

# MEASUREMENTS OF MAGNET PROTOTYPES FOR STORAGE RING OF SIAM PHOTON SOURCE II

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## Abstract

A series of magnet prototypes has been developed for the storage ring of Siam Photon Source II (SPS-II), the second synchrotron light source in Thailand. The prototypes include dipole, combined dipole, quadrupole, sextupole and octupole magnets designed for half of the Double Triple Bend Achromat lattice. To validate the performance of magnet prototype, magnetic field characterization was carried out using stretched wire and Hall probe measurement systems. Following some mechanical improvements, 10 out of 15 magnets met the specified field quality requirements, while possible sources of field errors in the remaining magnets were identified. This work represents a critical milestone toward SPS-II construction, as the storage ring magnets are planned to be manufactured domestically.

## INTRODUCTION

Siam Photon Source II (SPS-II), Thailand's next-generation synchrotron light source, has been designed to support the country's advanced manufacturing industry [1]. As one of the key components of the machine, magnet prototype for the SPS-II storage ring has been developed. A total of 15 magnets, corresponding to half of a Double Triple Bend Achromat (DTBA) lattice cell, were designed and fabricated through a collaboration between the Synchrotron Light Research Institute (SLRI) and a local manufacturer. These magnets comprise two dipole magnets (BM1, BM2), one combined dipole magnet (DQ1), eight quadrupole magnets (QF1, QD2, QD3, QF4, QF5, QD6, QF7, QF9), three sextupole magnets (SD1, SF2, SD3) and one octupole magnet (OF1) [2, 3]. To validate the prototype performance prior to finalizing the design and proceeding to mass production, comprehensive measurements including mechanical, electrical, hydraulic and magnetic field characterization were carried out. This paper presents the results of the magnetic field measurements. In addition, results from other measurements and the potential sources of magnetic field errors are discussed.

## MAGNET REQUIREMENTS

The magnetic field strength and required field quality of magnet prototype for SPS-II storage ring are summarized in Table 1. For the combined dipole magnet (DQ1), the design is based on the offset quadrupole concept as implemented in some facilities [4, 5]. In this approach, the required dipole field of 0.6 T is achieved by transversely

offsetting a quadrupole magnet with a field gradient of 26.4 T/m by 22.5 mm. The quadrupole magnets are divided into two groups with bore radii of 16 mm and 18 mm, corresponding to the Good Field Region (GFR) requirements of 10 mm and 15 mm, respectively. The normalized field errors listed in the table are defined differently depending on the magnet type. For dipole and combined dipole magnets, the values represent the normalized integrated field error evaluated at the mid-plane ( $y = 0$ ). For quadrupole, sextupole and octupole magnets, the values correspond to the normalized integrated multipole components obtained from Fourier analysis.

Table 1: Magnet Requirements for SPS-II Storage Ring

Magnet	Field Strength	GFR (mm)	Normalized Field Error
BM1 BM2	0.87 T	12	$1 \times 10^{-4}$
DQ1	0.6 T 26.4 T/m	8	$5 \times 10^{-3}$
QF1	45 T/m	10	$5 \times 10^{-4}$
QD2 QD3 QD6	51 T/m	10	$5 \times 10^{-4}$
QF4 QF5	44 T/m	15	$5 \times 10^{-4}$
QF7	60 T/m	10	$5 \times 10^{-4}$
QF9	50 T/m	10	$5 \times 10^{-4}$
SD1 SF2 SD3	1,800 T/m <sup>2</sup>	15	$1 \times 10^{-3}$
OF1	72,000 T/m <sup>3</sup>	13	$5 \times 10^{-3}$

## DIPOLE MAGNETS

The magnetic field homogeneity of the dipole magnets and combined dipole magnet was evaluated using a Hall probe measurement technique. The Hall sensor was scanned in the XZ plane along a curved trajectory within the magnet bending angle and along a straight trajectory outside the magnet. The magnetic field was then integrated along these trajectories at various horizontal (X) positions. The resulting normalized integrated field errors for the dipole and combined dipole magnets are presented in Fig. 1 and Fig.2, respectively. Within the GFR, the normalized field error is below  $1 \times 10^{-4}$  in the dipole magnets and below  $5 \times 10^{-3}$  in the combined dipole magnet. These values satisfy the tolerance requirements specified in Table 1. Multipole analysis of the measured fields indicates that the dominant error component in both magnet types is the sextupole term, with the normalized amplitudes of  $7 \times 10^{-5}$  for the dipole magnets and  $2 \times 10^{-3}$  for the combined dipole magnet.

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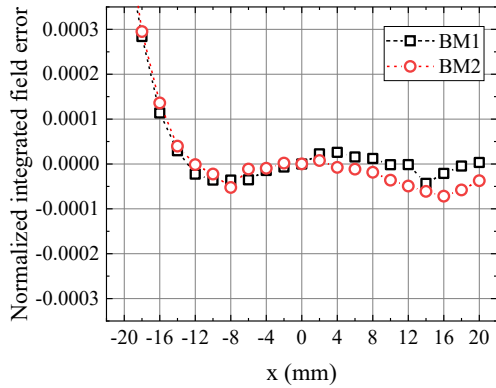


Figure 1: Normalized integrated field error of dipole BM1 and BM2 magnets.

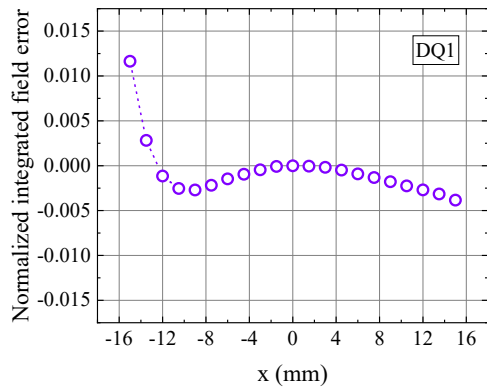


Figure 2: Normalized integrated field error of combined dipole DQ1 magnet.

## QUADRUPOLE MAGNETS

A stretched wire system [6] was employed to measure the magnetic field integrals of the quadrupole, sextupole and octupole magnet prototypes. Results from linear measurements (i.e., integrated field as a function of X or Y) were used to determine the magnetic field center and to analyze the excitation curves of the magnets. In contrast, circular measurements were used to evaluate the integrated multipole field components, with the reference radius defined to match the required GFR of each magnet.

Figure 3 and Fig. 4 present the normalized normal and skew multipole components of the quadrupole magnet prototypes for the SPS-II storage ring. Only higher-order multipole terms ( $n > 2$ ) are shown, as lower-order terms may be influenced by magnet misalignment during field mapping. The repeatability of the field center measurement is better than  $5 \mu\text{m}$  for all quadrupole magnets. For some magnets, the sextupole and octupole components, as well as the skew sextupole component, exceed the specified tolerance of  $5 \times 10^{-4}$ . These components are random multipole errors, primarily attributed to fabrication and assembly imperfections in the magnet yoke, as well as coil excitation errors.

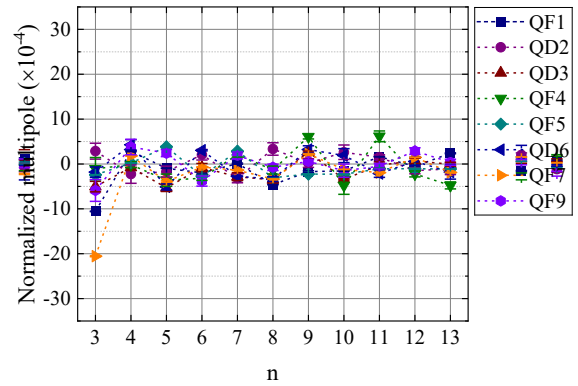


Figure 3: Normalized normal multipole components of quadrupole magnets.

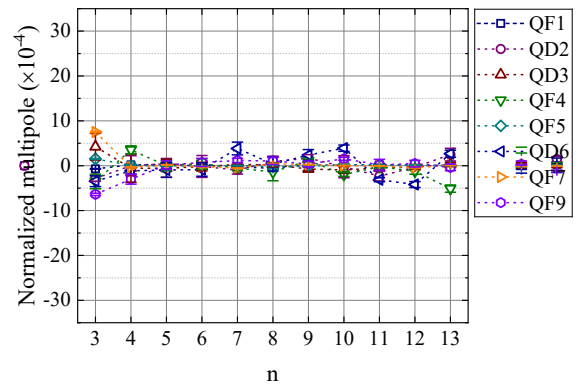


Figure 4: Normalized skew multipole components of quadrupole magnets.

## SEXTUPOLE MAGNETS

The integrated multipole components of the sextupole magnet prototypes are presented in Fig. 5. For SD1 and SF2, the higher-order multipole components ( $n > 3$ ) are within the specified tolerance. In contrast, SD3 exhibits significantly larger normal and skew components for  $n = 4$  and  $n = 5$  (octupole and decapole terms).

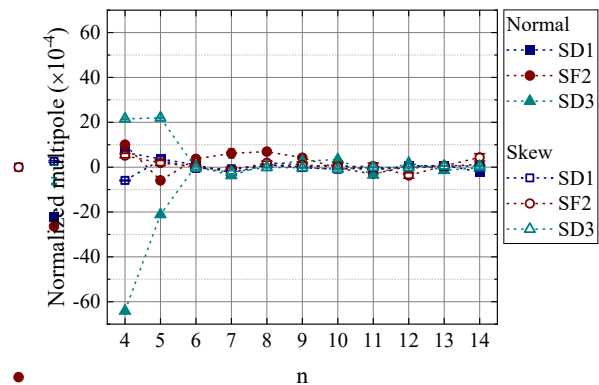


Figure 5: Normalized normal and skew multipole components of sextupole magnets.

The large octupole and decapole terms observed in SD3 are attributed primarily to coil excitation errors. This interpretation is supported by the fact that the assembly errors of SD1 and SD3 are comparable (27  $\mu\text{m}$  for SD1 and 28  $\mu\text{m}$  for SD3), while electrical measurements indicate a substantially larger deviation in coil resistance for SD3 (5.8%) compared to SD1 (2.1%) and SF2 (1.6%). Further investigation of the sextupole magnet coils is therefore required to confirm the origin of the observed multipole errors.

## OCTUPOLE MAGNET

Figure 6 presents the normalized normal and skew multipole components of the octupole magnet prototype measured using the stretched wire technique. The higher-order multipole components ( $n > 4$ ) are all within the specified tolerance of  $5 \times 10^{-3}$ . Due to the relatively flat magnetic field distribution near the magnet center in an octupole magnet, the accuracy of the field center determination is lower than that achieved for the quadrupole and sextupole magnets. Consequently, the repeatability of the field center measurement for the octupole magnet is in the range of 100 – 300  $\mu\text{m}$ .

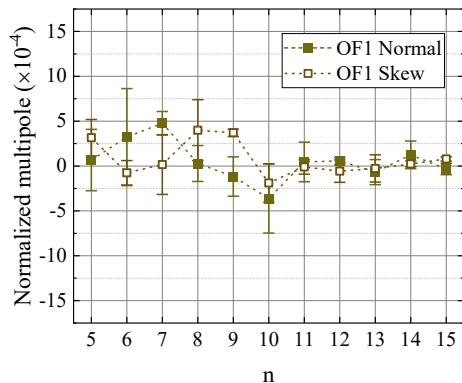


Figure 6: Normalized normal and skew multipole components of octupole magnet.

## ERROR SIMULATION

To investigate potential sources of magnetic field errors observed in the magnet prototypes, several error scenarios were simulated with Opera-3D. The following error scenarios were considered (with further details reported elsewhere):

- Fabrication and assembly errors in a quadrupole magnet (12 cases)
- Excitation errors in a quadrupole magnet (4 cases)
- Excitation errors in a sextupole magnet (4 cases)
- Misalignment errors in quadrupole, sextupole and octupole magnets

The simulations indicate that fabrication and assembly errors associated with a single pole can generate sextupole and skew sextupole components in a quadrupole magnet. For example, a pole rotation of 250  $\mu\text{rad}$  can cause these components to exceed the specified tolerance of  $5 \times 10^{-4}$ . Similarly, an upper yoke rotation of 1,000  $\mu\text{rad}$

(corresponding to approximately 40  $\mu\text{m}$  displacement at the pole) can also induce a significant sextupole term.

Excitation errors were also investigated for both quadrupole and sextupole magnets. Potential sources include variations in the number of coil turns and deficiencies in electrical insulation. The results show that asymmetric excitation errors produce sextupole and skew sextupole components in quadrupole magnets, as well as normal and skew octupole and decapole components in sextupole magnets, while the impact on higher-order terms is negligible. The sensitivity to excitation errors is estimated to be in the range of  $(7-14) \times 10^{-4}$  per 1% error for quadrupole magnets and  $(2-13) \times 10^{-4}$  per 1% error for sextupole magnets. These correspond to deviations of 0.5 and 0.3 coil turns for quadrupole and sextupole magnets, respectively.

Although it is not possible to conclusively attribute the measured multipole errors to a single source, the simulation results provide valuable insight into the dominant error mechanisms and offer guidance for improving the magnet prototype design and manufacturing process.

## CONCLUSION

The measurements of magnet prototypes for SPS-II storage ring demonstrate that, for each magnet type (dipole, combined dipole, quadrupole, sextupole and octupole), at least one magnet satisfies the specified field quality requirements within the GFR. These magnets include BM1, BM2, DQ1, QD2, QD3, QF5, QD6, SD1, SF2 and QF1. For the remaining magnets, where multipole errors exceed the specified tolerances, the observed error components are consistent with those predicted by simulations of fabrication, assembly and coil excitation errors. Overall, the results confirm the feasibility of achieving the required magnetic field quality for SPS-II storage ring magnets and provide valuable guidance for refining the design, fabrication and assembly processes prior to mass production.

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