ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRO094

MAGNETIC FIELD EVALUATION OF MULTIPOLE PERMANENT MAGNETS BY HARMONIC COIL WITH NOVEL CALIBRATION TECHNIQUE

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Abstract

We developed multipole permanent magnets that had a variable main magnetic harmonics. In order to evaluate the variation, we also developed a harmonic coil with tangential single-turn coil. Although one of the systematic errors of the harmonic coil is uncertainty of the position of coil wire because a harmonic coil is usually used by multi-turn coil, the systematic error was reduced by using single-turn coil. We calibrated the wire's position by using a pair of attracting pieces of 10 mm square NdFeB magnets, so that the influence of the position was calculated. Then we evaluated magnetic field of multipole permanent magnets, so that we discuss about performance of the magnets.

INTRODUCTION

Multipole magnetic fields are played an important role for a beam control. For focusing a charged particle beam, quadrupole magnets are used by Lorentz force. While for focusing a neutron beam, sextupole magnets are used by interaction between sextupole magnetic field and magnetic dipole moment of neutrons.

We have developed focusing magnets made with permanent magnets (PM). One is modulating permanent magnet sextupole (mod-PMSx)[1]. Another is 5-ring permanent magnet quadrupole(PMQ)[2]. They had a variable main magnetic harmonics. Permanent magnets compared by electric magnets and superconducting magnets have following advantages:

- <u>no electronic supply for generating magnetic field.</u>
- <u>no cooling system (like a cryostat) for generating strong magnetic field.</u>
- <u>a compact focusing system fabricated.</u>

For Measurement of multipole magnetic field, we also developed a harmonic coil with tangential single-turn coil. A systematic error caused by uncertainty of opening angle of a coil is usually reduced by using fine coil wire and measured the angler position. Then the coil was made with flexible print circuit. By using single-turn coil, however, low signal amplitude of the induced voltage is measured, so that pre-amplitude and data acquisition system was attached near the coil on the rotating part to reduce thermal noise in the signal.

We calibrated the position of the coil wire by new method using a pinpoint magnet, which comprised of a pair of attracting pieces of 10 mm square Neodymium magnets (pinpoint magnet)[3]. Then the multipole PMs were evaluated the variation of the main magnetic harmonics by the harmonic coil.

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HARMONIC COIL

Systematic Error of Harmonic Coil

Let us use coordinate system where beam direction is parallel to z axis as Fig. 1 [3]. A radial component of magnetic flux density B on a surface of the rod with radius R, is expressed by

$$B_r(\theta,z)=\sum_{n=1}^{\infty} b_n(z)R^{n-1}\sin(n\theta+\alpha_n) \qquad (1)$$

where n is a harmonics number, θ is a coil angle, α_n is phase angle of n-th component, $b_n=\int_{z1}^{z2} b_n(z)dz$ called BL is an integrated component of n along the axis, and $\Delta\theta=\theta_2-\theta_1$ is the opening angle of a coil .

The magnetic field harmonics b_n are also expressed by ,

$$b_n=\frac{F_n}{\kappa_n}\ ,\ \kappa_n=\frac{2R^n\sin\left(n\frac{\Delta\theta}{2}\right)\sin\left(n\omega\frac{\Delta t}{2}\right)}{n}, \qquad (2)$$

where κ_n is a constant coefficient for each n which depends on the magnification of circuit and coil form factor. F_n is a Fourier component of signal from harmonic coil. Eqs. (2) show systematic error is influenced by $\Delta\theta$, R and ω.

Calibration of the Position of Coil Wire

A pair of tangential single-turn coils whose longitudinal length is 30 cm has been printed on a FPC (flexible printed circuits). The FPC was glued on the rod. The coils were placed with an angle of 180 degrees apart. Three

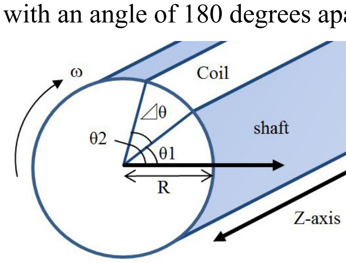

Figure 1: The coordinate system of a coil rod.

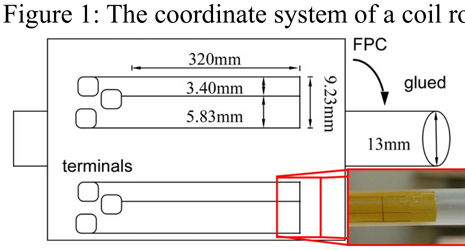

Figure 2: Two one turn coils on a flexible printed circuit (FPC) is glued on the rod. The coil has three terminals.

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opening angles, $\pi/12$, $\pi/7$, $(1/12+1/7)\pi$, are available from the combinations of three terminals in the system as shown in Fig. 2

The coil wire position on the rod has to be known for precise measurement. The single-turn coil has an advantage for giving a definite value, while that of a multi-turn coil is an averaged value. We use a novel method to measure the local coil wire coordinates by using a pinpoint magnet. As shown in Fig. 3(a), a local magnetic field can be generated by setting a pinpoint magnet nearby the rod. By measuring such pinpoint magnetic field, one can know the local coil position against the magnet position.

Magnetic field calculation Fig. 3 (b) shows calculated magnetic flux around the rod by PANDIRA. X axis denotes the distance between the pinpoint magnet and the rod surface, while Y axis denotes the height of the pinpoint magnet from the center of the rod. Z axis is along a longitudinal direction of the rod. Fig. 3(c) shows radial magnetic field strength B_r on the surface of the rod. A precise measurement of the coil wire position should be possible from the correlation between the ratio of two peak values B_r+/B_r- and the zero-crossing point.

Evaluation of the coil wire position The measurement procedure for the coil wire position we applied is following:

1. At z=0, adjust magnet position in y direction after scan of the magnet stage to find a y origin so that the ratio Br+/Br- becomes unity.
2. At x=y=0, z scanning : at each z, evaluate θ and $\Delta\theta$.

Fig. 4 shows the measured data with two pairs of bipolar peaks corresponding to two wire positions going (Coil 1-1, Coil 2-1) and returning (Coil 1-2, Coil 2-2) wires of a coil. The data was an average of signals from 8 turn sampling. The statistical error of each azimuthal point was less than 1 %.

The origin of x was a start point on z scanning from z=0 cm to z=27 cm with a three-axis translation stage, where the rough initial distance x was about 0.2 mm. The opening angle of the coil pattern in this measurement was maximum $\Delta\theta$ for a less interference between the signals from going and returning wire. Fig. 5(a) shows the recovered FPC Sheet of coil 1 from the measured values of θ. The deviations of the angular position of the coil wires were within ±50 mrad for coil 1 and ±100 mrad for

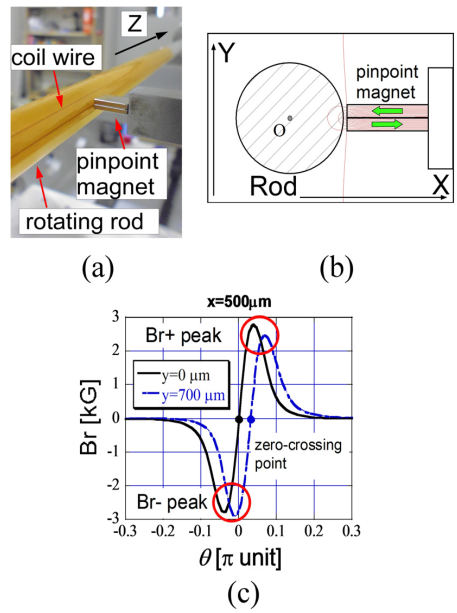

Figure 3: (a)Set up the pinpoint magnet. (b) Calculation of magnetic field generated by a pinpoint magnet. (c) Plot of B_r on the rod surface compared different y (y=0,700μm).

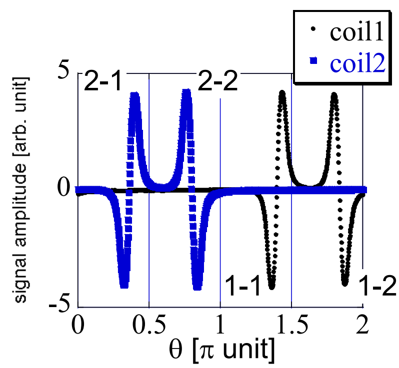

Figure 4: Plot of signals by a measurement of the pinpoint magnet at y=0.

coil 2. The measured opening angle $\Delta\theta$ shown by Fig. 5(b) was less about 0.04 rad, which corresponds to the wire lifting of about 0.3 mm. Although these deviations may be reduced with a better gluing process, the current set of the system seems to have enough accuracy.

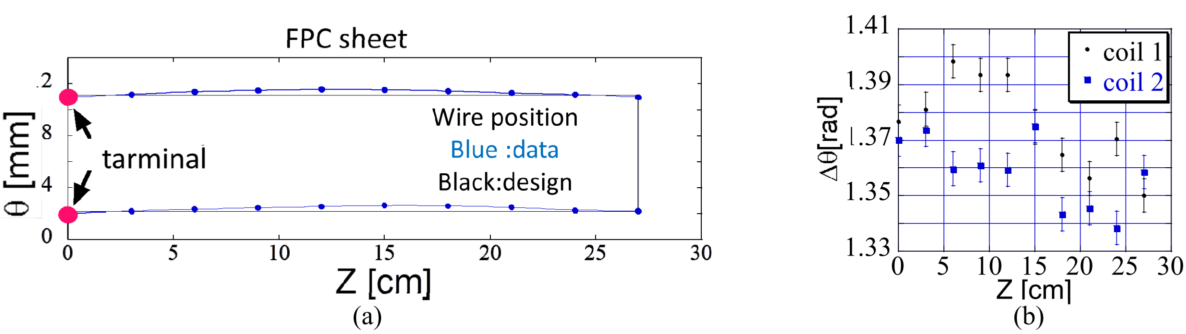

Figure 5: (a) Recovered FPC Sheet of coil 1 from the measured values of θ. (b)The measured opening angle $\Delta\theta$.

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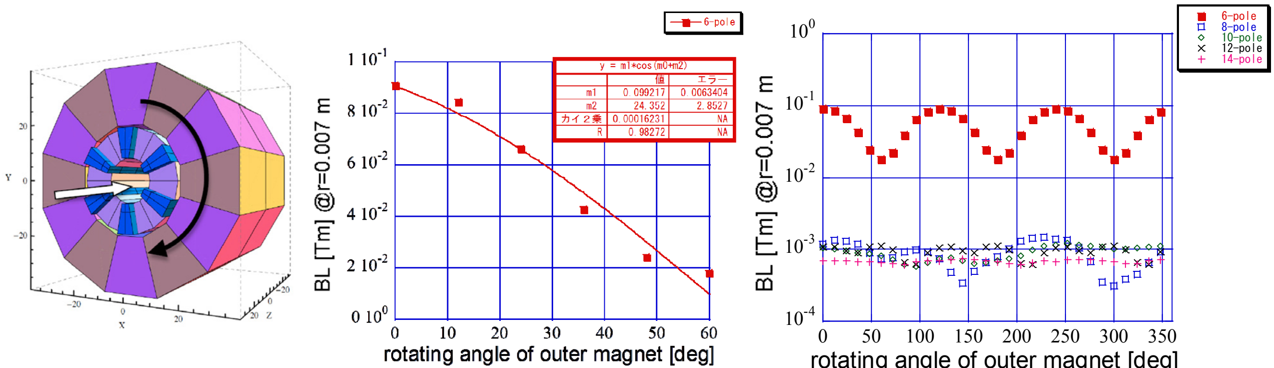

Figure 6: (a) Mod-PMSx consisted of inner and outer sextupole. (b) The variation of main harmonics by rotating outer magnet. (c)Main harmonics compared with higher harmonics.

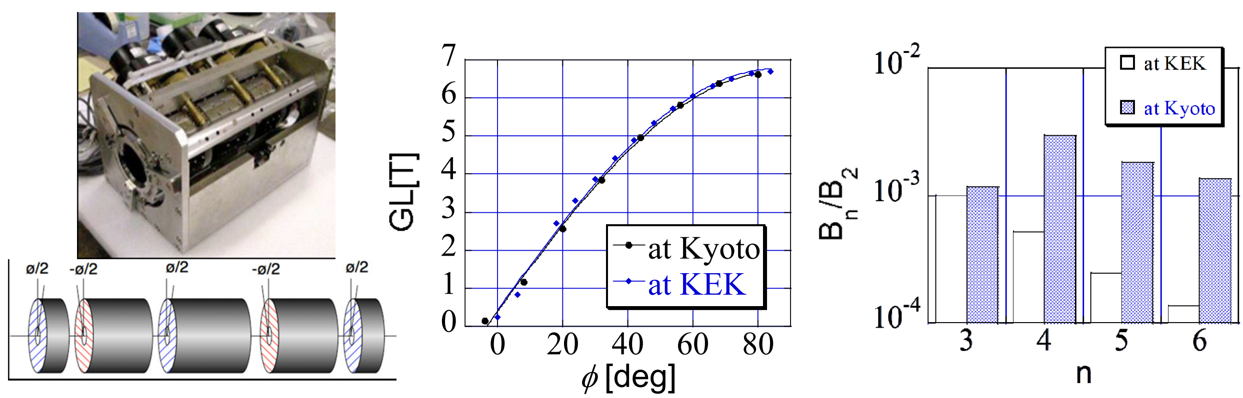

Figure 7: (a) 5-ring PMQ (b) GL of the 5-ring PMQ. (c)The relative magnetic field strength B_n/B_2 at ϕ =90 degree normalized by10 mm radius.

MULTIPOLE PERMANENT MAGNETS

Mod-PMSx

Mod-PMSx lens for focusing pulsed cold neutrons is developed [1]. This lens was achieved variable magnetic field amplitude in order to rotating outer magnet shown by Fig. 6. The higher harmonics were suppressed less 10^{-2} than main harmonics.

5-ring PMQ

The 5-ring PMQ is developed for a study of ILC final focusing magnet made of permanent magnet [2]. GL of the 5-ring PMQ can be changed by rotation of the odd number rings with angle $\phi/2$ and that of the even number rings with $-\phi/2$. GL and B_n/B_2 of 5-ring PMQ compared with the measurement it at KEK in 2010 [2]. The measured GL at Kyoto is consistent with the result of the measurement at KEK. Although it seems good coincidence of them, the relative magnetic field strength B_n/B_2 at f=90 degree is large different.

DISCUSSION

We evaluated the position of coil wire of max $\Delta\theta$, so that systematic error was able to be estimated. As a future study, we consider an estimation of systematic error for all $\Delta\theta$ and evaluation about R.

A variable main harmonics of the multipole magnets was observed. As to the measurements of 5-ring PMQ, larger high order harmonic components were observed compared with the result of measurement at KEK in 2010. This problem is currently under investigation.

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