FERMILAB-CONF-11-445-TD

Selection Tests of MnZn and NiZn ferrites for Mu2e 300 kHz and 5.1 MHz AC dipoles

G.V. Velev, K. Bourkland, E. Bulushev, L. Elementi, S. Feher, D.J. Harding, I. Iedemska,
V.S. Kashikhin, A. Makarov, H. Pfeffer, M. Venturini

***Abstract*— Mu2e, a charged lepton flavor violation (CLFV) experiment is planned to start at Fermilab late in this decade. The proposed experiment will search for neutrinoless muon to electron conversions with unprecedented sensitivity, better than 6x10^{-17} at 90% CL. To achieve this sensitivity the incoming proton beam must be highly suppressed during the window for detecting the muon decays. The current proposal for beam extinction is based on a collimator design with two dipoles running at ~300 kHz and 5.1 MHz and synchronized to the proton bunch spacing. The appropriate choice of ferrite material for the magnet yoke is a critical step in the overall design of the dipoles and their reliable operation at such high frequencies over the life of the experiment. This choice, based on a series of the thermal and magnetic measurements of the ferrite samples, is discussed in the paper. Additionally, the first results from the testing at 300 kHz of a prototype AC dipole are presented.**

***Index Terms*— Accelerator magnets, Ferrites, Magnetic measurements.**

I. INTRODUCTION

AFTER the completion of the Fermilab collider experimental program in September of 2011, several new experiments are proposed to be built on the existing accelerator complex. One of these 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 (CLFV) with an unprecedented sensitivity of 6x10^{-17} at a 90% confidence level. In the Standard Model of elementary particles, the CLFV processes are forbidden which means any observation over the experimental background is a sign for new physics.

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 (Fig.1). The proton beam produces muons in the primary target, some of which are captured in a secondary target, where $\mu \rightarrow e$ conversion can occur during the long gaps. The Mu2e detector will be triggered to record events only 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 the bunch gaps.

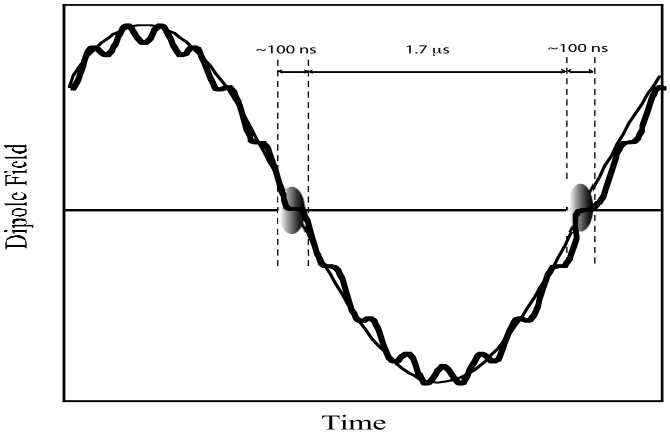

Fig. 1. A concept how the AC dipole should work to clean the protons between bunches using two magnets at 300 kHz and 5.1 MHz. The beam is transmitted when the modified sine field is practically zero.

Our initial approach to achieving this unprecedented level of proton suppression in the gaps was to use a pair of alternating current (AC) dipoles powered at 300 kHz to form a two-bump through a collimator, allowing beam to pass only when the fields were minimal. This scheme is discussed in [1] and presented in detail elsewhere [2]. In Ref. [3] we described the first measurements performed on MnZn type ferrites for this scheme and concluded that we cannot reach the required peak field of 600 G without overheating of the ferrite core.

After optimization of the beam lattice, several new magnet schemes were proposed [4]. The most promising candidate uses two AC dipoles: one powered at 300 kHz providing 156 G peak field and another at 5.1 MHz with a peak field of 9.2 G (seventeenth harmonic with 1/17 amplitude). Fig. 1, black curve, shows the sum of the two fields. At the nodes the sum of the field integrals is zero to first order and further correction for the field changes during the bunch passage is not required.

This paper describes the magnetic and thermal measurements of the ferrite samples considered for these magnets, as well as the magnet design and the first results from a prototype AC dipole magnet running at 300 kHz.

Manuscript received 12 September 2011. This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-07CH11359.

K. Bourkland, L. Elementi, S. Feher, D.J. Harding, V.S. Kashikhin, A. Makarov, H. Pfeffer and G. V. Velev are with Fermilab, P.O. Box 500, Batavia, IL 60510, USA, (e-mail: velev@fnal.gov).

E. Bulushev is with Institute of Automatics and Electrometry, Russian Academy of Science, Siberian Branch, Novosibirsk, Russia.

I. Iedemska is with Moscow Institute of Physics and Technology, Moscow, Russia.

M. Venturini is with University of Pisa, Pisa, Italy.

II. FERRITES MEASUREMENTS AND SELECTION

Initially, we chose MnZn ferrite material (MN60LL) for the 300 kHz dipole as a promising option due to its low hysteresis loss (0.52 W/cm^3 in the comparison tests at 300 kHz done by JC Sun [5]). We measured ferrite samples with a box shape and dimensions of 200 x 200 x 10 mm^3. The diameter of the conductor hole was 40 mm and the center of the hole was offset by 10 mm from the center of the square (Fig. 2). This ferrite shape was used in the initial design of the AC dipole as well as in our test samples.

Due to the low volume resistivity of the MnZn ferrite (~5x10^2 Ω-cm) we found that eddy currents caused the most of the heating of the test sample. With increasing of the sample temperature in the region from 25 to 80 C, we observed decreasing of the magnetic flux density (B) due to variation of the permeability of the MnZn material. The description of the measurement setup, the set of measurements and detailed results are summarized elsewhere [3].

The next logical step was to try to minimize the effect of the eddy current AC loss. We made a new test sample, gluing together two 5 mm MnZn ferrite plates to create the same thickness as the original sample with a thin layer of insulation between the plates. The results of tests are summarized in the Table 1. At the same current, the two-plate sample stabilized at lower temperature and similar or higher flux density B. Our ANSYS simulation confirmed the result [6]. We conclude that either configuration of MnZn ferrite can provide the required field of 156 G at 300 kHz, but the thinner plate sample will require much less cooling. Cooling is especially important for the magnet design where the ferrite core will operate in vacuum.

For the second magnet, which must operate at 5.1 MHz, our natural choice was to utilize NiZn type ferrites. These ferrites are known for higher volume resistivity (~10^7 Ω-cm), which makes them a preferred choice for high frequency applications, e.g. kicker magnets. The drawback of this material is a higher hysteresis loss at 300 kHz, on the order of 2.5 W/cm^3 or 5 times larger than MnZn based on measurements by Walker Scientific Inc. of the standard size toroids [7]. We chose to test CMD10-R15-30-10 NiZn ferrites due to our previous experience working with them on other accelerator projects [8]-[9].

The BH curves for typical NiZn measurements at different frequencies are shown in Fig. 3. The magnetic field strength (H) and the average magnetic flux density (B) are derived in the toroidal approximation with the internal and external radii of 20 mm and 90 mm correspondingly [3], [10]. The first number corresponds to the radius of the conductor hole (Fig. 2) and the second one is the distance from the center of the hole to the closest edge of the ferrite plate.

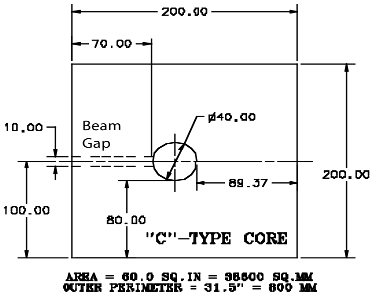

Fig. 2. A cross-section of the tested ferrite samples.

TABLE 1 MNZN FERRITE TEST RESULTS AT 300 KHZ

Current (A-turns)	Number of plates	B^{start} (G)	B^{end} (G)	Maximum T the end (C)
2	1	256	218	42.6
2	2	256	202	36.5
3	1	341	201	58.5
3	2	330	256	40.9

TABLE 2 NIZN FERRITE TEST RESULTS AT 5.1 MHZ

Current (A-turns)	B^{start} (G)	B^{end} (G)	Maximum T the end (C)
9.6	8.5	9.4	28.0
12.3	10.6	11.2	37.2
13.7	11.4	10.7	42.4

The total AC losses in the ferrite plates are proportional to the area inside B-H curve. A qualitatively conclusion from the B-H measurements, based on the slow increase of the B-H area with the frequency, is that the ferrite performance is not limited by the eddy current loss.

Table 2 summarizes the results of 5.1 MHz measurements at different currents. The starting temperature for all measurements was close to 20^{O} C. The B^{end}, after temperature reached equilibrium in the core, satisfies the requirement for the peak field of 9.2 G. The increase in B^{end} with temperature at two of the three currents needs further investigation.

A major problem in the initial design of the AC dipole was how to cool the ferrite around the current bus hole (Fig.2) where the magnetic flux is most dense and the heating most intense. To minimize power loss in the conductor, for the MnZn core we developed a complicated scheme using a Litz cable conductor. The Litz cable was spiraled around a water-cooled copper tube, inserted in a close-fitting ceramic tube, and vacuum impregnated with epoxy.

After the first test (Ref. [3]), we recognized the inability of this configuration to provide sufficient cooling to inner part of

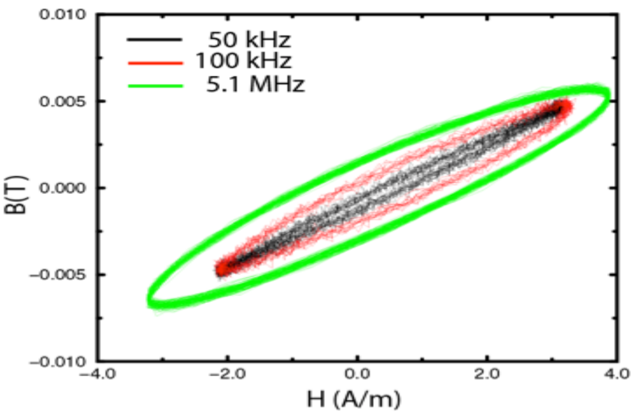

Fig. 3. B-H curves versus frequency For NiZn ferrite

the ferrite core. Moreover, additional tests validated our concern that with time the epoxy insulation will fail due to the corona effect (partial discharge) in the air bubbles in the epoxy layer in spite of vacuum impregnating the system, negating the advantage of the Litz cable in reducing power losses.

Fortunately, another benefit of the NiZn ferrite, beyond the reduction in eddy current losses, is that there is no need for high voltage insulation between the drive conductor and the ferrite plates. In this case, water cooled conductor could be pressed directly to ferrite plates, providing cooling to the inner surface of the cores.

Table 3 summarizes the results from the 300 kHz measurements at different currents for NiZn samples. The starting temperature for all measurements was close 20^{O} C. After the temperature of the test sample stabilized, we measured maximum peak field B^{end} = 116 G, which is below the required 156 G. In this case, the peak field was limited by the current provided by the power amplifier in use (200 W NIE power amplifier, model 2100L). Our ANSYS simulation confirmed that we had not saturated the ferrite samples and we should be able to reach the required magnetic field strength by increasing of the input current.

Based on the measurements, the ability of the NiZn ferrite material to provide the required field at 300 kHz and 5.1 MHz, and the additional design simplification of the insulation and cooling schemes, we selected NiZn ferrite to build the first AC dipole prototype.

TABLE 3 NIZN FERRITE TEST RESULTS AT 300 KHZ

Current (A-turns)	**B^{start} (G)**	**B^{end} (G)**	**Maximum T the end (C)**
3.6	61	64	23.5
5.7	101	95	28.3
7.8	143	111	40.1
9.3	160	116	55.0

III. AC DIPOLE PROTOTYPE DESIGN

Fig. 4 shows the 3D model of the AC dipole design. The magnet gap is 12 mm. The pole is 89 mm wide. The length is 445 mm. The core is enclosed in an aluminum case that serves as a vacuum vessel. The case can be split into two halves (the bottom half is shown in the Fig 4) on the middle plane for assembly and for maintenance of the internal instrumentation.

For the current design we selected an "H"-type core cross-section, as shown in Fig 5. For this cross-section, the conductor line is a simple 19 mm copper pipe passing through the ferrite holes. The copper pipe is used for direct water-cooling of the core. Due to the high resistivity of the NiZn material, the ferrite blocks can be compressed directly to the conductor lines without any high voltage insulation. A clear advantage of this geometry is better heat dissipation from the inner surfaces of the ferrites where the magnetic field flux is concentrated and the most of the heat is generated.

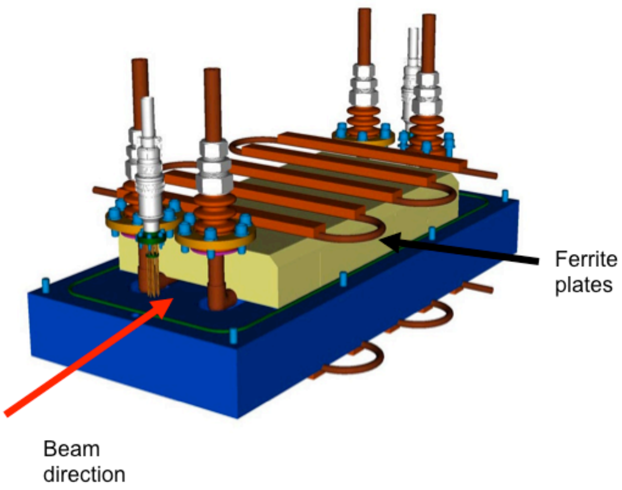

Fig. 4. AC dipole magnet conceptual design.

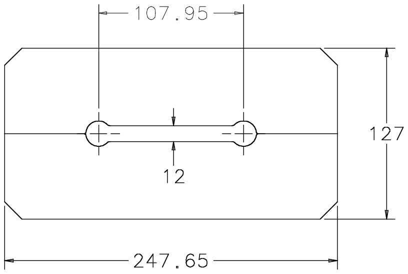

Fig. 5. Ferrite cross section of the "H"-type for current dipole. All dimensions are in millimeters.

The outer surface of the ferrite core is compressed to the aluminum body as well. This helps to remove any residual heat from the ferrites. Two copper cooling lines are attached to the upper and lower halves of the body for additional cooling.

The upper and lower sections of the ferrite core consist of five identical NiZn blocks (CMD10-R15-30-10), Fig.4. Due to the low electrical conductivity of the material, which nearly eliminates the eddy current losses, the core could be assembled in blocks as thick as convenient, 88.9 mm in the prototype.

A vacuum-tight feedthrough, consisting of a custom PEEK insulator and standard compression fittings, is used for the conductor line. Several monitoring instrumentations are placed in the aperture of the magnet. Fourteen resistance temperature detectors (RTDs) were arrayed on the ferrite surface inside of the gap to monitor the operating temperatures. Three voltage pickup loops (later reduced to one with smaller dimensions) were used to measure the magnet field strength.

IV. MAGNET TEST RESULT AT 300 KHZ

This first prototype AC dipole has been tested at the Fermilab Magnet Testing Facility (MTF). The magnet was cooled by the MTF low conductivity water-cooling system with the input cooling water temperature of 20 C.

To power the magnet at 300 kHz, a special H-type bridge converter was built at Fermilab. The converter operated at approximately 80 Vdc. Its output was put through a 6:1 stepdown transformer and drove the magnet configured as a series resonant circuit with four 240 nF capacitors. The magnet inductance primarily due to the air gap is modeled to be 4.8 μH, measured to be 4.6 μH at 300 KHz. This assembly provides the magnet with the full 160 A peak operational current. At this current the magnet dissipated 1.15 kW.

A simple data acquisition system was assembled to record the ferrite temperatures and the dipole field strength. A National Instruments PXI-4351 precision temperature logger was used to measure the voltages of the 14 RTDs. A 2 GHz LeCroy oscilloscope (model 204 MXi) was used to measure voltages proportional to the current in the magnet (a shunt) and to the field flux density (the pick-up coils).

During the magnet excitation, the magnetic field strength was measured approximately every 15 min. Fig 6 shows a typical measurement of the flux density (points) for a period of 12 μs. The sine wave fit (represented with the line) gave an amplitude of 162.4 G and a frequency of 298 kHz. This satisfies the requirement for the peak strength of 156 G of the dipole field.

Several long-term thermal experiments were executed during the 300 kHz test run. The main goal of these experiments was to monitor and record the temperature of the ferrite core. In a typical experiment we repeated several cycles of a one hour uninterrupted excitation of the magnet followed by a one minute temperature measurement. During the temperature measurement, we stopped the power supply to reduce the noise in the RTD readout.

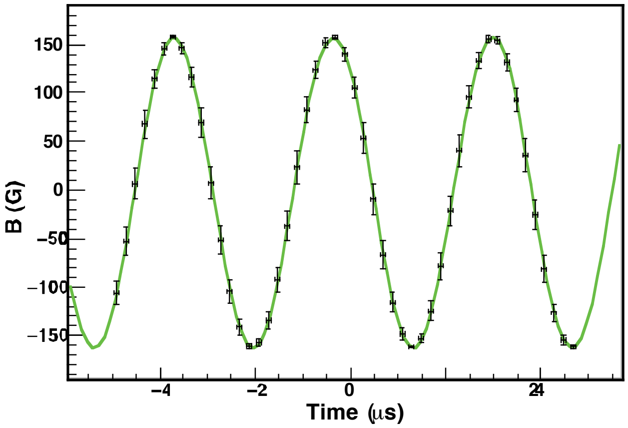

Fig. 6. Reconstructed magnetic field in the AC dipole.

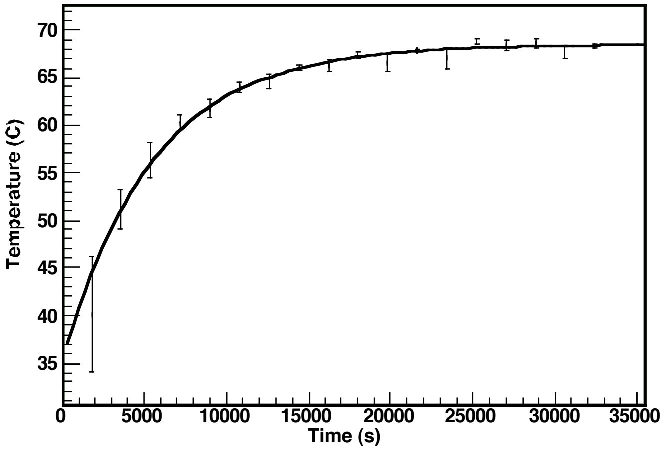

Fig. 7. Temperature profile at RTD number 11.

Fig. 7 shows the maximum-recorded temperature in the center of the magnet body versus time for the last thermal experiment. After 9 hours of operation at current close to 160 A the ferrite blocks approached equilibrium at 66^0 C. The fit returned maximum extrapolated temperature of 68.6^0 C with a lifetime of approximately 5550 s. This range of temperatures is acceptable for the operation of the CMD10 ferrite and it is far below the Curie point of 230 C.

V. SUMMARY AND PLANS

In this paper, we described measurements of MnZn and NiZn ferrites as candidates to build the magnet core for 300 kHz (156 G peak field) and 5.1 MHz (9.2 G peak field) AC dipoles. These magnets are a major component of the proposed inter-bunch extinction scheme for the proton line of the future Mu2e experiment.

In a continuation of the measurements described in Ref. [3], we measured thinner 5-mm plates of MnZn (MN60LL) ferrite material for the 300 kHz dipole core. For the 5.1 MHz magnet, we investigated NiZn (CMD10) ferrite material. Furthermore, we investigated and found that NiZn should be able to provide the required peak field for a 300 kHz dipole. Based on these results we decided to build a prototype magnet using a core from NiZn ferrite.

The design of this AC magnet and its 300 kHz test are described in the paper. We performed long-term thermal and magnetic measurements demonstrating that the magnet satisfies the peak field criterion without overheating. In the next step we will measure the prototype at 5.1 MHz. If the prototype satisfies the 5.1 MHz requirements, we will start the design optimization and possible fabrication of the first full size section of the 3-m long AC dipole.

REFERENCES

[1] Mu2e Collaboration, "Proposal to search for $\mu^- N \rightarrow e^- N$ with a single event sensitivity below 10^{-16}," FERMILAB-PROPOSAL-0973, Oct. 2008.

[2] E. J. Prebys *et al.*, "AC dipole system for inter-bunch beam extinction in the Mu2e beam line", in *Proc. 2009 Part. Acc. Conf.,* paper TU6RFP033.

[3] G.V. Velev *et al.*, "Measurement of the magnetic and thermal characteristics of ferrites for a 300 kHz AC dipole for the Mu2e experiment", IEEE Trans. Appl. Supercond.,Vol. 20, 2010, pp. 1642 – 1645.

[4] E. J. Prebys, "Extinction Magnet Specifications for the Mu2e Experiment AC dipole system for inter-bunch beam extinction in the Mu2e beam line," http://mu2e-docdb.fnal.gov/cgi-bin/ShowDocument?docid=709.

[5] J.C. Sun, "Testing report Bst-FL 0809_A," Fermilab report, unpublished.

[6] http://tdserver1.fnal.gov/tdlibry/TD-Notes/2010%20Tech%20Notes/TD-10-019.pdf

[7] Private measurement report by Walker Scientific Inc., http://www.laboratorio.elettrofisico.com, 2009.

[8] J.R. Lackey *et al.*, "New Pulsed Orbit Bump Magnets for the Fermilab Booster Synchrotron", Proc. of 2005 Particle Accelerator Conference, Knoxville, TN, May 2005, pp. 1341-1343.

[9] C. C. Jensen *et al.*, "Gap Clearing Kicker Magnet for Main Injector", Proc. of 2009 Particle Accelerator Conference, Vancouver , Canada, May 2009, pp. 1729-1731.

[10] "Calculation of the effective parameters of magnetic piece parts," International Electrotechnical Commission, IEC 60205, 2nd ed., 2001.