MU2E AC DIPOLE 300 KHz AND 5.1 MHz TESTS AND COMPARISON OF NICKEL-ZINC FERRITES*

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Abstract

To suppress any background events coming from the inter-bunch proton interactions during the muon transport and decay window for the Mu2e experiment, a beam extinction scheme based on two dipoles running at 300 kHz and 5.1 MHz is planned. The field of these magnets is synchronized to the proton bunch spacing in such a way that the bunches are transported at the sinus nodes. Two types of Ni-Zn ferrites are being considered for these dipoles. The ferrites, their characteristics and performances, are herein discussed in light of measurements performed under conditions close to operational. The excitation system, the field measurement system, and the measurements of some characteristics of the magnetic field and field are also presented.

INTRODUCTION

One of the proposed experiment in Fermilab's Intensity Frontier program is Mu2e, a search for the conversion of muons to electrons without the emission of a neutrino [1]. By design, this experiment will provide the capability to search for charged lepton flavor violation with an unprecedented sensitivity of $6x10^{-17}$ at a 90% confidence level.

As discussed in [1], an important part of the experiment is a specially structured 8 GeV proton beam that consists of short (~100 ns) bunches between longer (~1.7 µs) gaps, as a reference see Fig. 1 in [2]. During these long gaps, some of the muons produced in the primary target are captured in the secondary target where µ-to-e-conversion can occur. The Mu2e detector will be triggered to record events exactly during these 1.7 µs beam gaps. To suppress any background events, which may appear during the muon transport, it is crucial that protons are extinguished at the level of 10^{-9} between bunches an unprecedented level of proton suppression in the gaps. This is achievable using several suppressing methods.

One of these methods, in our current approach, is to use a pair of alternating current (AC) dipoles to sweep unwanted beam into a collimator, allowing beam through only when the fields are minimal. This scheme is discussed in [3] and presented in detail elsewhere [2,4,5]. One magnet, powered at 300 kHz with a 156 G peak field, provides the main bend.

The second magnet, powered at 5.1 MHz with a peak field of 9.2 G (seventeenth harmonic with 1/17 amplitude), keeps the total integrated field near zero for about 100 ns, then allows a sharp increase in the bend.

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This paper describes the techniques used to perform measurement of the field, the losses of the two Ni-Zn types of ferrites considered and the technique to minimize the noise of the pick-up coils for the field measurement and so of the errors effect on their readings. Other unexpected findings are also mentioned though further investigation and discussion is in progress.

The measurements were performed on a short prototype magnet described in [3] using the ferrite considered for these magnets.

PRELIMINARY TESTS AND EXPECTATIONS

Since both Ni-Zn ferrites tested, i.e. CMD10 and CMD5005, have high permeability (μ_r >= 600), the expected field is approximately given by the formula:

$$B(G) \approx \frac{1.25 * N * I}{g} \approx 1.04 * I(A)$$

where B is the field, g is the air gap in cm, and N is the number of turns. In the magnet g is 1.2 cm and N is 1.

We can therefore estimate a magnetic field approximately equivalent to the current reading.

One of the goals of these measurements was to determine our ability to discern possible variation in the field (field distribution) in the aperture, though the expected result is no difference unless there are air gaps present in the ferrite introduced during magnet assembly.

We measured the field distribution and the current inside the magnet using a custom-made circuit board with 11 loops distributed along the field region of the magnet (Fig. 1).

The loops have equal area of 400 mm^2. One square loop is located on each side of the aperture, evenly spaced down the length of the magnet. One loop, one millimeter wide, is centred in the aperture and runs along the whole magnet length.

The circuit board was carefully connected to twisted wires of equal lengths and to feedthroughs at the ends of the magnet to allow for voltage measurements.

A second purpose of these measurements was to determine the peak temperature reached by the ferrites and by other components of the magnet in specific locations.

For this purpose we applied non-resettable temperature stickers at selected location. The disadvantage of these devices is the inability to read the temperature in real time, and the need to wait until we open the magnet to determine the maximum temperature reached.

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A previous test with resistance temperature detectors (RTD) real-time reading [2] provided measurement of the temperature in predetermined area and served us as baseline for the expected temperature range. The asymptotic maximum estimated temperature of the ferrites was found to be less than 70 °C with the cooling water temperature of about 19 °C.

We utilized a different technique for these measurements because the RTD itself was subject to heating due to the high frequency fields present and eddy current heating. Also, we utilized the terminals previously utilized for the RTD readings for our pick-up coil voltages.

After the opening of the magnet our temperature stickers up to 75 °C resulted overheated; this result is inconclusive and requires further analysis.

A third, very important, goal of our measurement was to determine difference in power dissipation between the two Ni-Zn ferrites. As we shall see, the results from utilizing CMD5005 vs. CMD10 for our purpose have been disappointing.

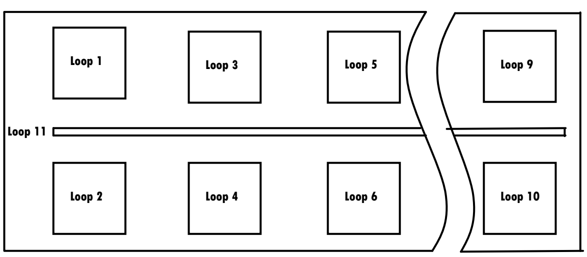

Figure 1: Field Distribution: probe layout.

MEASUREMENTS

From the readings of the voltages of the pick-up coils we deduce the excited sinusoidal field seen inside the magnet as

$$B = \frac{V}{2\pi f * A}$$

A is the area of the coils (400 mm^2 in our case).

300 Hz

To power the magnet at 300 kHz, a special H-type bridge power supply (PS) was built at Fermilab, capable of providing 160 A peak current at 1.3 kV. This is accomplished through excitation of the resonant mode of the magnet with four capacitor banks. The magnet inductance is primarily due to the air gap and modelled to be 4.8 µH therefore resonating at 300 kHz with 60 nF. The magnet inductance and its frequency response has been measured with a 4194A Impedance analyser and found to be approximately 4.6 µH between 300 kHz and about 3 MHz.

Four banks of 240 nF each have been connected to each power lead, therefore in series to the magnet coils. The excitation is supplied through a 6:1 impedance adapter and insulation transformer directly connected to the IGBT H Bridge output and loaded with a High Voltage DC Power Supply.

The excitation frequency has been matched to the resonating frequency of the system throughout the test and measured just about the required 300 kHz.

We assured at all time to have a water flow through the magnet to cool the ferrites of about 0.1 l/s. This was provided through an external recirculating pump and deionized water. The pump also provided cooling water to the excitation electronics. Throughout the experiment the water temperature did not rise more than 5 °C over six hours span.

Utilizing a LeCroy Wave Runner Xi oscilloscope and connecting two of its channels in a differential mode to the pin we executed some preliminary test of the voltages on the pick-up coils.

Initially the voltage spread resulted unexpectedly high (about 8%); we then worked to improve our measurement technique in successive steps obtaining more reliable and believable data.

We obtained our best results by moving the oscilloscope probes away from the magnet therefore reducing the high frequency interference. We also shielded all the connections

We did not observe improvement in our measurement by utilizing the differential mode techniques, and we proceeded in single-ended mode. Also a comparison of the readings of the voltages gathered directly via coaxial (RG58) cable did not show any significant difference to using oscilloscope probes. We took advantage of the oscilloscope high frequency filtering, and averaging capabilities.

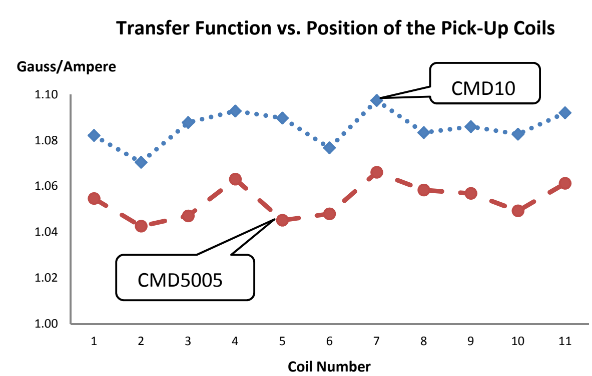

Figure 2: Measured field in the pick-up coils. It is about 346 Gauss peak-to-peak for CMD10, and about 338 Gauss peak-to-peak for CMD5005.

The data ultimately collected show a total spread of about 3%, or (if we exclude from the sample the two high and low limits only about 1%). The resulting data for the 300 kHz measures are shown in Fig. 2 with both CMD10 and CMD5005 ferrites.

5.1 MHz

To power the magnet at 5.1 MHz we built a special 4:1 high frequency transformer to better adapt the impedance to the nominal 50 Ω output and properly drive the magnet utilizing a commercial RF amplifier

We obtained the measurements in Fig. 3 at 4.99 MHz (the effective resonant frequency of our magnet-capacitor assembly) using the same excitation techniques previously described for the 300 kHz mode.

We achieved the goal of the required 18 amperes peak-to-peak excitation of the magnet and have been able to drive the magnet with 20 Amperes peak-to-peak by using about 190 watts of power measured at the amplifier. Calculation of the power with the magnet utilizing CMD5005 ferrites yielded 170 watts at 4.77 MHz.

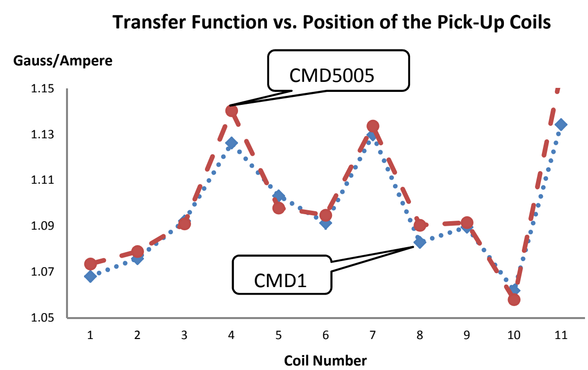

Figure 3: Measured field in the pick-up coils. It is about 22 Gauss peak-to-peak for both CMD10 and CMD5005 ferrites at resonance: 4.9 MHz, and 4.8 MHz respectively.

POWER MEASUREMENTS

One important characteristic we wanted to measure was the power used by the magnet during the excitation. This is an important parameter since it is directly related to the coercive force of the ferrites therefore to their heating.

For the CMD10 ferrites we had previously obtained a value of 1,120 Watts with an excitation current of 320 A peak-to-peak.

In the same fashion we have measured CMD5005 and obtained a power load value of 1,043 Watts for a comparable excitation current of 321 amperes.

It must be noted that these wattages include losses in the driving system. We expect that the magnet losses are about 120 Watts less.

This was a surprising result since the published value of the Coercive Force of the two types of ferrites differs considerably. In particular Ceramic Magnetics supplies a value of Coercive Force of 0.36 (with μ_r = 625) for CMD10 and supplies a value of Coercive Force of 0.12 (with μ_r = 2,100) for CMD5005. It was therefore expected to have a considerable reduced amount of power dissipated by the CMD5005 ferrites in their working condition.

It must be noted that the listed Curie temperature of the CMD5005 of 130 °C differs considerably from the Curie temperature of the CMD10 of 250 °C. This becomes relevant during the working condition of the magnet because the temperature margin is dramatically reduced. If the cooling water temperature is higher it is possible to have localized hot-spot in the ferrites possibly above the ferrite Curie temperature.

Reaching the Curie temperature causes the ferrite material to dramatically reduce the permeability and to change its properties in ways that are not acceptable for the experiment.

The above mentioned factors will play a role in the decision of the ferrites to utilize during the production of the magnets.

CONCLUSIONS

With the accuracy we were able to achieve through our pick-up coils signal reading system we can confidently say that the field is indeed uniform inside the magnet.

Our present temperature results have not yet been conclusive; we are currently experimenting with different range and methods.

We have been successful in exciting the magnet up to and above the required field at 5.1 MHz dissipating only a limited amount of power.

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