

Realization of compact permanent-magnet-based multibend-achromat lattice with magnetic crosstalk compensations

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(Received 24 October 2025; accepted 4 February 2026; published 25 February 2026)

Electron storage rings based on multibend-achromat (MBA) lattices can achieve exceptionally low natural emittances. At the Paul Scherrer Institute in Switzerland, the Swiss Light Source facility underwent an upgrade project, replacing its triple-bend achromat ring with a seven-bend achromat ring. Due to the compact nature of MBA lattices, magnetic fields can be influenced by neighboring magnets. These magnetic crosstalk effects turned out to be significant during the design phase: the integral fields of the magnets could be altered by several percent. We present how we incorporated compensations for these effects into the design and how we tuned the magnets prior to installation. The crosstalk compensations were validated through the accelerator commissioning.

DOI: [10.1103/tfjh-x49q](https://doi.org/10.1103/tfjh-x49q)

I. INTRODUCTION

The transition of light source facilities from the third to the fourth generation has been underway since the commissioning of MAX IV in 2015 [1,2]. Following this, ESRF-EBS [3,4], Sirius [5,6], APS-U [7], and HEPS [8] were realized. Many more facilities are currently in the planning or construction stage, including those described in [9–15]. The defining characteristic of fourth-generation light sources is their low natural emittance, achieved through the multibend-achromat (MBA) lattice [16–18], which enables the delivery of high-performance photon beams. At the Paul Scherrer Institute in Switzerland, the installation of a new storage ring in the Swiss Light Source (SLS) facility [19] has been completed. This new ring, employing a seven-bend achromat (7BA) lattice, is the first light-source storage ring to incorporate a substantial number of permanent magnets: the beam orbit and linear optics along the achromat arc are realized entirely with permanent magnets.

The new storage ring has been commissioned and has met its design specifications, currently serving the first set of user beamlines with high-performance photon beams. During the design phase, however, significant magnet crosstalk effects were identified: the integrated magnetic field of each magnet was influenced by adjacent magnets,

leading to variations. Initial estimates suggested that these variations could reach several percent.

Similar issues have been reported at ANL [20] and ESRF [21]. In the former study, the crosstalk effects were marginal and can be compensated by adjusting the operational currents of the electromagnets. In the latter case, it was necessary to adjust the fields of the permanent bending magnets prior to installation, while the gradients of the electromagnet quadrupoles were corrected based on beam measurements. Because of our permanent-magnet-based design, it was essential to include compensations for the significant crosstalk effects in the design, as well as to measure and tune all permanent magnets before installation. The large number of magnets further increased the difficulty of this challenging task [22].

The rest of the paper is organized as follows. In Sec. II, the layout of the seven-bend achromat lattice is briefly described, while more details can be found in [23]. In Sec. III, the crosstalk effects are quantified through finite element method (FEM) simulations, and the results are also used as input for the magnet tuning described in Sec. IV. The crosstalk compensations implemented are validated through commissioning, as discussed in Sec. V. Finally, we summarize our conclusions in Sec. VI.

II. NEW STORAGE RING LATTICE

The key parameters of the new storage ring are extracted and listed in Table I. The lattice of the new storage ring is based on a 7BA lattice, comprising five periodic cells and half-cell dispersion suppressors at both ends of the achromat arc. The ring consists of 12 arcs, 12 straight sections, and matching sections connecting them. The total circumference

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TABLE I. Key design parameters of the new SLS storage ring.

Parameters	Values
Beam energy	2.7 GeV
Circumference	288 m
Natural emittance	158 pm w/o insertion device
Lattice	7-BA, 12 sectors
Beam current	400 mA
Beam lifetime	9 h w/o insertion device

of the ring, 288 m, was dictated by the requirement to fit within the existing accelerator tunnel, allowing the reuse of the original building and injector with only minimal refurbishment. Implementing the 7BA design within this constrained circumference presented a significant engineering challenge.

To facilitate mechanical integration, we employed an aggressive magnet design strategy. Bending and focusing within the achromat arc are entirely realized using Nd-Fe-B permanent magnets (PMs), which eliminate the need for space-consuming electromagnet coils. Figure 1 illustrates the high density of the magnets and other components assembled on the support girders.

The magnets of a single achromat arc are listed in Table II [24]. The table also includes the bore radius or magnet gap, as well as the spaces between the magnets, which are relevant to the crosstalk effects. The spaces between adjacent magnets are relatively short and comparable to the bore radius or gap of the magnets.

The main bending magnets consist of three components: VB-BN-VB, with a central bending magnet (BN) flanked by two combined-function magnets (dipole plus quadrupole, VBs). The dipole fields of the combined-function magnets are weaker than that of the central dipole, forming a stepwise longitudinal gradient bend (LGB) [25–27]. The magnet VBX is a variant of VB, with its field gradient adjusted for dispersion suppression. The AN and ANM magnets are reverse bends combined with a horizontal

focusing gradient: these magnets are physically quadrupoles but are horizontally shifted to provide bending. Similarly to VBX, the magnet ANM is a variant of AN. At the beginning and end of the arc, the dispersion is suppressed along the BE-SXQ-VE/VE-SXQ-BE magnets. The magnet VE is also a shifted quadrupole. Except for the SXQ sextupole, the above-mentioned magnets are permanent magnets and define the design orbit and the linear optics along the achromat arc.

The electromagnets are installed to provide essential correction capabilities. Closed orbit distortions are corrected by the CH, CHS, and CV magnets. Normal and skew quadrupole functions for correcting the linear optics and transverse coupling are incorporated into the octupoles via additional coil windings. The strengths of the corrector magnets are, however, limited within the achromat arc based on permanent magnets. It is therefore important to adjust the strength of each permanent magnet within tolerance, including compensations for crosstalk effects.

The chromaticity correction sextupoles are arranged such that the SF magnets primarily correct horizontal chromaticity, while the SD and SXQ magnets correct vertical chromaticity. The OC octupoles are used to regulate higher-order chromaticity and amplitude-dependent tune shifts. In addition, a few harmonic sextupoles and octupoles are installed in each matching section. The nonlinear optics can be flexibly regulated by these magnets, and no critical issues are expected. However, these magnets themselves are sources of crosstalk effects.

III. FIELD SIMULATIONS

FEM simulation is capable of predicting magnetic fields, but achieving high precision requires a very fine mesh thus a large number of elements. For this reason, only a limited number of magnets were included in each computation. The arc was therefore divided into short sections that contain only a few magnets each. Table II indicates how magnets are grouped in the column “Group.”

The grouping shown in Table II was determined such that each group contains either a single permanent magnet (AN or ANM) or a series of permanent magnets (LGB). The neighboring upstream and downstream electromagnets were then included in the same group. At both ends of the arc, the BE and VE magnets were grouped together because the SXQ magnet influences both elements. This grouping strategy allows the magnetic fields of the permanent magnets to be calculated while incorporating crosstalk effects.

The entire arc was simulated and optimized piece by piece, whereas the matching sections and the straight sections were not included in this simulation campaign, since they consist of electromagnets with adjustable fields. A couple of examples illustrating the modeling in FEM code are shown in Fig. 2.

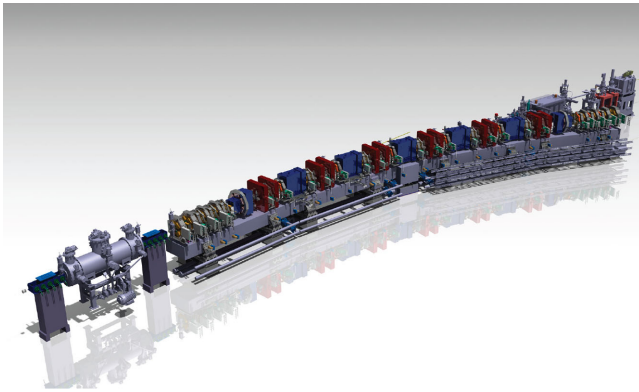


FIG. 1. One sector of the storage ring from a three-dimensional virtual model. The number of magnets per sector is more than 100 [19].

TABLE II. List of magnets from one achromat arc. “Length” is the length in the hard-edge optics model, and the actual magnet lengths are slightly different to provide approximately the same magnetic length. “Design field” is absolute value. The column “PM/EM” indicates the type of magnets, i.e., either permanent magnet (PM) or electromagnet (EM). “Aperture” is the bore radius or the half gap. The last column, “Space,” corresponds to the distance to a magnet listed in next row (the yoke-to-yoke space of the actual magnets). The field gradients of VB and VBX magnets, omitted in the list, are 40.6 and 33.1 T/m, respectively.

Magnet	Function	Design field	Length (mm)	PM/EM	Group	Aperture (mm)	Space (mm)
CHS-CV	Orbit correctors	...	40-40	EM	1	12.5-12.5	68.3
BE	Dipole	1.14 T	242.5	PM	1	22.0	46.3
SXQ	Sextupole	4703 T/m ²	90	EM	1	12.5	51.0
VE	Dipole + quadrupole	0.65 T + 45.7 T/m	240	PM	1	19.5	329.1
ANM	Dipole + quadrupole	0.27 T + 82.8 T/m	150	PM	2	13.0	42.5
SF	Sextupole	4661 T/m ²	80	EM	2	11.0	56.0
OC	Octupole	10, 871 T/m ³	50	EM	3	14.5	54.0
AN	Dipole + quadrupole	0.27 T + 77.6 T/m	140	PM	3	13.0	80.0
CHS-CV	Orbit correctors	...	40-40	EM	3	12.5-12.5	40.5
OC	Octupole	14, 843 T/m ³	50	EM	...	14.5	56.0
SD	Sextupole	4315 T/m ²	80	EM	4	11.0	64.5
VBX-BN-VB	LGB	0.85-1.32-0.85 T	185-405-185	PM	4	11-11-11	64.5
SD	Sextupole	4796 T/m ²	80	EM	4	11.0	56.0
OC	Octupole	14, 843 T/m ³	50	EM	5	14.5	214.1
AN	Dipole + quadrupole	0.27 T + 77.6 T/m	140	PM	5	13.0	55.0
SF	Sextupole	5127 T/m ²	80	EM	5	11.0	56.0
OC	Octupole	25, 217 T/m ³	50	EM	6	14.5	54.0
AN	Dipole + quadrupole	0.27 T + 77.6 T/m	140	PM	6	13.0	80.0
CHS-CV	Orbit correctors	...	40-40	EM	6	12.5-12.5	40.5
OC	Octupole	14, 843 T/m ³	50	EM	...	14.5	56.0
SD	Sextupole	4823 T/m ²	80	EM	7	11.0	64.5
VB-BN-VB	LGB	0.85-1.32-0.85 T	185-405-185	PM	7	11-11-11	64.5
SD	Sextupole	4501 T/m ²	80	EM	7	11.0	56.0
OC	Octupole	37, 463 T/m ³	50	EM	8	14.5	214.1
AN	Dipole + quadrupole	0.27 T + 77.6 T/m	140	PM	8	13.0	55.0
SF	Sextupole	3800 T/m ²	80	EM	8	11.0	56.0
OC	Octupole	24, 000 T/m ³	50	EM	9	14.5	54.0
AN	Dipole + quadrupole	0.27 T + 77.6 T/m	140	PM	9	13.0	80.0
CHS-CV	Orbit correctors	...	40-40	EM	9	12.5-12.5	40.5
OC	Octupole	37, 463 T/m ³	50	EM	...	14.5	56.0
SD	Sextupole	4774 T/m ²	80	EM	7	11.0	64.5
VB-BN-VB	LGB	0.85-1.32-0.85 T	185-405-185	PM	7	11-11-11	64.5
SD	Sextupole	4774 T/m ²	80	EM	7	11.0	56.0
OC	Octupole	37, 463 T/m ³	50	EM	10	14.5	214.1
AN	Dipole + quadrupole	0.27 T + 77.6 T/m	140	PM	10	13.0	54.0
OC	Octupole	24, 000 T/m ³	50	EM	10	14.5	56.0
SF	Sextupole	3800 T/m ²	80	EM	11	11.0	55.0
AN	Dipole + quadrupole	0.27 T + 77.6 T/m	140	PM	11	13.0	80.0
CHS-CV	Orbit correctors	...	40-40	EM	11	12.5-12.5	40.5
OC	Octupole	37, 463 T/m ³	50	EM	...	14.5	56.0
SD	Sextupole	4501 T/m ²	80	EM	7	11.0	64.5
VB-BN-VB	LGB	0.85-1.32-0.85 T	185-405-185	PM	7	11-11-11	64.5
SD	Sextupole	4823 T/m ²	80	EM	7	11.0	56.0
OC	Octupole	14, 843 T/m ³	50	EM	12	14.5	214.1
AN	Dipole + quadrupole	0.27 T + 77.6 T/m	140	PM	12	13.0	54.0
OC	Octupole	25, 217 T/m ³	50	EM	12	14.5	56.0
SF	Sextupole	5127 T/m ²	80	EM	13	11.0	55.0
AN	Dipole + quadrupole	0.27 T + 77.6 T/m	140	PM	13	13.0	80.0
CHS-CV	Orbit correctors	...	40-40	EM	13	12.5-12.5	40.5
OC	Octupole	14, 843 T/m ³	50	EM	...	14.5	56.0

(Table continued)

TABLE II. (Continued)

Magnet	Function	Design field	Length (mm)	PM/EM	Group	Aperture (mm)	Space (mm)
SD	Sextupole	4796 T/m ²	80	EM	14	11.0	64.5
VB-BN-VBX	LGB	0.85-1.32-0.85 T	185-405-185	PM	14	11-11-11	64.5
SD	Sextupole	4315 T/m ²	80	EM	14	11.0	56.0
OC	Octupole	14,843 T/m ³	50	EM	15	14.5	214.1
AN	Dipole + quadrupole	0.27 T + 77.6 T/m	140	PM	15	13.0	54.0
OC	Octupole	10,871 T/m ³	50	EM	15	14.5	56.0
SF	Sextupole	4661 T/m ²	80	EM	16	11.0	42.5
ANM	Dipole + quadrupole	0.27 T + 82.8 T/m	150	PM	16	13.0	67.0
CHS-CV	Orbit correctors	...	40-40	EM	16	12.5-12.5	164.0
VE	Dipole + quadrupole	0.65 T + 45.7 T/m	240	PM	17	19.5	51.0
SXQ	Sextupole	4703 T/m ²	90	EM	17	12.5	46.3
BE	Dipole	1.14 T	242.5	PM	17	22.0	

To quantify the crosstalk effect, it is a straightforward approach to compute the magnetic field with and without adjacent magnets. Figure 3 shows such a comparison for the AN magnet in the string of SF-AN-CHS-CV (Group 11): the gradient of the AN magnet is attenuated by 4.6%. A similar simulation for the string OC-AN-OC (Group 10) results in an attenuation of 3.5%.

An attenuation of 4.6% or 3.5% is significant when compared with the specification of the quadrupole corrector strength, which corresponds to about 2.6% of the AN integrated gradient. The length of the sextupole SF was actually shortened by 1 cm to increase the space between the magnets, and the result shown in Fig. 3 corresponds to the shorter sextupole. This was one design change we needed to implement; otherwise, the attenuation would have been too strong. The other change was the addition of

an iron shield to the CH corrector to prevent deep saturation; the corrector “CHS” stands for a CH magnet with shield. The implemented shield is seen in Fig. 2(a). Separate FEM simulations revealed that this significant crosstalk was largely due to the use of permanent magnet design as discussed in the Appendix.

The first and the last dipole magnets of the arc, the BE magnets, are part of the dispersion suppressor. The BE-VE pair essentially forms a half LGB, with the sextupole SXQ inserted. An important crosstalk effect identified here was that the SXQ sextupole truncates the fringe field of BE and VE magnets. This crosstalk effect is equivalent to longitudinal shifts of these magnets. At the entrance of the arc (Group 1), the CV corrector also truncates the BE fringe field, and thus the effect is limited. The BE magnet at the end of the arc (Group 17), however, lacks the neighboring

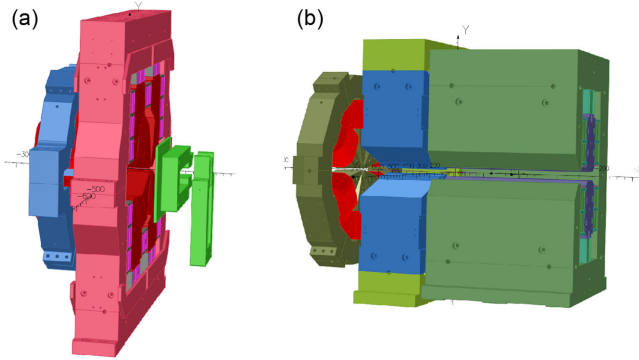


FIG. 2. Magnet modeling to investigate crosstalk effects. (a) SF-AN-CHS-CV: PM reverse bend (center) with adjacent sextupole (left) and orbit correctors (right). The reverse bend is a quadrupole magnet but shifted horizontally to provide a dipole field. The sextupole is excited with the operational current. (b) SD-VB-BN: PM bending (right) and PM combined-function magnet (center) with sextupole (left). The PM combined-function magnet on the right side of the bending is omitted since a boundary condition (left-right symmetry) is applied at the center of the bending when computing the field.

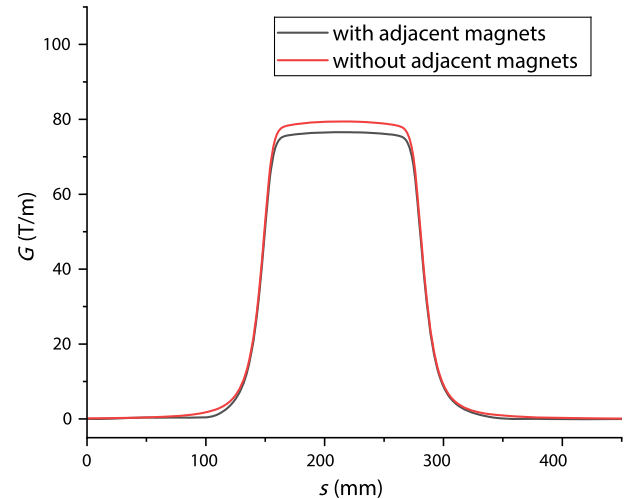


FIG. 3. Field gradient of the reverse bend, AN, with and without adjacent magnets (black and red curves). The integrated gradient of the AN magnet is attenuated by 4.6%. In addition to the field attenuation, it is seen that the fringe field is truncated by the adjacent magnets.

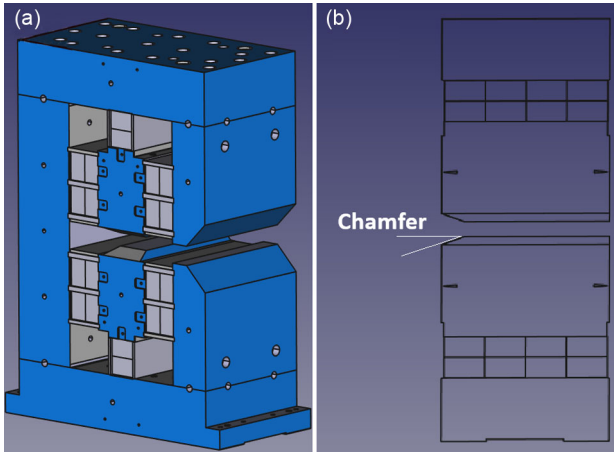


FIG. 4. Chamfer applied to the BE magnet at the end of the achromat arc. (a) View of BE magnet downstream side. (b) Cross section along the magnet pole. The pole is cut with a slope of about 24° .

corrector CHS-CV, resulting in a sizable effect. Therefore, a chamfer was applied to the pole of the BE magnet as compensation (Fig. 4). The dipole profiles of these two cases are shown in Fig. 5.

The LGB magnet, VB-BN-VB, did not require any design changes with respect to crosstalk, even though the space between the magnets is only 17 mm. The gradient of the VB was actually enhanced by about 10% by the BN magnet, but this effect was considered from the outset, as the LGB design was always based on FEM simulations including all three magnets together. The pole shape of the

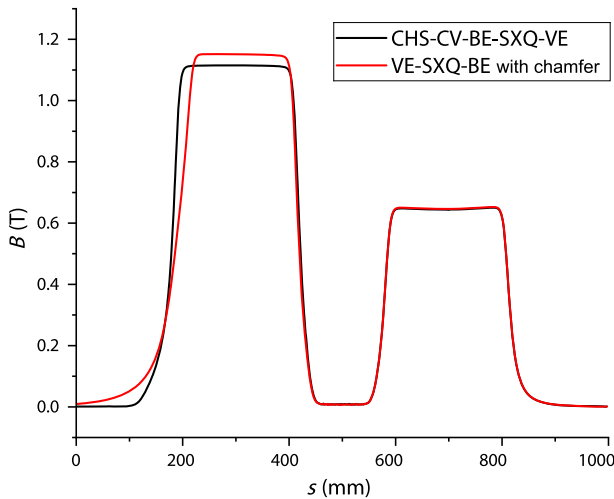


FIG. 5. Dipole field along the strings CHS-CV-BE-SXQ-VE (Group 1, black curve) and VE-SXQ-BE (Group 17, red curve). The horizontal axis is flipped for the latter string to compare the field profiles directly. The effect of the chamfer applied to the BE magnet of Group 17 is seen as a shorter flattop in the dipole profile at around $s = 300$ m.

VB magnet was, however, modified to regulate multipole components.

After these design changes, further FEM simulations were performed with the following objectives: (i) To adjust the field strengths of the permanent magnets so that the closed orbit and the linear optics of the ideal hard-edge optics model are reproduced. (ii) To provide reference field integrals for the magnet tunings (discussed in Sec. IV). (iii) To develop transfer functions for the electromagnet sextupoles and octupoles (current versus field) to facilitate accelerator commissioning and user operation. (iv) To consolidate the nonlinear optics model for better evaluation of the storage ring performance.

FEM simulations were iteratively repeated until the design orbit and linear optics were precisely reproduced, following the procedure outlined below.

The simulated three-dimensional field was converted into sliced elements representing the dipole and quadrupole field components along the electron trajectory. Prior to slicing, the trajectory was determined using numerical particle tracking (Fig. 6). For these computations, we employed the method described in [28]. The optical functions are then evaluated using accelerator code (e.g., MAD-X) by replacing the idealized hard-edge elements with the corresponding sliced elements. The magnets were optimized until the differences in the optical functions before and after replacement became acceptably small. The electron beam trajectory was adjusted simultaneously to approximately match the design closed orbit.

The optimization of the magnets primarily counteracted the crosstalk effects, while simultaneously compensating for minor effects such as the soft-edge effect. For example, after optimization, the integrated gradient of the AN

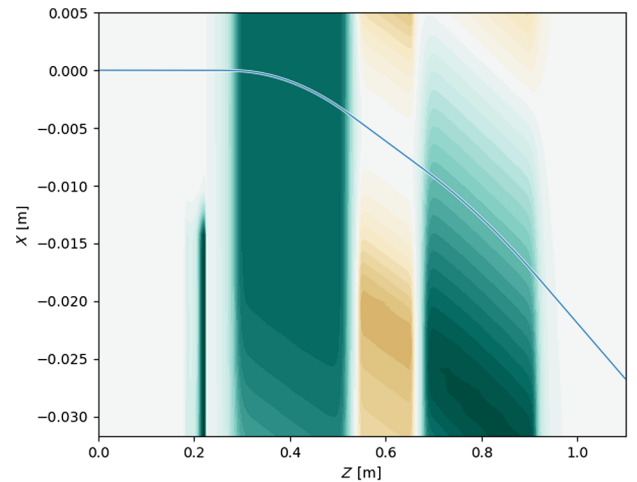


FIG. 6. Electron beam trajectory through the CHS-CV-BE-SXQ-VE string. The cyan line shows the trajectory of an electron tracked through the magnetic field obtained from FEM simulation. The background color map shows negative and positive fields in green and brown, respectively.

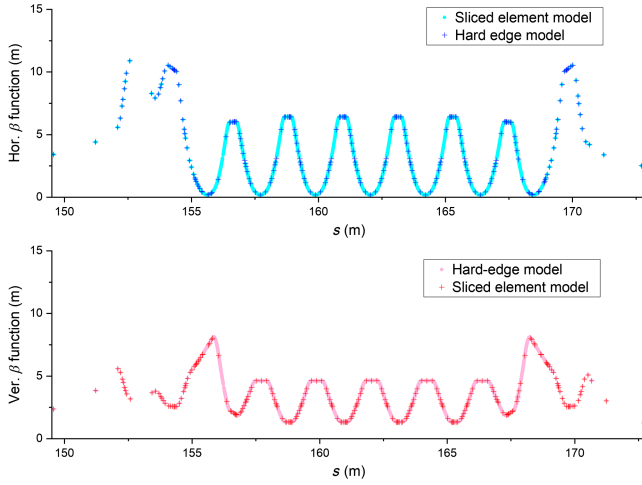


FIG. 7. β functions computed using the ideal hard-edge elements and with the achromat arcs replaced by sliced elements. One sector out of twelve is shown, including the matching section and half of the straight section on both sides. The difference between the two cases is less than 0.5%.

magnet was on average about 0.5% larger than that of the corresponding hard-edge AN model.

The final FEM simulation result of this iterative process was saved as the reference model, with each short section of the arc represented by its own model. The trajectory deviation within each section was at most 6.9 μm , and typically less than 5 μm . When the entire arc was modeled using the full series of sliced elements, the β functions were reproduced to within $\pm 0.5\%$ in both horizontal and vertical planes throughout the ring (Fig. 7). This level of accuracy ensures that the correction capacity remains available mostly for compensating field errors and misalignments, rather than being consumed by crosstalk effects.

In the above magnet optimization, we employed the following measures. The poles of the AN magnets were slightly thickened, as seen in Fig. 2, to approximately compensate for the gradient attenuation. The moderator plates (movable iron plates) used for fine field tuning were included in the FEM modeling of AN/ANM magnets. These magnets were also shifted horizontally and longitudinally by up to 1.0 mm.

The BE and VE magnets were shifted longitudinally by about 3 mm to compensate for the crosstalk effect previously discussed, namely, fringe-field truncation. In addition to the fringe-field truncation, the SXQ magnet influenced the fields of the BE and VE magnets. The field of the VE magnet was adjusted with the same approach to the AN magnet, i.e., varying pole thickness and moderator plate position. The field of the BE magnet was adjusted by varying the thickness of the *shunt*—iron plates attached to the permanent magnet blocks to short the magnetic circuit. In addition, a horizontal shift of the VE magnet served as an extra knob to adjust the dipole component along the beam path without changing the field gradient.

The strengths of the VB/VBX and BN magnets were likewise optimized by adjusting the shunt thickness. Similarly to the VE magnet tuning, the horizontal position of the VB/VBX magnets was adjusted to achieve the optimum bending and field gradient simultaneously. The moderator plates of the VB/VBX and BN magnets were not included in the FEM model, since it was sufficient to adjust the field by varying the thickness of the shunt for the optimization purpose. For the tuning of actual magnets, the shunts are used for coarse tuning while the moderator plates are used for the fine tuning.

With regard to the AN/ANM magnets, however, the optimization depends on which magnets are placed in the vicinity, e.g., a sextupole or an octupole. Furthermore, an additional, minor but non-negligible crosstalk effect depends on the sextupole/octupole field strength, which varies along the arc. For example, Groups 11 and 13 in Table II are the same string, but slightly different AN optimizations are applied because the SF sextupoles are excited differently to control the nonlinear optics: the optimized AN moderator plate position differs by 4 mm between the two, which corresponds to a change in the AN field gradient of approximately 0.4%. We distinguish “static” crosstalk effects, which arise solely from the presence of adjacent magnets, from this “dynamic” or “current-dependent” crosstalk effect. It was thus necessary to include the moderator plates in the FEM models of the AN/ANM magnets. The current-dependent effect between VB and SD magnets was marginal, and thus the LGB of Group 7 was optimized for a fixed SD current and adopted at three locations.

As a result of the magnet optimization based on FEM simulations, the design changes required to compensate for magnetic crosstalk were clearly identified. These changes were subsequently incorporated into the magnet designs either prior to the start of series production or during the early stages of manufacturing, when minor adjustments were still feasible.

Further simulations revealed another sizable effect in the BE-SXQ-VE string: the bending angle along these magnets is reduced by about 140 μrad when the SXQ magnet is turned off. The unsaturated SXQ yoke absorbs more field from the BE and VE magnets.

FEM simulations also revealed interesting effects other than the attenuation or enhancement of the field. For instance, within the SF sextupole placed in the vicinity of the AN reverse bend, some quadrupole and octupole components were excited. We used the FEM simulation results to improve our nonlinear optics model. The integrals of multipole components up to the 12-pole (dodecapole) were extracted from the reference models. The tracking study including these multipole errors showed only a minor influence on the storage ring performance, namely, the beam lifetime.

Finally, the measured transfer functions of the electro-magnet sextupoles and octupoles were modified based on

FEM simulations after the magnetic field measurement described in the next section. The sextupole/octupole components of the above multipole errors were added as offsets to the transfer functions of nearby sextupole/octupole magnets. The offset for octupoles reaches about 10% of the maximum field. Nevertheless, the crosstalk issue for multipole components is expected to be much less critical than that for dipole and quadrupole components, since the electromagnet sextupoles and octupoles can compensate for it.

IV. FIELD MEASUREMENT AND TUNING

The reference model obtained from the field simulation also serves as a crucial input for field measurements and tunings. The objective of the tuning was to adjust the magnetic field according to the reference model within a tolerance of 0.2% rms (maximum 0.4% with 2- σ cut), as discussed later in Sec. V.

The magnetic field measurements were performed using three complementary systems: a rotating coil, a moving wire, and a Hall probe. Rotating coil and Hall probe were calibrated against the moving-wire system, yielding an estimated absolute field accuracy of approximately 0.1%.

For the main bending magnet, LGB, the crosstalk field variation can reach up to about 10%: the gradient of the combined-function magnet is enhanced by the central bending magnet. To adjust the field of the LGB, which is subject to such strong crosstalk, several steps were taken, as outlined below.

In preparation, each magnet was retracted from the reference model, and FEM simulation was performed for each individual magnet in order to provide a reference integrated field excluding the crosstalk effects. Subsequently, we measured each of the three magnets of the LGB individually; the VB combined-function magnets using the rotating coil, and the BN bending magnets using the moving-wire system. These fields were then adjusted to match the corresponding single-magnet reference value. Afterward, the three magnets were assembled and measured together as a single entity (Fig. 8).

The assembled LGB was measured with the moving-wire system, which determines the field integral along a straight line. The LGB bends the electron beam by 5.48° and forms an arched orbit with a horizontal width of about 10 mm. Therefore, tuning the LGB based on a single measurement at a fixed horizontal position is insufficient. To properly cover the arched orbit, three measurement positions were selected, as shown in Fig. 9. The first position covers the beam orbit along the VB magnets, while the second and third positions cover the orbit along the BN magnets.

To adjust both the dipole and quadrupole components, two tuning knobs were employed. The moderator plates of the VB magnets were used as the first knob, which had also been used during the individual magnet tuning. The second

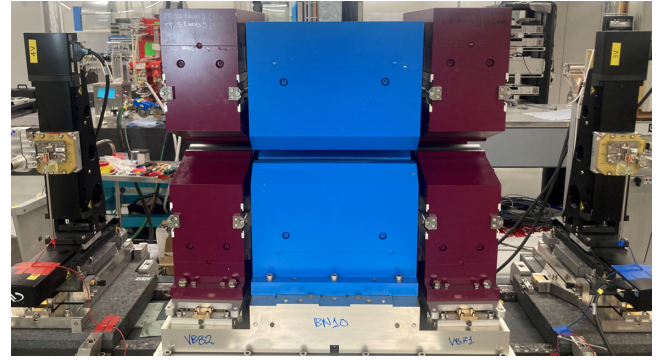


FIG. 8. LGB magnet assembly installed on the measurement bench.

knob functioned as a “virtual” knob, shifting the magnetic axis of the LGB horizontally without any physical modification. The first knob acted on both dipole and quadrupole components, whereas the second knob primarily affected the dipole component. Using this procedure, all 60 LGBs were measured and tuned. The tuning applied to the VB magnets was about 0.7% on average and an axis shift of up to about 200 μm . This axis shift was recorded and later used for the alignment of the LGB during installation in the accelerator tunnel.

The sextupoles located near the LGB were not included in the measurements, as they could not be accommodated on the measurement bench. To compensate for this, a modified reference model was prepared with the sextupoles removed; this version was used exclusively for tuning the assembled LGB.

In Fig. 10, the measurement at position 3 shows a systematically lower gradient. This deviation, however, does not affect the storage ring optics, since the electron beam orbit at position 3 does not overlap with the VB magnets, which are the source of the field gradient. Figure 10 also shows that the tuning left an offset in the integrated dipole for all measurement positions, which was about 0.15%. This can be compensated by either the orbit

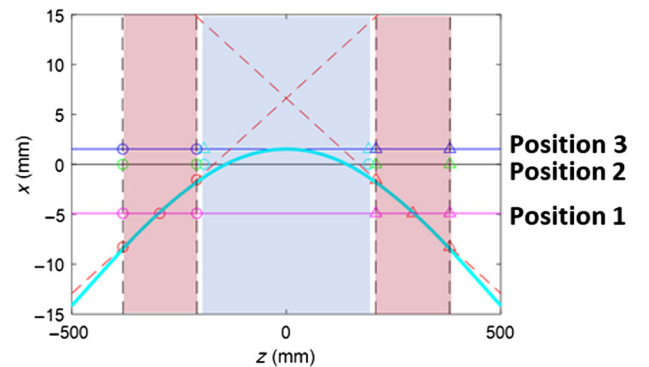


FIG. 9. Electron beam orbit through the main bending magnet, LGB. The field integrals were measured at three horizontal positions to cover the arched orbit (cyan curve).

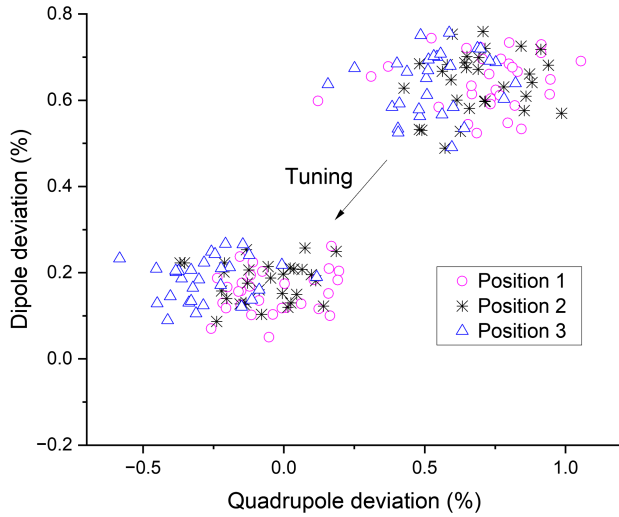


FIG. 10. Integrated-field deviation before and after tuning of VB-BN-VB magnets. The deviation is computed with respect to a reference model without SD magnets, which is prepared exclusively for the tuning.

correctors or a slightly different beam energy. Further details on the LGB measurement and tuning procedure are provided in [29].

The crosstalk effect between the AN magnet and nearby magnets was also evaluated through magnetic field measurements. A procedure similar to that used for the LGB tuning was employed. First, the field of the AN magnet was measured and tuned individually. Since the sextupole and octupole magnets are electromagnets, their transfer functions (field versus current) were measured separately. The magnets were then installed on the measurement bench as a string and measured using a Hall probe, with the electromagnets excited at their nominal operating currents (Fig. 11).

In these measurements, the misalignment of the magnets can lead to an error in evaluating the AN gradient attenuation. To mitigate such a systematic error, the reference model was modified to include the actual alignment data of each crosstalk measurement setup. The most effective mitigation was, however, to set the region of integral within the AN magnet yoke length when computing and comparing the gradient.

This measurement, aimed at evaluating the crosstalk effect on the AN magnet, was time-consuming because it required setting up and aligning a string of magnets. Consequently, only five magnet strings were measured. The averaged result, however, indicated that the AN gradient attenuation was slightly smaller than the FEM-predicted values. Therefore, the AN field strength was adjusted based on the reference values, with a correction of approximately 0.4%.

In addition to the above correction, the magnet-to-magnet spread was a concern, since only a limited number of magnets were sampled. Although the number of measurements was small, the spread was smaller than the field

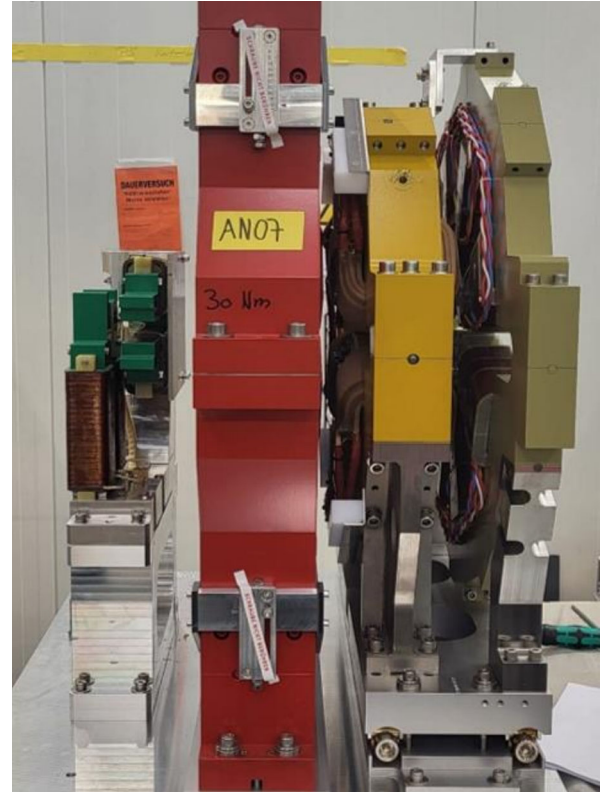


FIG. 11. Magnet string installed on the measurement bench, CV-CHS-AN-SF(-OC), corresponds to Group 11.

error tolerance. This is because the spread can be regulated through individual magnet tuning. Therefore, applying the averaged correction obtained from the string measurements to all magnets may be justified as a reasonable compromise to complete the magnet measurements and tunings within the given construction schedule.

Based on the above simulation and measurement campaign, we concluded that the crosstalk effect, i.e., the field variation, was predicted with high accuracy. For instance, the difference in AN field attenuation between simulation and measurement was about 0.4% of the predicted attenuation of 3.5%–4.6%. For the LGB, an average tuning of 0.7% was required for the VB magnets, representing the residual of the 10% crosstalk effect predicted by the FEM simulation. The crosstalk measurements were extended to other types of magnets and are summarized in Table III, together with the accuracy of the FEM prediction.

Apart from the magnet measurements and tunings, an additional simulation study was carried out to better understand the observed discrepancy in the crosstalk effect between simulation and measurement. It was found that the material properties of the magnet yoke (B-H curve) slightly differed between the reference model and the actual magnets. Although this discrepancy was within the tuning range of the magnets, it could have been reduced if the material properties used in the reference model were more accurate.

TABLE III. Summary of crosstalk measurements. Concerning the combined-function magnets, VBs and VEs, the values listed are for the field gradient.

Magnet type	Crosstalk effect	Average discrepancy (%)	Accuracy (%)	Spread (maximum–minimum)
AN	3.5%–4.6% attenuation	0.39	88–91	$\pm 0.08\%$
ANM	3.1% attenuation	0.60	81	$\pm 0.35\%$
VB	10.7% enhancement	0.71	95	$\pm 0.27\%$
VE	3.3% attenuation	0.40	88	0.01%
BE	6.8% attenuation	0.45	93	$\pm 0.05\%$

Concerning the electromagnets, the transfer functions of all quadrupoles installed outside the achromat arcs, i.e., in the matching sections and straight sections, were measured. For approximately 30% of the sextupoles and octupoles, the transfer functions were measured using a rotating coil; the spread among these sampled magnets was below the field error tolerance. Accordingly, we applied averaged transfer functions with the modifications described in Sec. III.

V. FIRST RESULT WITH BEAM

Meeting the magnetic field and alignment tolerances for the large number of magnets in the new storage ring (854 electromagnets and 372 permanent magnets) presents a significant challenge. The ring is equipped with 115 orbit correctors in each transverse plane, as well as 264 quadrupole correctors integrated into the octupole magnets. Owing to the highly compact lattice, the strengths of these correctors are inherently limited. The design specifications for the orbit corrector deflections are 600 μrad horizontally and 400 μrad vertically. The quadrupole correctors embedded in the octupoles are designed to provide an integral gradient of 0.28 T.

During the lattice design phase, magnetic field and alignment tolerances were evaluated using numerical particle tracking simulations. When the error sources listed in Table IV were applied, the resulting orbit and optics corrections approached the maximum capacities of the corrector magnets. The values in Table IV were therefore adopted as the construction tolerances.

TABLE IV. Machine imperfections applied to the lattice design simulations. Misalignments and field errors are given by a Gaussian distribution truncated at two standard deviations.

Parameter	Value
<i>Misalignment</i>	
Magnet-to-magnet	30 μm rms
Magnet rotation	300 μrad rms
Girder center	60 μm rms
Girder-to-girder	20 μm rms
<i>Field error</i>	
Field strength	0.2% rms

The actual corrector magnets are, however, stronger than the specifications; the orbit correctors are capable of about 800 and 600 μrad in the horizontal and vertical planes, respectively, while the quadrupole correctors can provide an integrated gradient of about 0.32 T. The actual machine can therefore tolerate larger errors, owing to these extra corrector strengths. Nevertheless, the correction capacity remains rather limited compared to that of a conventional machine based on electromagnets.

Commissioning of the new ring began in January 2025, and by April 2025 the design performance was achieved in terms of both beam current and beam lifetime. During the early stage of commissioning, before the beam was able to circulate for several turns, the sextupole and octupole magnets were switched off so as not to introduce significant nonlinearities into the beam optics. They were turned on later when the beam circulated for several tens of turns. The SXQ sextupoles (24 magnets), however, were kept on at all times to avoid the current-dependent effect discussed in Sec. III.

Once a stored beam was established, the orbit and linear optics were sufficiently corrected within the limits of the corrector strengths. However, complete orbit correction could not be achieved at three specific locations. At these points, the horizontal orbit had to be deliberately offset by a few hundred μm to prevent the correctors from reaching their limits.

To investigate this issue, the alignment of nearby magnets was checked, but no significant misalignments were found that could account for the anomaly. *In situ* magnetic field checks of the relevant orbit correctors also revealed no evidence of installation errors. The investigation into this issue is ongoing and may eventually reveal the underlying cause. Nonetheless, the fact that the orbit and optics were corrected within the given corrector strengths, except for the horizontal orbit at the three locations, demonstrates that the magnet modeling, magnetic field tuning based on measurements, and magnet alignment were all properly carried out.

Concerning the nonlinear optics, the sextupole settings were varied by up to 1.6% to adjust the chromaticity to the design value. The design lifetime was achieved with only minor tunings of the harmonic sextupoles outside the achromat arc. No significant issues related to the multipole

components were observed, as anticipated from the FEM simulations.

VI. CONCLUSION

The implementation of the MBA design tends to pose technical challenges due to its compact nature. We encountered magnetic crosstalk issues during the design and construction of the new SLS 7BA storage ring, since the spaces between magnets had to be kept short to accommodate a large number of magnets as well as other accelerator components. A key design concept was to achieve both bending and focusing along the achromat arcs using permanent magnets, in order to meet the design constraints and desired performance. Correction capabilities are inherently limited within the compact MBA lattice based on permanent magnets. Hence, our main challenge was to adjust the strength of each permanent magnet within the tolerance, taking the significant crosstalk effects into account.

We managed this challenging task through a combination of FEM simulations, magnetic field measurements, and magnet tunings. Static crosstalk, current-dependent crosstalk, and minor effects such as the soft-edge effect were all addressed. These effects were compensated by optimizing the magnets based on FEM simulations. The crosstalk was particularly critical for the dipole and quadrupole components of the permanent magnets, whereas its impact on the multipole components could be readily compensated using electromagnet sextupoles and octupoles. FEM simulations (see the Appendix) further indicated that permanent magnets can be more prone to crosstalk.

The fields of the permanent magnets were measured and adjusted according to the reference values obtained from FEM simulations. It was confirmed with the beam during the accelerator commissioning that the error tolerances were essentially satisfied: sufficient orbit and linear optics corrections were achievable within the limits of the corrector magnet strengths.

In summary, our study demonstrates that crosstalk effects in a highly compact lattice can be accurately predicted using FEM simulations. Magnet optimization can effectively render the crosstalk effects on dipole and quadrupole components transparent to the orbit and linear optics and prevent the limited correction capacity from being consumed by crosstalk compensation. Magnetic field tolerances, typically on the order of a few permil, can be achieved even for complex magnets such as the LGB, which exhibit significant crosstalk effects. Overall, while the construction of a compact MBA storage ring using a large number of permanent magnets presents considerable challenges, our results show that it is indeed feasible.

ACKNOWLEDGMENTS

The magnet measurement and tuning campaign in the lab was assisted by skillful technicians, and we are grateful

especially to Roland Deckardt, Roland Felder, and Yannik Studer. We also thank Tino Höwler for his contribution to achieving the alignment tolerances. We appreciate careful proofreading by Thomas Schietinger.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX: CROSSTALK WITH PERMANENT MAGNET

FEM simulations revealed significant crosstalk effects between the reverse bend magnet (AN) and the octupole/sextupole magnets. We ran additional simulations to gain further insight into the crosstalk issue: the AN magnet was converted into an electromagnet. Some permanent magnet pieces were removed, and other pieces were replaced by iron blocks with the same material properties as the magnet poles. Thin coils were added to fit within the limited space between the magnets. The current density of the coils was unrealistically high, but these simulations were exclusively intended for the crosstalk study, not for magnet design. Figure 12 shows the original AN magnet and the converted version.

The integrated gradient of the AN magnet in Fig. 12(b) was then computed with and without neighboring magnets, similarly to Fig. 3. Interestingly, the field attenuation was 1.6% for the electromagnet AN, while the attenuation for the original AN in this configuration was 4.6% (Fig. 3). These simulations therefore indicate that the permanent magnet can be more prone to crosstalk.

The following interpretation appears plausible. From the perspective of the magnetic circuit, the magnetic reluctance is reduced when the AN magnet is converted into an electromagnet, as the permanent magnet blocks, whose permeability is close to 1, are replaced by iron. Each permanent magnet block has a length of 30 mm along the direction of magnetization. In the permanent-magnet

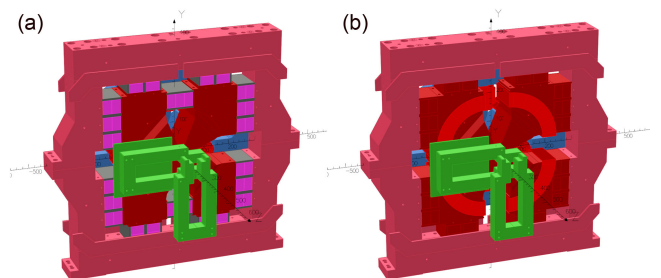


FIG. 12. Magnet string, SF-AN-CHS-CV, (a) with the original AN and (b) with the electromagnet version.

configuration of the AN magnet, shown in Fig. 12(a), the arrangement of these blocks introduces disruptions of 30, 60, and 90 mm in the magnetic circuit, while the spacing between the AN and SF magnets is approximately 60 mm. Consequently, in the electromagnet AN, the magnetic flux can be more effectively confined within the AN yoke.

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