CALIBRATION EXPERIMENT OF EQUIVALENT AREA OF INDUCTION COIL FOR MAGNETIC FIELD MEASUREMENT OF SUPERCONDUCTING CYCLOTRON

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Abstract

China Institute of Atomic Energy's 250MeV superconducting cyclotron (CYCIAE-250) uses the induction coil method to measure the magnetic field in its airgap. To ensure the precision of magnetic field measurement, area of the induction coil needs to be calibrated. This paper designs a set of coil calibration technique based on flipping coil method. The uniform magnetic field needed for calibration is provided by a permanent magnet with good static performance, its field is measured through high-precision nuclear magnetic resonance (NMR) probe. Then the induction coil will then be installed at the same position of the NMR probe. During the calibration process, induction coil is rotated 180 degrees and magnetic flux through it will be recorded by a high-speed digital integrator. Corresponding equipment is also designed to finish this task. This Paper describes this magnetic field measurement method, corresponding magnetic measurement equipment, calibration process of the induction coil and calibrated area of the coil.

BACKGROUND

Magnetic Field measurement and shimming is one essential part of cyclotron. There are three main methods of field measurement: hall probe, induction coil and nuclear magnetic resonance [2]. China Institute of Atomic Energy's 250MeV superconducting cyclotron (CYCIAE-250), uses induction coil as field measurement device, which requires the precise area of induction coil.

Calibration method for induction coils used in CYCIAE-230 and other cyclotrons only considers the start point and end point of voltage integral data and can be influenced by nonlinear noise [1, 3, 4, 6]. To improve the accuracy of calibration, this article designs a new calibration method and equipment, and then describes the calibration result of +the equivalent area of induction coil used for CYCIAE-250.

CALIBRATION METHOD

According to Faraday law of electromagnetic induction, change of magnetic flux through a close circuit will create an induced electromotive force (EMF), of which the amplitude is proportional to the change rate of magnetic flux and the winding number of the circuit:

$$E = -n \cdot \frac{d\Phi}{dt} = -n \cdot \frac{d}{dt}\int \vec{B} \cdot d\vec{S} \quad (1)$$

The induction coil used for CYCIAE-250 has a small radius and a large winding number, and is connected to digital integrator with twisted pair. The resistance or induction coil and twisted pair's resistance can be neglected, thus the relation between Voltage on the integrator and field through the coil can be described as:

$$V = E = -nS \cdot \frac{dB}{dt} \quad (2)$$

$$B = -\frac{1}{nS}\int V \cdot dt \quad (3)$$

According to Eq. (3), difference of magnet field between two points in the magnetic field can be calculated by recording the voltage produced by induction coil with fast digital integrator. Accordingly, by changing the magnetic field through the coil at a given amount, the equivalent area of coil can be calibrated according to following equation:

$$nS = \frac{1}{\Delta B}\left|\int_{t1}^{t2} V \cdot dt\right| \quad (4)$$

Clearing up Linear Drift

When using digital integrator to record induction voltage and its integral value, drift caused by electrical noise must be cleared up [1, 4, 6]. High order cumulant of noise tend to be cancelled out after integration and can be neglected, only the average value of noise voltage will cause a linear drift to the integration result. As a result, real value of coil's equivalent area can be described as:

$$nS = \frac{1}{\Delta B}\left|\int_{t1}^{t2} V \cdot dt - V_{off} \cdot T\right| \quad (5)$$

Among the expression, nS is equivalent area of coil, V_{off} is the average value of noise, and T is the integration time.

Calibration Method

A permanent magnet is used to create a constant uniform magnetic field needed for calibration, together with a set of positioning equipment to locate the coil at the centre of magnetic field. First step of calibration is to calibrate the field of permanent magnet with nuclear magnetic resonance (NMR) probe.

NMR probe measures magnetic field through the coupling of hydrogen's nuclear spin (proton spin) and external magnetic field. When applying a external magnetic field, proton spin will precess in the direction of magnetic field. Protons absorb electromagnetic waves at precession frequency and become excited, creating a loss of incident electromagnetic waves [5]. Field intensity can be determined by this resonance frequency and the magnetogyric ratio of proton.

The calibration procedure of induction coil is as follows:

- Locate NMR probe at the centre of permanent magnet and measure magnetic field intensity;
- Remove NMR probe, then locate induction coil at the same position
- Initialize digital integrator and begin recording data, which contains two steps: (1) Hold still the coil and record drift voltage; (2) Rotate the coil in 180 degrees and record voltage integral with integrator. There is a measuring equipment to ensure the accuracy of rotation.
- Repeat the measurement process multiple times and calculate the equivalent area of induction coil.

CALIBRATION EXPERIMENT

We calibrated two induction coils of same parameter, one actually used for magnetic field measurement of CYCIAE-250 (coli 1), one as backup device (coil 2). According to calibration procedure, we first measured the precise field intensity at the center of permanent magnet is measured, the value is 1.021624T, denoted as B_0, as shown in Fig. 1.

Figure 1: Field intensity measured by NMR probe.

The next step is to locate the induction coil and calibrate its equivalent area. Several tests were first conducted to figure out the appropriate gain of digital integrator in order to improve signal to noise ratio (SNR). We finally choose a gain of 40 times for the integrator.

Calibration of Coil 2

We conducted the calibration experiment twice at two separate gain settings of the integrator: one at gain 20 and one at gain 40. In each calibration experiment, Voltage integral data was measured 10 times, including 5 times clockwise and 5 times counterclockwise. In each measurement, we keep the coil still for about 2.5 second, and then rotate the coil in 3 second, the total integral time is 6 second, total voltage integral was denoted as I_0.

First 2 second of data is used to calculate drift time. We use least square method and calculate integral data's slope under the condition of zero intercept, denoted as V_{off}, the equivalent area of coil can be calculated by following equation:

$$nS = \frac{1}{2B_0}\left|I_0 - V_{off}T\right| \qquad (6)$$

During data handling process, we notice some bad data caused by misoperation of integrator and no overrange phenomenon. the calculate result is shown in Fig. 2.

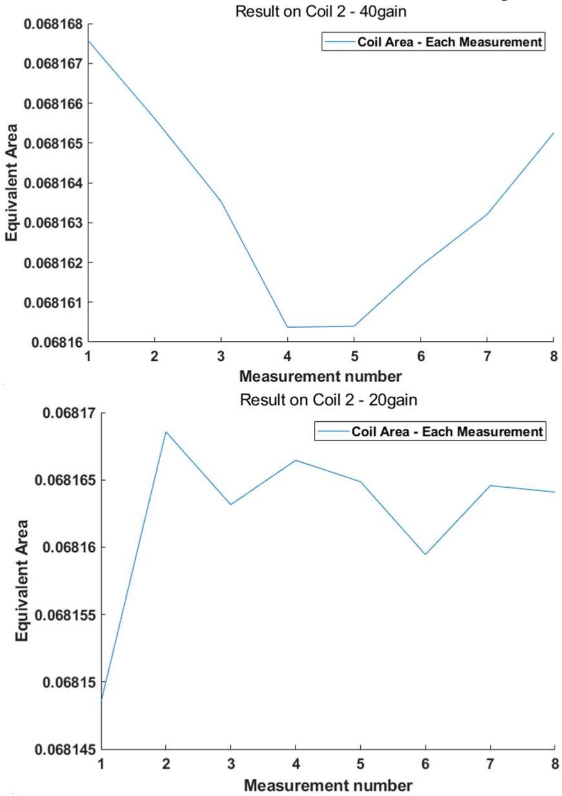

Figure 2: Calculated result of equivalent area of coil 2.

In the case of 20 times gain, one record differs significantly from others and is excluded from final averaging. Average area of coil 2 is described in Table 1 together with that of coil 1.

Overrange Analysis

By using high gain setting, the SNR of integrator can be improved. However, the integrator has a finite range of 10V, if the multiplied voltage exceeds range, it will be recorded as 10V, causing a mismatch in voltage data record and voltage integral record. To determine whether setting gain to 40 will cause data overrange or not, we calculated the gradient of voltage integrals, and compares it with induced voltage data. In practice, aforementioned difference in voltage and integral is also influenced by noise, so we compare result under gain 20 and gain 40. If only the result under gain 40 is significantly higher, than that under gain 20, we can determine that the recorded voltage data is overrange.

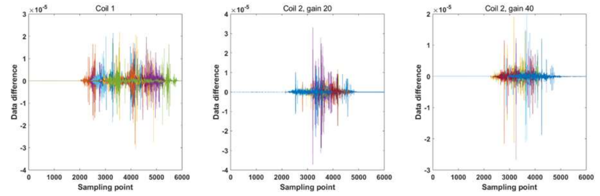

Figure 3: Difference in integral's gradient and voltage data.

As is shown in Fig. 3, calculation result shows similar difference in integral's gradient and voltage data under two different gain settings. We also checked the difference of the sum of induced voltage data and voltage integral, and the result does not exceed $\pm 1.2\times10^{-7}$.

Calibration of Coil 1

As the experiment and data handling show, choosing a gain of 40 times didn't cause recorded value to be overrange, and calculated area matches well, we only use voltage integral data in the gain of 40 times to calculate the equivalent area of coil 1, the result shows in Fig. 4.

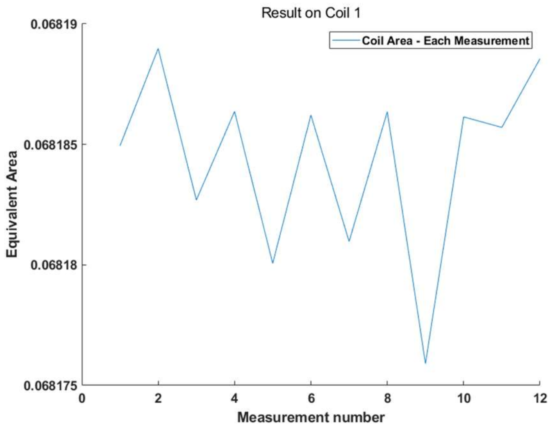

Figure 4: Calculated result of equivalent area of coil 1.

Record with number 9 differs significantly and is excluded from calculating average area. Final calculation result shows in Table 1.

Table 1: Average Area of Two Coils

Coil number	Coil 1	Coil 2, 20 gain	Coil2, 40 gain
Equivalent area(m^2)	0.06818520	0.0681645	0.0681635

According to experiment results, the consistency of coil area in different gain settings is good, difference in calculated area of coil 2 is less than 20 ppm. Further analysis of data overrange also shows that induced voltage keeps below range, thus we choose calibration result under the gain of 40 times as final calibrated area of coils.

CONCLUSION

In order to calibrate the equivalent area of induction coil used for magnetic measurement and shimming system of CYCIAE-250, this article designed a new calibration method and equipment. Calibration experiment is conducted successfully according to this new method, and the precise equivalent area of two induction coil is measured.

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