PROGRESS IN THE PM BASED LGBM MAGNETS FOR K-4GSR

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Abstract

A 4th generation storage ring based light source is being developed in Korea since 2021. It features <60 pm rad intrinsic beam emittance, about 800 m circumference, 4 GeV e-beam energy, full energy booster injection, and more than 40 beamlines which includes more than 24 insertion device (ID) beamlines. To optimize the beam emittances, longitudinal gradient bending magnet is applied in the storage ring design. To minimize the operation costs, and to save the lattice space, Sm_2Co_{17} based Longitudinal Gradient Bending Magnet (LGBM) is being developed following ESRF-EBS, and HEPS. It has 5 steps of field level ranging from 0.73 T ~ 0.15 T with approximately 2 m total length. In this report, the compensation scheme of temperature dependence, and field tuning to meet the bending angle, and apex points will be described.

INTRODUCTION

Third generation storage ring based light sources have been used as a bright light source for many years. Recently multi-bend achromat (MBA) lattice presents a further decrease in the electron beam emittances and becoming a new standard for next generation light source like MAX-IV in Sweden, ESRF-EBS in France, SIRIUS in Brazil. Many other laboratories are also preparing their own version of 4th generation light sources. In this context, Korea is trying to build a 4th generation light source (K-4GSR) based on modified hybrid multi-bend achromat lattice (MHMBA). The Korea fourth-generation storage ring (K-4GSR) adopt H7BA considering better nonlinear beam dynamics compared to the conventional 7BA and lower emittance compared to MH6BA [1–3].

K-4GSR consists of total 28 periodic sectors. As shown in Fig. 1, each sector is equipped with 1 center bending (CB) magnet, 4 longitudinal gradient bending (LGBM) magnets, 2 transverse gradient bending (DQ51) magnets, 6 reverse-bending combined quadruple magnets (RDQ), 12 quadrupole magnets, 6 sextupole magnets (S), 2 octupole magnets, and 4 fast correctors, totaling 37 main electromagnets.

In most types of 4GSR based light sources, longitudinal gradient magnet (LGBM) is routinely used to achieve low bending field in high dispersion area. APS-U [4] tried current excited 5 step longitudinal gradient magnet. ESRF-EBS [5], and HEPS [6] are using permanent magnet (PM) excitation to reduce operating costs. PM excitation has an advantage of compact magnet size, and nearly zero operating energy costs. However, there is a possibility of long term degradation (although small) due to the radiation damage, and lack of tunability. ESRF-EBS and HEPS are adopting Sm_2Co_{17} for their magnet material which shows minimal radiation damage compared to NdFeB based magnet.

K-4GSR LGBM DESIGN

K-4GSR LGBM magnet has also 5 step field profile ranging from 0.15 T to 0.734 T with varying magnetic length. The magnetic geometry is similar to ESRF-EBS and HEPS although the field strength and file profile is different. Sm_2Co_{17} rare earth magnet is adopted for magnetic material for stronger resistance to the radiation damage. Permanent magnet version has additional advantage of small longitudinal space since there is no excitation coil. The field shape has a 5-step profile which is not easy to match precisely. The magnet is designed to have the design value of the 1st integral (bend angle) and the 2nd integral (apex points). The beam dynamics study confirmed that exact profile is not important for beam emitances. It should be also noted that the upstream and downstream version of LGBM has mirror symmetric field profile. The LGBMs are composed of 5 modules depending on the required field level. A central pole is surrounded by PM magnets to produce magnetic field. The field level is adjusted by controlling the number of full size blocks, and quarter sized blocks, with longitudinal spacing. After assembling each module, field uniformity is measured, and temperature compensation experiment is carried out using FeNi plates at two temperatures with Δ T = 3.0 K. The major parameters of the LGBMs are listed in the Table 1.

Table 1: Major Parameters of LGBM1, LGBM2 Magnet

Parameter	**LGBM1**	**LGBM2**
Magnet Type	LGBM1U/D	LGBM2U/D
PM type	Sm_2Co_{17}	-
B_r	1.08 ~ 1.12 T	-
Required Num.	28/28	28/28
B range	0.734 T-0.150 T	0.312 T-0.153 T
Uni. |x| < 10 mm	< 1.0E-3	< 1.0E-3
Min. Pole gap.	24.4 mm	24.4 mm
Total Bend	41.69 mrad	33.56 mrad
Apex point	0.7425 m	0.8500 m
B_1 /L_1	0.7342 T/0.1649 m	0.3121 T/ 0.5397 m
B_2 /L_2	0.4302 T/0.2061 m	0.2396 T/ 0.3076 m
B_3 /L_3	0.2870 T/0.4662 m	0.2026 T/ 0.4869 m
B_4 /L_4	0.1972 T/0.6441 m	0.1732 T/ 0.3586 m
B_5 /L_5	0.1504 T/0.5690 m	0.1535 T/ 0.2912 m
Total Len.	2.0505 m	1.9847 m

NMR Calibration of the Hall Probe

Before any serious measurement, the existing Hall probe system is calibrated using NMR system. Precise fixtures are designed to place the NMR teslameter at the center of each

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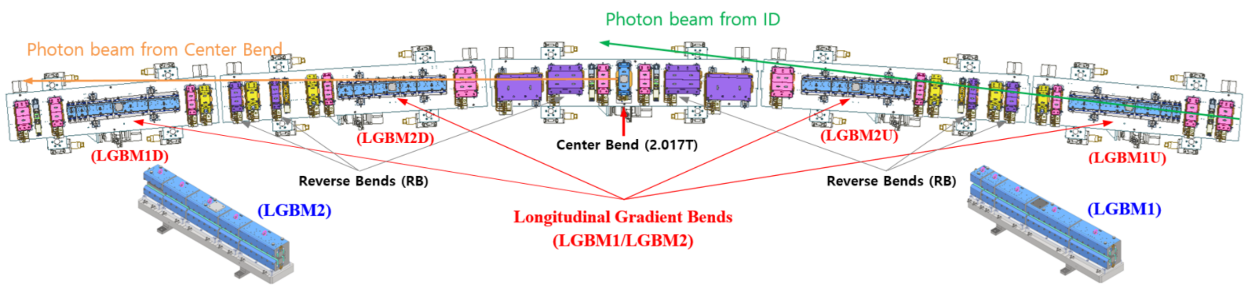

Figure 1: Lattice layout of K-4GSR.

magnet module where the field is most uniform. Hall probe is scanned along the magnet and the magnetic field from Hall system is extracted at the same position. The field from NMR teslameter, and the calculated field from Hall probe system is compared for the center of 5 magnet modules. The ratio between the NMR sensor and Hall probes were nearly same upto < 1.0×10^{-4} for all 5 modules. For calibration, the Hall source current is slightly (< 0.1%) adjusted to match the Hall probe results with NMR results. The procedure is repeated after adjusting the Hall source current, and the ratio of NMR and Hall sensor results were less than 1.0×10^{-4} for all modules confirming that the Hall scan is matching the NMR field values.

Temperature Compensation

The magnetic material for LGBM magnets are Sm_2Co_{17} rare earth magnet. The advantage of the materiel compared to NdFeB type is that it has a strong long term radiation damage, weaker temperature sensitivity (~ -350 ppm/K) and good corrosion resistance. The disadvantages are weaker remanance compared to NdFeB type, brittleness, and higher costs. Due to the concern for long term radiation damage, Sm7Co17 is chosen as a permanent magnetic material. The material has B_r=1.08 T ~1.12 T, H_{cJ} > 25 kOe, and temperature coefficient of Br α< -350 ppm/K. Although the temperature coefficient is weaker than NdFeB type, -350 ppm/K temperature dependence is too steep and should be reduced. To reduce the temperature dependence, FeNi plate is utilized following ESRF and HEPS. A simple 2D simulation is carried out using BH curves of FeNi for 23°C, and 28°C which are supplied by the vendor. The required thickness of the FeNi plate is calculated to be mostly linear with central field with slope of 5.11 mm/T. The supplied shape of the FeNi from the vendor is a plate with 1 mm, and 2 mm. Using this calculation, the required volume of FeNi plate is calculated combining the two thickness and placed on the surface of the PM blocks. After placing the FeNi plate, the central field of the module is measured using NMR probe up to μT precision using fixtures to locate the probe at the center of the module for 23.5°C, and 26.5°C. Figure 2 shows the impact of FeNi plate on the temperature variation. Without FeNi compensation, the temperature dependence was about -400 ppm/K, with addition of FeNi plate, it reduced to -70 ppm/K. The meet the target <-50 ppm/K, additional 10% more FeNi plate is installed and the temperature coefficient is reduced to -36 ppm/K which is within the specification. All 5 modules went through this kind of thermal testing and the temperature coefficient of all modules were tuned to be less than -50 ppm/K.

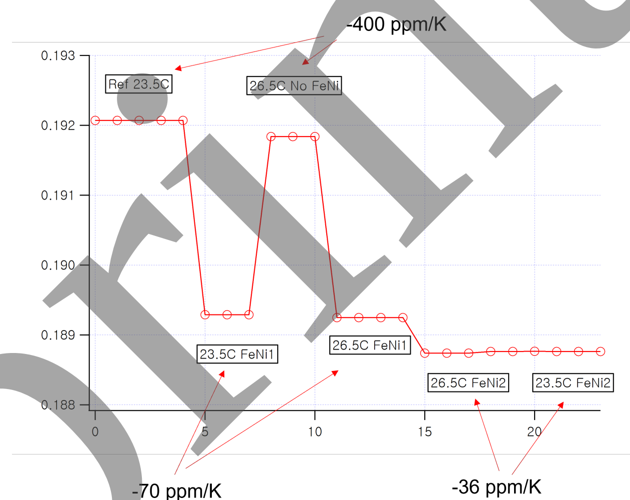

Figure 2: Example of the compensation of temperature effect of FeNi plate of a module.

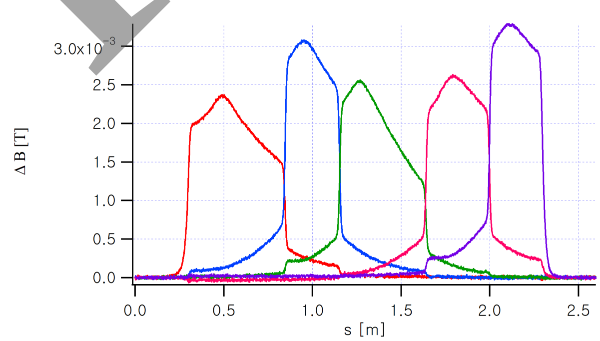

Figure 3: Impact of a bolt tuning signature for each module.

Field Tuning

Since PM version of LGBM has no online tuning capability, the LGBM field should be tuned to match the beam dynamics requirement of 1st field integral, and 2nd field integral precisely. Since 2nd integral depends on the longitudinal extent of the measurement, apex point which is the intersection of the tangent of the transverse orbit in the field free region with longitudinal axis is tuned to the ideal value. The total bending angle at 4 GeV is 33.5637 mrad for LGBM2. When the origin of the longitudinal coordinate is the pole face, and the field profile is from bigger to lower direction, the ideal apex coordinate is 0.8500 m. The field profile is measured using NMR calibrated Hall system, and the orbit is calculated based on the measured field that includes the bend angle, and the apex points.

For field tuning, FeSi plate [5] and tuning bolts [6] are used. FeSi plates are used to shunt fluxes decreasing the field in coarse fashion. Tuning bolts are used to tune the magnet more precisely. The signature of bolt insertion/removal is measured for each module and the result is shown in Fig. 3. Each bolt pair decrease the field integral of the magnet about 1,200 Gcm, which is about 2.5×10^{-3} of the total field integral. For finer tuning, the impact of the bolt screwing is also measured. All the signatures are implemented in a simple program to expect the final results from a specific bolt tuning. The angle error were less than 1.0 10^{-4}, orbit difference from the ideal orbit at the end of the magnet was less than 10 µm. The field profile of the tuned magnet is shown in Fig. 4, and the difference or ideal orbit and real measured orbit is shown in Fig. 5.

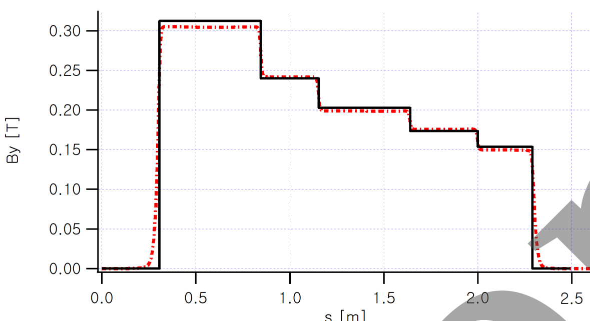

Figure 4: Optimized By field profile compares with the ideal field.

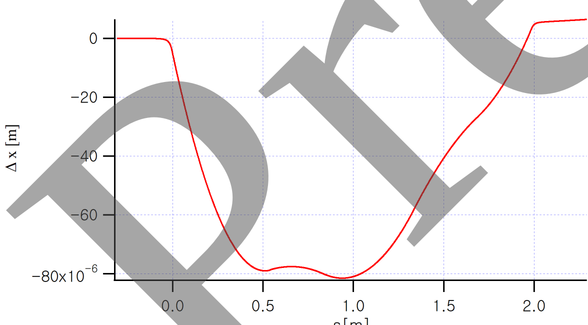

Figure 5: Difference between the ideal orbit and the actual orbit.

SUMMARY

K-4GSR storage ring is using 5 step longitudinal gradient bending magnet to minimize the intrinsic beam emittance. Using Sm_2Co_{17} rare earth magnet, ESRF-EBS type LGBM2 magnet prototype is developed. Each module is tested with NMR teslameter at two temperatures with Δ T= 3.0 K. FeNi plates are installed to tune the temperature dependence less than 50 ppm/K. The magnetic field is fined tuned using NMR calibrated Hall probe scanning system. Field tuning was carried out using FeSi plate for rough fixed adjustments, and using ferromagnetic bolts shunting the pole and return yokes. Signature of installed tuning bolts, and signature for each rotation of the tuning bolts are measured. Field profile is estimated for a set of tuning bolts arrangements, using linear combination of the tuning signatures as a first approximation. This approximation was good enough and a simple optimization program is developed to determine the required tuning bolt configuration. The procedure is applied successfully and the final field profile meeting the beam dynamics requirements could be achieved with 1 or 2 iterations.

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REFERENCES

[1] G. S. Jang, S. Shin, M. Yoon, J. Ko, Y. D. Yoon, J. Lee, B-H. Oh, “Low emittance lattice design for Korea-4GSR”, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 1034, p. 166779, 2022. doi:10.1016/j.nima.2022.166779.

[2] S. Shin, “New era of synchrotron radiation: fourth-generation storage ring”, *AAPPS Bull.*, vol. 31, p. 21, 2021. doi:10.1007/s43673-021-00021-4

[3] S. H. Park, H. Suk, and M. Chung, “Accelerator science in Korea: current challenges and future opportunities” *J. Korean Phys. Soc.*, vol. pp. , 2025. doi:10.1007/s40042-025-01546-9

[4] T. Fornek “Advanced photon source upgrade project, final design report”, Argonne Nat. Lab., Tech. Rep. APSU-2.01-RPT-003, May 2019. doi:10.2172/1543138

[5] C. Benabderrahmane *et al.*, “Magnets for the ESRF-EBS project”, in *Proc. IPAC’16*, Busan, Korea, May 2016, pp. 1096–1099. doi:10.18429/JACoW-IPAC2016-TUPMB001

[6] Q. Li, F. Chen, C. Li, *et al.*, “Design of the longitudinal-gradient dipole magnets for HEPS”, *Radiat. Detect. Technol. Methods*, vol. 5, pp. 1–7, 2021. doi:10.1007/s41605-020-00224-7