A FAST-SAMPLING, PLANAR ARRAY FOR MEASURING THE AC FIELD OF FERMILAB PULSED EXTRACTION MAGNETS*

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Abstract

A system employing a planar array of inductive pick-up coils has been developed for measurements of the rapidly changing dipole field in pulsed extraction magnets for the Fermilab MuCool project. The magnets are of C-type and desined to support a peak field of 0.65 T during 8.33 millisecond half-sine pulse at a 15 Hz repetition rate. The coils of the measurement system are fabricated on a single, 97.5 mm wide, 2-layer circuit board. The array of coils is simultaneously sampled at data rates of up to 100 kHz with 10 kHz bandwidth using 24-bit ADC's. A detailed overview of the system and data analysis is presented, along with a characterization of results and system performance.

INTRODUCTION

In order to test basic techniques and components proposed for muon ionization and cooling, and provide accurate measurements of linac beam properties, Fermilab is constructing a new beamline and test facility which is capable of accepting the full Fermilab Linac beam intensity. Two pulsed C-magnets are key components for the beam extraction from the end of the Fermilab Linac and into the MuCool Test Area (MTA) beamline [1]. These two magnets have the same cross section and construction, but have two different steel lengths: 254 mm and 660 mm in the short/long versions respectively. Since this is a pulsed magnet, the contributions of eddy currents to the integrated strength need to be measured and understood. The design field parameters of these pulsed C-magnets are shown in Table 1. The magnets were designed and built to Fermilab specification by Everson-Tesla.

TABLE 1 Field Parameters for the Linac C-magnets

B_{peak}, range	6.0 - 6.5 kG
Repetition Rate	15 Hz
Pulse Length (half sine wave)	8.33 msec
Integrated strength, 1st magnet	0.1668 T-m, $\pm 1\%$ at peak
Integrated strength 2nd magnet	$2.5 \times$ 1st magnet strength
Good field aperture width, error	0.0600 m, 10^{-3} at peak
Gap	0.0510 m

MEASUREMENT PROBE

The magnetic fields of the Linac C-magnets were measured using a planar array of 15 inductive pick-up loops fabricated on the top layer of a single 2-layer 97.5 mm wide printed circuit board. The boards have a simple design and were procured quickly and at minimal cost. Each loop is a single turn, 5 mm wide and 550 mm long. The circuit board is 0.5 mm thick, but is supported on a 3 mm thick G-10 'strongback'. The assembly is constrained in an elliptical stainless steel beam tube having width of 123 mm, and height of 43 mm by means of foam blocks so as to keep the probe vertically centered in the magnet aperture. For measurements without beam tube, a different set of foam blocks are used for mechanical constraint in the gap. Figure 1 shows the magnet and probe during measurements.

Figure 1: Circuit board probe array in C-magnet

The bottom layer of the circuit board has a similar arrangement of coils, except each is bucked against the central winding to suppress the main dipole field. When the dynamic range of data acquisition is an issue, this may allow for more sensitive measurements of higher-order harmonics across the magnet mid-plane. A photo of the top and bottom layers of the circuit board is shown in Figure 2.
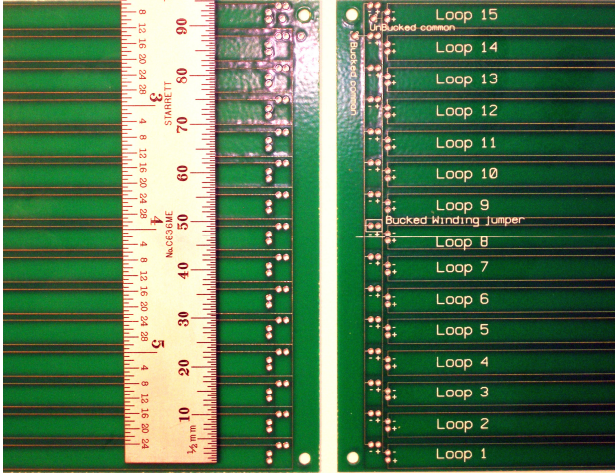
Figure 2: Bottom (left) and top (right) layers of the circuit board probe array

The probe signals are simultaneously sampled at 100 KHz with 24-bit National Instruments NI PXI-4472B ADC modules. Only 7 of the 15 top layer loops and 8 of the bottom layer loops are actually sampled with the ADCs. This simplified the wiring to the board and reduced the total number of channels required for the data acquisition system. This number of signals is sufficient to measure the fields of interest.

DATA ANALYSIS

The flux seen by each of the j stationary loops because of a change in magnet current during ramping is

$$\phi_j = \Re \sum_{n=1} K_n^j \left(B_n + iA_n \right) \qquad (1)$$

where $\Re$ indicates the real part of the complex quantity and

$$C_n = B_n + iA_n$$

defines the normal and skew components of the field. The generalized sensitivity for each of the j loops is represented by $K_n^{\,j}$, defined as the sum over all wires for that loop [2].

$$K_n^j = \sum_{m=1}^{N_{wires}} \frac{L_{m,j}R}{n} \left(\frac{(x_{m,j} + iy_{m,j})}{R} \right)^n (-1)^m \qquad (2)$$

Here L is the length of a given wire and R is the reference radius. The $(-1)^{\,m}$ gives the sign of the current flow of each wire and the $(x_{m,j}, y_{m,j})$ are the locations of the wires with respect to the chosen probe coordinate system origin.

Since the $K_n^{\,j}$ are known from calculation and the ϕ_j are measured during sampling, (1) and (2) can be used

to determine the magnet harmonic fields during ramp by solving the matrix equation

$$\begin{pmatrix} K_1^1 & K_2^1 & K_3^1 & \cdots \\ K_1^2 & K_2^2 & K_3^2 & \cdots \\ K_1^3 & K_2^3 & K_3^3 & \cdots \\ \vdots & \vdots & \vdots & \end{pmatrix} \begin{pmatrix} B_1 \\ B_2 \\ B_3 \\ \vdots \end{pmatrix} = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \vdots \end{pmatrix} \qquad (3)$$

for the unknown array of B_n. Once the harmonic fields are determined, the field shape across the aperture is calculated from

$$B_y(x) = \sum_{n=1} B_n \left(\frac{x}{R} \right)^{n-1} \qquad (4)$$

MEASUREMENT RESULTS

For the short magnet, data were taken to 1500 A. Because of the additional inductance of the long magnet, the power supply could only reach about 1200 A for those tests. Operating current is expected to be about 1400 A. The probe was long enough to extend beyond both ends of the short magnet for an integrated measurement. For the long magnet, the probe was carefully positioned so that one end was at magnet center while the other extended out from the end of the magnet: thus the actual measurement represented a half-integral one. Measurements were repeated from the opposite magnet end to insure an accurate result for the full integral.

In order to ascertain the performance of the magnet and the influence of the beam tube, measurements were made both with and without beam tube.

DC measurements were also made with a rotating coil probe at low current (to prevent magnet overheating) for comparison.
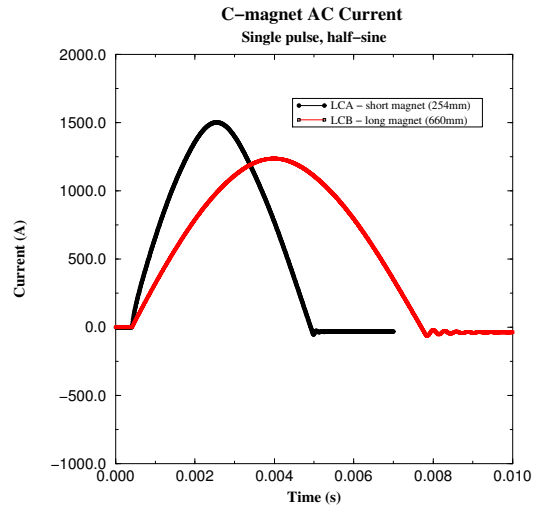

Figure 3: Current pulses used for the C-magnets

The current pulse seen by the magnet is shown in Figure 3 for the short and long magnets. There are limitations in the pulse height and duration owing to the different magnet inductances.

LCA001 AC Field TF
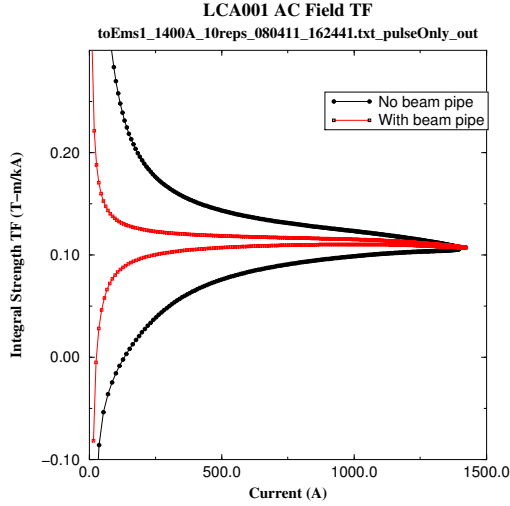toEms1_1400A_10reps_080411_162441.txt_pulseOnly_out

Figure 4: Strength transfer function with and without beam pipe.

The strength transfer function during the current ramp with and without the beam pipe is shown in Figure 4. The presence of eddy currents during ramping shifts the delay between peak field and peak current from ~43μs in the case with no beam pipe, to about 164 μs in the case with one. This delay is about 200 μs for the long magnet.

The reconstructed field shape across the aperture measured at 100 kHz sampling rate to 1400 A is shown in Figure 5 for the short magnet LCA001 (data are plotted every 250 μs for clarity).

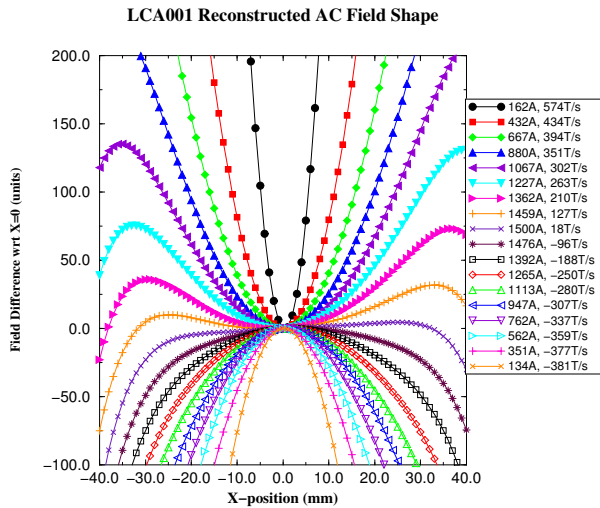**LCA001 Reconstructed AC Field Shape**

Figure 5: Reconstructed field shape during ramp with beam pipe present.

It is clear that the presence of eddy currents bucking the field at the (flat) central region of the pipe serves to delay the field there, while the increasing field at the edges has less such bucking and increases more rapidly; a strong sextupole component is thus generated. From the data one can also observe that for currents above ~1300 A (near peak field), corresponding to field ramp rates below 250 T/s (0.5 MA/s), the beam tube eddy currents are less than about 0.5% and the field is fairly flat out to ± 40mm. Below about 900 A, where field ramp rates are greater than 350 T/s (~1 MA/s), the beam pipe eddy currents cause 1% effects at distances within ± 30 mm. A comparison to the DC measurement with no beam pipe is shown in Figure 6.

LCA001 Reconstructed AC/DC Field Shape
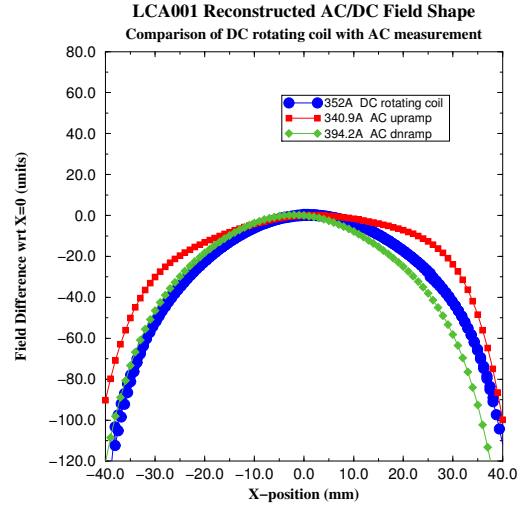Comparison of DC rotating coil with AC measurement

Figure 6: Field shape with no beam pipe. AC fixed probe data is shown compared to rotating coil at DC current.

SUMMARY

Long and short C-magnets for the extraction of Linac beam to the MuCool Test Area have been tested with a flat coil array fabricated on a printed circuit board sampled at 100 kHz. The AC behavior of the magnets is well characterized by the probe array. Strength and field shape across the aperture are measured with 10 ppm resolution (~ 4 μT), and time resolution of 10 μs. At peak field, where extraction takes place, the magnet strength and field shape are well within the original specification, and the delay between peak current and peak field is about 160 μs / 200 μs for the short/long magnets.

REFERENCES

[1] E. Black, D. Harding, C. Johnstone, and F. Mills, "C-Magnet Specifications for Beam Extraction from Fermilab Linac", internal memo, Aug., 2005.
[2] J. DiMarco et al., "A Fast-Sampling, Fixed Coil Array for Measuring the AC Field of Fermilab Booster Corrector Magnets", IEEE Trans. on Applied Superconductivity, Vol. 18, No. 2, June 2008.