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DEVELOPMENT AND COMMISSIONING OF A FLIP COIL SYSTEM FOR MEASURING FIELD INTEGRALS*

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Abstract

Many techniques for measuring magnetic fields are available for accelerator magnets. In general, methods based upon moving wires are suitable for characterizing field harmonics, and first and second field integrals. The flip coil moving wire technique stands out due to simplicity, speed, precision, and accuracy. We aimed to develop a reliable, fast and precise flip coil system capable of characterizing field integrals in the two transverse axes. The coil was a single turn loop made of insulated beryllium copper wire. The width of the loop was 5 mm. The approach of measuring second field integrals by changing the coil's width at one of the ends was analyzed and included in the system. High-performance motorized stages performed angular and transverse positioning of the coil, while manual stages were used to stretch the wire, execute fine adjustments in its transverse position, and change coil's geometry. Initial tests with the Earth's field and also with a reference magnet of 126 Gauss-centimeter (G cm) demonstrated that the system achieves repeatability of 0.2 G cm for a 60-cm long coil. This work was carried out for the LCLS-II project at SLAC.

INTRODUCTION AND FLIP COIL SYSTEM OVERVIEW

Various methods are available for the measurement of the magnetic field. The choice of a method depends on many requirements, such as precision, accuracy, speed, geometric constraints, field measurements range, etc [1]. A complete magnetic measurements laboratory would have most of the main available techniques, given that each method offers distinct advantages and the ability to cross-check the results.

The available techniques for characterizing magnetic field at the SLAC Magnetic Measurement Facility (MMF) includes a rotating coil for measuring magnetic center in quadrupoles, a vibrating wire used to fiducialize the quadrupoles, a moving wire for measuring field integrals and Hall probes used to map magnetic fields [2–6]. This paper describes the development of a new flip coil moving wire system to measure field integrals at the SLAC MMF for the LCLS-II project.

In the flip coil technique a long coil is rotated within the magnet by 180° during the measurement, and the induced voltage V is recorded. The flux change $\Delta\phi$ during the measurement is equal to twice the flux ϕ_0 linked with the coil in the initial angular position θ_0, so $\int V dt = -2N\phi_0$ (N is the number of turns). If the loop of the coil forms two parallel wires with a small distance of W along the magnet's length, $\phi_0 = WI_1$, where I_1 is the first field integral of the field component perpendicular to the plane θ_0 constant. Therefore, $|I_1| = \int V dt/(2NW)$. If the coil's width is set to zero at one of the ends, it is possible to proof that $\phi_0 = WI_2/L$, where L is the coil's length and I_2 is the second field integral of the field component perpendicular to the plane θ_0 constant. Therefore, $|I_2| = L\int V dt/(2NW)$. For both cases, we assume that the field does not depend on the radial axis of the coil.

SYSTEM DEVELOPMENT

Mechanical Design and Motion

The flip coil is mounted in two towers, each composed of two motorized Newport stages model MTMPP.1 with 250 mm of travel attached at right angles for y (vertical) and x (horizontal) movements. Each tower has one motorized Newport rotation stage model RGV100BL that holds two manual Edmund linear stages with 13 mm of travel for fine adjustments in x-axis and y-axis. All motorized stages are controlled by the Newport Motion Control XPS-Q8. Each end has also one linear stage that moves towards z-axis and is used to stretch the coil. Figure 1 shows the system. A zoomed picture of each end of the system (called End A and End B in Fig. 1) is presented in Fig. 2.

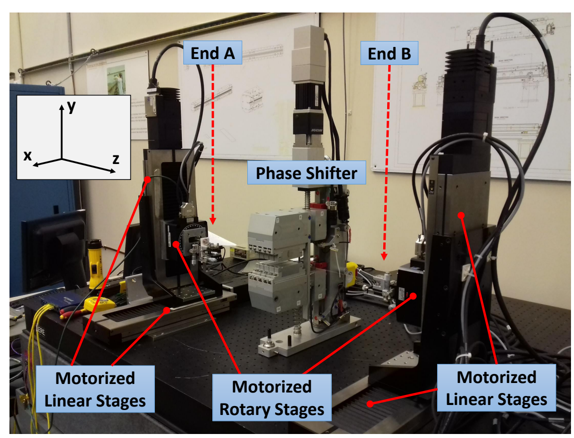

Figure 1: Flip coil system set up at the SLAC MMF.

The coil is a single turn of a 100 µm diameter insulated beryllium copper wire looped between two spools placed on each end, which forms one continuous loop of 5 mm of width (the minimum LCLS-II undulators' gap is 7.2 mm). The coil's length is approximately 60 cm. The End A has one manual Edmund rotary stage with 30 mm of diameter that allows changing the coil's width to measure second field integrals (see details 7 and 8 in Fig. 2). A low noise

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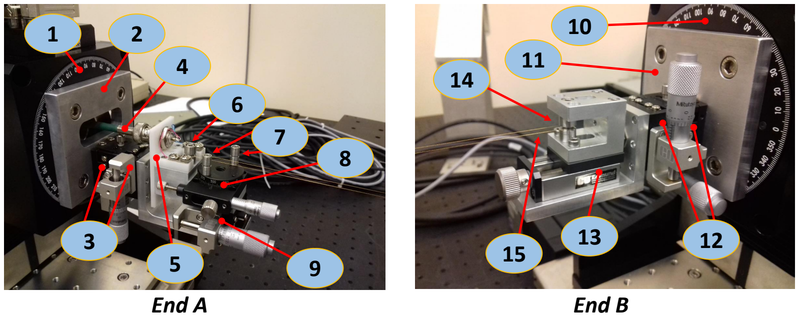

Legend:

(1) Motorized rotary stage; (2) Bracket; (3) Manual linear stages used for fine adjustments in the coil's transverse position; (4) BNC cable; (5) Delrin plates; (6) Spool for holding the wire; (7) Spools on the manual rotary stage for changing coil's width; (8) Manual rotary stage; (9) Manual linear stage for stretching the wire; (10) Motorized rotary stage; (11) Bracket; (12) Manual linear stages used for fine adjustments in the coil's transverse position; (13) Manual linear stage for stretching the wire. (14) Spool for holding the wire; (15) Insulated beryllium copper wire.

Figure 2: Zoomed picture of the ends of the flip coil system.

amplifier module model EM DC A22 [7] operating as a low-pass filter with cutoff frequency of 15 Hz is coupled to the wire. The terminals of the amplifier's output are connected to the voltmeter HP3458 to record the voltage signal induced during the coil's rotation and determine the flux change. The angular speed and angular acceleration of the coil are 1,5 turns/s and 1,5 turns/s^2, respectively. The coil only performs half revolutions (i.e. angular variation of 180°), starting either from the horizontal position in 0° (measures vertical field component) or from the vertical position in 90° (measures horizontal field component). Then, the coil reverses its direction to return to the starting position, during which data is also taken.

Software and Measurement Procedure

LabWindows/CVI-based system software was developed to coordinate the motorized stages and data acquisition. A graphical user interface shows the voltage and flux change samples, with the latter being calculated by numerically integrating the voltage samples by the trapezoidal rule, or

$$\Psi_i = \frac{\Delta t}{2}(V_i + V_{i-1}) + \Psi_{i-1}, \, i = 2, 3, \ldots n\,, \qquad (1)$$

where $\Psi_1 = 0$ and n is the number of samples for a single flip. The average of the last eight samples of Ψ_i corresponds to the total flux change $-\Delta\phi$ (or $\int V dt$) associated with the flip. Figure 3 shows an example of the voltage and flux change samples taken during the clockwise and counterclockwise movement for a test with a dipole field.

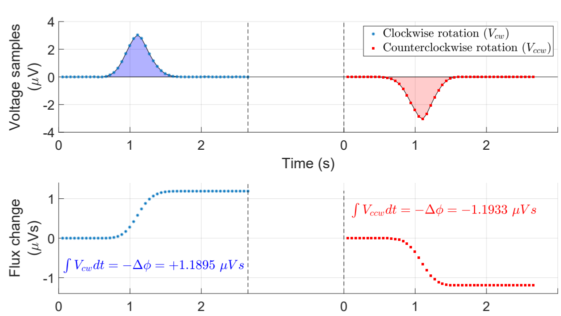

Figure 3: Example of voltage samples, flux change samples (clockwise and counterclockwise rotations) and value of the total flux change for a measurement of a dipole field.

Once the user selects either vertical or horizontal field measurements, the software defines the starting position of the coil as $\theta_0 = 0°$ or $\theta_0 = 90°$, respectively. The system starts the voltage acquisition, waits 0.5 seconds, flips the coil from θ_0 to $\theta_0 + 180°$ (clockwise rotation), waits 1 second, and then stops the voltage acquisition. Integration period of 3 power line cycles (sampling time of 50 ms) is used, which shows good performance since it suppresses 60 Hz noise. One flip takes approximately 3 seconds. The voltage samples taken during the initial and final delay (before and after the angular movement) are used to perform offset corrections, which increases the precision. The software reads all the voltage samples, applies the offset correction, and calculates the flux change samples using Eq. (1). The same procedure is repeated with the coil rotating back to the initial position (counterclockwise rotation). Since the integration is applied for both clockwise and counterclockwise rotations, these integrals have opposite polarity, being subtracted and divided by 2 to determine $\int V dt$. For instance, the example shown in Fig. 3 gives $\int V dt = [1.1895-(-1.1933)]/2 = 1.1914\,\mu V s$. In addition, due to the short time separation between each rotation, such procedure contributes to cancel voltage offsets. After the coil rotates forth and back and $\int V dt$ is determined, the software calculates the field integral. A few seconds of delay between the flips is required to assure the coil is static. To improve the repeatability, a set of 10 samples of $\int V dt$[1] is averaged, and the error is expressed as the standard deviation over these samples. The system takes less than three minutes to perform and measure this set of samples.

System Validation and Results

The flip coil system was used to measure the first field integral of a small reference magnet that had its strength estimated as 126 G cm (Gauss-centimeter) by an independent system. We tested both vertical and horizontal field integral measurements by changing the reference magnet's field orientation.

Let I_{yB} and I_{xB} be the first field integral of the background fields on y-axis and x-axis, respectively. Furthermore, let I_{y+} and I_{y-} be the first field integral measured with the flip coil system when a magnet is placed in such a way that its

[1] 10 samples of $\int V dt$ corresponds to 20 flips: 10 repetitions of clockwise and counterclockwise movements.

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Table 1: First Field Integral Measurements with a Reference Magnet, the Background Fields and a Phase Shifter

#	Magnet / condition		Field component	With the low noise amp. EM DC A22 Result ± Error (G cm)	Without the low noise amp. EM DC A22 Result ± Error (G cm)
1	Reference magnet's field pointing to	positive y-axis	I_{y+}	+120.75 ± 0.20	+120.90 ± 2.13
2		negative y-axis	I_{y-}	-134.48 ± 0.10 [2]	-133.54 ± 0.84 [2]
3		positive x-axis	I_{x+}	+142.28 ± 0.13	+140.99 ± 1.67
4		negative x-axis	I_{x-}	-116.73 ± 0.11	-119.09 ± 1.94
5	Reference magnet first field integral		$(I_{y+} - I_{y-})/2$	+127.62 ± 0.11 [3]	+127.22 ± 1.15 [3]
6			$(I_{x+} - I_{x-})/2$	+129.51 ± 0.08 [3]	+130.04 ± 1.28 [3]
7	Background first field integral (estimated from the ref. mag. results)		$(I_{y+} + I_{y-})/2$	-6.87 ± 0.11 [3]	-6.32 ± 1.15 [3]
8			$(I_{x+} + I_{x-})/2$	+12.77 ± 0.08 [3]	+10.95 ± 1.28 [3]
9	Backgroud Fields		I_y	-7.36 ± 0.14	-7.03 ± 2.16
10			I_x	+11.37 ± 0.12	+12.09 ± 1.83
11	Phase Shifter (see Fig. 1)		I_y	-10.93 ± 0.15	—
12			I_x	+8.88 ± 0.12	—

[2] A similar result was obtained with the long coil and the fluxgate probe, as shown in the technical report [5].
[3] Error estimated by propagating the error of the terms I_{y+}, I_{y-}, I_{x+} and I_{x-}.

field points to the positive and negative y-axis, respectively. If the magnet's first field integral is I, then $I_{y+} = I + I_{yB}$ and $I_{y-} = -I + I_{yB}$. Therefore, $(I_{y+} - I_{y-})/2$ is, in theory, equal to I, and may be applied to test the system for vertical field integrals measurements. The same is valid for testing horizontal field integrals by setting the reference magnet's field to point to x-axis.

It is interesting to notice that summing I_{y+} and I_{y-} (or I_{x+} and I_{x-}) and dividing by 2, the reference magnet's field is canceled, and only I_{yB} (or I_{xB}) remains. In this case, I_{yB} and I_{xB} may be compared to the background field obtained directly with the flip coil system without any magnets nearby. The next section presents the measurements we performed with the reference magnet and background fields. We tested the system with and without the amplifier module. An additional set of tests was made with a phase shifter. Table 1 summarizes the results of the measurements performed with the reference magnet (lines 1-8), the background fields (lines 9-10), and a phase shifter (lines 11-12).

DISCUSSION

We designed, built, and commissioned a new flip coil moving wire system for measuring magnetic field integrals. The system is capable of measuring field with a precision of 0.2 G cm for a 60-cm long coil, and takes less than three minutes to perform a complete measurement.

Coupling the EM DC A22 module to the coil reduced the error (standard deviation of the mean) in one order of magnitude —from 2 G cm to 0.2 G cm—, which demonstrates the high stability of the results. Besides, the field strength obtained with and without the EM DC A22 module showed no significant difference. These facts support some of the main features expected from the amplifier module, including high gain stability and low drifts.

Comparing the reference value of 126 G cm obtained by independent measurements and the values calculated in lines 5-6 shows that the measurements performed with the flip coil system agreed at the level of 3%. We believe that the error of the coil's width determination and small displacements of the reference magnet are the main sources of errors that justify the slight disparity. Further studies are necessary to define the optimum coil's width.

We may assume that the most significant influence in the background fields comes from the Earth's magnetic field, which is supposed to induce a very weak signal to the coil. Even so, the background fields measurements exhibited the same order of error observed for the other measurements, as shown in lines 9-10. It is worthy to notice that lines 7-8 present an estimative for background field based on the measurements with the reference magnet —considerable field strength in comparison with the Earth's field strength. The agreement among the results presented in lines 7-8 and 9-10 at the level of 1 G cm confirms that the system detects small field integrals.

A mechanical adaptation was made as an attempt to measure second field integrals by changing the coil's width at one of the ends. The precision of 0.2 G cm for the first field integrals suggests that the precision of second field integrals measurements would be about 0.1 μTm^2 for a 60-cm long coil. Still, further tests have to be taken to evaluate the system performance for determining second field integrals. Although the coil's length is suitable for measuring small magnets (e.g.dipoles, quadrupoles, phase shifters, etc.), tests with a longer coil need to be performed with LCLS-II undulators in the future.

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