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PARAMETER DESIGN OF A ROTATING COIL MEASUREMENT SYSTEM FOR QUADRUPOLES

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Abstract

This paper describes the design research on a rotating coil measurement system, which is used to measure the integral field harmonics components of quadrupoles in the beamline. The structure of the measurement system, parameters design of the rotating coils and main error analysis are described.

INTRODUCTION

For the integral harmonic field components measurement of the quadrupole, the rotating coil method has several advantages over Hall probe methods. Hall probe method can't directly measure the harmonic field components. Besides, rotating coil method measures far faster than Hall probe method [1].

The rotating coil measurement system introduced in this paper can be applied to a normal conducting quadrupole with pole aperture 80 mm (L270), which is the main focusing element in a proton therapy beamline. The cross section of the L270 quadrupole are shown in Fig. 1. The main parameters are listed in Table 1.

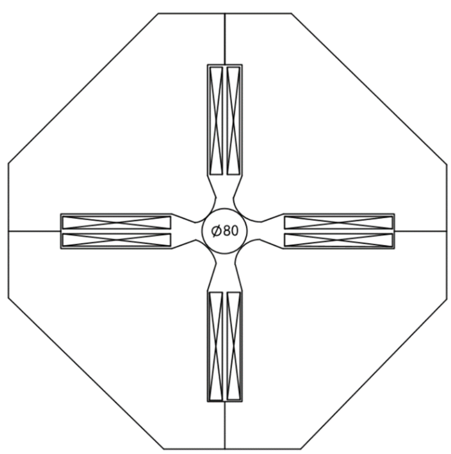

Figure 1: Cross section of the L270 quadrupole.

Table 1: Quadrupole Parameters

Parameters	Value
Pole radius(mm)	40
Radius of good field region(mm)	32
Maximum gradient(T/m)	18.0
Effective length(mm)	270
Magnet yoke length(mm)	240
Higher order harmonic error	⩽5.0E-4

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ROTATING COIL INTEGRAL HARMONIC FIELD COMPONENTS MEASUREMENT SYSTEM

The rotating coil includes a primary coil and a compensated coil. The rotating coil is shown in Fig. 2, where the outer ring is the primary coil, the inner ring is the compensated coil. The rotating coil is driven by the stepping motor, which adopts the double-shaft extension structure, whose one end drives the rotating coil and the other end drives the angle encoder [2].

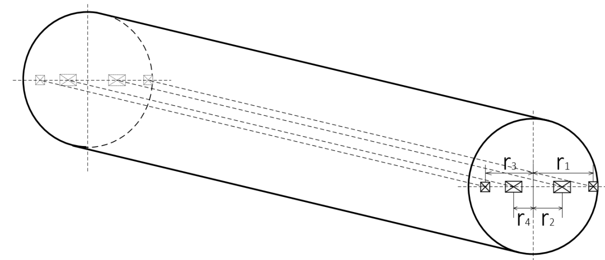

Figure 2: Schematic diagram of the rotating coil.

The structure of the rotating coil magnetic measurement system is shown in Fig. 3. Main components of the system include: computer-controlled module, digital integrator, axis decoder, moving motor, rotating coil and so on. The quadrupole is placed horizontally on a six-dimensional adjustable platform. The rotating coil is wrapped by an aluminium cylinder. One end of the coil is connected to the moving motor and the other end is connected to the angle encoder. The motor and the coil shaft are connected by a coupling.

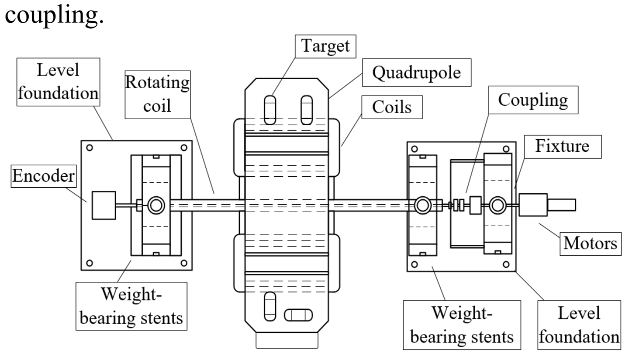

Figure 3: Structure diagram of the rotating coil measuring system.

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ROTATING COIL PARAMETER DESIGN

Determination of Radial Size

In Fig. 2, the radius of the primary coil are r_1,r_3, and the number of turns is M_{outer}; the radius of the compensated coil are r_2,r_4, and the number of turns is M_{inner}.

We define that:

$$\beta_1 = -\frac{r_3}{r_1} = \left|\frac{r_3}{r_1}\right| \quad (1)$$

$$\beta_2 = \left|\frac{r_4}{r_2}\right| \quad (2)$$

$$\rho = \frac{r_2}{r_1} \quad (3)$$

$$\mu = \frac{M_{inner}}{M_{outer}} \quad (4)$$

The coil sensitivity coefficient [3] is expressed as:

$$s_n = 1 - (-\beta_1)^n - \mu\rho^n[1 - (-\beta_2)^n] \quad (5)$$

For a quadrupole (N=2), when high-order quantities are ignored, the expression of the fundamental field [5] is:

$$F = C_2(z^2 + 2z \cdot \Delta z) \quad (6)$$

Both a quadrupole component $F = C_2 z^2$ and a dipole magnet component $F = (2C_2 \cdot \Delta z) \cdot z$ are contained. Therefore, when measuring the field of a quadrupole, we must counteract the dipole component while reversing the quadrupole component [4], expressions [3] are:

$$s_2 = 1 - {\beta_1}^2 - \mu\rho^2(1 - {\beta_2}^2) = 0 \quad (7)$$

$$s_1 = 1 + \beta_1 - \mu\rho(1 - \beta_2) = 0 \quad (8)$$

Other conditions to determine the radial sizes are as follows.

1. First we determine the outer radius r_1 of the primary coil. Since the inner radius of the magnet is 40 mm, to make sure the outer radius of the coil is as close as possible to the designed good field edge, the primary coil outer radius is r_1= 36 mm, in consideration of the rotation gap.
2. Set the inner radius to outer radius proportional coefficient of the primary coil to β_1=0.75.
3. Set the turns ratio of the compensated coil to the primary coil to μ =1.5.

Determination of Coil Turns

The higher harmonic amplitude is pretty small, usually the coil is wound more than 100 turns. A sufficient number of turns ensures that the signal-to-noise ratio is increased during the compensation measurement. However, the high resistance caused by excessive coil turns will vary with ambient temperature, affecting the calibration and stability of the measurement system [5].

When deciding the number of turns, not only must the signal satisfy the demand of signal-to-noise ratio, but also the amplitude of the fundamental wave signal in the uncompensated measurement is smaller than the maximum range of the digital integrator input signal. *Metrolab*'s high-precision integrator PDI5025 is used to process measurement results, which has a maximum range of 5V and a minimum range of 5mV [3].

Fundamental wave voltage signal induced by quadrupole field during uncompensated measurement is:

$$E_2 = M_{outer} L_{eff} {r_1}^2 B'(1 - {\beta_1}^2) \cdot \omega \quad (9)$$

Where L_{eff} is the effective length of the magnet, B` is the gradient，w is the rotating speed of the coil. To make E_2 about 70~80% of the maximum range (5V) of the integrator, the turns number of the coil should be as small as possible to reduce the self-inductance and capacitance. The spinning speed of the coil ω is 1r/2s.

Determination of Coil Length

When the length of the coil is designed, the fringe field including both ends of the magnet should be taken into consideration, which can reduce the requirement for longitudinal positioning of the coil during the magnetic measurement [6]. The empirical formula is:

$$L_C \approx L_{Fe} + 4D \quad (10)$$

Where Lc is the coil length，L_{Fe} is the length of the magnet core, D is the working aperture of the magnet.

Summary of Rotating Coil Parameters

When values of r_1, β_1 and μ are respectively 36mm, 0.75, and 1.5, the calculation results include the four radii of the rotating coil and two turns number are shown in Table 2. The advantage of this scheme is that the sensitivity s_2 is close to the ideal value of 0, indicating that the compensation is complete; the turns number of the coil is appropriate, the signal-to-noise ratio is high when measuring the multipole field, and the error caused by the change of the resistance with temperature is small; the four radii values are large which lower requirements for machining accuracy.

Table 2: Rotating Coil Parameters

Parameters	**Value**
r_1(mm)	36.00
r_2(mm)	25.49
r_3 (mm)	27.00
r_4 (mm)	16.50
M_{outer}	200
M_{inner}	300
L_c(mm)	560
s_2	4.23E-5

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ERROR ANALYSIS

Error Caused by Changes in Ambient Temperature

The coil material is G11, and the length of the coil changes as the ambient temperature changes. The thermal expansion coefficient of G11 material is $\alpha = 1.7 \times 10^{-4}/(^{\circ}C \cdot m)$.

In Eq.9, as the length of the coil is the length of the magnet core plus 4 times the working aperture of the magnet, the fringe field is already included, so the change of the length L_{eff} has no effect on the measurement results. In addition, the parameters M_{outer}, $B^{'}$ and ω are not affected by temperature. Therefore, the effect of temperature on E_2 is

$$\frac{\Delta E_2}{E_2} = \frac{(r_1+\Delta r_1)^2[1-(\beta_1+\Delta\beta_1)^2]-r_1{}^2\cdot(1-\beta_1{}^2)}{r_1{}^2\cdot(1-\beta_1{}^2)} = \frac{[r_1(1+\alpha\cdot\Delta T)]^2\left\{1-\left[\frac{r_3(1+\alpha\cdot\Delta T)}{r_1(1+\alpha\cdot\Delta T)}\right]^2\right\}-r_1{}^2\cdot(1-\beta_1{}^2)}{r_1{}^2\cdot(1-\beta_1{}^2)} \quad (11)$$

Where ΔT is the temperature change, considering $\alpha \cdot \Delta T$ is a small amount, its high order term is negligible. Simplify the above formula:

$$\frac{\Delta E_2}{E_2} = 2\alpha \cdot \Delta T \quad (12)$$

To make the error less than 1E-4, the temperature change ΔT should be less than ± 0.3 ° C. Considering that one measurement takes little time so the temperature is almost unchanged, it provides reference for multiple and repeated measurement.

Sensitivity Error Analysis

The smaller the sensitivity coefficient is, the better the measurement accuracy is. Sensitivity error [3] is

$$(\Delta s_2)_{max} = 2\beta_1|\Delta\beta_1| + 2\mu\rho^2\beta_2|\Delta\beta_2| + 2\mu\rho(1-\beta_2{}^2)\Delta\rho \quad (13)$$

According to formula (13), we can get:

$$\Delta\beta_1 = \frac{\partial\beta_1}{\partial r_3}\Delta r_3 + \frac{\partial\beta_1}{\partial r_1}\Delta r_1 = \frac{1}{r_1}\Delta r_3 + r_3 \cdot \frac{1}{r_1{}^2} \cdot \Delta r_1 \quad (14)$$

$$\Delta\beta_2 = \frac{1}{r_2}\Delta r_4 + r_4 \cdot \frac{1}{r_2{}^2} \cdot \Delta r_2 \quad (15)$$

$$\Delta\rho = \frac{1}{r_1}\Delta r_2 + r_2 \cdot \frac{1}{r_1{}^2} \cdot \Delta r_1 \quad (16)$$

If the winding error of the coil is 0.01mm, according to the above formulae, $\Delta\beta_1 = 4.86E-4$, $\Delta\beta_2 = 7.09E-4$, $\Delta\rho$=4.75E-4, $(\Delta s_2)_{max}$=2.156E-3. Bucking ratio, which is the reciprocal of sensitivity error and is used to estimate the compensation level, is 463.78.

If the winding error of the coil is 0.02mm, bucking ratio will reduce to half of the original and is 231.89, which weakens the compensation effect. It indicates that reducing the winding error of the coil is of great significance to improve the compensation level of the rotating coil.

CONCLUSION

Quadrupoles are of great importance to the beamline, so the accuracy of quadrupoles are crucial. To measure the accuracy of quadrupoles, we employ the rotating coil measurement system which has advantage on measuring the integral field harmonics components. This article introduces the rotating coil measurement system at first, then focuses on the rotating coil parameter design and gives detailed analysis process and complete parameters for the L270 quadrupole including radial size, coil turns and coil length.

Besides, the errors analysis is carried out. We analyses the error caused by the change of ambient temperature and sensitivity error caused by the coil winding error. Together, they provide a reference on coil fabrication and calibration.

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