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DESIGN AND FABRICATION OF A COMBINED FUNCTION MAGNET PROTOTYPE FOR SIAM PHOTON SOURCE*

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Abstract

A prototype of combined function magnet has been developed for a new facility of Siam Photon Source (SPS). The magnet is a combined dipole and quadrupole with the required dipole field and quadrupole gradient of 0.6 T and 30 T/m, respectively. The high field gradient is attained from an offset quadrupole design pioneered by the European Synchrotron Radiation Facility (ESRF). The prototype magnet is fabricated and tested in-house. Magnetic field quality is characterized by the field homogeneity in the central field region and multipole components of the magnetic field. Calculated results show that the gradient deviation and the normalized multipole error are less than 10^{-2} within the good field region of ±8 mm. Preliminary measurements show a good agreement with the calculation, although further measurements are required to verify the results and the multipole error of magnetic field.

INTRODUCTION

Combined function magnets are implemented in many accelerator systems and synchrotron radiation sources where the high-performance and compact machine is required. Magnetic field with different functionalities such as dipole, quadrupole and sextupole are put together either by having multiple coil windings on the same yoke and/or by adjusting the magnet pole profile. For combined dipole-quadrupole (DQ) magnet, tapered dipole design is widely used because of its simplicity and a large good field region (GFR) can be achieved. However, quadrupole gradient of the tapered dipole is not high, generally less than 10 T/m with the exception of DQ magnet designed for Diamond's double-double bend achromat (DDBA) lattice upgrade where the gradient of 14.38 T/m is obtained [1]. High-gradient DQ magnet is successfully designed by the European Synchrotron Radiation Facility (ESRF) based on offset quadrupole concept with single-sided design to reduce power consumption [2]. The quadrupole gradient is 36.8 T/m with the dipole field component of 0.56 T.

In this work, a prototype of DQ magnet is designed based on the offset quadrupole concept similar to ESRF's design. The DQ magnet is planned for a new storage ring of Siam Photon Source (SPS), or so-called SPS-II, with the magnetic fields of 0.6 T and 27 T/m [3]. The prototype was designed when the SPS-II magnet specification was not finalized, hence the estimated gradient of 30 T/m was chosen. The magnet offset is 20 mm, which is a challenge for the magnet design as it is far from the center of the original good field and also constricts the space for beam vacuum chamber.

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MAGNET DESIGN

Specification and Requirement

Specification of the DQ magnet prototype is summarized in Table 1. The dipole field component is 0.6 T and the quadrupole gradient is 30 T/m. The required beam stay-clear (BSC) is ±20 mm and ±4.5 mm in horizontal and vertical directions, respectively. The BSC requirement limits the minimum magnet gap to 14 mm, taking into account the total thickness of 2.5 mm for the chamber wall (made of stainless steel) and the clearance. The required GFR where the gradient error is less than 10^{-2} is ±8 mm. Magnet aperture, or the bore radius, is not a limiting factor.

Table 1: Specification of DQ Magnet Prototype

Parameter	Value	Unit
Dipole field strength	0.6	T
Quadrupole gradient	30	T/m
Horizontal BSC	±20	mm
Vertical BSC	±4.5	mm
Minimum magnet gap	14	mm
GFR where $\Delta G/G < 10^{-2}$	±8	mm

2D Design and Optimization

In order to achieve the quadrupole gradient of 30 T/m, the offset quadrupole design is complemented. One side of the magnet consists of two quadrupole-type poles (main poles), while another side consists of two poles with smaller pole radius and off-center hyperbolic profile (auxiliary poles). Cross-section of the DQ magnet prototype on the x-y plane is illustrated in Fig. 1, which also presents the magnetic field distribution extracted from POISSON simulation [4].

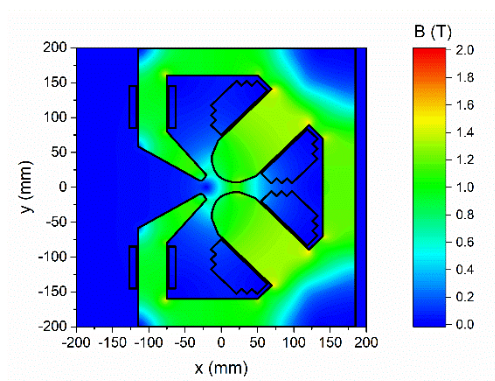

Figure 1: Cross-section and magnetic field distribution of DQ magnet prototype obtained from POISSON.

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Several parameters such as yoke thickness, pole radius, applied current, number of turns for both pole types, quadrupole offset, center of auxiliary poles, vertical gap and shimming geometry were adjusted for the desired magnetic field strength and quality while maintaining the engineering feasibility. The yoke's material is standard S10C low-carbon steel. Magnet coil is water-cooled type made from 7.5 mm × 7.5 mm copper conductor with 4 mm-diameter hole for water cooling. Number of turns is 30 for the main poles and 6 for the auxiliary poles. The coils are connected in series with the operating current of 215 A.

Magnetic field quality of the DQ magnet is determined by the quadrupole gradient (G) error, ΔG/G. The normalized field gradient of the DQ magnet prototype is plotted in Fig. 2 for the applied current up to 250 A. The gradient error at -8 mm < x < 8 mm is within 2×10^{-3} for all applied currents. Pole profile of the magnet was optimized by shimming technique at the operating current of 215 A, therefore ΔG/G is minimized at this current. The multipole components of magnetic field are also obtained from POISSON calculation. The multipole fields normalized to the quadrupole component (result not shown here) are below 3×10^{-4} for the applied current of 215 A.

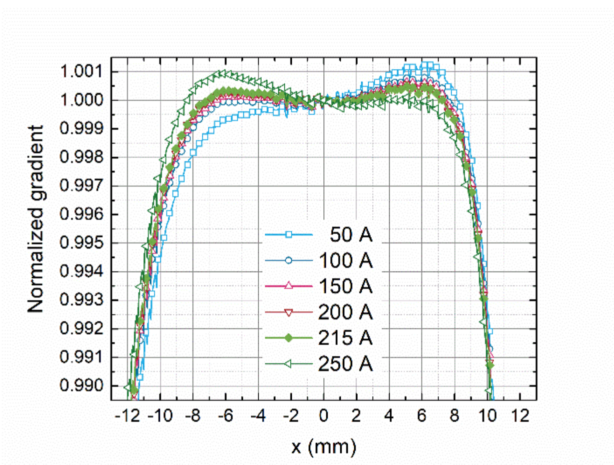

Figure 2: Normalized field gradient of DQ magnet prototype along x coordinate obtained from POISSON.

3D Simulation

A model of the DQ magnet prototype with the optimized 2D pole profile is created in RADIA [5] as shown in Fig. 3 for 3D simulation of magnetic field. Segmentation of the model along the magnet cross-section or the x-y plane is performed as a set of multiple extruded triangles. The main purpose of 3D simulation in this work is to calculate magnetic field along the magnet length. The effective length of the magnet can be calculated from $\int B_y dz/B_0$ where B_0 is the magnetic field at z = 0. The physical length of the DQ magnet prototype is 300 mm, results in the calculated magnet effective length of 333.92 mm.

Furthermore, 3D simulation can be used to cross-check the calculated results from 2D simulation. Detailed simulation in 3D is beyond the scope of this paper and is currently in progress.

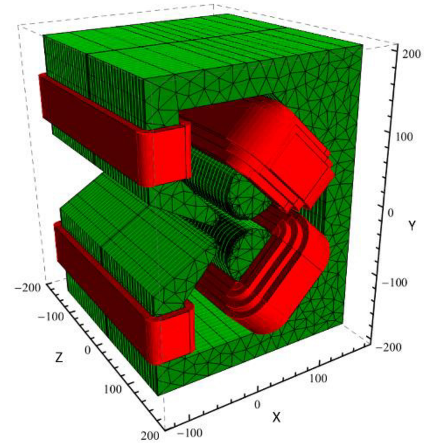

Figure 3: 3D model of DQ magnet prototype for RADIA simulation.

MAGNET FABRICATION

The prototype of DQ magnet was fabricated in-house at the SPS laboratory. The pole and yoke were fabricated from low-carbon steel using Computer Numerical Control (CNC) milling machine and Electrical Discharge Machining (EDM) wire cutting machine. The coils were made from 7.5 mm × 7.5 mm hollow conductor which was insulated with mica tape before winding. The finished wound coils were impregnated in epoxy by vacuum pressure impregnation process. Tedlar® polyvinyl fluoride (PVF) film was used for easy release of the cured epoxy, therefore a precisely-shaped mold is not needed in this case.

PRELIMINARY MEASUREMENTS

Magnetic Field Measurement

Preliminary measurement of magnetic field of the DQ magnet prototype was performed using Hall probe technique. The measured results of vertical magnetic field, in comparison with the calculations, are presented in Fig. 4.

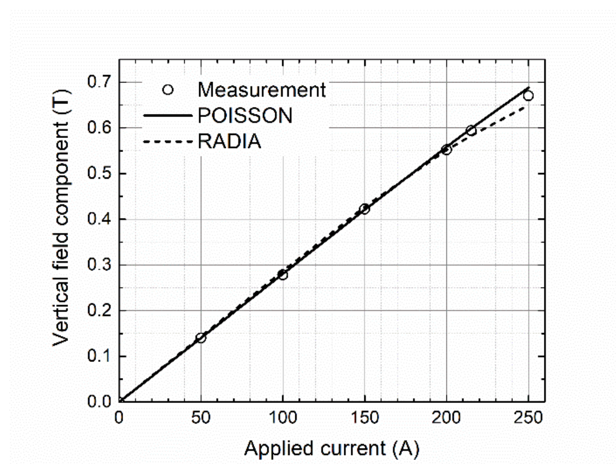

Figure 4: Vertical field component of DQ magnet prototype as a function of applied current from the measurement and calculations.

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The results in Fig. 4 show a good agreement between the measured magnetic field and the calculated magnetic field obtained from POISSON. The errors are less than 1.0%, with the exception of the data for 250 A where the saturation effect occurs. The results from RADIA simulation, on the other hand, show the saturation effect at the lower current. Calculation of magnetic field homogeneity and multipole field components in RADIA also demonstrates a large deviation and large value of the normalized multipoles up to 5×10^{-2}. Although the 3D simulation takes the saturation effect in all dimensions into account and should give an accurate result, subdivision value in RADIA is a crucial parameter determining the accuracy. Detailed investigation will be carried out to clarify this issue.

Figure 5 shows the normalized field gradient of the DQ magnet prototype measured at the applied current of 215 A. The result from POISSON simulation is also plotted for comparison. The measured gradient error within -8 mm < x < 8 mm is less than 1.5×10^{-2} but there is noise presented in the data. Slow measurement with smaller Δx is necessary to verify the result. In addition, measurement of magnetic field along z coordinate was also performed. The calculated magnet effective length from the measurement is 333.15 mm, which is 0.2% lower than the value obtained from RADIA simulation.

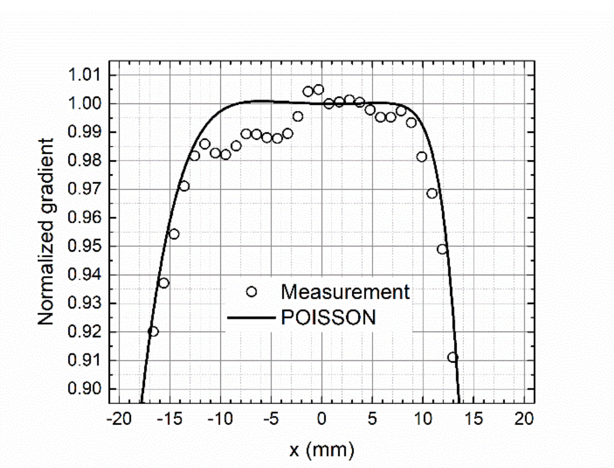

Figure 5: Normalized field gradient of DQ magnet prototype along x coordinate measured at 215 A, in comparison with the result obtained from POISSON.

Water Cooling Test

Electrical and cooling test of the DQ magnet prototype was conducted to determine the applicability of the calculation adapt from Tanabe's method [6]. The coil hydraulic circuit is connected in parallel between the upper coils and the lower coils. The cooling water's temperature is between 24 - 25°C at the inlet of magnet coils with the total water flow of 3 L/min. The operation of cooling unit is trig-gered when the water's temperature is above 25°C. At the applied current of 215 A, the measured water's temperature rise at the outlet is around 6°C, in agreement with the calculated value. Figure 6 shows plots of the inlet and outlet wa-ter's temperatures over the period of 1 hour.

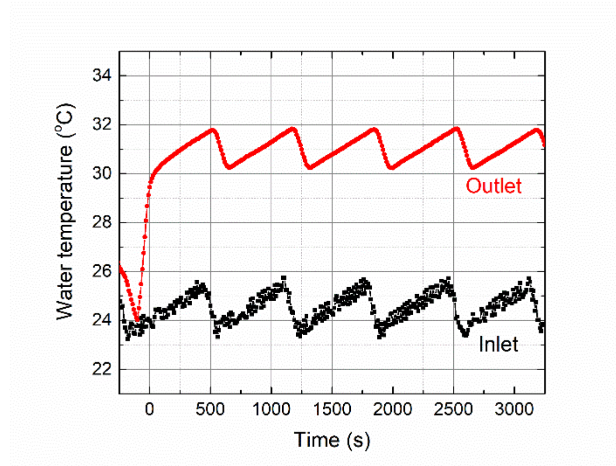

Figure 6: Inlet and outlet water's temperatures at the magnet coils as a function of time when the current of 215A is applied.

CONCLUSION

A prototype of DQ magnet was designed and fabricated in preparation for a new facility of Siam Photon Source. The design process deployed POISSON simulation to determine a suitable pole profile to attain the required magnetic field quality, while RADIA simulation was used to calculate the magnet effective length. The DQ magnet prototype was designed for the dipole filed of 0.6 T, the quadrupole gradient of 30 T/m and the field homogeneity better than 10^{-2}. Calculation and preliminary measurement of magnetic field show some deviation of the results obtained from RADIA due to segmentation level of the model. This issue will be investigated, along with further measurements of the multipole components of magnetic field using rotating coil technique.

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