

PAUL SCHERRER INSTITUT 	Projekt / Project SLS 2.0
Titel / Title SLS 2.0 Baseline Lattice	Dokument Nummer / Document Identification SLS2-SA81-004-13
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Summary This note describes the lattice configuration to be used as base for the technical design report, as decided by the project management at June 18, 2020. The final lattice has the following features: • 3-fold geometric symmetry to avoid tunnel modifications. • 12-fold dynamic symmetry by tuning all straights to same phase advances. • 3 long, 3 medium and 6 short straight sections. • 4 superbends included. • based on 18 mm beam pipe inner diameter. • beam energy 2.7 GeV. • circumference 288 m. Corresponding files • MasterLayout.B062.txt with HolyListPattern.B062.py ⇒ "Heilige Liste", SLS2-SA81-005-18 • Lattice files for OPA, TRACY, MAD-X, ELEGANT: B062... • Magnet specifications, SLS2-SA81-007-6 • Naming convention, SLS2-SA81-001-9 • Injection concept, SLS2-AM81-003-3 These documents are available on afs/psi.ch/project/SLS2 → Docs/Notes for tech notes and → BD/Lattices/Reference for the lattice files.	

Modification History

Version 004-13 (18.6.2020 [25.6.2020 typos corrected]) – Lattice B062

- Re-introduced medium straights with lattice version B057 in order to minimize the radial shifts of beam lines, such that they all pass the existing openings in the tunnel front walls.
- Modified optics of dispersion suppressor section for higher brightness.
 - As a consequence, introduction of a new magnet VBX and modification of ANM.
 - Modification of dispersion suppressor magnets BEV and BE.

Version 004-11/12 (3.3.2020) – Lattice B046 (which is almost identical to B039)

- Increased energy to 2.7 GeV
- Abandoned “phase 2” due to infeasibility with regard to dynamic aperture.
- Return to QA-SLS type quads of 20 cm length in injection straight.
- Included new superbend designs (C. Calzolaio, 10.2.2020) for 2.7, 4.0, 5.0 T for 2.4 GeV, used 2.7 and 4.0 T fields for scaling to approx. 2.4/3.5/5.0 T
- Keeping QPH for smaller betas in straights, although no feasible DA found yet.
- Return to horizontal injection scheme

Version 004-10 (28.11.2019) – Lattice B039/B139

- Established injection straight layout for phase 1 and phase 2. This required to change two quad types in injection straight.
- The standalone sextupole in the dispersion suppressor actually will become a modified sextupole (SXQ) with elliptic or enlarged aperture.

Version 004-9 (10.10.2019) – Lattice B038/B138

- A modification of the dispersion suppressor region was required to obtain sufficiently large stay clear apertures for outcoupling of photon beams. Compound magnet BE was split into two parts BEV and BEH with a standalone sextupole (SDM) between. The octupole (OCYM) was removed.

Version 004-8 (25.9.2019) – Lattice B036/B136

- Including injection straight design
- Vacuum chamber design (space for flanges!) required minor changes of distances/lengths for BPMs/Correctors [in mm]:
 - new: 12.5 – 25 (BPM) – 23 – 105 (Corr) – 4.5 (dist to adjacent SOQ)
 - prev.: 15 – 20 (BPM) – 15 – 110 (Corr) – 10 (dist to adjacent SOQ)
- Modification of quad types mag. length and max. gradient
 - QP : 120 mm / 80 T/m → 100 mm / 92 T/m
 - QPH: 120 mm / 105 T/m → 140 mm / 100 T/m
 → Wider tuning range for split standard straights and smoother optics
- Modification of main bend BN: longitudinal gradient replaced by homogenous bend.
 - this caused tiny changes of layout (microns) and AN, VB parameters ($<10^{-3}$)
- Replaced doublet in long straight by triplet
- Redesign of injection straight for vertical injection

Version 004-7 (19.07.2019) – Lattice B025-125

- Update/rewrite for completely new lattice of type "B+"
- Magnet specs moved out to note SLS2-SA81-007-1

Previous modifications are irrelevant now but may be looked up in SLS2-SA81-004-6 OUTDATED.

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Introduction

As decided by project management on June 18, 2020, lattice version B062 is the final layout of the SLS 2.0 storage ring with regard to

- locations of all arc elements in the hall (i.e. magnet vertices),
- direction of all photon beams (i.e. straight section midpoint locations and angles)
- specifications of all magnets (see corresponding document SLS2-SA81-007-6).

Following issues – which do not affect the above mentioned items! – are still work in progress:

- design of injection straight 1L: locations of components and specifications of pulsed magnets.
- split ratio of long straights 5L, 9L, i.e. position of central triplet.
- mirror-symmetric alternative for medium straights.

These and other issues, where final designs or alternatives are still under discussion, are marked in blue in text.

Lattice geometry

Like all previous versions, the lattice is composed from 12 7-bend-achromatic arcs replacing the 12 3-BA arcs of the existing SLS (SLS 1.0). Like SLS 1.0 the lattice has 3 long, 3 medium and 6 short straight sections in order to follow closely the existing footprint:

- Since the photon beam pipes have 50 mm diameter and the hole in the front wall wall is 200 mm wide, a shift of max ± 75 mm is possible, in principle.
- Exploiting this margin (minus some tolerance) for the M- and L-straights as well as for the bending magnet beam lines provides maximum length for the S-straights while almost maintaining their radial positions. Thus beamlines 4S, 6S, 10S, 12S don't need to be realigned.

Table 1 displays straight gross length, net length, and radial and longitudinal shifts of straight midpoints.

- Gross length is between last quadrupoles and includes sector valves,
- Net length is available for installations.
- A *positive* radial shift is towards the ring *outside*.
- A *positive* longitudinal shift is *downstream* (i.e. makes beamline shorter).
- All numbers are in mm.

Table 1: Straight section lengths and shifts compared to SLS 1.0

	SLS 1.0	SLS 2.0, Lattice B062			
Source	gross length	gross length	net length	radial shift	long. shift
Long straights (1,5,9)	11730	12710	2×5785^a	+67.3	$\pm 3368^b$
Medium straights (3,7,11)	6970	6550	$5270 + 530$	+67.3	+540 ^c
Short straights (2,4,6,8,10,12)	3970	4310	4110	-2.4	0
Bending magnets (all sectors)				-62.9 ^d	$\pm 135^e$

^a applies to 5L, 9L in case of symmetric split (injection straight 1L is different).

^b for first and second half of straight in case of symmetric split.

^c could as well be negative, if M-straight is built as mirror image.

^d radial shift for a normal dipole; for a superbend it may be up to 0.6 mm less shift depending on field.

^e positive for even numbered sectors, refers to the middle bend in the 7-BA arc.

Lengths and spaces

Magnet parameters, as magnetic length and total length are found in detail in SLS2-SA81-007-6. Table 2 gives the gross length of components to be installed, and Table 3 displays a matrix of minimum distances between components preserved for mounting.

Table 2: Gross lengths of components

Component	Length (mm)
BNV compound bending magnet, or superbend with adjacent VB magnets	776.0
BE dispersion suppressor end bending magnet	242.5
BEV dispersion suppressor combined function magnet	240.0
AN reverse bending magnet	140.0
ANM reverse bending magnet in dispersion suppressor	150.0
QP small quadrupole	170.0
QPH large quadrupole	210.0
QA-SLS old SLS quadrupole to be re-used in 1L	340.0
SOQ compound magnet: sextupole and [octupole with quad and skew quad coils]	230.0
SXQ standalone sextupole magnet with quad corrector coil	140.0
CHV BPM horizontal/vertical corrector and beam position monitor unit	130.0
CHV BPM-SLS large aperture corr/BPM unit for injection straight (not designed yet)	170.0
Thick injection septum (without flanges)	991.0
Thin injection septum (without flanges)	500.0
Bump kickers (without tapers and flanges)	850.0
Fast kickers (without tapers and flanges)	800.0

Table 3: Distances between components (with gross lengths from Table 2)

(-/- means that this combination does not occur)

to entry → distance exit ↓	Bends	Reverse Bends	Quad	SOQ	SXQ	Corr/ BPM
Bends BNV, BE, BEV	-/-	-/-	-/-	30	10	-/-
Reverse bends AN, ANM	-/-	-/-	-/-	10	-/-	22.5
Quadrupole QP, QPH, QA-SLS	-/-	-/-	-/-	10	-/-	22.5
SOQ magnet SOQ	30	10	10	-/-	-/-	-/-
Sextupole SXQ	10	-/-	-/-	-/-	-/-	-/-
Corrector/Monitor [BPM CHV]	47.5	-/-	17.5	17.5	-/-	-/-

Lattice concept

- The lattice is made from 12 arcs, which are basically identical, however the central bending magnet of any arc can be replaced by a superbend.
- The straights are of different length and content, but in order to emulate a 12-fold lattice periodicity with respect to beam dynamics (in order to maintain sufficient dynamic acceptance) all straights are tuned to exactly same betatron phase advances.
- Low emittance is achieved through miniaturization of components down to a beam pipe inner diameter of 18 mm, and by combining longitudinal gradient bends and reverse bends.
- Magnet bore is 21 mm in regions where the beam pipe is a simple round tube (quadrupoles, reverse bends, correctors), and 22 mm if there is an antechamber (bending magnets, sextupole/octupoles).
- All bending magnets are based on permanent magnets in order to save space required for coils and to minimize power consumption. There are 84 pure dipoles and 288 combined function magnets.
- The center bends in arcs 1 / 2 / 6 / 10 will be replaced by superbends of about 3.5 / 5.0 / 2.4 / 3.5 T peak field.
- A total of 112 electromagnetic quadrupoles is used for matching to the straight sections and for moving the working point around. 96 quads are located as 2×12 quadruplets in the matching sections

to the straights, the other ones are located inside the medium (3×2) and long (2×3+4) straights for tuning them to the same phase advances like the short straights and for special purposes (splitting, injection).

- 264 sextupole/octupole compound magnets (SOQ) and 24 standalone sextupoles (SXQ) are used for chromaticity correction and dynamic acceptance optimization
- The 264 octupoles are equipped with quadrupole and skew quadrupole coils. The quads are used for gradient corrections, matching to superbends and beam based alignment, the skew quads for coupling control and correction.
- Closed orbit is controlled by 114 BPMs and by 114 horizontal and vertical dipole correctors, 12×9 in the arcs and 3×2 in the long straights.
- Another 12 BPMs after the dispersion suppressors may be added for better control of the orbit in the straight sections if feasible (space conflict with absorber).

The 7BA arc

An arc contains 7 bending magnets (blue), where the center bend can be replaced by a superbend, as shown in the sketch below. Apart from that, all 12 arcs are identical. The center bend sits on a plinth, all other elements on 4 girders (light grey):

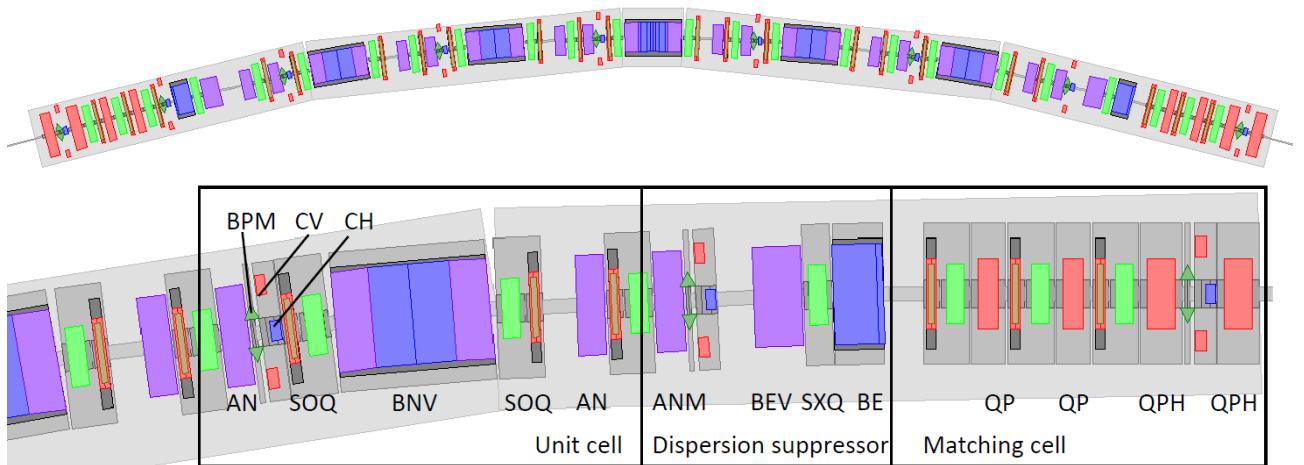


Figure 1: Layout of an arc containing a central superbend, and magnified view of downstream end

An arc is made from 5 unit cells, 2 dispersion suppressor cells and 2 matching cells.

The 5 unit cells are identical (except that one may contain a superbend). Each unit cell contains a BNV = {VB|BN|VB} composite dipole (or a superbend BS flanked by two standalone VB magnets), two reverse bends AN, three SOQ-compound magnets, one BPM and one hor/vert. corrector CHV. Note, that BPM/CHV stations alternate with absorbers (not shown), i.e. the BPM/CHV pattern is not symmetric.

The dispersion suppressor cell is derived from a half unit cell, but the bending magnet is split into two parts, a combined function bend BEV and a compound dipole BE = {BES|BEH} with a sextupole SXQ between. The dispersion suppressor at the end of the arc contains a BPM/CHV station, whereas the one at the entry of the arc contains an absorber. Note that the VB-magnet of the BNVs facing the dispersion suppressors is a modified type named VBX. So we have the following line-up of bending magnets:

BEI - BEV - {VBX|BN|VB} - {VB|BN|VB} - {VB|BN|VB} - {VB|BN|VB} - {VB|BN|VBX} - BEV - BEO

The matching cells are identical independent of the type of straight that follows. The cell contains four quadrupoles (two moderate gradient, QP, and two high gradient, QPH), three SOQs and one (downstream) or two (upstream) BPM/CHV stations.

With regard to beam optics, the 12 arcs are identical except the QPH pairs at both ends, which are tuned differently for matching to different straights, see orange box in Fig. 2. All straights are tuned to the same betatron phase advances, so all non-linear elements (sextupoles and octupoles) "see" a 12-fold optical symmetry.

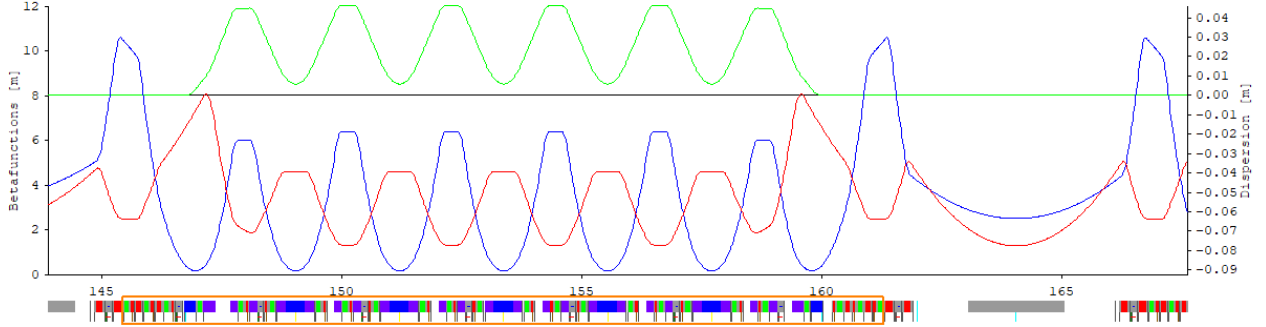


Figure 2: the 7BA arc (here arc 07 between 7M and 8S): optics (beta-x, beta-y, dispersion) and magnet line-up (dipoles, combined function magnets, quadrupoles, sextupoles). The optics of all 12 arcs is identical in the region containing sextupoles (orange box).

Installation of a superbend causes a minor perturbation of the optics due to different edge focusing properties, which is corrected by means of small quadrupole correctors located in the SOQ magnets.

The unit cell

Figure 3. left shows the optical function of the unit cell (from/to bend centers). The red squares indicate the combined octupole/quadrupole/skew quadrupole magnets (OC|QA|QS). The two next to the bend, called QAY, are for correction of vertical tune, and the one at center, called QAX, is for correction of horizontal tune. With max. gradients of **2.8 T/m** these tuning quads are able to compensate a gradient error up to 1.9% in VB and up to 0.6% in AN. Alternatively, these quads can be used for fine tuning of the cell. The design tunes of the cells are at $0.429 \approx 3/7$ and $0.143 \approx 1/7$. Figure 3 right shows the tuning range of the cell for full variation of QAX, QAY. Using these correction quads in the arc to move the tune (QAX,QAY) while keeping the straights achromatic by means of the quads in the dispersion suppressor (QAXM, QAYM), the total ring tunes can be changed in a range of $\sim \{\pm 0.35, \pm 0.30\}$.

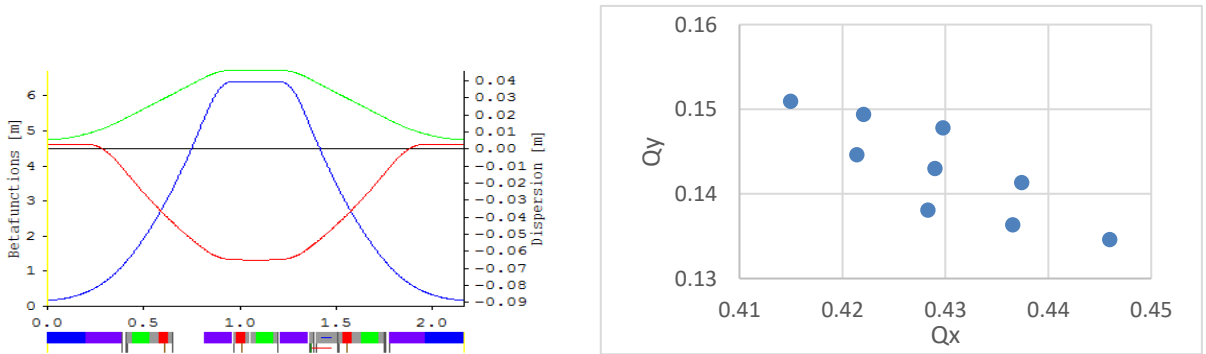


Figure 3: optical functions of unit cell (beta-x, beta-y, dispersion), and tuning range for full variation of QAX, QAY quads.

Dispersion suppressor

In lattice version B038 the end bend magnet was split in two pieces with the special sextupole of type SXQ between to solve problems with aperture restrictions for the photon beam coming from the straight. In lattice version B057 the medium straights were introduced again and the dispersion suppressor cell was modified to enable matching to all straight types. In the process another optics for lower beta functions in the straights was found, which increases the brightness by up to 50%. This required to change the parameters of reverse bend ANM that much, that it cannot be made anymore from a modified AN but requires its own design. Further a

modified combined function bend VBX was introduced (right purple part of BNV in Fig. 1). Angles between BEV and BE are redistributed, mitigating the photon beam outcoupling problem compared to the previous version by increasing the stay clear at the location of SXQ outgoing edge by 0.5 mm.

Thus it may be considered if the elliptical sextupole SXQ could have a slightly smaller aperture radius of 12.5_H instead of 13.0_H mm as previously foreseen.

Superbend matching

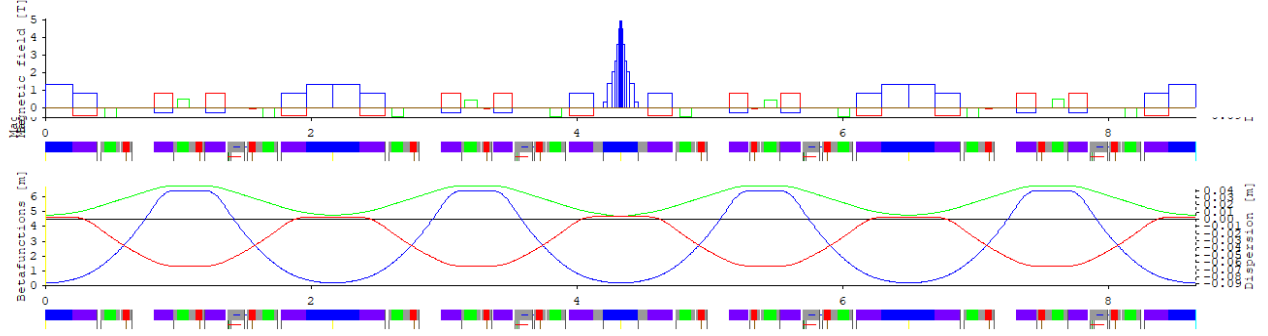


Figure 4: Arc 2 with 5 T superbend. Top, magnetic fields (B , $B'R$, $\frac{1}{2}B''R^2$ with $R = 11$ mm); bottom, optical functions.

The edge focusing effect of the superbend is different to the normal bend, so 2×5 quadrupole correctors incorporated in the octupoles (shown as red boxes in Fig. 4), are used to match the periodic solution of the four central arc cells to the two tunes and to the two beta functions and the dispersion of the unit cell.

Short straights

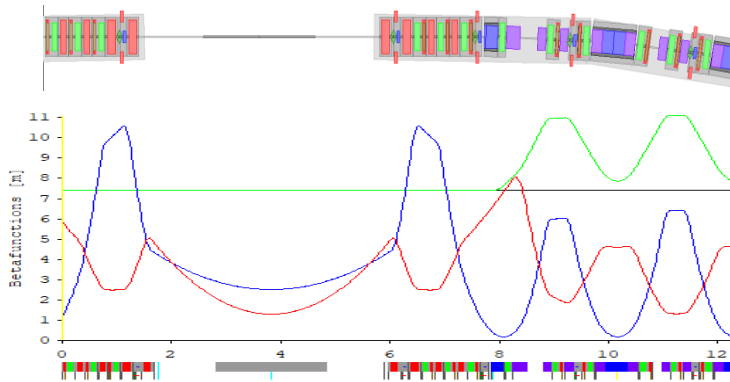


Figure 5: Layout (top) and optics of one of the short straights (4S).

Quadrupole pattern: **D F F D — D F F D**

(D/F indicate horizontally defocusing/focusing polarity. D/F are of QP, **D/F** of QPH-type.)

Sector length = 21.34 m. Gross straight length = 4.31 m. Net straight length = 4.11 m.

The matching requires four quadrupole (pairs) to set $\alpha_x = \alpha_y = 0$ in the middle of the straight, and to set the sector tunes to exactly $1/12$ of the desired working point $\{Q_x, Q_y\}$.

The last sextupole of the arc is located between the 2nd and 3rd quadrupole of the matching section, so the 1st and the 2nd quadrupole are not available for matching at the other straights in order to maintain same optics parameter at sextupoles in all sectors.

Straight 2S accommodates fast kickers for on-axis injection and will be discussed below in the context of injection.

Medium straights

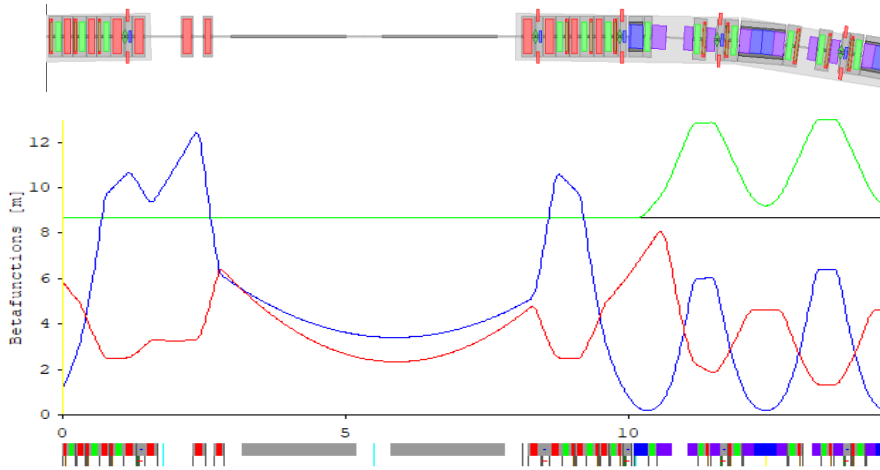


Figure 6: Layout (top) and optics of one of the medium straights (3M).

Quadrupole pattern: $\overline{D} \overline{F} F D - F D \text{ — } D F \overline{F} \overline{D}$
 ($\overline{D} \overline{F}$ indicates that these quadrupoles are not available for matching.)

Sector length = 23.58 m. Gross straight length = 6.55 m. Net straight length = 0.53 + 5.27 m.

The 1st and 2nd quadrupole on each side are not available for matching, because the optical functions at the sextupoles between must not be changed. The remaining six quadrupoles are used to match the horizontal and vertical β - and α -functions for periodic continuation, and to set the two sector tunes to exactly 1/12 of the ring tunes. A small straight had to be introduced to provide sufficient lever arm for the doublet inserted. This straight is 53 cm long and appears three times. It may be used to accommodate machine equipment like multi bunch feedback kicker, current transformer or scraper.

Each of the medium straights could as well built as mirror image, i.e. with the small straight after the main straight, if desired (perhaps for making the beam line a bit longer).

Long straights 5L and 9L

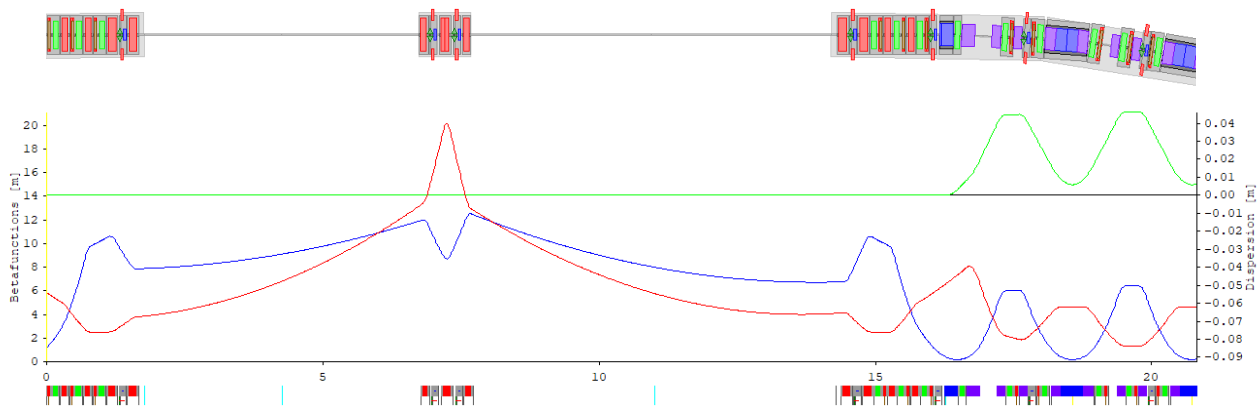


Figure 7: Layout (top) and optics of long straight 5L

Quadrupole pattern: $\overline{D} \overline{F} F D \text{ — } F D F \text{ — } D F \overline{F} \overline{D}$
 ($\overline{D} \overline{F}$ indicates that these quadrupoles are not available for matching.)

Sector length = 29.74 m. Gross straight length = 12.71 m.

Net straight lengths = 5.00 + 6.56 m (5L) and 2×5.78^5 (9L)

In the symmetric case (9L) three quadrupole pairs and the central quadrupole are used to set $\alpha_x = \alpha_y = 0$ at the triplet center and to adjust the sector tunes. In the asymmetric case seven quadrupoles are used to match the β - and α -functions for periodic continuation, and to set the sector tunes. Six quadrupoles would be sufficient, so the 7th can be used to further tailor the optics. The polarity of the triplet can as well be opposite, here it was set to avoid high horizontal beta function. Two BPM/CHV stations are inserted for independent control of the photon beams from the first and second sub-straight.

Since the long straights have to provide the same phase advances like the short straights, the beta functions are rather large, which however is well compatible with the VUV and soft X-ray beam lines, which are diffraction limited anyway and use Apple-X type undulators with gaps of 8 mm diameter.

The final split ratios of 5L and 9L have not yet been decided. Even more asymmetric layouts are possible too, or a split in three sub-straights, using two doublets instead of the triplet.

Injection straight 1L (preliminary)

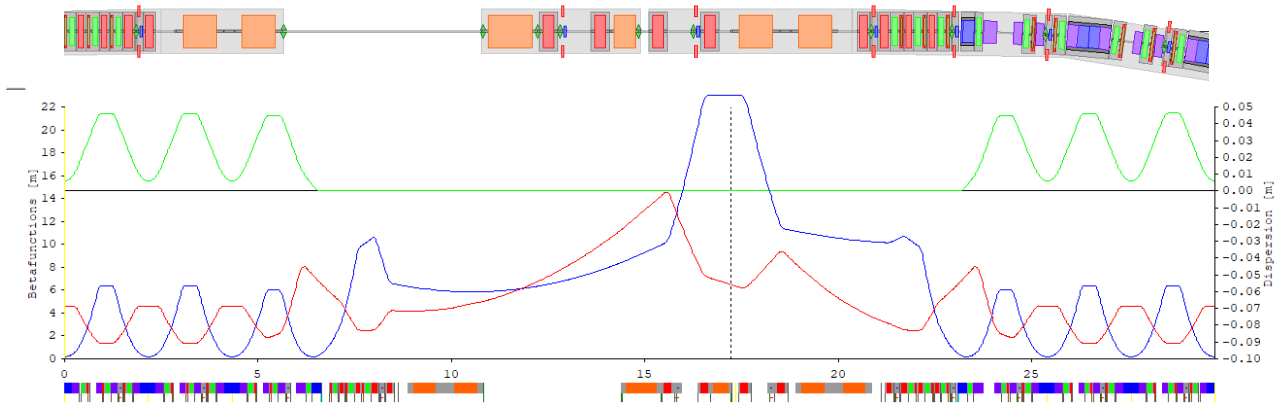


Figure 8: Layout (top) and optics of injection straight 1L

Orange boxes from left to right: kicker 1 and 2, thick septum, thin septum, kicker 3 and 4.

Quadrupole pattern: $\text{D F F D} \text{ — } \text{D F F D} \text{ — } \text{D F F D}$

(D F indicate SLS 1.0 quadrupoles of QA-SLS type, to be re-used.)

Sector length = 29.74 m. Gross straight length = 12.71 m.

Net straight length = 3.58 m in front of thick septum.

The eight available quadrupoles are used to match the β - and α -functions and sector tunes (six constraints), and to set $\alpha_x = 0$ at the thin septum exit and to either adjust β_x at the septum or to set the horizontal phase advance at the septum. Four 60Ø mm bore QA-SLS quad are used in the central region to accommodate both injected and bumped beams.

As described in note SLS2-MA81-003 on injection, it is planned to re-use the four “slow” kickers (6 μ s half sine) from SLS 1.0 to start with a classical bumped orbit injection scheme. Two septa will be used: a thick (3 mm) septum with a large deflection angle (in the order of 5°) to deflect the beam from the transfer line, and a thin (1 mm) septum with small deflection angle (in the order of 10 mrad) to minimize the distance between stored and injected beam.

Later, a fast kicker in straight 2S will be employed, first at a pulse length of about 10 ns for pseudo-on-axis injection, i.e. aperture sharing, and then at a pulse length of < 2 ns for true on-axis injection with longitudinal capture. This concept requires the horizontal phase advance between thin septum and fast kicker to be close to an odd multiple of 90°, in the case of lattice B062 realized by a tune advance of $\Delta Q_x \approx 3/4$.

A further upgrade option would consider an even stronger fast kicker at the end of straight 1L to perform a “brute force” on-axis injection irrespective of phase advance, and thus free straight 2S again. However this would required to squeeze the 1L-layout in order to make room after kicker 4 for installation of the fast kicker.

In the layout and optics as shown here, the option for possible future installation of a fast kicker after the fourth slow kicker was dropped in favor of large space in front of the septum in order to relax the specifications of the thick septum and to enable design of a new booster-to-ring transferline with more diagnostic capabilities than the existing one. The space in front of the septum may partially be used for installation of machine devices, e.g. pingers magnets.

Note that tuning of phase advance between thin septum and fast kicker in 2S while maintaining the sector tune is constrained to a narrow range. Previous layouts included quadrupoles between or close to the bump kickers for that purpose, however these kickers have rather wide ceramic chambers of $92_H \times 28_V$ mm and require 250 mm long tapers to connect to the nominal beam pipe, which is compatible with the QP/QPH bore of $21\varnothing$ mm [C.H.Gough, “Injection hardware layout”, May 19, 2020]. However, some variation of the effective phase advance can be achieved by injecting the beam at an angle.

Layout of short straight 2S

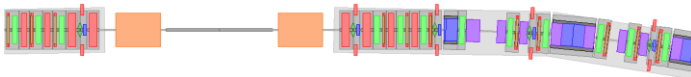


Figure 9: Layout of fast kicker straight 2S. Optical functions like any other short straight (see Fig. 5).

The fast kicker and a hard X-ray undulator (i-TomCat) will share straight 2S. Development is in progress for kicker modules which provide a deflection of >0.5 mrad at 2.7 GeV within a net length of 800 mm [M. Paraliyev, “Fast kicker 1 mrad feasibility”, May 26, 2020]. The fast kicker in 2S would be made from two modules, which could be placed in the first half, or in the second half, or separately at the ends as shown in Fig. 9.

The third option is preferred for the following reasons:

- Since tuning of phase advance between septum and straight 2S is very restricted, two kicker modules with some space between are required to control angle and position of the beam and put the injected beam on axis for different working points of the storage ring. Note, that the phase advance also depends on the amplitude of the injected beam due to the down-feed from the sextupoles, and with it on the sextupole pattern itself. Decoupled kicker modules together with variation of injection angle would provide two independent knobs to fine-tune injection.
- Admittedly, since the kickers are located at about $\pm 30^\circ$ horizontal phase advance relative to the straight center, about 13% ($=1-\cos 30^\circ$) of their strength is wasted compared to only 1% if they would sit close together. But on the other hand, if the hard-X-ray undulator is located at the center of the straight, it provides about 20% higher brightness due to the smaller β -functions (rough estimate, to be refined), which overcompensates a possible length reduction in favor of making the kickers longer if needed.
- The fast kickers and the undulators are both small gap devices (3.5 mm), so no or only very small tapers are required between the undulator and the fast kicker(s), so probably no space is lost with separate kicker modules.

Storage Ring Parameters

Table 4 gives the most important lattice parameters in comparison to SLS 1.0.

- Arrows indicate how parameters change when including the four superbends (of about 3.5/5.0/2.4/3.5 T peak field in arcs 1/2/6/10), and when assuming that all insertion devices operate at minimum gap, which would result in a total 110 kW radiated power at 400 mA beam current [T. Schmidt, Beam line portfolio from 28.1.2020].

- Values for SLS 1.0 are without IDs but including the three superbends (2.9 T peak field, in arcs 2,6,10) and the FEMTO-chicane.
- The four superbends increase the circumference of SLS 2.0 by 0.236 mm. The circumference of SLS 1.0 was increased by 7.3 mm through installation of FEMTO, which caused -13 kHz frequency change. The total frequency change is -18 kHz compared to the original design frequency, this includes settlement of the building over the years. SLS 2.0 will return to the original frequency.
- Intrabeam scattering effects are rather small: emittance increases by 2.6% and energy spread by 1.4% (400 mA beam current in 460 bunches, 3rd harmonic cavity for factor 3 bunch lengthening, 10 pm of vertical emittance) [Calculation by M. Aiba].

Table 4: Lattice parameters at 2.4 GeV

	SLS today	SLS 2.0
Circumference [m]	288.007'289	288.000'236
Energy [GeV]	2.411	2.700
Working point Q_x / Q_y	20.43 / 8.74	39.35 / 15.25
Natural chromaticity ξ_x / ξ_y	$-67.3 / -21.0$	$-99.0 / -33.4$
Emittance [pm.rad]	5630	149 $\rightarrow$ 156 $\rightarrow$ 129
Energy spread [10^{-3}]	0.878	1.103 $\rightarrow$ 1.145 $\rightarrow$ 1.024
Radiation loss per turn [keV/turn]	549	666 $\rightarrow$ 690 $\rightarrow$ 965
Momentum compaction factor [10^{-4}]	+6.04	+1.06 $\rightarrow$ +1.04 $\rightarrow$ +1.04
Horizontal damping partition J_x	1.00	1.85 $\rightarrow$ 1.82 $\rightarrow$ 1.59
Damping times [ms]		4.2/7.7/6.6 $\rightarrow$ 4.1/7.5/6.3 $\rightarrow$ 3.4/5.3/3.8

Tuning range and beta functions

In order to preserve sufficient dynamic aperture, the lattice emulates a periodicity of 12 by maintaining the same phase advances in all straights between the adjacent sextupoles, no matter what is the length and layout of the straight.

Phase advances have to match for all combinations of ring tunes within some operating range. The nominal working point at 39.35/15.25 is called “NN”. Matching was tested for the four corner points of the rectangular tuning area [39.10...39.85/15.10...15.75], which are named “LL”, “LH”, “HL”, “HH”. The initial demand for a ± 0.5 or even ± 1.0 tuning range in both dimensions could not be fulfilled due to the different nature of the various straights. Dynamic aperture has only been optimized for the NN optics mode. The modes at high horizontal tune, HL, HH are probably infeasible, because close to $Q_x = 40$ the third integer drive term is too strong.

Table 5: Beta functions at different working points

		S-straight	M-straight	L-straight	Septum
Point	Q_x / Q_y	β_x / β_y [m]	β_x / β_y [m]	β_x / β_y [m]	β_x [m]
NN	39.35 / 15.25	2.52 / 1.30	3.45 / 2.40	7.2 $\rightarrow$ 12.1 / 4.0 $\rightarrow$ 12.6	23.0
LL	39.10 / 15.10	2.87 / 1.45	3.91 / 2.74	7.6 $\rightarrow$ 13.4 / 3.7 $\rightarrow$ 14.5	24.0
LH	39.10 / 15.75	2.88 / 0.71	4.00 / 1.28	6.8 $\rightarrow$ 15.1 / 6.3 $\rightarrow$ 6.3	26.7
HL	39.85 / 15.10	1.93 / 1.46	2.63 / 2.73	7.3 $\rightarrow$ 9.2 / 3.8 $\rightarrow$ 14.4	19.2
HH	39.85 / 15.75	1.94 / 0.71	2.69 / 1.29	6.6 $\rightarrow$ 10.2 / 6.3 $\rightarrow$ 6.3	20.1

Table 5 gives tunes and beta functions at the midpoints of the straights for various working points. In the M-straights, the focus is close to but not exactly at the midpoint (see Fig. 6). In the half L-straights the beam is strongly convergent or divergent, therefore the variation of the beta function over the length of the half

L-straight is given for the case of a symmetric split. A slightly asymmetric split does not change much the betas.

The beam parameters at the [super]bend centers are $\beta_x = 0.18$ m, $\beta_y = 4.6$ m; $\alpha_x = \alpha_y = D' = 0$;
Dispersion $D = 5.8$ mm (normal bend), 4.9 mm (2.4T S.B.), 4.2 mm (3.5T S.B.), 4.0 mm (5T S.B.)

Quadrupole strengths

When moving the working point between the above mentioned 5 optics modes, the three types of quadrupoles used in the lattice reach following maximum gradients:

- QP ($L_{\text{tot}} = 170$ mm, bore = 21 mm) : $|B'|_{\text{max}} = 92.1$ T/m $\rightarrow |k|_{\text{max}} = 10.23$ m⁻²
- QPH ($L_{\text{tot}} = 210$ mm, bore = 21 mm) : $|B'|_{\text{max}} = 97.2$ T/m $\rightarrow |k|_{\text{max}} = 10.80$ m⁻²
- QA-SLS ($L_{\text{tot}} = 340$ mm, bore = 60 mm) : $|B'|_{\text{max}} = 23.2$ T/m $\rightarrow |k|_{\text{max}} = 2.58$ m⁻²

Source size and divergence

For experiments, the rms beam size and divergence may be more useful, which are calculated from $\sigma^2 = \varepsilon \beta + (\sigma_\delta D)^2$ and $\sigma'^2 = \varepsilon (1 + \alpha^2)/\beta + (\sigma_\delta D')^2$ with ε emittance and σ_δ rms relative energy spread. Note that in case of $\alpha \neq 0$ there is a correlation term which can be calculated from $\langle xx' \rangle = -\varepsilon \alpha$ (not shown here).

Table 6 gives the source size and divergence for lattice B062 in nominal optics mode (NN), with emittance and energy spread from Table 4 (middle numbers), and assuming 10 pm of vertical emittance:

Table 6: Source size and divergence

Source	σ_x [μm]	σ_x' [μrad]	σ_y [μm]	σ_y' [μrad]
Long straights 5, 9 (middle of sub-straight)	37	4.5	8.3	1.7
Medium straights 3,7,11	23	6.8	4.9	2.1
Short straights 2,4,6,8,10,12	20	7.9	3.6	2.78
Bending magnets (1.3 / 2.4 / 3.5 / 5.0 T)	8.5 / 7.7 / 7.2 / 7.0	30	6.8	1.5

Note, that these data give only the electron beam size and divergence, which has to be convoluted with the diffraction properties of the radiation source. In particular for bending magnets, diffraction divergence completely dominates the electron beam divergence.

The RF bucket

Without IDs a total RF voltage of 1440 kV is required to provide a momentum acceptance of $[-6.0\% \mid +4.5\%]$. With all IDs closed to minimum gap, a voltage of 1780 kV is required to maintain the same momentum acceptance. Higher voltage does not gain significant further lifetime.

Due to large 2nd order momentum compaction the RF bucket becomes asymmetric as shown in Fig. 10 for a main voltage of 1440 kV and a 3rd harmonic voltage of 375 kV for lengthening the bunch by a factor 3 (to about 8.5 mm rms). Note that transition to alpha-bucket occurs at 1835 kV already.

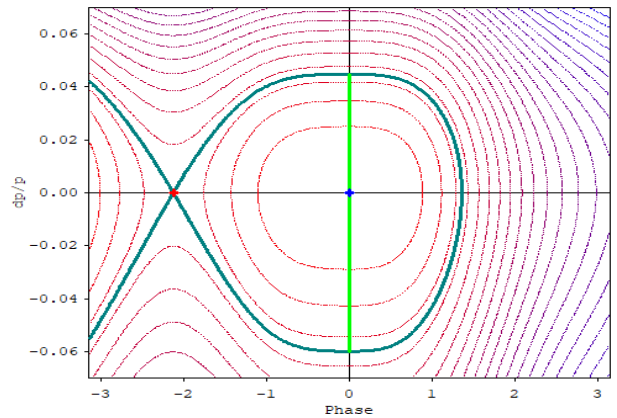


Figure 10: RF bucket including non-linear momentum compaction for 1440 kV fundamental and 375 kV 3rd harmonic voltage. The green bar indicates the momentum acceptance.

Dynamic Aperture

Optimization of non-linear optics, i.e. providing large dynamic acceptance, is crucial in order to provide sufficient beam life time and injection efficiency.

Concept

Unit cell tunes of approx $3/7$ and $1/7$ provide cancellation of most 1st and 2nd order sextupole resonance drive terms (RDT) over 7 unit cells. Completion of this pattern includes the dispersion suppressor and matching cells too, where the dispersion is different or even zero. As a consequence, the terms H_{20001} and H_{00201} , which depend on dispersion ($H \sim \sum (b_{3l} \eta - b_{2l}) e^{i2\phi} \beta$) are not well suppressed. These RDTs drive chromatic half integer resonances, and with it the chromatic beta beat, and with it the 2nd order chromaticities.

A kind of (-I)-transformer for these double-phase terms is realized, if the phase advance over one arc is close to an odd multiple of 90° . With a tune advance of $\{3, 1\}$ for 7 unit cells, this calls for approx. $\{3\frac{1}{4}, 1\frac{1}{4}\}$ arc tune, where $\frac{1}{4}$ in tune ($= 90^\circ$ in phase) results in beta functions of about the half straight length (phase advance $= 2 \times \arctan [\text{beta} / \text{half straight length}]$), and a working point near $\{39, 15\}$. Good solutions (in terms of nonlinear dynamics) are found in the region above this point, e.g. at $\{39.35, 15.25\}$. 90° phase advance per arc are also required for the on-axis scheme based on the fast kicker in straight 2.

It should be mentioned that the dynamics of the ring is essentially period-12, because all straights are matched to the same phase advance. Off-momentum, the symmetry conditions are not fulfilled exactly, also the matching to the superbends perturbs the periodicity, but the degradations are marginal. However the half integer drive terms also contain quadrupole contributions (see equation above), and thus are excited in period-1 due to non-periodic distribution and powering of the quadrupoles

264 SOQ magnets contain each a sextupole and an octupole (which also has quad and skew quad corrector coils), and 24 SXQ modified sextupoles are without octupole but contain only a quadrupole winding for beam based alignment. The 288 sextupoles are grouped in 9 families, the 264 octupoles in 8 families. Usually, after suppression of 1st orders with a regular sextupole pattern as expected from the phase cancellation scheme, one is still left with rather large amplitude dependent tune shifts (ADTS). Basically the octupoles handle this in 1st order, but they are too weak, therefore the nice sextupole patterns has to be perturbed to reduce the ADTS. Octupoles are used eventually for shaping the tune footprint and for suppression of octupolar resonances.

The standard method in OPA uses a gradient search with a penalty function composed from the various terms with empirical weight factors. Better results are obtained by selecting particular RDTs, some of even higher order, which affect the dynamics, and attack these [M. Aiba]. Another approach applies genetic optimizers to tracking results for direct dynamic aperture optimization [M. Kranjcevic & B. Riemann].

Performance

The sextupole pattern is still based on an optimization for lattice B046 [by M. Aiba], only the harmonic sextupoles were adjusted to the changed optics in the matching sections, and the chromaticity was corrected to $+1/+1$ for the whole ring, and the octupoles were tweaked a little to shape the tune footprint.

Figure 11 shows the tune footprint with amplitude and with momentum, and the dynamic aperture at the injection point. The thin septum's inner edge is located at $x = -5.5$ mm (determined by the requirement to not affect Touschek lifetime) and limits the physical horizontal acceptance. The projection of the undulator gaps (4 mm gaps in S-straights) to the trackpoint determines a limit of about $y = 3.2$ mm for the vertical acceptance. As to be seen in Fig. 11 the chromatic and amplitude dependent tune shifts are well confined in the tune diagram, and the dynamic aperture exceeds the physical acceptances.

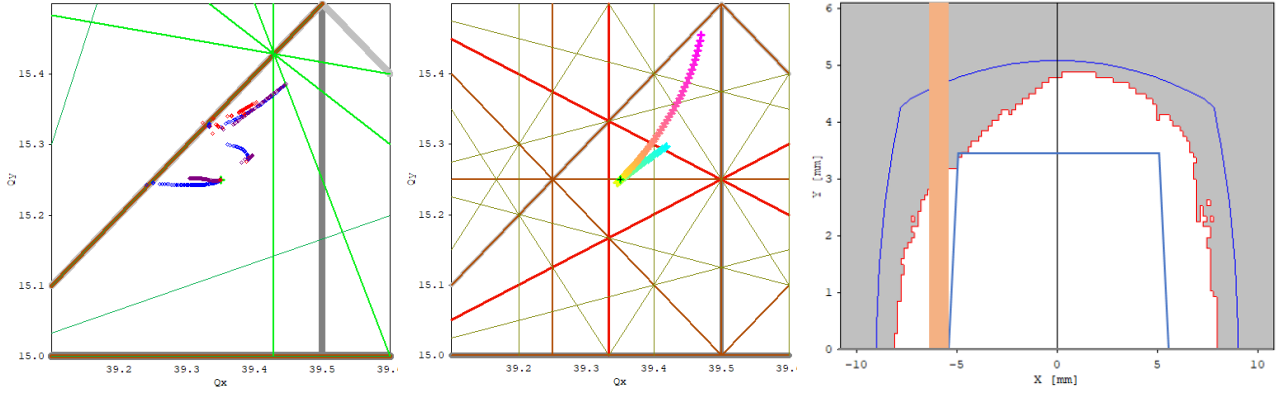


Figure 11 Beam footprint in tune diagram: left plot tune with amplitude for $dpp = \{0, -4\%, +4\%\}$ (bottom to top; horizontal, vertical, mixed) showing resonances up to 8th order, period-12. Mid plot tune for $\pm 5\%$ energy variation and chromaticities of +1, showing resonances up to 5th order, period-1. The right plot shows the dynamic aperture (300 turns), track point at injection ($\beta_x/\beta_y = 23/6.4$ m). The blue contour is the silhouette of a 18 mm inner diameter beam pipe which was used in all three calculations, the blue trapezoid the physical aperture including 2 m long undulators with 4 mm vertical gap and the injection septum, which is shown as orange bar.

Beam Lifetime

Figure 12 shows the lattice momentum acceptance obtained by 4D tracking for the ideal lattice (OPA, 300 turns). The linear Touschek lifetime as determined by the beam pipe is 20.0 h, the non-linear lifetime from tracking is 15.7 h. Vertical emittance is set to 10 pm by assuming 6.6% coupling, which reduces horizontal emittance to 151 pm. Beam current is 400 mA in 390 of 480 bunches (i.e. 0.985 nC/bunch). RF voltage is 1.44 MV for the fundamental and 375 kV for the 3rd harmonic to triple bunch length to 8.5 mm. Assuming 10^{-9} mbar partial pressure of carbon monoxide as residual gas, the elastic scattering lifetime is 40 h, determined by the mini-gap undulators (2 m long undulators of 4 mm full gap in all short straights). Bremsstrahlung lifetime is 93 h. Thus the total beam lifetime is 10.0 h.

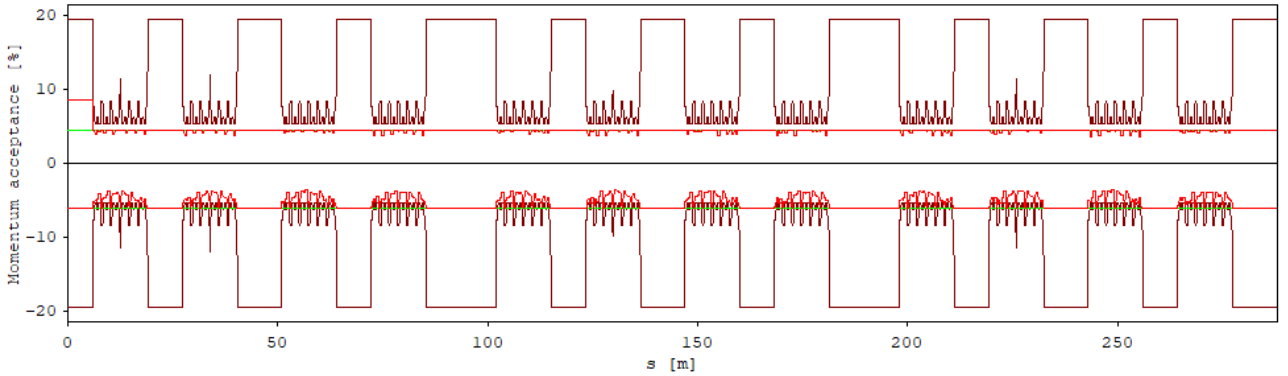


Figure 12: momentum acceptance as determined by the RF-bucket, the beam pipe and obtained by tracking.

Injection (preliminary)

Based on the preliminary kicker arrangement in straight 1L and 2S, three injection methods will be applied as demonstrated in Fig. 13:

- Off-axis: in the beginning, the classical bump injection like at SLS 1.0 will be applied re-using the four slow kickers: The stored beam is moved close to the septum, to $x = -4.5$ mm. The injected beam comes in on the other side of the thin septum at $x = -7.5$ mm and will oscillate around the stored beam, filament quickly and finally merge into the stored beam due to radiation damping.
- Pseudo on-axis: in a second phase, the fast kickers in straight 2S will operate at a longer pulse of about 20 ns and reduced power, while the slow kickers are switched off. Then the injected beam is

kicked half-way in and a few bunches of the stored beam are kicked out partially such that both beam share the available aperture.

- On-axis: finally, when the fast kickers will be operated at < 2 ns pulse length and at full power, the injected beam is kicked onto the design orbit at about 0.5...1.0 ns before the stored bunch, such that the stored bunch is not affected, and the injected beam is still captured by the RF-bucket. This minimizes the distortion to the stored beam.

The figures demonstrate that the dynamic aperture is sufficient for all three types of injection. No particles were lost after 1024 turns. Radiation was not included. The injected beam emittance of about 12 nm is delivered by the booster synchrotron at 2.7 GeV (but can be reduced, if needed, by means of emittance exchange).

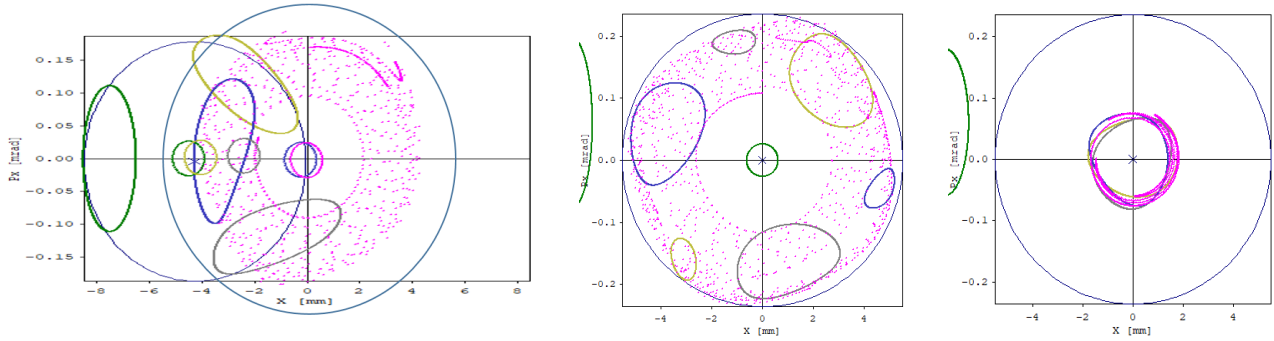


Figure 13: injection process in horizontal phase space, showing turns 0, 1, 2, 3, 1024.

Large ellipses show the $3\text{-}\sigma$ injected beam ($3^2 \times 12$ nm) coming in at $x = -7.5$ mm.

Small ellipses show the $10\text{-}\sigma$ stored beam ($10^2 \times 0.16$ nm, $\beta = 23$ m).

The septum (not shown) extends from $x = -6.5$ to -5.5 mm. The big blue circle corresponds to the linear acceptance.

Left: classical off-axis injection with bump kickers set to $-1.44 / +1.15 / +2.73 / -2.85$ mrad. Injected beam $\beta = 9$ m.

Middle: aperture sharing (pseudo on-axis injection) with fast kickers set to -330 mrad kick each. Injected beam $\beta = 5$ m, injected beam incoming angle set to $x' = +0.06$ mrad.

Right: true on-axis injection with fast kickers set to -585 mrad kick each. Injected beam $\beta = 8$ m.

Conclusion and Outlook

B062 is the final lattice with regard to lattice geometry and enables to proceed with detailed magnet and girder designs and beam line modification planning.

Work is in progress on the following issues:

- Magnet parameters in detail depend on simulations of cross-talk between magnets (field maps) and subsequent fine tuning in order to realize the design optics. This issue is critical since most magnets are permanent and cannot be changed during operation.
- The layout of the injection straight will be discussed between beam dynamics and pulsed magnets groups mainly, in order to find a feasible and convenient solution.
- The split ratio of the 5L and 9L straights will be fixed based on discussions with the beam lines.
- Detailed tracking studies in complete 6D-dynamics including lattice imperfections and corresponding correction methods as well as coupling control will be repeated for lattice B062 to get a realistic estimate on injection efficiency and beam lifetime.