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A NEW PCB ROTATING COIL AT NSLS-II*

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Abstract

Several R&D projects are underway at NSLS-II towards an upgrade of its storage ring with a new lattice that will use high field magnets with small bores of 16-22 mm. A large fraction of the high field magnets is expected to be of permanent magnet technology that will require precise magnetic measurements and field harmonics corrections. A new magnetic measurement bench has been built based on a printed circuit board (PCB) coil of 12 mm diameter and 270 mm active length. This PCB coil has the capability of measuring field quality to a level of 10 ppm of the main field up to the 15th harmonic with a sensitivity between 0.01 m^2 and 0.02 m^2 at the reference radius of 5 mm. This paper will describe the main features of the rotating coil bench and discuss the measurement results of a permanent-magnet Halbach quadrupole of 12.7 mm bore diameter.

INTRODUCTION

The National Synchrotron Light Source II (NSLS-II) is a 3 GeV, 500 mA, high-brightness synchrotron light source facility at the Brookhaven National Laboratory. A double-bend achromat (DBA) lattice was used for the storage ring.

A new lattice design based on a Complex Bend concept has been proposed for the future NSLS-II upgrade [1-2]. This new novel lattice consists of combined-function high-gradient quadrupoles to provide bending and focusing in the same physical space. This approach promises a reduction of the horizontal electron beam emittance and, consequently, a significant increase of the spectral brightness [3]. In order to demonstrate the Complex Bend approach, a prototype will be built by using high-gradient permanent magnet quadrupoles (PMQs) [4-6]. The PCB rotating coil system has been built to verify the field quality of these PMQs.

PCB ROTATING COIL

A 12-mm diameter PCB-based rotating coil was designed at Fermilab with specifications of measuring 10 ppm of the main field (0.1 “unit”) up to the 15th harmonic at the reference radius of 5 mm. It is the smallest PCB coil built to date with an active coil length of 270 mm and an overall probe length of 390 mm, capable to measure both quadrupole and sextupole magnets. The main parameters are shown in Table 1. The PCB rotating coil measurement bench, shown in the Fig. 1, uses essentially the same hardware and software for the motion control as the rotating wire system [7].

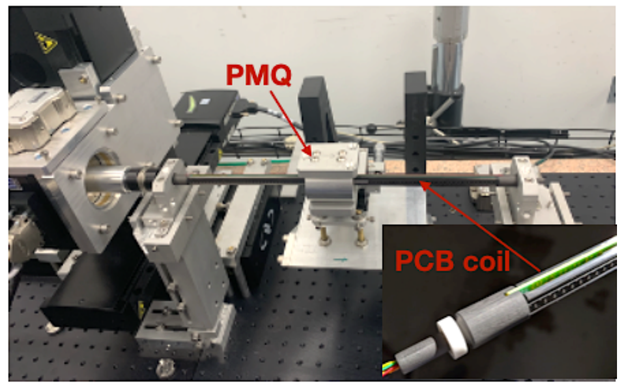

Figure 1: PCB rotating coil measurement bench.

This new bench has interchangeable supports to perform both rotating coil measurements, for field harmonics characterization, and rotating wire to determine the magnetic field center of the magnet with an RMS error less than 5 µm. This measurement system is based on the hardware design and LabView software developed for APS-U [8]. As shown in Fig. 1 the rotary stage is mounted on XYZ linear stages which permits the probe to be positioned within the aperture of the magnet under test. Three PCB coils were built. Each coil is encased in carbon-fiber supports to ensure sufficient stiffness against vibration and sag. The outer diameter of the PCB coil-structure is 12 mm. The ends have 6-mm outer/ 3-mm inner diameters to accommodate the 1.8 mm thick printed circuit board, wiring and ABEC 5 all-ceramic bearings.

Table 1: PCB Coil Parameters

Probe Diameter	12 mm
Reference Radius	5 mm
Probe Active Length	270 mm
Length of each end stem	25 mm
Total Probe Length	350 mm
Bucking	DB, DQB, DQSB

These PCB coils provide 4 signals: un-bucked (UB), dipole bucked (DB), dipole-quadrupole bucked (DQB) and dipole-quadrupole-sextupole bucked (DQSB) in order to ensure minimal spurious harmonics in measurements of both quadrupole and sextupole magnets. The quadrupole gradient measured with DB winding has an accuracy at the level of 0.1%-0.2%.

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PCB Rotating Coil Design

The PCB coil is designed with a high density of turns and multiple layers with 75 µm wide traces and with 75 µm space between them. The trace pattern and the entire printed circuit board are shown in Fig. 2. The layers are very thin (~100 µm) and the connection 'vias' between the layers are 350 µm in diameter.

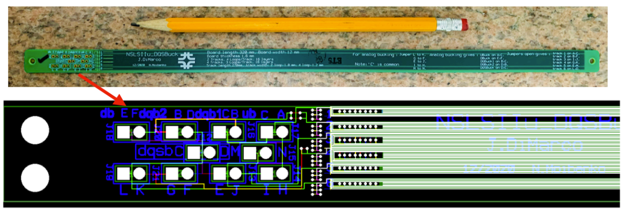

Figure 2: Printed circuit board structure with 16 layers with 75 µm wide trace/space.

For location and dimension control of the traces, a Laser Direct Imaging (LDI) process has been used, which is a precise means of fabrication that avoids physical contact effects, diffraction, temperature and humidity distortions, dimensional changes, etc. Therefore, the PCB coil has traces with micron level control of both size and position. The wires placement accuracy is typically less than 2 µm. As shown in Fig. 3, the circuit board has a total of six tracks and 16 layers. Tracks 1, 2, 5 and 6 have 48 turns and the tracks 3 and 4 have 64 turns. Combining tracks 5 and 2 creates a signal in which the dipole is bucked (DB signal). To create a signal in which both dipole and quadrupole are bucked (DQB signal), a combination of the tracks 1, 3 and 5 are used. Furthermore, a signal which has dipole, quadrupole, and sextupole bucking (DQSB signal) is created combining all the tracks. In addition to the bucked signals, one un-bucked signal (outermost track) is also available on the probe. Using the bucked and un-bucked signals, a high-accuracy calibration technique has been applied to determine, at the level of microns, the radial and vertical offset of the PCB coil placement in the carbon-fiber structure relative to its rotation axis [9].

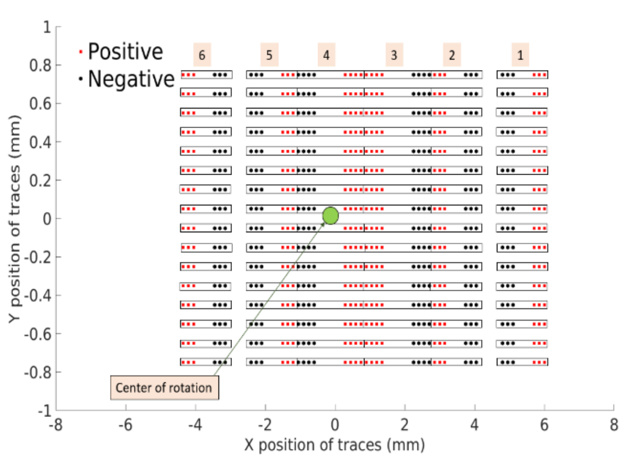

Figure 3: PCB design cross-section showing positive (red dots) and negative (black dots) wires of the 6 windings and the rotation center.

PCB Coil Acquisition System

A National Instrument (NI) PXI system is employed for trigger generation and data acquisition (DAQ) and a Newport controller is used for the linear and rotary stages motion. The full control of the measuring bench, such as homing, multi-axis positioning and movement, as well as data acquisition and signal processing are driven by an APS custom-made LabView Virtual Instrument.

The voltage induced, as the coil rotates about the longitudinal magnet axis, is picked up by a Mercotac six conductor slip-ring and sent to the PXIe-4464 Dynamic Signal Analyzer module, which is set to 200 kS/s and acquires 10 revolutions of rotating coil signal. Changes in flux as the probe rotates at 1 rev/s are measured at the angular intervals of 0.36 degrees. The rotary data acquisition is trigged by a signal from the FPGA module after an index pulse from the rotary stage is detected. The FPGA code counts the level-shifted and squared sin/cos rotary encoder signals generated by a comparator circuit and fed into the NI SCB- 68A terminal box. The rotary stage has 60k encoder counts per revolution and the time is captured for each 1/1000th of a revolution.

HARMONIC MEASUREMENTS

According to Faraday's law of induction, the change of the magnetic flux in time induces a measurable voltage signal. The magnetic flux linked by the coil as a function of the rotation angle θ can be expressed by:

$$\phi(\theta) = \Re \sum_{n=1}^{\infty} C_n K_n e^{(in\theta)}, \quad (1)$$

where $\Re$ indicates the real part of the complex quantity, and:

$$C_n = B_n + iA_n \quad (2)$$

defines the field. B_n and A_n are the $2n$-pole normal and skew harmonic field coefficients at the reference radius R. The winding sensitivity is represented by K_n defined as the sum over all wires of the probe:

$$K_n = \sum_{j=1}^{N_{\text{wires}}} \frac{L_j R}{n} \left(\frac{(x_j + iy_j)}{R} \right)^n (-1)^j. \quad (3)$$

Here L is the length of a given wire and $(-1)^j$ gives the sign of the current flow of each wire and the (x_j, y_j) are the locations of the wires with respect to the rotation axis. The sensitivity factors K_n characterize the coil geometry and yield a measure for the capability to acquire a certain multipole of n-th order [10]. The harmonic fields can then be determined by obtaining the complex Fourier coefficients F_n from an FFT of the measured $\phi(\theta)$ data and then dividing by the complex sensitivities:

$$C_n = \frac{F_n}{K_n}. \quad (4)$$

These coefficients are usually normalized with respect to the main field component and expressed in units of 10^{-4} of Tesla at a given reference radius.

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TESTS WITH A HALBACH PMQ

A set of nine nominally identical PMQs of 46.7-mm length were procured from RadiaBeam® for testing the Complex Bend concept [6]. The PMQ design is based on 16 wedge Halbach configuration assembled in an aluminum keeper with a detachable baseplate as shown in Fig. 4 (left). The PM wedges are made from Samarium Cobalt (Sm_2Co_{17}) Recoma-18 permanent magnet material with a nominal remanent field of 0.82 T. The inner and outer radii of the wedges are 6.35 mm and 15.875 mm, respectively. The cross-section of the PMQ with the magnetization directions of the PM wedges are shown in the Fig. 4 (right) below. The nominal integrated gradient is 7.0 T and along the longitudinal direction the gradient on-axis reaches the peak value of 149.6 T/m and remains constant inside the magnet.

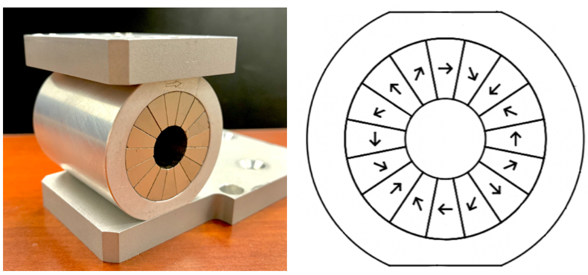


Figure 4: The Permanent Magnet Quadrupole and the PM wedges with their magnetization directions.

One of these nine PMQs was used at Fermilab as a reference magnet for measurement tests and calibration of the three PCB probes. The same PMQ has been also used for commissioning of the PCB rotating coil system at NSLS-II. Figure 5 shows the normal (b_n) and skew (a_n) harmonic measurements in units at the reference radius of 5 mm along with the difference (*delta*) between the harmonics measured at Fermilab and NSLS-II.

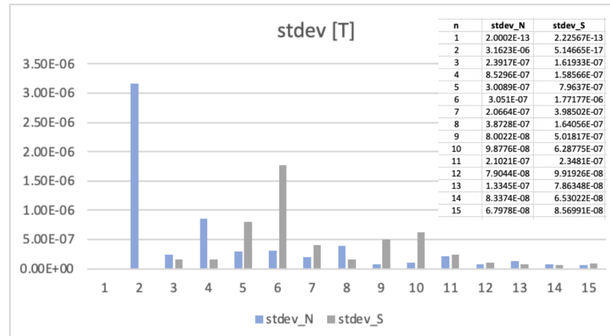
SKEW Terms	a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12	a13	a14	a15
	0.0	0.0	-88.2	33.7	-20.9	-11.4	3.3	6.7	-3.1	-0.4	-3.0	0.0	0.5	-0.6	0.7
NORMAL Terms	b1	b2	b3	b4	b5	b6	b7	b8	b9	b10	b11	b12	b13	b14	b15
	0.0	10000.0	64.5	3.4	-22.7	-55.0	-11.5	3.5	-6.9	-9.9	3.6	-0.7	0.0	-0.2	0.1

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Delta an	0.2	0.0	2.1	2.1	6.3	2.9	1.3	1.1	2.6	1.0	0.2	0.3	0.3	0.2	0.2
Delta_bn	0.0	0.0	3.0	3.0	4.9	3.1	0.2	0.7	1.5	1.0	0.4	0.3	0.3	0.2	0.2

Figure 5: PMQ skew and normal harmonic measurements up to the 15th harmonic and comparison between Fermilab and NSLS-II data.

Discrepancies of several units are observed between Fermilab and NSLS-II harmonics values. These are probably in part due to a lack of temperature stability, presently ~ ±2° C, in the NSLS-II measurement lab. Work is in progress to improve the temperature stability to ± 0.1° C.

Several measurements have been performed to determine the reproducibility of the data. The standard deviation of a set of harmonic measurements reaches values below the 10-ppm requirement up to 15th harmonic as shown in Fig. 6.



n	stdev_N	stdev_S
1	2.0002E-13	2.22567E-13
2	3.1623E-06	5.14665E-17
3	2.3917E-07	1.61933E-07
4	8.5296E-07	1.58566E-07
5	3.0089E-07	7.9637E-07
6	3.051E-07	1.77177E-06
7	2.0664E-07	3.98502E-07
8	3.8728E-07	1.64056E-07
9	8.0022E-08	5.01817E-07
10	9.8776E-08	6.28775E-07
11	2.1021E-07	2.3481E-07
12	7.9044E-08	9.91926E-08
13	1.3345E-07	7.86348E-08
14	8.3374E-08	6.53022E-08
15	6.7978E-08	8.56991E-08

Figure 6: Standard deviation of a set of PCB rotating coil harmonic measurements.

CONCLUSION

A new 12-mm diameter PCB rotating coil bench has been built at NSLS-II for magnetic measurements of high-strength PMQs. The commissioning of the PCB rotating coil has been successfully completed achieving the 10-ppm field quality requirement. Additional tests are planned after improving the temperature stability of the measurement lab.

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