EVALUATION AND MITIGATION OF MAGNETIC CROSS-TALK IN THE KOREA-4GSR STORAGE RING

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Abstract

Korea-4GSR is a new 4-GeV synchrotron light source under construction since 2021, targeting ultralow emittance performance of 60 pm rad. To reach this regime, the lattice uses a hybrid multi-bend achromat (HMBA) configuration, which increases the number of magnets per cell and raises concerns about magnetic cross-talk. The short magnet spacing may degrade field quality, perturbing particle orbits and enhancing nonlinear effects in beam dynamics. 3D finite-element simulations were performed for all magnet pairs in the ring, and no meaningful cross-talk was identified in most configurations. Magnet pairs involving dipoles, however, can alter the bending strength and thus directly impact the beam trajectory, necessitating focused evaluation. For these dipole pairs, we performed both simulations and magnetic measurements and demonstrated that a field-clamp effectively suppresses the cross-talk. This paper highlights the mitigation capability of the field-clamp approach.

INTRODUCTION

Korea-4GSR is a new 4-th generation storage ring under construction in Ochang, Korea, designed to achieve an ultralow emittance of 60 pm rad via a hybrid multi-bend achromat (HMBA) lattice [1]. To realize this lattice within the available cell length, the HMBA design packs standard multipoles together with combined-function magnets such as dipole-quadrupole to their physical limits [2]. The resulting narrow magnet-to-magnet separation makes magnetic cross-talk one of the principal challenges of the design: it alters the multipole components and the integrated bending strength, consuming the correction margin reserved for manufacturing tolerance and misalignments, and – in dipole-bearing pairs – can directly steer the beam trajectory.

Similar cross-talk issues have been reported across modern low-emittance storage rings, with mitigation strategies ranging from passive shielding (TPS [3]) and software-based current compensation (APS-U [4]) to lattice-integrated correction informed by 3D finite-element (FEM) simulations (ESRF-EBS [5]); PETRA IV [6] and SLS-2.0 [7] have more recently reported nonlinear cross-talk behaviors and tailored compensation schemes. The specific combinations of longitudinal-gradient bending magnet (LGBM) and center bending magnet (CBM) in the Korea-4GSR HMBA cell, however, have not yet been characterized in this context.

In this work, we evaluate cross-talk on multipole components and beam trajectory through 3D FEM simulations of every magnet pair in the storage ring. Most pairs exhibit negligible cross-talk, and the present analysis therefore focuses on dipole-quadrupole combinations, which dominate the effect. We then demonstrate mitigation via field clamps and apply feed-forward pre-tuning to compensate for the combined field deficit that remains after clamp installation.

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EVALUATION

Cross-talk in the Korea-4GSR storage ring was evaluated by 3D FEM simulations in Opera-3D. Because the effect is short-range and geometry-sensitive, the full ring was decomposed into magnet pairs comprising one main magnet and one neighbor with longitudinal separation. This pair-wise approach, adopted in most prior studies [3–7], keeps the simulation tractable while preserving the dominant interactions. Non-dipole pairs were retained only when their longitudinal separation did not exceed 110 mm, beyond which neighbor effects become negligible. Dipole-bearing pairs were evaluated at all longitudinal separations, because even a small decrease in their integrated field directly perturbs the beam trajectory. Each pair was modeled in its actual lattice geometry; whenever a pair contained a dipole, the dipole's bending introduces a small longitudinal angle between two magnets, and this geometry was preserved in the simulation. Each LGBM consists of five modules; only the edge modules facing the neighbor were retained, while the central modules are too far away to contribute to the cross-talk. An initial survey of all such pairs identified no meaningful cross-talk in configurations not involving a dipole; only dipole-bearing pairs are therefore retained for detailed analysis.

Two scope decisions further narrow the analysis. First, dipole-bearing pairs are retained at all longitudinal separations, including those exceeding 110 mm, because even a small reduction in their integrated field directly perturbs the beam trajectory. Second, the leakage of the DQ32 quadrupole field into the neighboring octupole (about 2.0 % of the octupole's design field) is absorbed at the source by adjusting the DQ32 operating current, an approach distinct from the lattice rematching adopted for the same cross-talk channel at ESRF-EBS [5], and is therefore not discussed further here. The five dipole-quadrupole combinations retained for the detailed analysis are listed in Table 1, and a representative pair as modeled in Opera-3D is shown in Fig. 1.

Each pair was simulated in three configurations: both magnets fully powered (*paired*), and each magnet powered in isolation with its neighbor replaced by a non-magnetic block of identical geometry but vacuum permeability (*main isolated* and *neighbor isolated*, respectively). The block removes both the neighbor's yoke material and its excitation,

Table 1: Geometry of the Investigated Dipole-Quadrupole Pairs. Other magnet pairs produced no meaningful cross-talk and are not listed.

Pair	Separation [mm]	Angle [deg]
CBM–Q52	190.8	0.796
LGBM1(M1)–Q12	105.1	0.260
LGBM1(M5)–Q31	101.1	0.184
LGBM2(M1)–Q32	106.1	0.101
LGBM2(M5)–Q51	168.0	0.357

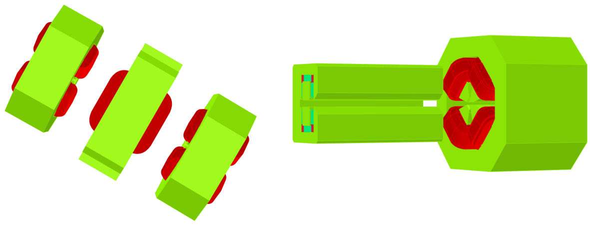

Figure 1: Representative magnet-pair models in Opera-3D: Q52–CBM–Q52 (left) and LGBM2(M5)–Q51 (right). Each quadrupole is rotated by the dipole's bending angle.

so the residual-yoke and current-excitation contributions are reported together as a single cross-talk effect. For each configuration, the integrated multipoles were extracted along the beam trajectory at the reference radius $r_0 = 5\,\text{mm}$.

$$B_{n,\text{main}} = \frac{1}{\pi} \oint \vec{B}(\theta)\Big|_{r=r_0} \cdot \hat{r}\, \sin(n\theta)\, d\theta \tag{1}$$

The cross-talk perturbation of each magnet's n-th harmonic is defined as the difference between its paired field and its corresponding isolated reference,

$$\Delta B_n = B_{n,\text{pair}} - B_{n,\text{isolated}}, \tag{2}$$

where the main isolated configuration is used as the reference for the main magnet and the neighbor isolated configuration for the neighbor.

The integrated dipole-field perturbations $\int \Delta B_1\, dl$ for all dipole-quadrupole pairs are summarized in the "w/o clamp" column of Table 2. The largest perturbation, -9.63×10^{-4} T m (1.06 %) of the integrated dipole field, occurs in the LGBM1(M5)-Q31 pair; the corresponding overlap of fringe fields is visible in the blue trace of Fig. 2. The corresponding quadrupole-field perturbation $\int \Delta B_2\, dl$ reaches at most 0.13 % in the worst case and is not reported here, since it is not directly addressed by the present mitigation.

MITIGATION

The cross-talk identified above is mitigated by a soft-iron field clamp, combined with a feed-forward pre-tuning scheme that compensates the integrated field deficit remaining after clamp installation. Cross-talk in compact lattices originates from the extended fringing fields of adjacent magnets that overlap in the inter-magnet drift [8]. Truncating these extended fringing fields therefore removes the dominant source of cross-talk. A field clamp is a high-permeability soft-iron piece (1010 low-carbon steel in our case) installed between the main magnet and its neighbor, providing a low-reluctance return path that captures the fringe flux and sharply terminates the field at the clamp location – the same principle that underlies the magnetic shielding adopted at TPS [3], and acting symmetrically on both magnets.

Figure 2 compares the dipole field profile before and after clamp installation. Two effects reduce the integrated dipole field after clamp installation: the clamp itself modifies the main magnet's magnetic circuit, and a residual cross-talk that the clamp does not fully suppress. In simulation the two contributions can be separated, but from the magnet's perspective in operation they appear together; the pre-tuning therefore targets the combined deficit. This combined deficit was quantified by 3D FEM and is summarized in Table 2.

Table 2: Integrated Dipole-Field Perturbation Without and With Field Clamp

	$\int \Delta B_1\, dl$ [T m]	
Pair	w/o clamp	w/ clamp
CBM–Q52	-6.65×10^{-4}	-2.50×10^{-5}
LGBM1(M1)–Q12	-9.34×10^{-4}	-3.52×10^{-4}
LGBM1(M5)–Q31	-9.63×10^{-4}	4.69×10^{-6}
LGBM2(M1)–Q32	-1.81×10^{-4}	5.13×10^{-6}
LGBM2(M5)–Q51	-1.61×10^{-4}	5.15×10^{-5}

The combined deficit is pre-compensated by a magnet-by-magnet feed-forward scheme, in line with the bending-angle correction applied to the permanent dipoles at ESRF-EBS prior to installation [5] and the moderator-plate tuning recently demonstrated at SLS-2.0 (0.7 % tuning range) [7]. For the CBM, the deficit is absorbed by adjusting the main excitation current, which preserves the optical correction margin of the lattice. For the LGBM, a permanent-magnet module [9] that cannot be re-tuned in situ, the deficit is pre-compensated mechanically through dedicated tuning bolts before installation. The pre-tuning amount is determined per magnet from its measured combined deficit.

MEASUREMENT

To validate the simulation predictions, two prototype magnets – a CBM and a fully assembled LGBM2 (all five modules) – were measured at the Pohang Accelerator Laboratory magnet test bench, both with and without the field clamp installed. The LGBM1 prototypes await measurement and will be reported in a future study. Photographs of the assembled prototypes are shown in Fig. 3. The mid-plane field of each magnet was mapped by a 2D Hall-probe scan, and the beam trajectory was reconstructed numerically from the measured field map.

For the CBM, the combined deficit after clamp installation was absorbed by adjusting the main excitation current, and the measured trajectory recovered the design apex within

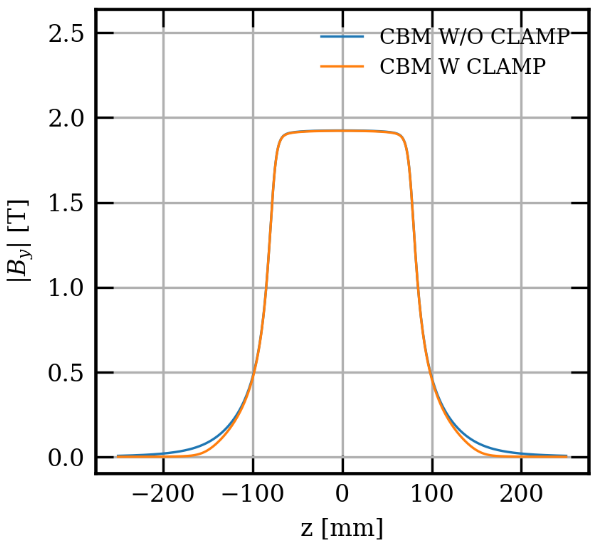

Figure 2: Representative case (Q52–CBM–Q52): dipole field B_1 along the beam trajectory before (blue) and after (orange) field-clamp installation, showing how the clamp truncates the extended fringe field that originally overlaps with the adjacent magnet.

the alignment tolerance; the residual is therefore not tabulated. For the LGBM2, only the clamp-induced reduction is directly measurable on the bench, because the adjacent quadrupole cannot be mounted with the LGBM on the test stand. This reduction was compensated by adjusting the dedicated tuning bolts before installation. The cross-talk-induced reduction, predicted by FEM to be smaller than the clamp-induced part, was not addressed in the present pre-tuning. The resulting LGBM2 residual is summarized in Table 3; the measured integrated field agrees with the 3D FEM prediction within 0.01 %, validating the simulation chain used in the preceding sections.

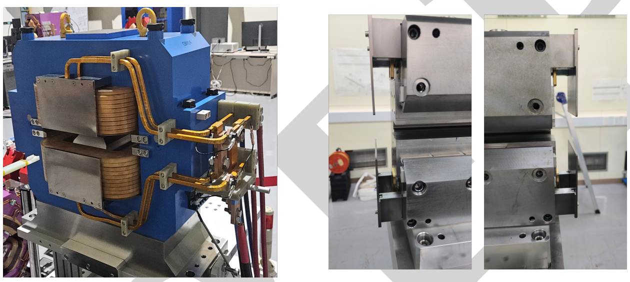

Figure 3: Prototypes on the magnet test bench: the CBM (left) and a close-up of the field clamp installed on the LGBM2 (right). The LGBM2 measurement was performed on the fully assembled five-module unit.

SUMMARY

3D FEM simulations and multipole analyses were performed for all dipole-bearing magnet pairs in the Korea-4GSR storage ring. Without field clamps, cross-talk reduces the integrated dipole field by up to 1.06 %, with the worst case occurring in the LGBM1(M5)-Q31 pair. Field clamps suppress the fringe-field leakage effectively but introduce their own field deficit, which together with the residual cross-talk forms a combined deficit compensated by feed-forward pre-tuning. For the CBM the deficit is absorbed by adjusting the main excitation current. For the LGBM2 the clamp-induced deficit is compensated by the tuning bolts before installation. Cross-talk in Korea-4GSR dipoles is therefore manageable through a combination of field clamps and feed-forward pre-compensation; the LGBM1 measurement campaign is planned as the next step.

Table 3: LGBM2 Residual After Field-Clamp Installation and Pre-Tuning

Quantity	**Value**
$\int \Delta B_y \, dl$	1.25×10^{-4} T m
Apex shift	1.00×10^{-2} mm
$\Delta\theta$	2.90×10^{-3} mrad

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