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MAGNET CROSSTALK IN HIGHLY-COMPACT LIGHT-SOURCE STORAGE RING

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Abstract

Electron storage rings based on multi-bend achromat (MBA) lattices can achieve exceptionally low natural emittances. Several fourth-generation light sources employing such lattices have been constructed and are currently in operation, with natural emittances in the order of 100 pm or even below, delivering high-brightness photon beams to users. 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 study of the new Swiss Light Source storage ring: the integral fields of the magnets may be altered by a few percent. We present how we reproduced the beam optics while accounting for the effects of magnetic crosstalk.

INTRODUCTION

The upgrade of the Swiss Light Source (SLS) [1] has been completed, and the new multi-bend achromat (MBA) storage ring is currently undergoing commissioning. The design specifications, namely a beam current of 400 mA and a beam lifetime exceeding 8 hours, were achieved within the first three months, corresponding to the accelerator-dedicated commissioning period.

During the design phase, however, significant magnet crosstalk effects were identified: the integrated magnetic fields of individual magnets were influenced by adjacent magnets, leading to variations. Initial estimates indicated that these variations could reach a few percent, which is beyond the correction capability that we can implement. We tackled the problem through finite element method (FEM) simulations and tuning based on the magnetic field measurements.

NEW STORAGE RING LATTICE

The lattice of the new storage ring is based on a 7-bend achromat (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 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. A detailed description of the lattice design is provided in Ref. [2], while the key parameters of the new storage ring are extracted and listed in Table 1.

Table 1: Key Parameters of the New SLS Storage Ring

Parameter	Value
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	>8 hours w/o insertion device

To facilitate mechanical integration, we employed an aggressive magnet design strategy. Bending and focusing within the achromat arc are entirely realized using permanent magnets (PMs), which eliminate the need for space-consuming electromagnet coils. In either design, the distances between adjacent magnets are relatively short and comparable to the bore radius (or gap) of the magnets [3]. Figure 1 illustrates the high density of the magnets and other components assembled on the support girders.

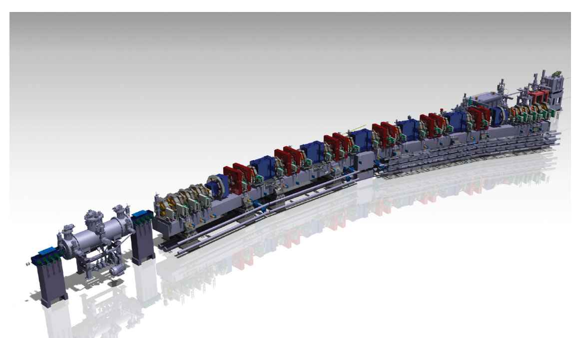

Figure 1: One sector of the storage ring from a three-dimensional virtual model. The number of magnets per sector is more than 100 [1].

FIELD SIMULATIONS

FEM simulation is capable of predicting the magnetic field, but achieving high precision requires a large number of elements in the model. Consequently, we have to limit the number of magnets simulated in a single computation. The arc was therefore divided into short sections that contain only a few magnets each. The entire arc was simulated and optimized piece by piece.

Two particular magnet configurations are highlighted in this paper: one contains a reverse bend with a sextupole

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and orbit correctors, while the other features the PM main bending, which includes a central bending magnet flanked by two combined-function magnets (dipole plus quadrupole). A sextupole at a distance is also included, as its crosstalk effect is minor but not fully negligible. A schematic representation of these configurations is provided in Fig. 2.

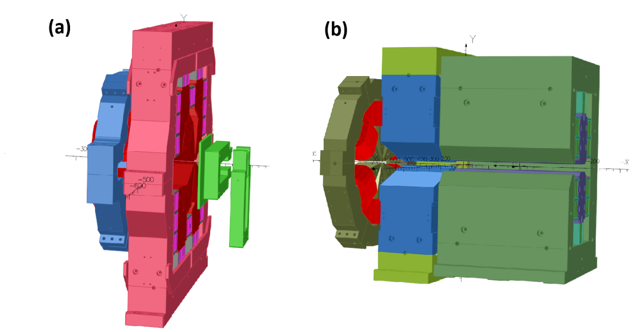

Figure 2: Magnet modeling to investigate crosstalk effects. (a) PM reverse bend (center) with adjacent sextupole (left) and orbit correctors (right). The reverse bend is a quadrupole magnet but shifted horizontally to provide a dipole field. The orbit correctors in the simulation were not excited with current, limiting our scope to static crosstalk effects. (b) 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 middle of the bending, when computing the field.

The FEM simulations for the reverse bend showed that the field variation (attenuation) can be a few percent, see Fig. 3. Therefore, it was crucial to adjust the magnetic field, compensating for the crosstalk effects.

FEM simulations were performed to establish what we refer to as the "reference model". Simulations were iteratively repeated until the design orbit and linear optics were approximately reproduced, following the procedure outlined below.

The obtained three-dimensional field is converted to a sliced element representing the bending and quadrupolar field components along the electron trajectory. Prior to slicing, the trajectory is determined using numerical particle tracking. For these computations, we employed the method described in Ref. [4]. The optical functions are then evaluated, using accelerator code (e.g. MAD-X), by replacing idealized hard-edge elements with the corresponding sliced elements. Magnet parameters are adjusted until the differences in the optical functions before and after replacement become acceptably small. The electron beam trajectory is adjusted simultaneously to match approximately the design closed orbit.

The final result of this iterative process was saved as the reference model. Each short section of the arc was represented by its own reference model. The trajectory deviation within each section was typically less than 5 µm. When the entire arc was modeled using the full series of sliced elements, the beta functions were reproduced to within ±0.4 % in both horizontal and vertical planes throughout the ring. 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.

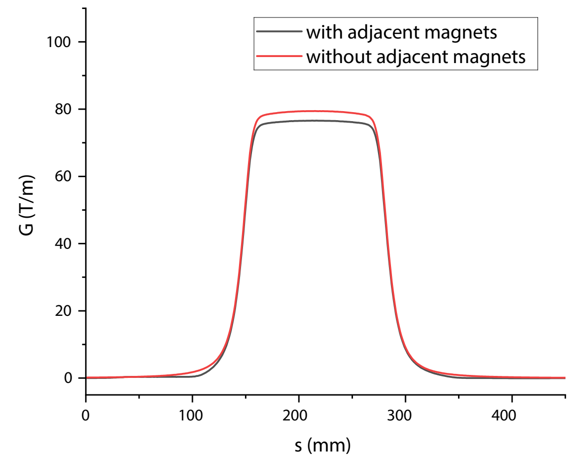

Figure 3: Field gradient of the reverse bend with (black curve) the sextupole and the correctors as in Fig. 2 (a) and without (red curve). In addition to the field attenuation, it is seen that the fringing field is more truncated on the left side by the sextupole. The sextupole is closer to the reverse bend than the corrector is.

FIELD MEASUREMENT AND TUNING

The reference model obtained from the field simulation also serves as a crucial input for field measurements and tuning. For the main bending magnet, referred to as "triplet" hereafter, the crosstalk field variation can reach up to about 10 %: the gradient of the combined function magnet is varied (enhanced) by the central bending magnet. To adjust the field of the triplet, 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. We then measured each of the three magnets in the triplet individually using rotating coils (combined-function magnets) and moving wire (bending magnets) measurement systems and adjusted the field according to the above reference value. Afterward, the three magnets were assembled and measured as an entity. The tuning of the triplet was then completed to meet the given tolerance. To adjust both the dipole and quadrupole components, two tuning knobs were employed. The combined-function magnet was tuned using moderator plates (movable iron plates), which were also used during individual magnet tuning. The second knob functioned as a "virtual" knob, shifting the magnetic axis of the triplet horizontally. The

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first knob acts on both dipole and quadrupole components, while the second primarily affects the dipole component. Following this procedure, 60 triplets were measured and tuned. The tuning applied reached to about 70 units (0.7 %) for the combined-function magnets and an axis shift of up to 200 µrad. This axis shift was recorded and used for the alignment of the triplet later during the installation.

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

The configuration shown in Fig. 2 (a) was also evaluated with magnetic field measurements. A procedure similar to the one used for triplet tuning was adopted.

The reverse bend magnet was first measured and tuned individually. Since the sextupole is an electromagnet, its transfer function (field versus current) was measured separately. The two components together with the orbit correctors were then installed on the measurement bench and measured using a Hall probe. The electromagnet sextupole was excited at the operating current during the measurement. The results showed that the field of the reverse bend was attenuated by approximately 3.2 % when the sextupole and the correctors were present, while the FEM simulation predicted an attenuation of 3.6 %. The discrepancy of about 40 units was within the tuning range of the moderator plates.

Based on the above simulation and measurement campaign, we concluded that the crosstalk effect, i.e., the field variation, was predicted with an accuracy of about 90 %. For instance, the measured field variation was 3.2 % compared to a simulated value of 3.6 % for the configuration of Fig. 2 (a). For the triplet, a tuning of 0.7 % was required for the combined function magnets, which was a residual of the 10 % crosstalk effect predicted by the FEM simulation after the compensation by the individual magnet tuning.

Apart from the magnet measurements and tunings, another simulation study was performed to better understand the discrepancy. It turned out that the material property of the magnet yoke (B-H curve) was slightly different between the ones used in the reference model and the actual magnet. Although the discrepancy was within the magnet tuning range, it could be smaller if the material property used in the reference model was more accurate.

FIRST RESULT WITH BEAM

Meeting the magnetic field and alignment tolerances for the large number of magnets installed in the new storage ring (854 electromagnets and 372 permanent magnets) poses a significant challenge. We have 115 orbit correctors in each transverse plane, as well as 264 quadrupole correctors integrated into the octupole magnets. Due to the highly compact lattice, the strengths of these correctors are inherently limited. The design specifications are 600 µrad and 400 µrad for the horizontal and vertical orbit correctors, respectively. The quadrupole correctors, embedded within the octupoles, are designed to provide an integral gradient of 0.28 T.

During the lattice design phase, magnetic field and alignment tolerances were assessed through numerical particle tracking simulations. When the error sources listed in Table 2 were applied, the resulting orbit correction was close to the maximum capacities of the correctors. The values in the table were therefore used to define the construction tolerances.

Table 2: 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
Misalignment	
Magnet-to-magnet	30 µm rms
Magnet rotation	300 µrad rms
Girder center	60 µm rms
Girder-to-girder	20 µm rms
Field error	
Dipole and quadrupole	0.2 % rms

Commissioning of the new ring began in January 2025, and by April 2025, the design performance was achieved in terms of beam current and beam lifetime. The orbit and linear optics were sufficiently corrected within the limits of the corrector strengths. However, we observed that complete orbit correction could not be achieved at three specific locations. At these points, the horizontal orbit had to be intentionally deviated 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, although it is not expected to impact the forthcoming user operation. The fact that the orbit and optics were corrected within the given corrector strengths, except at the three locations, demonstrates that the magnet modeling, magnetic field tuning based on measurements, and magnet alignment were all carried out appropriately.

CONCLUSION

Our achievement leads to the following conclusions:

- The crosstalk effects in a highly compact lattice can be accurately predicted through FEM simulations.
- Our optics modeling based on the FEM simulations proved to be valid and was crucial so as not to expend the correction capacity unnecessarily.
- Tolerances on the magnetic field, typically in the order of 10 units, can be met for complex magnets such as the triplet, even when considering crosstalk effects.
- Constructing an MBA storage ring using a large number of permanent magnets is challenging but feasible.

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