Design and test of a special magnet for the Mu2e experiment

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1. Introduction

1.1 Mu2e Experiment

The Mu2e experiment (Muon-to-Electron Conversion Experiment) is looking for evidence that a muon can change into an electron without the emission of neutrinos. The experiment will search for the charged-lepton flavor violating (CLFV) neutrino-less conversion of a negative muon into an electron in the field of a nucleus. The conversion process results in a monochromatic electron with an energy of 104.97 MeV, slightly below the muon rest mass. The goal of the experiment is to improve the previous upper limit by four orders of magnitude and reach a SES (single event sensitivity) of 3×10^{-17} on the conversion rate, a 90% CL of 8×10^{-17}, and a 5σ discovery reach at 2×10^{-16}. The experiment will use an intense pulsed negative muon beam, which is essential to reducing backgrounds. The other essential element is a sophisticated magnetic system composed of three consecutive solenoids (figure 1) that form the muon beam. [1]

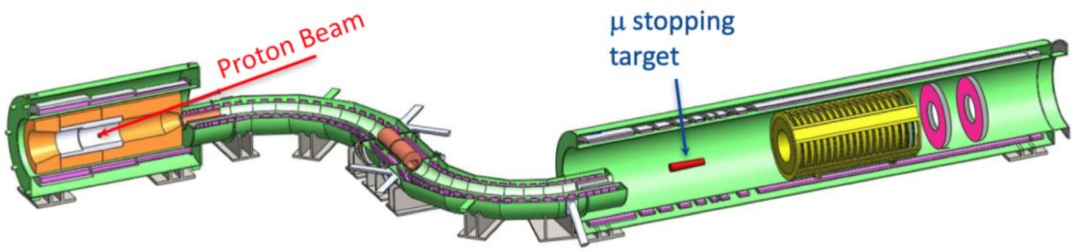

Figure 1: The Mu2e Solenoid system, also showing the tracking detector, calorimeter, and stopping target [2]

1.2 Timing requirements for the proton beam

In the Mu2e experiment protons are sent from the main injector to the delivery ring in bunches and it's vital that the interval between the bunches be free of protons at a level of at least 10^{-10}, relative to the beam in the bunches (figure 2).

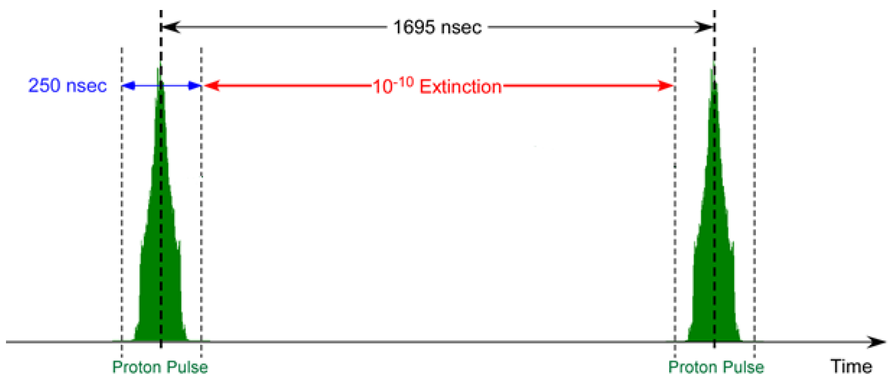

Figure 2: The proton bunch structure required by the Mu2e experiment.

This will be achieved in two steps: the first step will be in the formation of the bunches, which is expected to achieve an extinction on the order of 10^{-5}. The remaining extinction will be provided by a system of resonant magnets (AC Dipole) and collimators in beam line (figure 3), configured such that only the in-time beam is transmitted to the target. This system is designed to provide an additional extinction factor of below 10^{-7} [3].

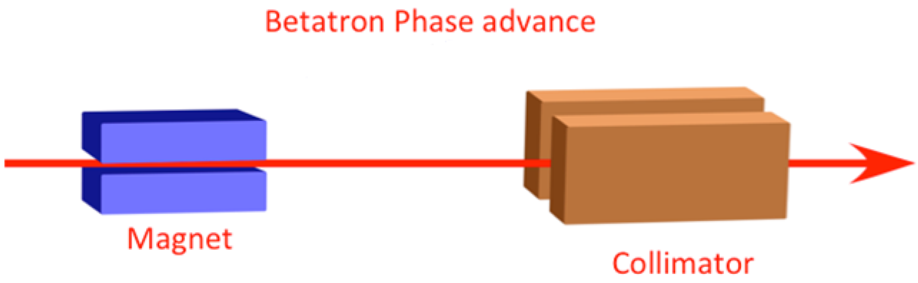

Figure 3: Magnet and collimator in the beamline

1.3 Goal of the internship

The building blocks of the magnet are ferrite bricks that arrived in different batches over a time period of one year. The first goal of my internship was to test ferrites and measure power losses inside the material to verify each batch behave in the same way and they can actually be used to build the AC Dipole.
Furthermore, the second goal of my internship was to work on a transmission line transformer used as an impedance transformer between the magnet and the power supply.

2. The AC Dipole

The goal of the AC Dipole is to stop the proton beam between pulses. To achieve the goal, the magnet is driven by two harmonics: 300 kHz to sweep out of time beam into collimators and 4.4 MHz to maximize transmission of in-time beam, so this are the two frequencies of interest while testing the ferrite plates.

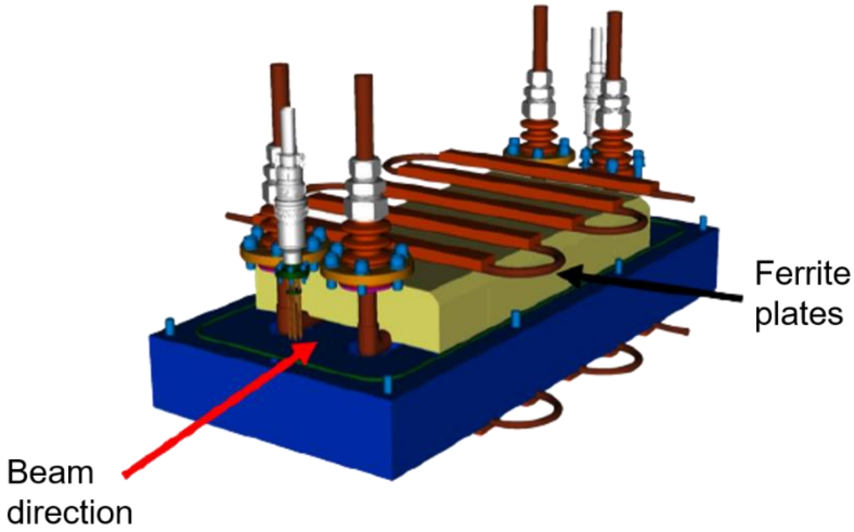

Figure 4: 3D model of the AC Dipole

Figure 4 shows the 3D model of the AC Dipole design. The core is enclosed in a case that can be split into two halves on the middle plane for assembly and for maintenance of the internal instrumentation. For the current design an "H"-type core cross-section was selected, as shown in figure 5.

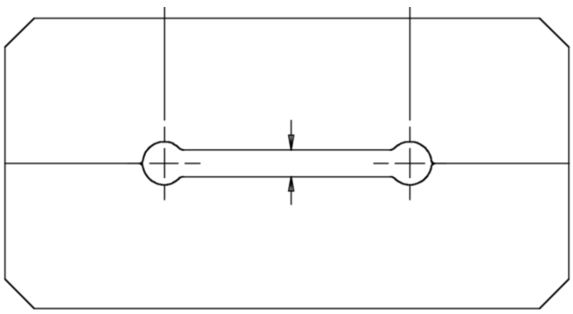

Figure 5: Cross-section of the AC Dipole

The conductor line is a copper pipe passing through the ferrite holes and it is used for direct water-cooling of the core. A clear advantage of this geometry is that heat dissipation from the inner surfaces of the ferrites is very efficient since it is where the magnetic field flux is concentrated and the most of the heat is generated. 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 magnet core consist of identical ferrite blocks [4].

2.1 Ferrite plates

A ferrite is a ceramic material made by mixing and firing large proportions of iron oxide with small proportions of a metallic element. They are a common choice for building magnets because of their high magnetic permeability (μ_r = 620 in this case) and their low Electrical Conductivity which result in very little losses due to Eddy currents.
Figure 6 shows the geometry of a single ferrite brick.

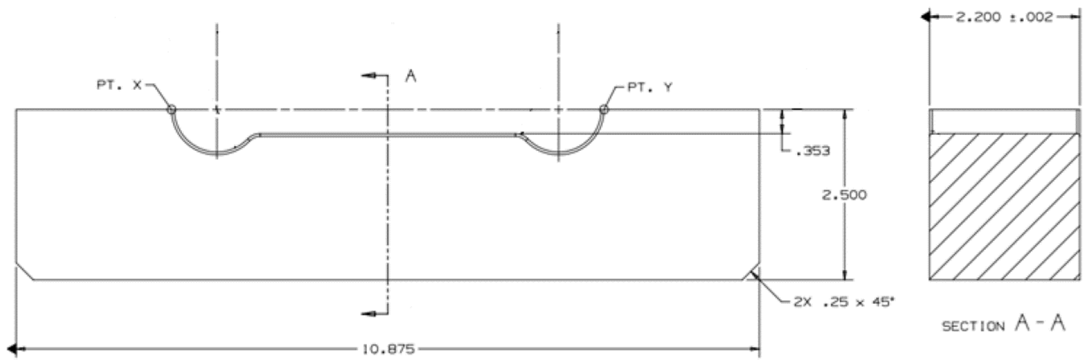

Figure 6: Single ferrite brick

3. Testing ferrite plates

The main purpose of the first half of my internship has been to test the ferrites from different batches to verify that all batches arrived have the same behavior. We measured power dissipation in the ferrites as a function of the magnetic field variation (due to Eddy currents). Measurements were taken in two different setups: toroid mode and dipole mode. In both setups two measurements were taken, one where the ferrites are driven by a sinusoidal wave at 300kHz and another one at 4.4MHz.

3.1 Toroid Mode

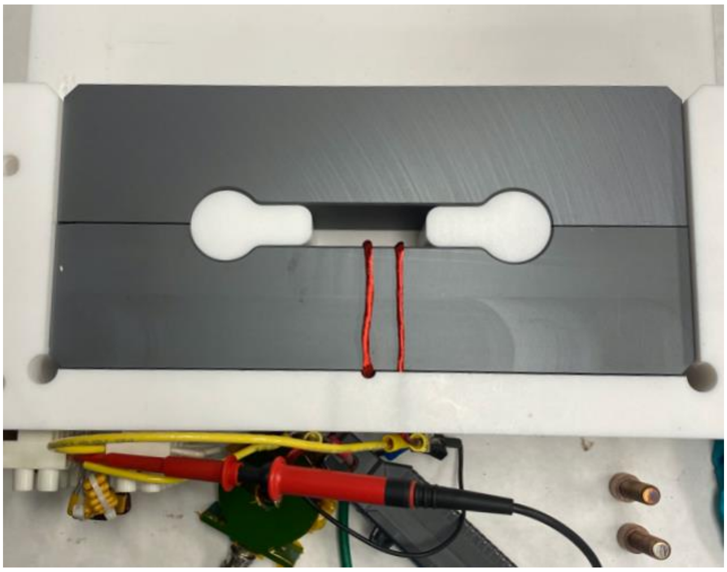

Figure 7: Toroid Mode

In the toroid mode (figure 7) an inductor is built with two ferrite plates. The ferrite plate with the coil is always the same between different measurements (brick number 9) while the other one changes. In the toroid mode the magnetic field is always inside the ferrite plates.

The measurements setup is shown in figure 8. We built an LC resonant circuit with a sinusoidal wave as input (at 300kHz or 4.4MHz), the wave is created by a function generator and is amplified before entering the circuit. There is also a RC filter to ensure that no DC current arrives into the LC circuit. The value of the C is chosen to make the circuit resonate at the interesting frequency (300kHz or 4.4MHz).

To calculate losses, we used an oscilloscope to measure voltage across the inductor, current in the coil and current through the coil. Mathematic analysis will be discussed on chapter 3.3.

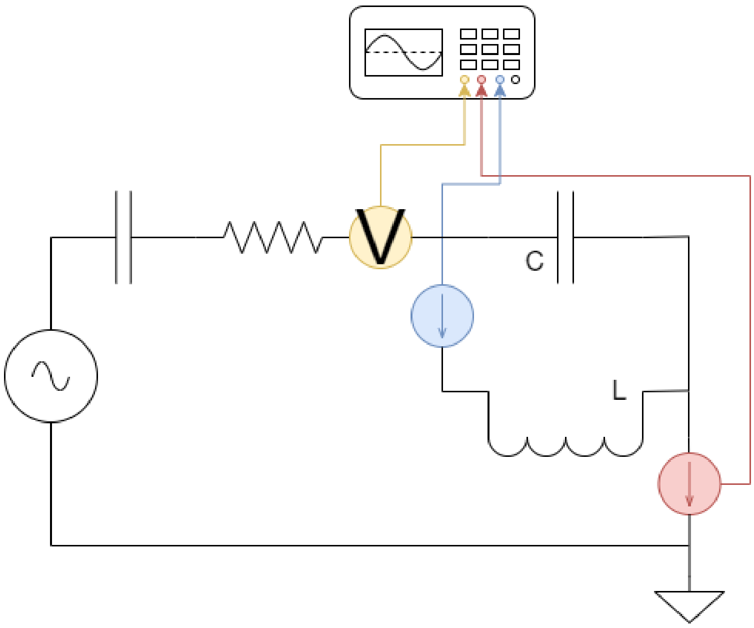

Figure 8: Measurements setup of both Toroid and Dipole Mode

3.2 Dipole Mode

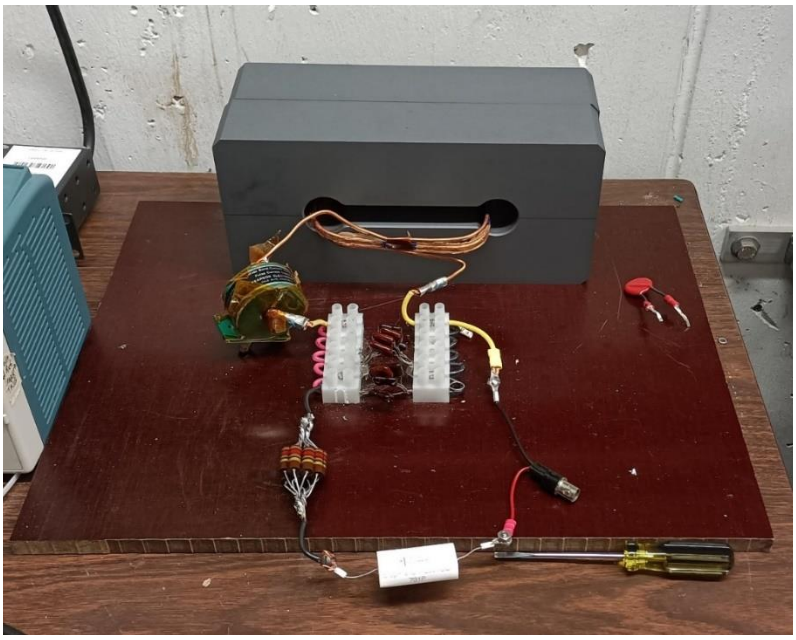

Figure 9: Dipole Mode

In the Dipole Mode (figure 9), the inductor is built with 4 ferrite plates, all of them change between different measurements. The coil is in the air gap between ferrites, therefore the magnetic field is not just inside the ferrites plates but it goes also into the air.
The electric schematic of the circuit and measurement setup (figure 8) are the same as the Toroid Mode, so measurements taken and mathematic analysis are identical in both cases.

3.3 Mathematics analysis

We want to calculate power dissipation (per volume unit) as a function of the magnetic field variation. To calculate the magnetic field variation, we start from Faraday-Neumann-Lenz law (equation 1) where N is the number of turns in the coil, A_C is the area of the coil, B is the magnetic field (in Gauss units) and ε(t) is the sinusoidal input with an amplitude of V_P.

$$\varepsilon(t) = -N\frac{d\Phi(B)}{dt} = -NA_c\frac{d\mathrm{B(t)}}{dt}$$

Equation 1: Faraday-Neumann-Lenz law

From here we can invert the formula and find the magnetic field variation by integrating in half period of the sinusoidal wave, we do not integrate in a complete period because the magnetic field variation in the whole period is zero (equation 2 and 3).

$$\int_{B(0)}^{B(^T/_2)} dB(t) = \int_{0}^{^T/_2} \frac{\varepsilon(t)}{NA_c}dt = \frac{V_p}{NA_c}\int_0^{^T/_2}\sin(\omega t)\,dt$$

Equation 2: Faraday-Nemumann-Lenz law inverted

$$\Delta B = \frac{V_pT}{NA_c\pi}$$

Equation 3: Magnetic field variation in half period

To calculate power dissipation, we can do a simple discrete mean of all the value taken from the oscilloscope (equation 4) and then divide by the total volume to obtain the loss per unit volume.

$$P = \frac{1}{M}\sum_i I_iV_i$$

Equation 4: Power dissipation

4. Results

In all plots of the results the magnetic field variation (in Gauss units) is on the x-axis and losses per volume unit are on the y-axis, on the right you can find the legend that explain which number of ferrites were tested for each measurement.

4.1 Toroid Mode

In the Toroid Mode, both for 300kHz and 4.4MHz, plots are really similar in their behavior (figure 10 and 11). That means that all measurements taken are consistent and no ferrite batch seems to be defective.

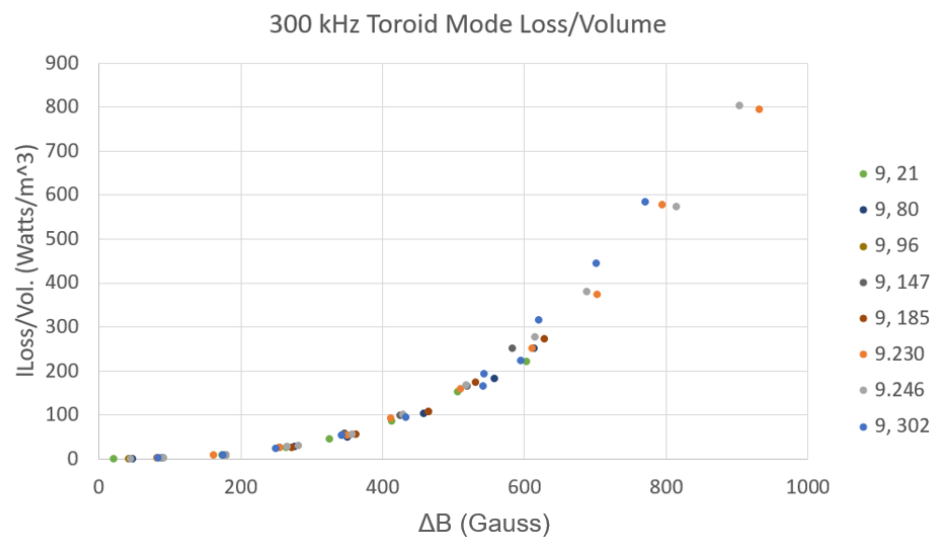

Figure 10: Losses in the Toroid Mode with the input sinusoidal wave at 300kHz

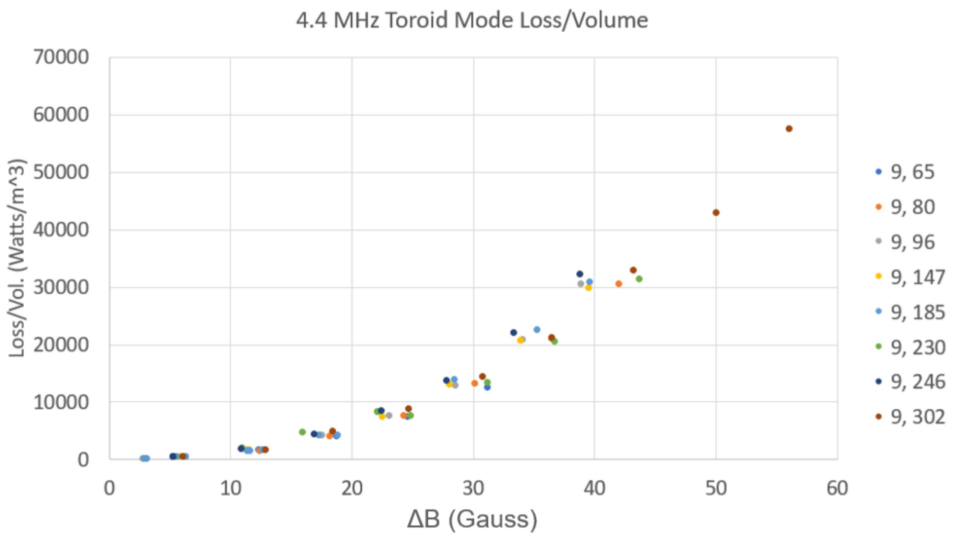

Figure 11: Losses in the Toroid Mode with the input sinusoidal wave at 4.4MHz

4.2 Dipole Mode

In the Dipole Mode at 300kHz we have the same results as the Toroid Mode. Therefore, all plots are similar (figure 12) and no ferrite batch seems to be defective.

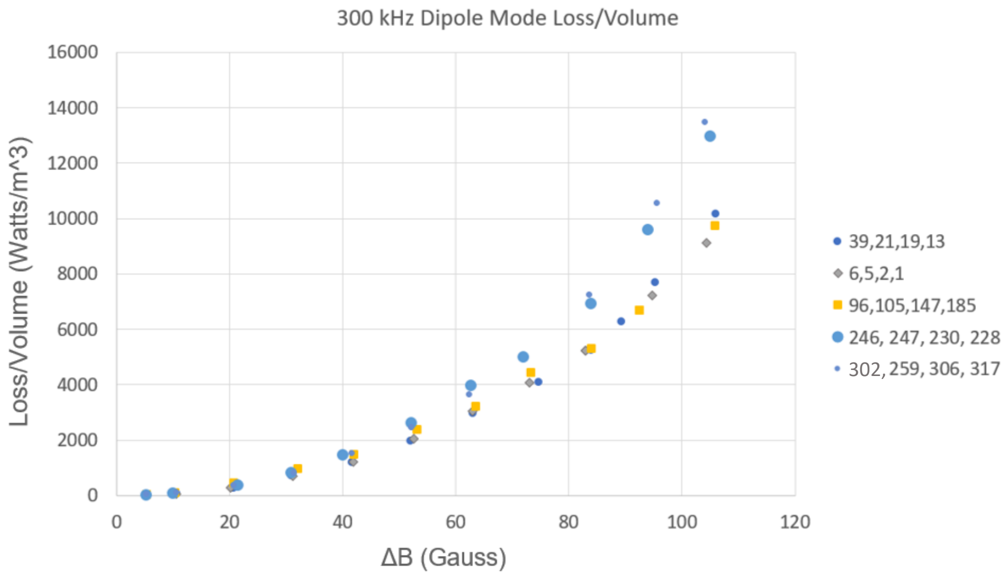

Figure 12: Losses in the Dipole Mode with the input sinusoidal wave at 300kHz

However, at 4.4MHz power dissipation of the last batch (ferrites number: 302, 317, 259, 306) is much higher (figure 13). This could happen due to different reasons:

- the problem could be the last batch being defective, but this is improbable since all other measurements were suggesting the opposite.
- Between measurements the setup changed (for example the oscilloscope was different) and this could have led to changes between the measurements.

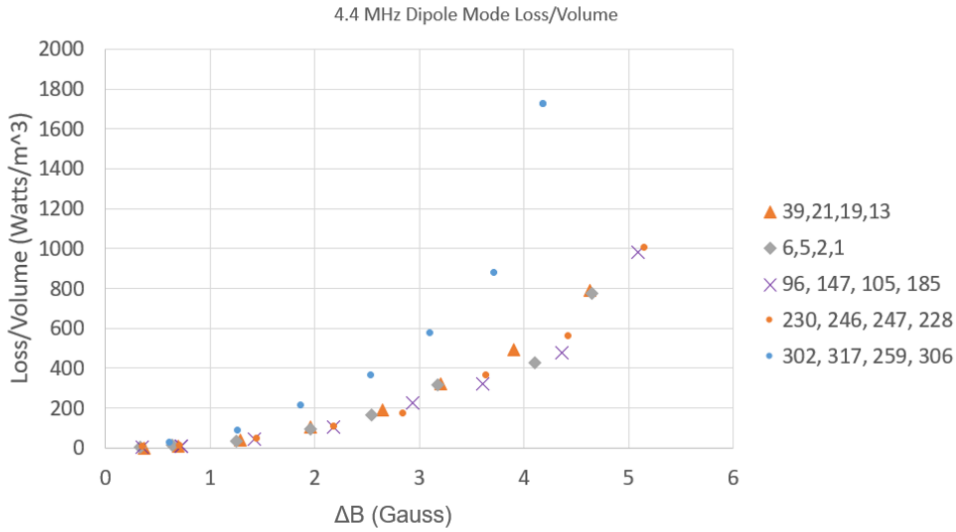

Figure 13: Losses in the Dipole Mode with the input sinusoidal wave at 4.4MHz

4.3 Dipole Mode at 4.4MHz

To be sure the problem was not the last batch of ferrites being defective, we re-measured losses of the last batch and also of the previous one (ferrites number: 230, 246, 247, 228) in the new setup. As it turned out, these two measurements were consistent with each other (figure 14), meaning that the problem was probably in the setup changing and not in the ferrite plates being defective.

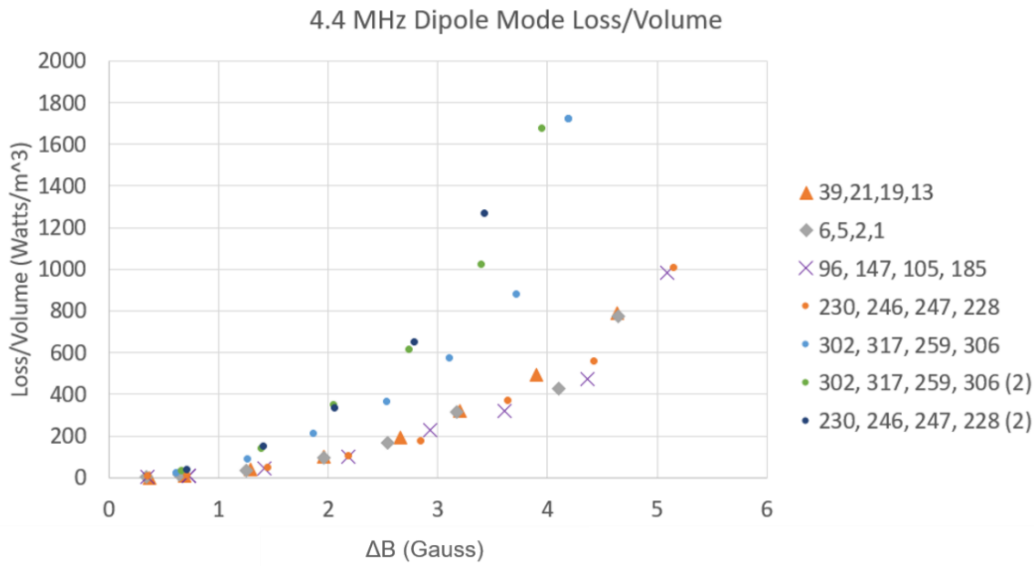

Figure 14: Losses in the Dipole Mode with the input sinusoidal wave at 4.4MHz

5. Transmission Line Transformer (TLT)

In the second half of my internship I've worked on the transformer used to match the impedance of the AC Dipole with the power supply at 4.4MHz. We chose to use a transmission line transformer instead of a traditional one because the TLT has a much wider bandwidth and less power dissipation. However, there is not so much flexibility in the value of impedance it can transform. For instance, given a TLT with 1:4 impedance ratio and a characteristic impedance of 50Ω, it can transform just 25Ω into 100Ω.

5.1 The impedance matching problem

First of all, I have measured the impedance of the magnet in series with the capacitors to verify it was resonant at 4.4MHz and to measure the value of the impedance at 4.4MHz, which is around 3Ω, as shown in figure 15.

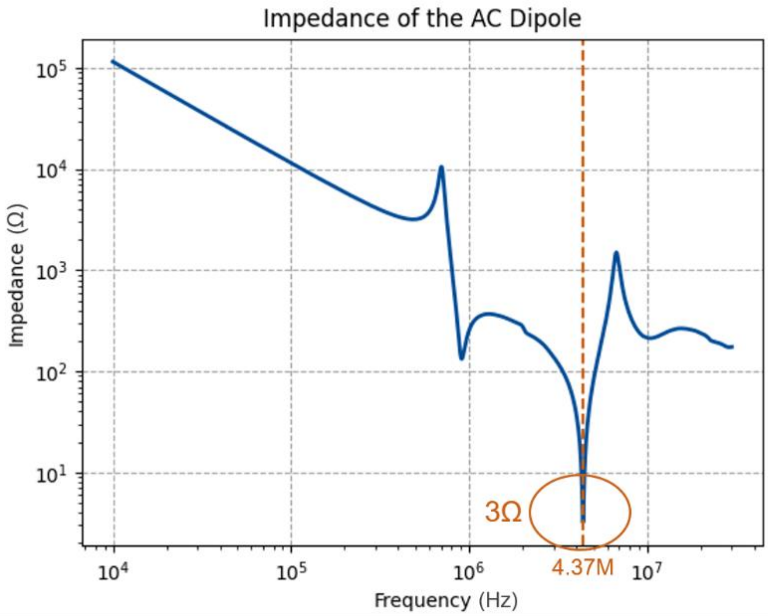

Figure 15: Impedance of the AC Dipole as a function of frequency

However, the power supply need to see a 50Ω load to minimize the power dissipation and reflections in the cable, so there is the need of an impedance transformer (which is the TLT) that changes the 3Ω of the AC Dipole into 50Ω (figure 16).

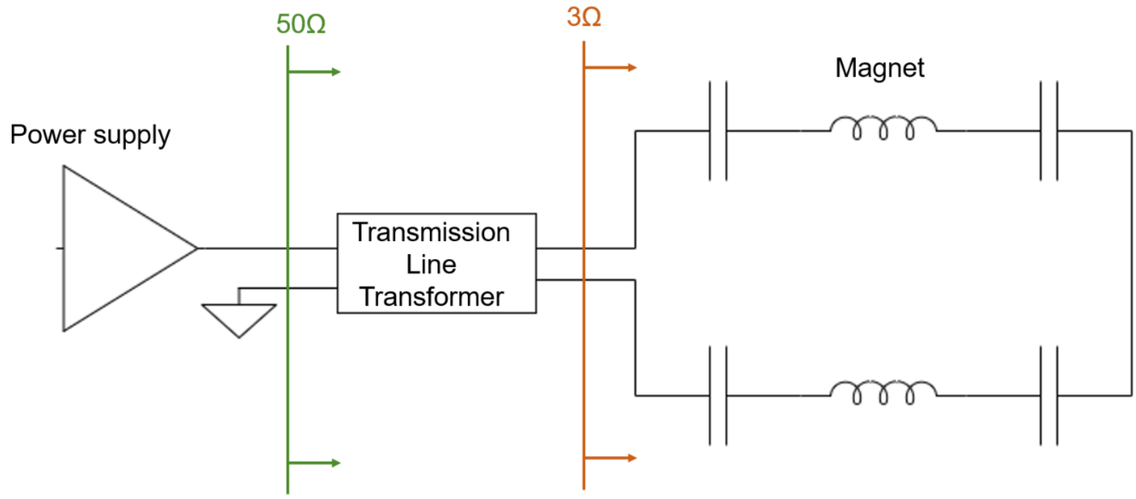

Figure 16: Impedance matching problem between the power supply and the magnet

5.2 Example of a 1:4 Transmission Line Transformer

Transmission line transformers are transmission lines connected in series on one side and in parallel on the other side. Figure 17 shows a simple example of a 1:4 TLT, please note that 1:4 is the impedance ratio, while the voltage ratio is 1:$\sqrt{4}$ = 1:2.

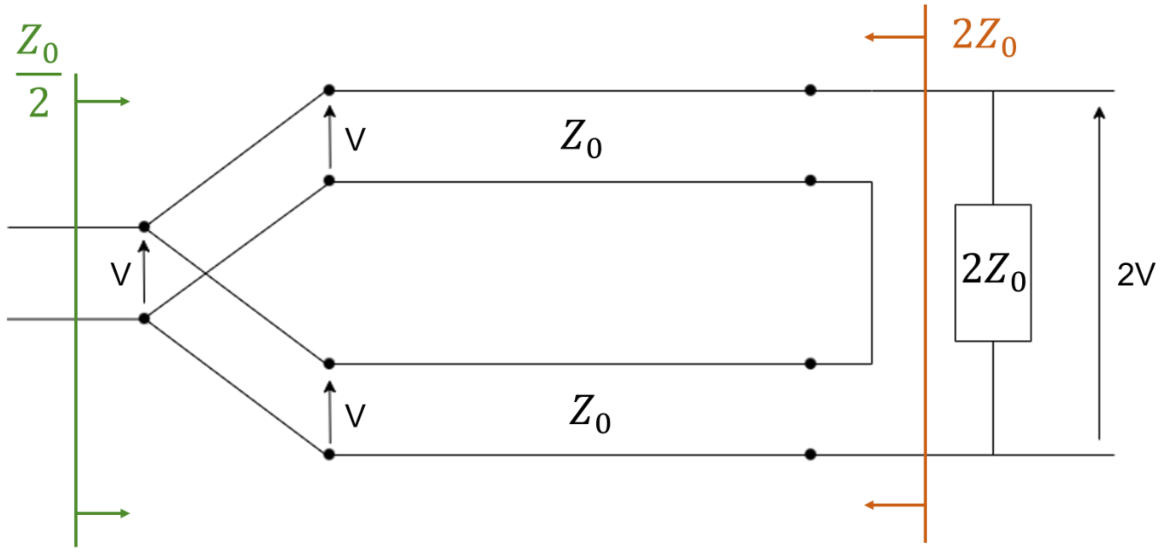

Figure 17: 1:4 Transmission Line Transformer

The two lines has the same characteristic impedance Z_0, on the left, where they are connected in parallel, we see an impedance of Z_0 / 2 while on the right, where they are in series, we see an impedance of 2*Z_0, resulting in an impedance ratio of 1:4.
On the side where the two lines are connected in parallel, they both have 1V tension, on the other side, where they are connected in series, we have 1V + 1V = 2V tension across the load, resulting in a voltage ratio of 1:2.

5.3 The real 1:16 Transmission Line Transformer

In our case, we want to transform 3Ω into 50Ω so we need an impedance ratio around 1:16. The schematic of the TLT is shown in figure 18. There are two identical transformers that share the same magnetic core, each of them drives one half of the magnet (1.5Ω). Each transformer is made with four lines of 6Ω; on the right they are connected in parallel so we see 1.5Ω, as the magnet half, on the other side they are connected in series and we see 24Ω. Connecting the two halves, we obtain 24Ω + 24Ω = 48Ω as a balanced load. However, the power supply is unbalanced and it needs 50Ω, so we add another transformer with a matching network to go from 48Ω balanced to 50Ω unbalanced.

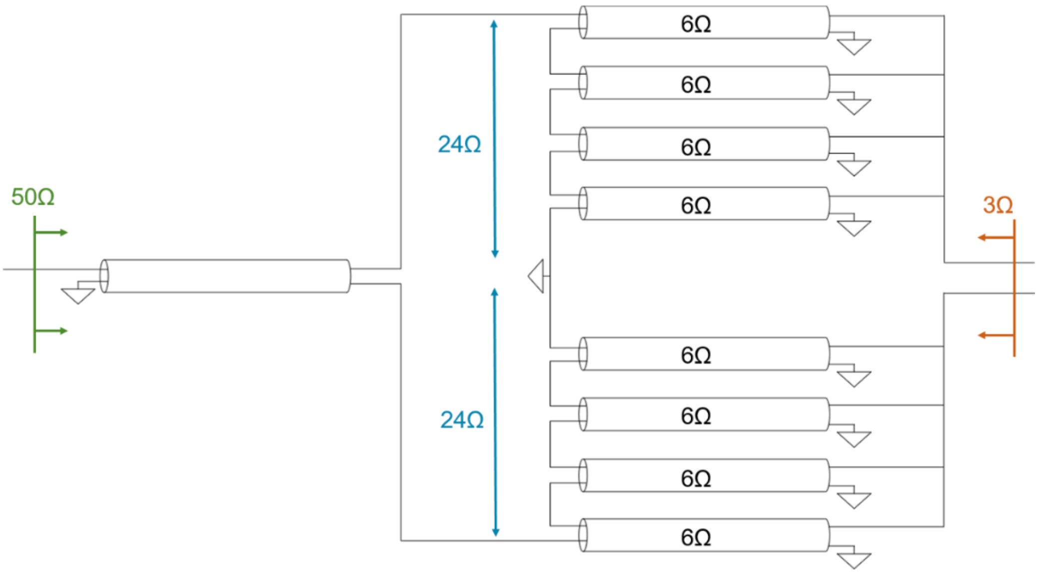

Figure 18: The 1:16 Transmission Line Transformer

5.4 Frequency behavior of the 1:16 Transmission Line Transformer

Using the impedance analyzer, we have measured the impedance of the transformer as a function of frequency with a simple 3Ω resistor as a load (figure 19).

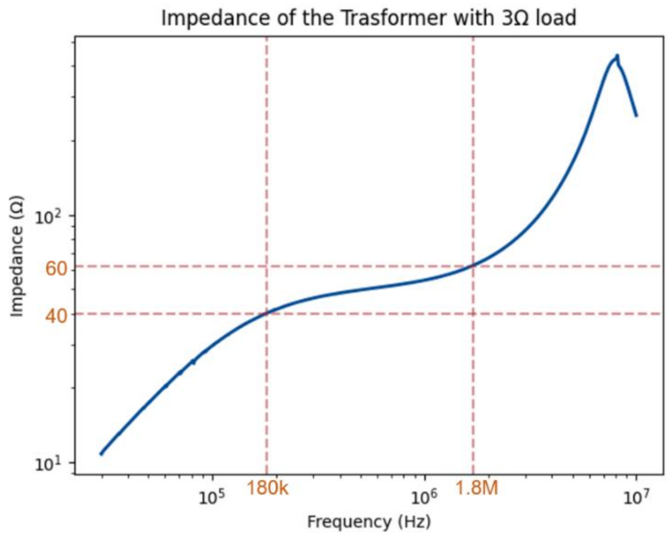

Figure 19: Impedance of the TLT with 3Ω resistor as the load

The transformer has the correct behavior (1:16 impedance ratio) between 180kHz and 1.8MHz, so it cannot be used at 4.4MHz without any modification.
Furthermore, with an oscilloscope and a function generator I have measured the voltage ratio at 1MHz and 4.4MHz (figure 20). At 1MHz the voltage ratio is the one expected, so 1:4, while at 4.4MHz the TLT has a voltage ratio on 1:5, resulting in an impedance ratio of 1:25, which is not the one needed for the impedance matching problem.

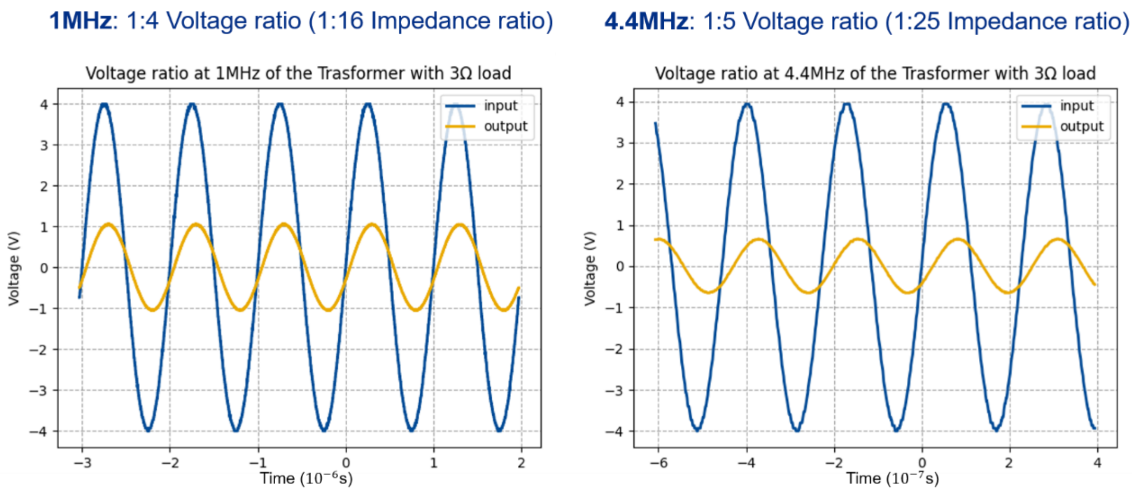

Figure 20: Voltage ratios of the TLT at 1MHz (left) and 4.4MHz (right)

6. Complete System

Figure 21 shows what the schematic of the complete system looks like.

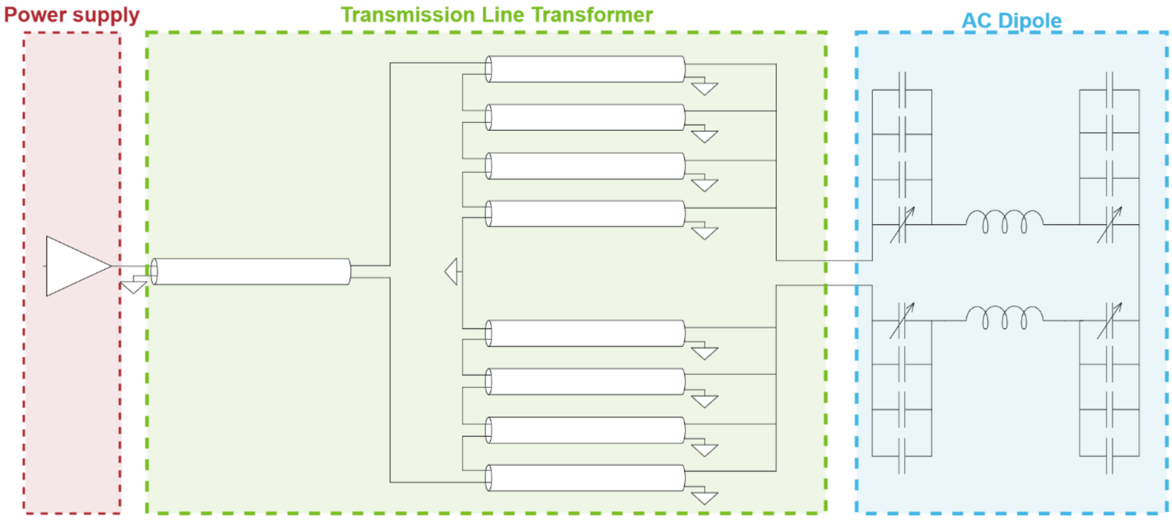

Figure 21: schematic of the complete system

6.1 Impedance analysis

After replacing the 3Ω resistor load with the real magnet, I have re-measured the impedance, as a function of frequency, seen from the TLT (figure 22).

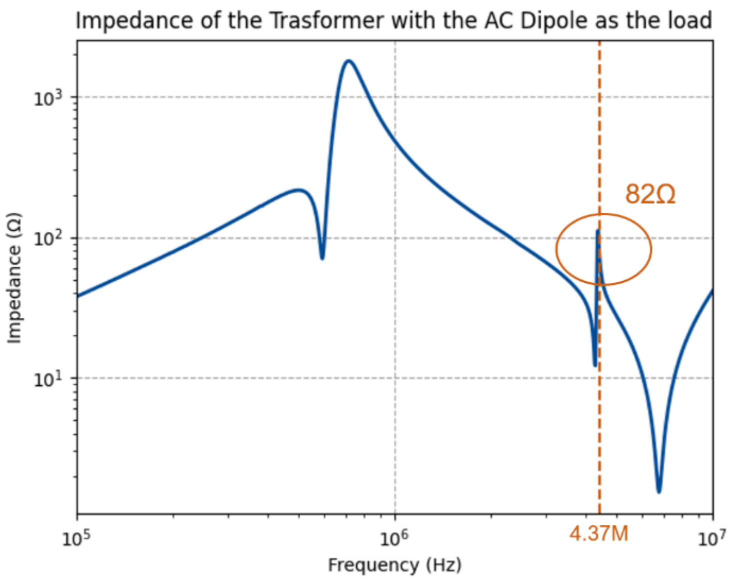

Figure 22: Impedance of the TLT with the magnet as the load

As expected, the impedance at 4.4MHz is not 50Ω but the experimental value is still consistent with the expected one. In fact, the voltage ratio of the transformer at 4.4MHz is 1:5, resulting into an impedance ratio of 1:25, so the 3Ω impedance of the AC Dipole is transformed into something around $3\Omega * 25\Omega = 75\Omega$. Therefore, those measurements are consistent with the ones taken with the 3Ω resistor load, but the TLT needs some work to operate well at the frequency of interest (4.4MHz).

6.2 Future work

All my work has been done on the prototype of the magnet, which is just 1m long (figure 23), while the real magnet will be 3m long (figure 24).

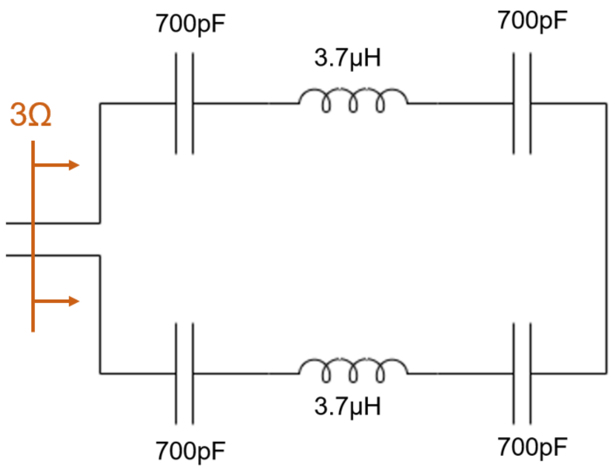

Figure 23: Schematic of the magnet prototype in series with the capacitors for 4.4MHz

It will be like having a series of three 1m magnets, so the impedance will be 9Ω instead of just 3Ω. Therefore, a complete new TLT that matches 9Ω with 50Ω will be needed.

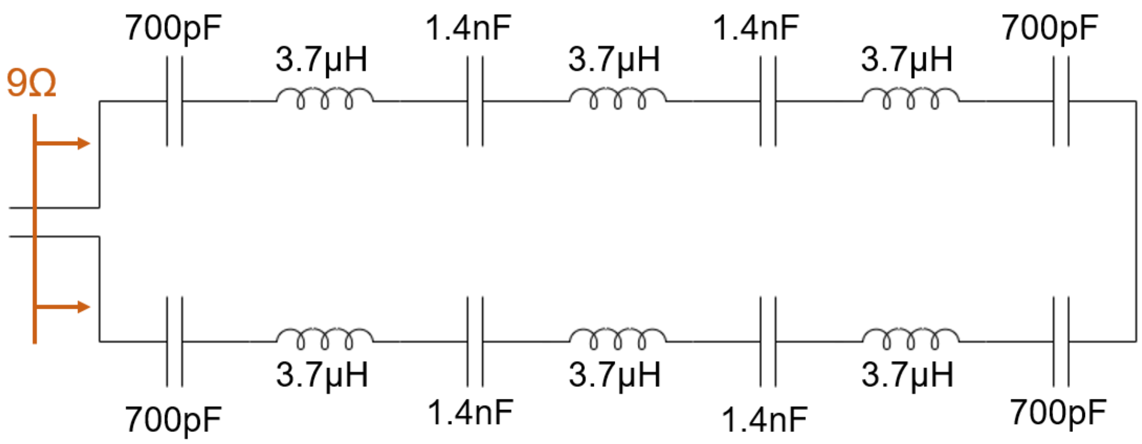

Figure 24: Schematic of the real magnet in series with the capacitors for 4.4MHz

7. Bibliography

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[3] E. J. Prebys and S. Werkema, “OUT OF TIME BEAM EXTINCTION IN THE MU2E EXPERIMENT ∗,” pp. 3–6.

[4] G. V. Velev *et al.*, “Selection tests of MnZn and NiZn ferrites for Mu2e 300 kHz and 5.1 MHz AC dipoles,” *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, 2012, doi: 10.1109/TASC.2011.2176705.