PRECISE ROTATING COIL SYSTEM FOR CHARACTERIZING THE TPS MAGNETS

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Abstract

Many multipole magnets will be fabricated for storage-ring magnets, booster-ring magnets and transfer-line magnets of the Taiwan Photon Source (TPS). For this purpose several precise rotating-coil systems (RCS) for high-speed measurements have been developed to characterize the magnetic field of quadrupole (QM) and sextupole (SM) magnets. Printed-circuit coils comprising normal coils and bucking coils are adopted to measure the absolute and relative values of multipole components, respectively. A comparison between bucking coils and normal coils, and a method of continuous winding for a bucking coil, are presented. A precision testing bench was adopted to test the performance of this system. We describe the design and fabrication of the measurement system, and discuss its precision and accuracy.

INTRODUCTION

The Taiwan Photon Source (TPS) is a third-generation radiation light source. Forty-eight dipoles (DM), 240 quadrupoles (QM) and 168 sextupoles (SM) will be constructed in the storage ring. To control accurately the trajectory of the electron beam, a high-quality lattice magnetic field is required. Many precision field measurement methods have therefore been developed in the laboratory including a Hall-measurement system, a rotating-coil system (RCS) and a stretch-wire system. In particular, RCS is a highly precise, easily implemented and quick measurement method. The two kinds of coil are normal coil and bucking coil (or compensating coil), which are designed to measure the absolute and relative multipole components of the magnet, respectively. The normal coil has a single loop with many turns to improve the multipole signal, whereas the bucking coil has two loops of coils in series to decrease the main harmonic and to strengthen the higher harmonic multipoles. The bucking coil is generally wound with Litz wire and with welding of each strand, but multiple welding points cause difficulty of fabrication, and the measurement signal is readily subject to drift [1]. We developed a continuous-winding method for the bucking-coil. An artifical defect was made to test the properties of the normal and bucking coils.

EXPERIMENTAL SETUP

Figures 1 (a) depicts schematically the normal coil, and figure 1 (b) the bucking coil. The wires of the printed-circuit coil are 0.3 mm wide and the distance between them is 0.3 mm. These wires are printed on a printed-circuit board (PCB) of thickness 1 mm. The total width of the coils, including the coil with three turns (inset in Fig. 1 (a)), is 1.5 mm, and the interval space between wires is 0.3 mm. The measured radius of the normal coil is 33 mm on a PCB of width 70 mm. We adopted normal coils to measure the absolute value of the magnet, and verified the results with Hall measurements [2]. The space resolution of the normal coil was better than 10 µm according to our measurements. To amplify the higher-order multipoles, we developed a precise bucking coil. We adopted a bucking coil with 150 turns and another with 300 turns to cancel the main harmonic contribution while retaining the higher-order multipoles. The coils with the 150 turns and 300 turns are continuously wound with enamel-insulated wires of diameter 0.05 mm. The coil with 150 turns (300 turns) is placed in a groove of width 1 mm (1.4 mm) and depth 1.5 mm (1.7 mm) on a PCB 2 mm thick. The PCB has four contacts, contacts A and B for the coil with 150 turns and C and D for the coil with 300 turns. Contacts B and C were connected with an extension wire from the PCB base. These coils were assembled in the measurement unit. A test quadrupole magnet (QM) of the Taiwan Light Source (TLS) was used to test these coils on the RCS bench [3].

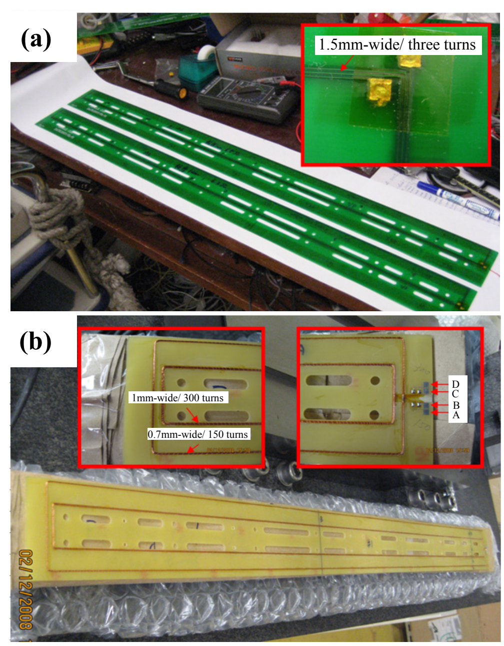

Figure 1: (a) and (b) are photographs of the normal and bucking coils, respectively. The normal coil has three turns and a width 0.3 mm per coil. The bucking coils have 150 and 300 turns with diameter 0.05 mm per coil.

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EXPERIMENTAL RESULTS

Figures 2 (a) and (b) present the measured spectra of the normal and bucking coils, respectively. These spectra were acquired at 23±0.5°. The former spectrum was obtained with a coil of three turns and integrator gain 500. The normal spectra were sinusoidal with an interval 90° between maxima in Fig. 2 (a). The sinusoidal spectra with four half-periods in 360° are consistent with the main contribution from the quadrupole component. The amplitude of the signal of the quadrupole component is strong and covers the higher-order multipoles. Therefore, a bucking coil was designed to detect the higher-order multipoles. The spectra of the bucking coil were obtained from the difference signal between the coils with 150 and 300 turns, with integrator gain 1000, as presented in Fig. 2 (b). The spectra are asymmetric, but the period of the maxima is 90°. This result indicates that the main contribution to the bucking-coil signal is the quadrupole term, but is less then the contribution from the normal coil. The asymmetric signal arises from the higher-order multipoles of the test-QM and/or systematic errors.

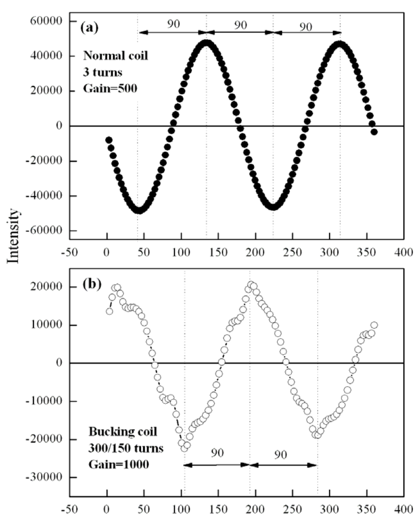

Figure 2: (a) and (b) show measured spectra of the normal and bucking coils.

Figure 3 presents the reproducibility (Δ, max - min / average) and the signal magnification (M) of the normal and bucking coils. After reinstallation of the measurement unit, the reproducibilities of the normal and bucking coils were denoted ΔN and ΔB, respectively. Measurements 1 – 5 are for the normal coil and 6 – 10 for the bucking coil. These spectra were analyzed with the Fast Fourier Transform (FFT) method, and each component was normalized to 30 mm. The *C1*(n) is the relative multipole components at n^{th} harmonic. The reproducibility of the field measured by the normal (bucking) coil, including *C1(0)*, *C1(1)*, *C1(2)*, *C1(3)*, *C1(5)*, *C1(9)*, *C1(13)* and *C1(17)* are 0.00409 (0.02260), 0.00006 (0.00028), 0.04320 (0.00189), 0.26070 (0.00780), 0.44730 (0.01870), 0.02421 (0.00048), 0.12974 (0.0007) and 0.91393 (0.00180), respectively. These values show that the structure of the RSC is rigid and has satisfactory reproducibility when the measurement unit was reinstalled. The *C1(0)* and *C1(1)* components of the bucking coil were less than the normal coil by factors of 0.077 and 0.367, respectively. The magnifications of the signal by the bucking coil were greater than those of the normal coil by factors of 51, 16, 232, 46, 50 and 61 in *C1(2)*, *C1(3)*, *C1(5)*, *C1(9)*, *C1(13)* and *C1(17)*, respectively.

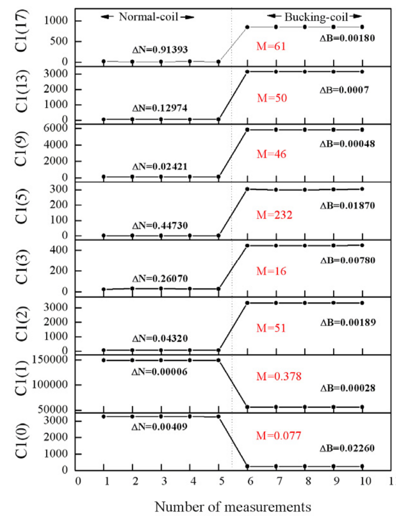

Figure 3: Systematic reproducibility (Δ) and signal magnification (M) of the normal and bucking coils when the coil was reinstalled.

Figure 4 shows the systematic error test of the normal and bucking coils. The lines through the solid and open circles are the spectra of the normal and bucking coils, respectively, when the test QM is shifted along the z-axis. The z-axis is the direction defined by the electron beam. The multipole field variations of the field measured by normal and bucking coils are plotted in solid and open circles line when the QM shifts from -100 mm to 100 mm, respectively. The bucking-coil spectra are strongly related to the test-QM position, because the higher-order multipoles were amplified in the bucking coil; the mounting position of the test QM along the z-axis is important in the measurements of the bucking coil.

To understand the sensitivity of the bucking coil, we glued an artificial defect with a volume 1 mm^3 to the surface of the iron-pole tip on the test QM. The total surface of the test-QM pole tip is about 48000 mm^3. A local defect with 0.0021 % error was simulated in the integrated field of the test QM. Figures 5 and 6 present the defect test spectra of allowed and forbidden terms, respectively. In the analysis, the allowed multipole terms of the quadrupole ($n=1$) are $n=5$, 9, 13 and 17. Figure 5 shows that the defects had no effect on the normal coil, as revealed by the lines through the solid circles, but the defects clearly had an effect in the bucking coil, and especially at *C1(5)* and *C1(17)*, as revealed by the lines through the open circles. Figure 6 demonstrates the effect of the defects on the forbidden term. The spectra of the normal coil exhibit no effect of the defect, but the bucking coil clearly detects the effects of the defects on the magnet. In the bucking spectra, the signal intensity of the allowed terms exceeds that of the forbidden terms. The tiny signal of the defect is thus negligible in the spectra of the allowed terms, but this tiny signal was enhanced by the bucking coil especially for the higher-order multipoles. In this way the bucking coil readily senses the defects in the magnetic pole tip.

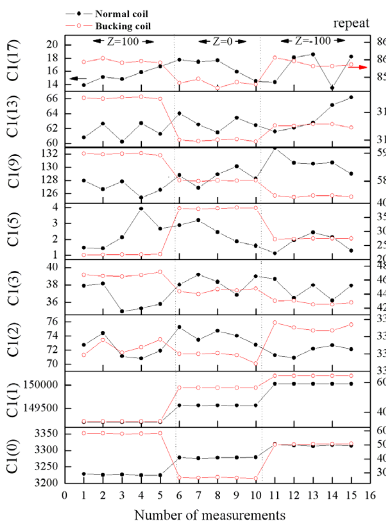

Figure 4: Systematic error test of the normal and bucking coils. The errors for the normal and bucking coils are plotted with lines through the solid (black) and open (red) circles, respectively.

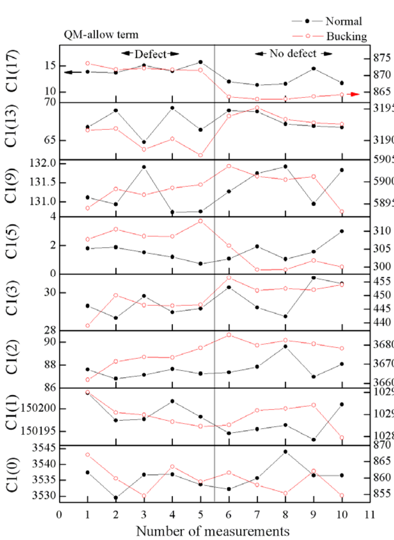

Figure 5: Artificial defect test spectra of the allowed term measured with the normal (black) and bucking (red) coils.

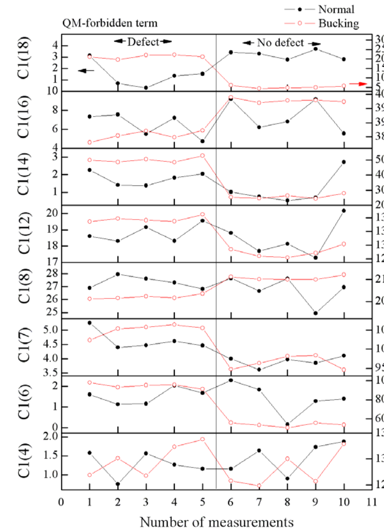

Figure 6: Defect test spectra of the forbidden term measured with the normal (black) and bucking (red) coils.

SUMMARY

A bucking coil was wound by the continuous-winding method and tested with a test QM. The measurement spectra of the bucking coil are asymmetric with four maxima in a period. This result indicates that the main contribution to the bucking-coil signal is the quadrupole term, but smaller contribution from the normal coil. The bucking coil enhances the higher harmonic multipoles signal more than the normal coil by a factor in a range 16 – 232. An artificial defect test demonstrated that the bucking coil is sensitive to tiny defects on the magnet pole tip, especially for the higher-order forbidden terms.

REFERENCES

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