BNL-226067-2024-JAAM

Field Harmonic Measurement of High-Gradient Permanent Magnet Quadrupoles for NSLS- II Upgrade

A. Banerjee, M. Musardo

To be published in "IEEE Transactions on Applied Superconductivity"

January 2024

Photon Sciences

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC), Basic Energy Sciences (BES)

DISCLAIMER

Field Harmonic Measurement of High-Gradient Permanent Magnet Quadrupoles for NSLS- II Upgrade*

Anushka Banerjee[1], Marco Musardo[2], Oleg Chubar[2], Sushil Sharma[2], Frank DePaola[2], Frank Lincoln[2], Rodger Hubbard[2], Richard Faussete[2], Guimei Wang[2], Chris Hall[3]

[1]Stony Brook University, 100 Nicolls Rd, Stony Brook, NY 11794, USA

[2]Brookhaven National Laboratory, 98 Rochester St, Upton, NY 11973, USA

[3]RadiaSoft LLC, 3380 Mitchell Lane, Boulder, CO 80301, USA

Abstract: NSLS-II is preparing for a major upgrade based on a new lattice concept, known as "Complex Bend," to replace its existing Double Bend Achromat lattice (DBA). This novel lattice will use high-gradient permanent magnet quadrupoles (PMQs) with small apertures in the range of 16-22 mm. A prototype complex bend branch with 8 PMQs has been installed in the NSLS-II linac to evaluate the lattice's performance. An accurate and precise magnetic measurement system is required for field harmonic characterization and magnetic tuning of these PMQs. As part of this project a Rotating-Coil bench, based on a Printed Circuit Board (PCB) coil with a 12 mm diameter, has been configured to measure nine PMQs with bore diameter of 12.7 mm. This PCB coil has an active length of 270 mm and is able to measure field up to 15th harmonic while maintaining quality levels within 10 ppm of the main field at the reference radius of 5 mm. This paper will present the PCB coil setup, the harmonic measurement results and their temperature dependencies and repeatability. Simulation results on compensation of undesired multipoles using "IDBuilder", a genetic algorithm-based optimizer code for magnetic tuning will be included for field harmonic corrections.

*Work supported by DOE under contract DE-SC0012704

Introduction

The National Synchrotron Light Source II (NSLS-II) at the Brookhaven National Laboratory is a well-known high-brightness synchrotron light source facility operating at 3 GeV with a current of 500 mA. The facility is preparing for a future upgrade, with plans to replace its existing double-bend achromat (DBA) lattice with an innovative Complex Bend component [1]. This novel approach aims to incorporate combined-function high-gradient quadrupoles and dipoles to the storage ring design, thereby simultaneously providing bending and focusing within the same physical space [2]. It will be a crucial step towards developing a high-brightness synchrotron light source with a low-emittance ring design [3]. However, as a result of the overlapping arrangement of dipoles and quadrupoles, there is a possibility of

generating additional harmonics. A PCB rotating coil bench has been developed to assess the field quality of permanent magnet quadrupoles (PMQs) that will be used to build a prototype for estimating the effectiveness of the Complex Bend approach [4]. Our intention is to measure and quantify all the existing multipoles. Subsequently, we plan to address and mitigate the undesired multipoles by implementing structural modifications, such as utilizing calculated values from ID Builder to incorporate techniques like ‘magic fingers’. In this paper, we will provide a brief overview of the specifications of the rotating coil system. Furthermore, we will extensively examine the measurements carried out on nine PMQs using this setup. Additionally, we will explore the potential for field harmonic corrections using 'magic fingers' in the following sections.

System Overview

As part of this project, a magnetic measurement bench has been established using a Printed Circuit Board (PCB) coil designed by Fermilab with a diameter of 12mm to measure the Halbach PMQs with a bore diameter of 12.7mm [5]. The PCB coil used in the setup is the smallest coil designed till date with overall probe length of 390mm and an active length of 270mm, specifically engineered to gauge the main field extending to the 15th harmonic, up to a reference radius of 5 mm, with a precision of 10 ppm (parts per million), equivalent to 0.1 "unit". Not only quadrupoles but this PCB coil can also be used to measure sextupole magnets. A Newport controller is employed to control the motion of the linear and rotary stages while a National Instrument (NI) PXI system is utilized for the trigger generation and data acquisition (DAQ). The overall measurement system is developed based on the hardware configuration and LabView software used at the APS-U [6]. Fig. 1 represents the measurement bench setup at BNL for measuring the Halbach PMQs.

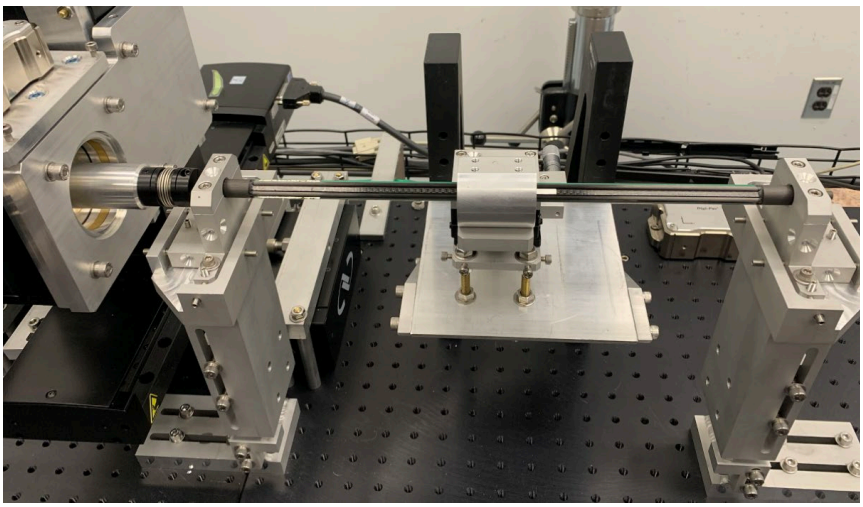


Fig.1: Rotating PCB coil measurement bench

Harmonics

Magnets employed in light sources are typically designed to produce a singular/pure multipolar field. In contrast, combined magnets are specifically engineered to generate multiple field harmonic components concurrently. Therefore, it is imperative to measure all the multipoles that are present and subsequently correct for any undesired multipoles. From Maxwell's equations at constant longitudinal field ($\frac{\partial B_z}{\partial z} = 0$) and considering the function $B_y + iB_x$ is analytic since they satisfy Cauchy-Riemann conditions for an analytic function, we can write:

$$B_y(x,y) + iB_x(x,y) = \sum_{n=0}^{\infty} C_n(x+iy)^n$$

where C_n are the complex coefficients.

In rotary systems for measurement of harmonics, the above equation in terms of z can be expressed as:

$$B_y(x,y) + iB_x(x,y) = \sum_{n=0}^{\infty} C_n(x+iy)^n = \sum_{n=0}^{\infty} C_n e^{-i(n+1)\alpha_n} \left(\frac{z}{R_{ref}}\right)^n$$

where $B_n = C_n \cos\{(n+1)\alpha_n\}$ are the Normal terms and,

$A_n = -C_n \sin\{(n+1)\alpha_n\}$ are the Skew terms.

Here R_{ref} is the reference radius introduced to obtain dimensionless coefficients and the coefficients B_n and A_n represent the normal and skew terms in the power series that describe the absolute strength of the field components at the n-th harmonic. These coefficients are functions of the magnet excitation. To comprehend how the field's shape varies with excitation, the coefficients are normalized using a suitable reference field, denoted as B_{ref}. This normalization aids in understanding the relationship between the field's shape and the level of excitation, and can be represented as:

$$B_z = \sum_{n=0}^{\infty} (b_n + ia_n) \left(\frac{z}{R_{ref}}\right)^n$$

where, $b_n = B_n / B_{ref}$ are the normal multipoles and $a_n = A_n / B_{ref}$ are the skew multipoles [7]. b_n and a_n are scaled by a factor of 10^4 when expressed in units.

Measurements

Measurements were conducted on a batch of nine PMQs obtained from RadiaBeam®. Their design is based on a 16-wedge Halbach configuration, and they measure 46.7 mm in length with the inner and outer radii of the wedges being 6.35 mm and 15.875 mm, respectively. The wedges have been constructed using

Samarium Cobalt (Sm2Co17) Recoma-18 permanent magnet material, with a nominal remanent field of 0.82 T. The nominal integrated gradient the PMQs are measured to be 7.0 T longitudinally with the peak value of the on-axis gradient reaching 149.6 T/m (remains constant inside the magnet). The results of the measurements are summarized in the following tables 1 and 2:

Multipoles->	b'0	b'1	b'2	b'3	b'4	b'5	b'6	b'7	b'8	b'9	b'10	b'11	b'12	b'13	b'14
pmq1	0	10000	35.8	2.7	9.7	-83.8	-8.7	0.8	-1.3	-10.2	1.1	0.7	0.9	2.4	-0.3
pmq2	0	10000	-52.3	-1.5	-7.9	-40.0	20.0	-10.4	-0.6	-1.7	-1.0	2.3	-2.0	0.4	0.6
pmq3	0	10000	27.3	26.6	-40.7	-59.0	7.3	-7.2	-6.9	-4.3	1.6	1.0	-0.2	1.4	0.0
pmq4	0	10000	-40.0	1.9	-2.4	-33.3	-0.5	8.2	3.3	-7.9	-0.9	-1.8	-0.9	0.4	0.4
pmq5	0	10000	-59.5	-23.2	2.7	-71.8	-0.7	-1.5	1.5	-5.1	-2.1	-0.9	-0.5	0.8	0.4
pmq6	0	10000	-8.7	-6.0	-1.3	-65.6	15.6	1.9	-3.7	-15.3	-2.3	1.4	-1.1	1.6	0.6
pmq7	0	10000	31.9	-8.2	-19.0	-14.3	-7.8	-9.6	0.0	-13.3	1.9	-0.5	1.9	-1.6	-0.4
pmq8	0	10000	0.6	-22.4	1.1	-68.8	2.7	-14.5	8.5	-10.7	-2.3	-0.1	-1.7	-0.9	0.4
pmq9	0	10000	64.5	3.4	-22.7	-55.0	-11.5	3.5	-6.9	-9.9	3.6	-0.7	0.0	-0.2	0.1
Std_dev	0.0	0.0	41.0	14.1	14.9	20.5	10.2	7.1	4.6	4.2	2.0	1.2	1.2	1.2	0.4

Table 1: Normalized normal field harmonic components for PMQs 1-9.

Multipoles->	a'0	a'1	a'2	a'3	a'4	a'5	a'6	a'7	a'8	a'9	a'10	a'11	a'12	a'13	a'14
pmq1	0	0	-36.9	23.7	-5.5	-11.8	6.4	2.4	-0.7	2.5	0.9	0.6	0.6	-0.8	0.3
pmq2	0	0	12.5	25.4	15.6	22.9	-5.3	6.8	0.6	0.0	-0.4	-0.9	-2.4	1.1	0.6
pmq3	0	0	-36.9	39.2	-17.5	-11.5	-0.5	-3.8	-1.6	1.1	-1.7	-1.1	-0.7	-0.7	-0.3
pmq4	0	0	-41.1	14.3	19.4	10.8	8.1	-3.1	-1.4	3.8	-2.2	1.0	1.9	0.1	0.4
pmq5	0	0	-20.6	29.8	-31.5	10.0	-15.8	-2.7	0.0	0.8	1.9	-0.6	0.0	-0.1	0.1
pmq6	0	0	17.4	4.8	-41.9	8.7	5.4	8.7	4.8	2.3	-0.8	0.3	0.1	0.8	-0.3
pmq7	0	0	1.8	37.3	-49.6	-5.0	19.5	10.5	6.4	1.0	4.8	2.7	-0.2	0.0	-0.4
pmq8	0	0	-51.4	14.2	-32.7	9.4	-13.2	11.3	2.3	0.8	5.3	-1.4	-2.0	0.6	-0.2
pmq9	0	0	-88.2	33.7	-20.9	-11.4	3.3	6.7	-3.1	-0.4	-3.0	0.0	0.5	-0.6	0.7
Std_dev	0.0	0.0	31.9	11.0	22.7	11.9	10.4	5.7	2.9	1.3	2.8	1.2	1.2	0.6	0.4

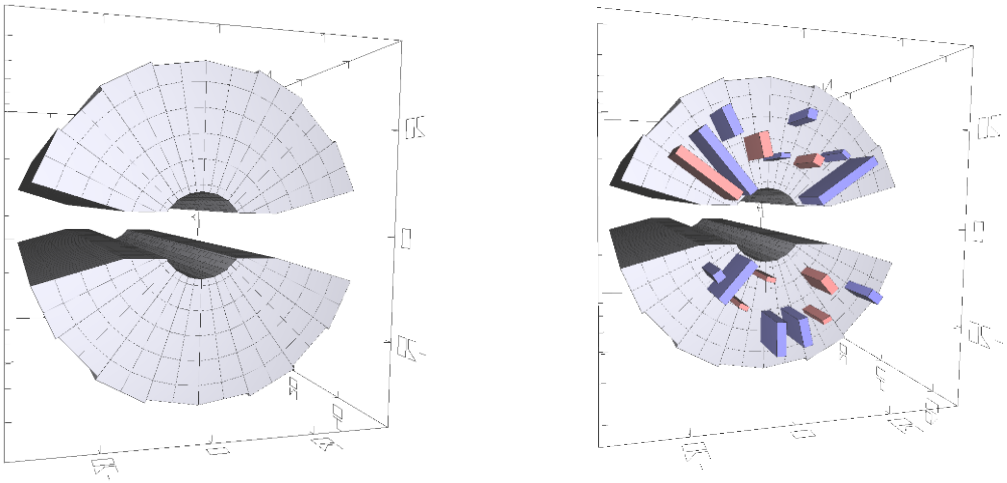
Table 2: Normalized skew field harmonic components for PMQs 1-9.

Here (a'0, b'0) corresponds to dipole, (a'1, b'1) corresponds to quadrupole and so on. Each reading mentioned in tables 1 and 2 have been averaged over at least 10 sets of measurements to avoid any possibility of random error. The maximum deviation for these repeatability tests encountered was within 0.1 units. Temperature values were recorded during and in between the measurements to interpret its effect on the harmonics measured. It was observed that the temperature of the measuring facility during the entire day had an overall increasing trend (2°F increment during the working hours). Temperature in the apparatus rose by about 0.2°F during the measurements (set of 10 consecutive measurements) and registered approximate 0.6°F increment in between subsequent measurements. The maximum deviation in the measurements of the harmonics due to temperature variation was recorded to be ~0.3units/°F. Few of the field harmonics, specifically the normal octupole (increasing) and dodecapole (decreasing) or the skew

sextupole (decreasing) components exhibited specific trends in their behavior depending on temperature variation. We were able to detect these sensitivities owing to the 10 ppm or 0.1 unit precision of the rotating coil.

Discussions

As is evident from the measurement results presented in this paper, it is imperative that the higher order of harmonics resultant of the combined magnetic field generation need to be 'corrected'. The Python version of the Radia code [8], along with optimizations performed through IDBuilder is being used to passively correct the PMQ field using 'Magic Fingers', results summarized in figure 2 and table 3.



(a) (b)

Fig.2: Geometries for linear anisotropic material (~SmCo) based PMQ without any magnetic or geometric errors (a), and after Magic Finger adjustment (b), generated and calculated using Radia.

Multipoles->	b'0	b'1	b'2	b'3	b'4	b'5	b'6	b'7	b'8	b'9
Pure geometry	0	10000	0	-2.3	0	-0.1	0	-4.1	0	-0.3
With Magic Fingers	0.4	10000	-0.2	1.0	-2.3	0	0.5	-3.9	0	-0.3
Multipoles->	a'0	a'1	a'2	a'3	a'4	a'5	a'6	a'7	a'8	a'9
Pure geometry	0	0	0	0	0	0	0	0	0	0
With Magic Fingers	0.2	-0.5	-0.1	0.8	-0.1	0.2	-0.2	-0.2	0	0

Table 3: Field harmonics for PMQ structures with and without Magic Fingers calculated using Radia.

Conclusion

After measuring all the nine PMQs procured from RadiaBeam®, it can be concluded that the new PCB rotating coil test bench has been delivering consistent results so far, the repeatability measures being not greater than 0.1units. Attempts are underway to mitigate/tune the prominent harmonics detected in the measurements in order to meet the specifications of the lattice. The 0.1unit precision of the rotating coil

aided in detecting the temperature dependent deviation of ~0.3units/°F. This deviation is expressed in normalized units and hence will be of higher value when considered in its absolute terms. The temperature influenced fluctuations observed in the harmonic measurements could potentially result from a combination of temperature sensitivities of the rotating coil and the temperature coefficient of Samarium Cobalt. However, the precise origin of these variations remains an unanswered question, awaiting further investigation. Adjustments to improve the temperature stability of the measurement facility are ongoing. New batches of Halbach type PMQs are to be measured in the upcoming months. Efforts are ongoing to achieve precise agreement between the measured and simulated results.

References

[1] V. V. Smaluk and T. V. Shaftan, “Realizing Low-Emittance Lattice Solutions with Complex Bends”, in Proc. IPAC'19, Melbourne, Australia, May 2019, pp. 1906-1908. doi:10.18429/JACoW-IPAC2019-TUPRB105

[2] T. Shaftan et al., “The Concept of Complex Bend”, BNL Tech. Note BNL-211211-2019-TECH.

[3] G. Wang et al., “Complex Bend: Strong-focusing magnet for low emittance synchrotrons”, Phys. Rev. Accel. Beams, vol. 21, p. 100703, 2018.

[4] S. K. Sharma et al., “High Gradient Quadrupoles for Low Emittance Synchrotrons”, in Proc. IPAC’19, Melbourne, Australia, May 2019, pp. 4332-4334. doi:10.18429/JACoWIPAC2019-THPTS094

[5] M. Musardo et al., “A New PCB Rotating Coil at NSLS-II” United States: N. p., 2022. Web. doi:10.18429/JACoW-NAPAC2022-WEPA77.

[6] S. J. Izzo et al., “Magnet Measurement Systems for the Advanced Photon Source Upgrade”, in Proc. MEDSI’20, Chicago, IL, USA, Jul. 2021, p. 269. doi:10.18429/JACoWMEDSI2020-WEPB03

[7] https://indico.cern.ch/event/411995/attachments/840286/1168841/2DFields_2.pdf

[8] A. Banerjee et al. "Parallelization of Radia magnetostatics code." *Journal of Physics: Conference Series*. Vol. 2420. No. 1. IOP Publishing, 2023.