HIGH-PRECISION PCB-BASED ROTATING COIL SYSTEM FOR MULTIPOLE MAGNET MEASUREMENTS IN THE 4GSR STORAGE RING

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Abstract

For the reduction of beam emittance in a Korea-4GSR project, the storage ring will be equipped with 344 quadrupole, 168 sextupole, and 56 octupole magnets. These multipole magnets require precise magnetic measurements to verify not only the field strength but also harmonic components within the specified tolerances over a good field region with a diameter of 30 mm. To meet this requirement, a PCB-based rotating coil measurement system has been developed. The PCB consists of a 14-layer multilayer structure incorporating both main and bucking coils, enabling high-precision measurement of allowed and higher-order harmonic components. The PCB length was designed to be 660 mm, considering to the effective magnetic length of the 4GSR multipole magnets. To minimize mechanical sag, the rotating shaft was fabricated from ceramic material and positioned at the magnetic field center using a high-precision XY stage with 0.1 μm resolution. The developed rotating coil system achieves a measurement precision better than 5×10^{-4}, demonstrating its suitability for high-accuracy characterization of small-aperture multipole magnets in the 4GSR project.

INTRODUCTION

The Korea-4GSR (Fourth-Generation Synchrotron Radiation Source) is currently under construction in Ochang, Korea, with facility completion scheduled for 2028, followed by accelerator installation and beam commissioning in 2029, and user operation beginning in 2030. Unlike conventional third-generation synchrotron light sources based on Double-Bend Achromat (DBA) lattices with nanometer-scale emittance, the 4GSR storage ring adopts a Hybrid 7-Bend Achromat (H7BA) lattice based on the Multi-Bend Achromat (MBA) concept. By employing multiple bending magnets with reduced bending angles within a single lattice cell, the MBA lattice achieves ultralow emittance at the picometer scale, enabling significantly enhanced brightness and transverse coherence compared with previous-generation light sources [1].

The MBA lattice substantially increases the magnet density within each cell and consequently amplifies the influence of magnetic field errors on beam dynamics. In addition, the magnet aperture is reduced to approximately 30 mm, resulting in a limited Good Field Region (GFR) and requiring highly precise magnetic field characterization for quality assurance. A total of approximately 420 quadrupole magnets, including 344 storage-ring and 76 booster-ring magnets, are planned for the 4GSR accelerator complex (Fig. 1). Quadrupole magnets play a critical role in beam focusing and in controlling the beta and dispersion functions. Therefore, accurate evaluation of both the integrated gradient and higher-order harmonic components is essential. However, in conventional non-bucking single-coil measurements, the dominant quadrupole fundamental component occupies most of the signal amplitude, limiting the sensitivities of higher-order harmonics [2]. This degrades measurement repeatability and long-term stability and limits the consistency of large-scale magnet quality control.

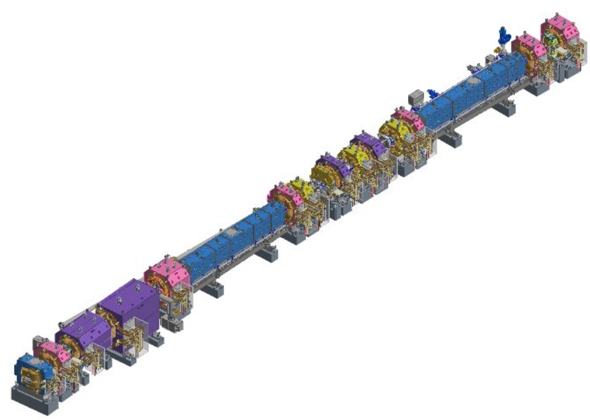

Figure 1: Half-cell layout of the 4th Generation Synchrotron Radiation Accelerator (4GSR) storage ring.

DEVELOPED ROTATING BUCKING COIL SYSTEM

To overcome the limited sensitivity to higher-order harmonics in conventional non-bucking measurements, a PCB-based bucking rotating coil system was developed for high-precision harmonic measurements of small-aperture quadrupole magnets for the Korea-4GSR (Fig. 2). The proposed system employs a multilayer PCB structure to realize a highly reproducible coil geometry and electrically suppresses the dominant quadrupole fundamental component in bucking mode, thereby significantly enhancing sensitivity to higher-order harmonics. The effective coil length was designed to be 660 mm, sufficient to cover the longest quadrupole magnets used in both the storage ring and booster ring. In addition, a high-resolution digital integrator and a precision motion-control system were implemented to achieve a repeatability better than 3×10^{-4} and an absolute accuracy below 5×10^{-4}. Consequently, the developed system provides a standardized measurement infrastructure suitable for full inspection of 4GSR quadrupole magnets.

The developed sensor consists of a 14-layer multilayer PCB structure with 84-turn main coils and 126-turn compensated coils. The coil radii were designed as $r_1 = 12$ mm,

$r_3 = 9$ mm, $r_2 = 8.5$ mm, and $r_4 = 5.5$ mm to suppress dipole and quadrupole components in bucking mode.

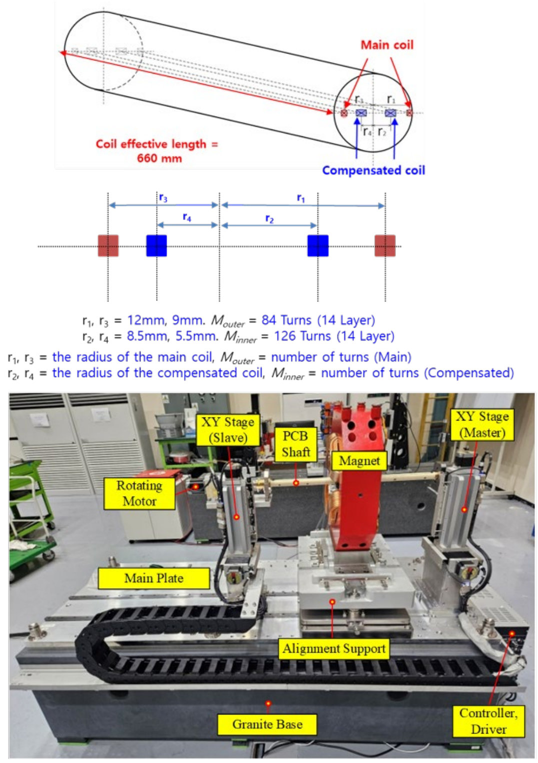

Figure 2: PCB sensor and photo of the rotating coil system.

The PCB thickness was 2 mm with a trace width and spacing of 0.1 mm. To ensure long-term mechanical stability, the rotating coil system was installed on a granite base with a flatness below ± 15 µm. The ceramic rotating shaft was supported by dual XY stages aligned within 4 µm in the X-axis and 10 µm in the Y-axis using CMM measurements. Shaft position and tilt were controlled using Renishaw linear encoders with a resolution of 0.1 µm. Angular synchronization was achieved using a Heidenhain RON275 encoder divided to 10,000 pulses/rev for triggering of the 18-bit digital integrator (FDI2056). The shaft rotation speed was set to 1 rev/s, and the measured angular error was below ±0.0014°. Harmonic analysis was performed using DFT from nine consecutive constant-speed rotations.

The performance of the developed rotating coil system was evaluated using a prototype Q31 quadrupole magnet (Table 1) for the Korea-4GSR storage ring. The Q31 magnet has the shortest effective magnetic length (145 mm) and a relatively low field gradient of 25 T/m among the 4GSR quadrupole magnets. All storage-ring quadrupoles share a common aperture diameter of 30 mm. The PCB sensor was calibrated using an NMR-referenced Hall probe system based on a SENIS I3C-03C10L teslameter and a Metrolab PT2025 NMR teslameter with 5 ppm accuracy. The integrated quadrupole field measured by the Hall probe system was $B_2 = 0.102561895$ Tm. Before geometric offset correction, the rotating coil system measured $B_2 = 0.105269591$ Tm in unbucking mode, corresponding to an error of approximately 2.5%. After applying a 40 µm horizontal center-offset correction to the PCB coil geometry, the discrepancy was reduced to approximately 0.003%.

Table 1: Main parameters of Q31

Parameter	Q31
Aperture diameter [mm]	30
Max. field gradient [T/m]	25
Effective magnetic length [mm]	145
Core length [mm]	134.4
Coil turn number per pole	46
Current [A]	117.7
Current density [A/mm²]	3.7
Voltage [V]	6.46
Resistance [Ohm]	0.0549
Power [W]	761
Inductance [H]	0.026
Mass [kg]	285

EXPERIMENTAL RESULTS

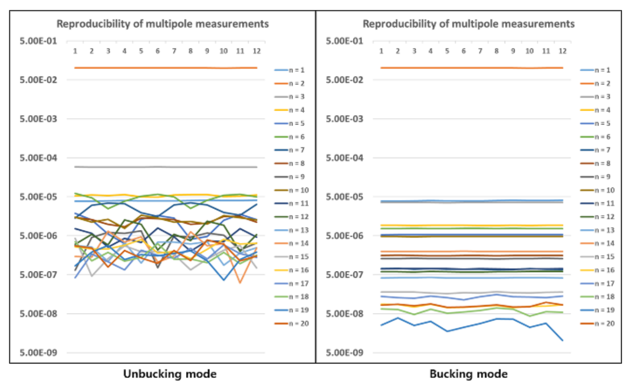

Figure 3: Repeated measurement results of multipole harmonic components in unbucking mode (left) and bucking mode (right).

In unbucking mode, the measured main quadrupole field was $B_2 = 0.10256542$ Tm. The measurement repeatability over 12 consecutive measurements was 6.91×10^{-5}. The normalized sextupole and allowed harmonic components were measured as $B_3/B_2 = 2.28 \times 10^{-3}$ and $B_6/B_2 = 4.55 \times 10^{-4}$, respectively. In bucking mode, the harmonic components were significantly reduced to $B_3/B_2 = 3.33 \times 10^{-4}$ and $B_6/B_2 = 7.46 \times 10^{-5}$ (Fig. 3). The reduction of the main field component in bucking mode improved the higher-order harmonic measurement sensitivity by approximately one order of magnitude. The dominant multipole component was B_3/B_2, which satisfies the 4GSR field quality requirement of less than 1.0×10^{-3}. The measured peak main flux was $\Phi_2 = 2.322 \times 10^{-2}$ Wb in non-bucking mode and $\Phi_2 = 3.06 \times 10^{-5}$ Wb in bucking mode, corresponding to a bucking ratio of 758.

CONCLUSION

In this study, a PCB-based bucking rotating coil system was successfully developed and validated for high-precision harmonic measurements of small-aperture quadrupole magnets for the Korea-4GSR. The developed system achieved stable harmonic measurements with high repeatability and significantly improved sensitivity to higher-order harmonics through electrical suppression of the dominant quadrupole component. Experimental results obtained from the Q31 prototype magnet confirmed that the measured harmonic components satisfy the 4GSR field quality requirements, while the bucking mode improved higher-order harmonic sensitivity by approximately one order of magnitude with a bucking ratio of 758.

These results demonstrate that the developed rotating coil system provides sufficient accuracy, stability, and measurement reproducibility for standardized quality control of the 4GSR quadrupole magnets. Therefore, the system is expected to be effectively applied to full-series measurements and quality assurance of all production quadrupole magnets for the Korea-4GSR project.

REFERENCES

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