchange in electron booster synchrotron by coupling resonance crossing", *Phys. Rev. Accel. Beams*, vol. 23, p. 020701, 2020. `doi:10.1103/PhysRevAccelBeams.23.044003`