Summer internship at Fermilab
Final report

Ferrites Analysis for the AC-Dipole

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Contents

Abstract

This report is the result of a two months internship in which the author worked in the Technical Division of Fermilab, supervised by Luciano Elementi.

It's presented the AC-Dipole magnet structure and a method to measure and model bricks of ferrite. These are the building blocks of the magnet. Aim of the project is obtaining a model of the magnetic permeability of the chosen material to get satisfying simulation of the AC-Dipole magnet's behavior and to size power supply and cooling system.

1 Mu2e experiment requirements

1.1 The Mu2e experiment

The Mu2e 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. The experiment uses an intense pulsed negative muon beam as starting signal. Cleaning this one is essential to reduce background noise.
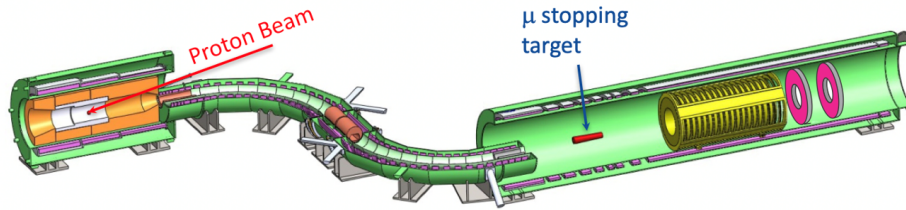
Figure 1: Structure of the Mu2e experiment

1.2 Timing requirements for the proton beam

The mentioned proton beam must respect specific timing conditions in order to reduce the noise during the interval time used for collect data. In Figure 2, the proton pulse is represented in grey, the time window in which takes place the collection of data in red, and other noise sources in different colors.
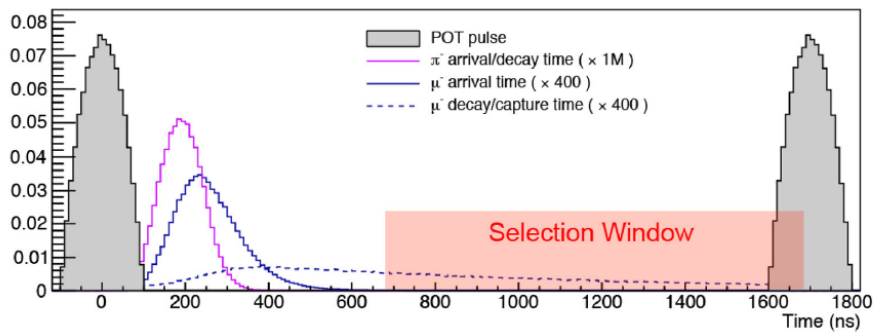

Figure 2: Proton beam timing

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2 AC-Dipole magnet

Referring to Figure 2, it's clear that the proton beam has to be completely stopped during the *selection window*: this is the goal of the AC-Dipole. **The working principle is to create a sinusoidal magnetic field to periodically direct the proton beam towards a collimator only when the pulse is required**. Using a sinusoidal magnetic field, the beam can pass through the collimator only when the magnetic field value is near to zero, condition happening twice during the period of a sine.

2.1 Structure

The AC-Dipole magnet is made by two blocks of thirty ferrite bricks each and a copper tube coil inserted in. In Figure 3, a section of the AC-Dipole is shown: the copper tube is represented in orange and two bricks connected (one is flipped down) in blue. The single brick is shown in Figure 4. To obtain the structure of AC-Dipole magnet, fifteen bricks are set in a row with small gaps between them, a copper tube is positioned as represented in Figure 5 in order to create a coil and, finally, other fifteen bricks are placed on the first ones.
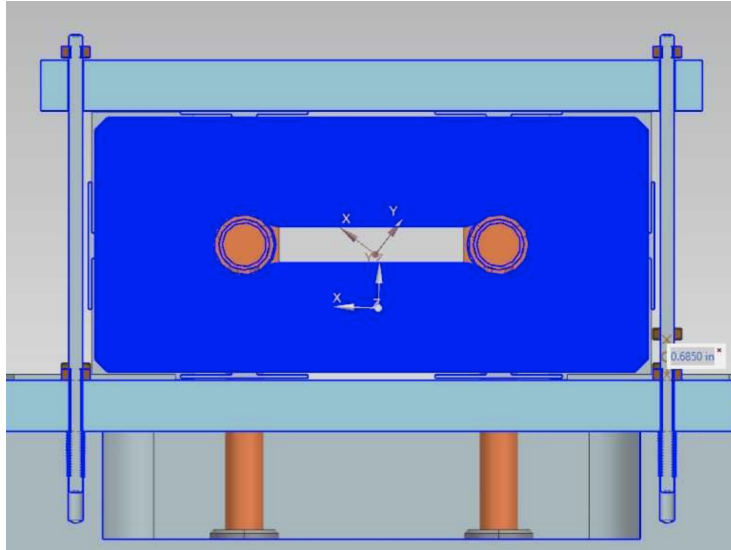
Figure 3: Section of the AC-Dipole
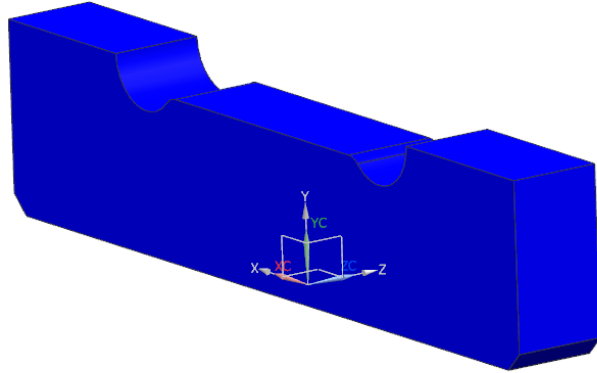
Figure 4: Single brick of ferrite
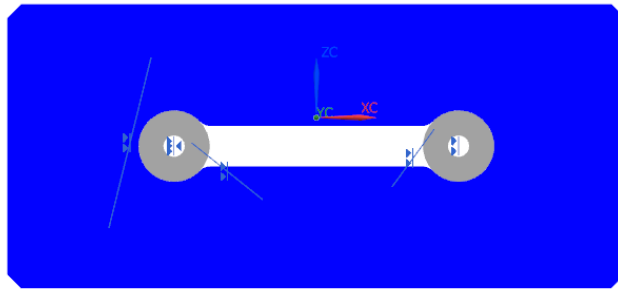
Figure 5: Structure of a block

2.2 Ferrite properties

Ferrite is a compound of iron oxide Fe_2O_3 and other metallic elements. Ferrites can be divided in two families based on their resistance to being demagnetized (called magnetic coercivity): hard (high coercivity) and soft (low coercivity). The project requires a soft ferrite that can easily change their magnetization and act as conductors of magnetic fields in order to concentrate it within the air gap in which the proton beam has to pass.

2.3 Working principle

The main idea is to produce a periodic magnetic field within the air gap of the blocks in order to steer the proton beam and delete it out of the pulse interval. The copper tube is traversed by a sinusoidal current at about 300 kHz. The current induces a magnetic field within the ferrite block and in the air gap (where magnetic field lines close on themselves), according with the Ampere's Law:

$$\oint_{\partial S} \mathbf{H} \mathrm{d}r = \mathbf{I} \tag{1}$$

Through this law it's possible to determinate the **H**-field, not the **B** one because of its dependence on material property. Indeed, the main problem in this article is the complex behavior of **B**-field in ferrite. Once **B** is found, the magnetic force applied to the proton beam can be written using the Lorentz's equation.

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B}) \tag{2}$$

Through this simple formula it's possible to size the system to obtain the exact force needed to direct the proton beam.

2.4 Stimulation frequencies

The AC-Dipole magnet is made by two different groups of blocks, in series. To increase the interval time in which the proton beam pass through the collimator, the second block's contribute is used to plan the magnetic field wave when it is near to zero. The first block is stimulated with a high amplitude sinusoidal current at 295 kHz and the second one with a lower amplitude current at 4.4 MHz. Summing fields of the two blocks, the total magnetic field is a curve of the same period with a smooth profile near to zero as shown in blue in Figure 6.The total magnetic field has these properties because the second frequency is an odd harmonic of the first one: indeed 4.4 MHz is exactly the fifteen harmonic of 295 kHz.
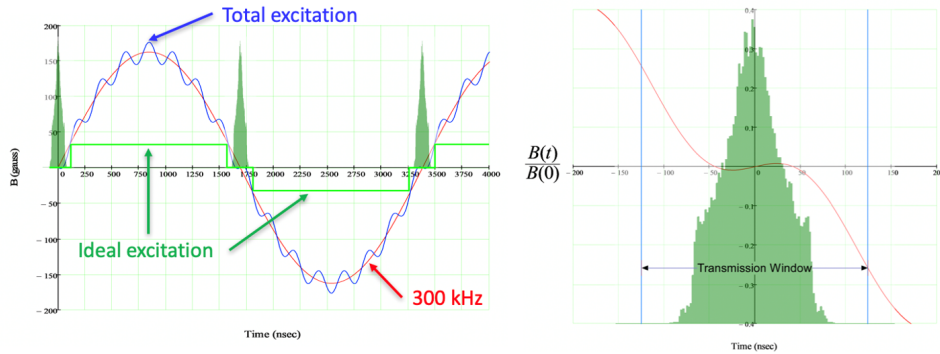

Figure 6: Diagram of magnetic field in the AC-Dipole

In Figure 6 is shown the proton pulse with the timing seen in Figure 2 in green, the first block's magnetic field in red and the total AC-Dipole's magnetic field in blue.

3 Magnetic permeability

The magnetic permeability μ is the measure of the ability of a material to support the formation of a magnetic field within itself. Using **H** for the magnetic field and **B** for the induced magnetic field that consider the magnetization of material, magnetic permeability represents how magnetic field **H** influences magnetic flux density **B** in the medium.

$$\mathbf{B} = \mu \mathbf{H} \tag{3}$$

This property depends on frequency, amplitude of applied magnetic field, position in the medium and other parameters.

3.1 Complex magnetic permeability

While at low frequencies, in a linear material, it's possible to consider linear the relationship between **H** and **B**, at high frequencies there is a phase delay δ between the two fields. Writing them as phasors:

$$H = H_0 e^{jwt} \qquad B = B_0 e^{j(wt-\delta)} \tag{4}$$

From the (3) the magnetic permeability results:

$$\mu = \frac{B_0 \ e^{j(wt-\delta)}}{H_0 \ e^{jwt}} = \frac{B_0}{H_0} \ e^{-j\delta} \tag{5}$$

From the Eulero's formula:

$$\mu = \frac{B_0}{H_0} \cos(\delta) - j\frac{B_0}{H_0} \sin(\delta) = \mu^{'} - j\mu^{''} \tag{6}$$

The real part of the complex permeability is proportional to the inductance of medium and reactive power stored while the imaginary part is proportional to the loss energy.

4 Ferrite behavior

4.1 Choice of the material

There are several types of ferrites, the relevant parameters in the choice of the material for this project are: magnetic permeability, electrical resistivity, hysteresis losses, Curie temperature. One of the best available choice based on these factors is CMD10 material, shown in Figure 7.
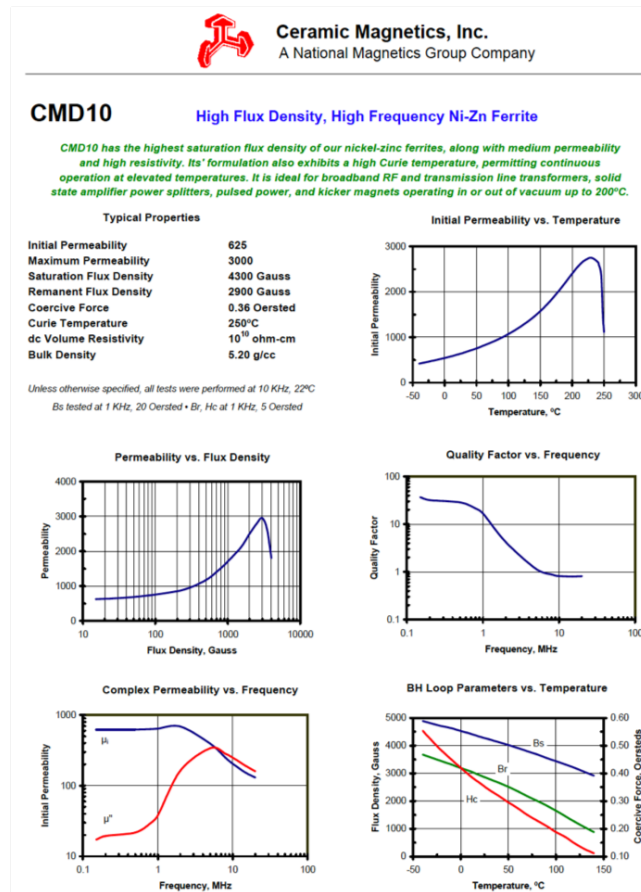

Figure 7: CMD10 datasheet

From data provided by the fabric, CMD10 promises very low losses, both electrical (due to high resistivity) and magnetic (due to low hysteresis losses). Furthermore, CMD10 has a high Curie temperature that reduces the requirements concerning the cooling system.

4.2   Issues in ferrite data

Fabric data have several problems. It's shown the dependence of the real part of magnetic permeability on the amplitude of magnetic field at a certain frequency. It's also represented the dependence of real and imaginary part of magnetic permeability on the frequency but at a certain magnetic field amplitude. **To completely understand the behavior of the material, the 3D characteristic of the complex magnetic permeability dependence on both magnetic field amplitude and frequency simultaneously is necessary.** This means that fabric data are insufficient to a complete analysis of the magnetic properties of blocks. Furthermore, instead of the material expected from fabric data, blocks of ferrite arrived have a different behavior: fabric tests material on small rings that don't have the same behavior of bigger blocks needed for the AC-Dipole magnet. There are a lot of differences even between batches of the same material. Because of these issues, **the aim of the project is to obtain a measure of complex magnetic permeability at different levels of magnetic field amplitude at the interested frequency.**

5 Measuring ferrite bricks

To obtain a ferrite model, firstly blocks must be measured. There are two different ways to do it: dipole and toroidal mode, shown in Figure 8.

(a) Dipole mode   (b) Toroidal mode

Figure 8

5.1 Dipole mode

Dipole mode is the way in which blocks have to work when they will be mounted in the AC-Dipole magnet. In this situation, a sinusoidal current through the copper tube excites the block and produces a magnetic field around the two circular regions in the block's shape.

5.2 Toroidal mode

Toroidal mode is another way to excite blocks and has two advantages: there is no air gap through the path of magnetic field and it's easier to obtain higher magnetic field amplitude with low excitation voltage. Also in this situation, a sinusoid current through the coil excites the block but the whole path of magnetic field is contained in it.

5.3 Measurement circuit

In Figure 9, it's represented the circuit used to take measures of the blocks. On the left side, there are a waveform generator, an amplifier and a 50 Ω resistance (to adjust the output impedance seen by the amplifier). The aim of the coupling network is to block DC-current. There are some capacitors in parallel with the ferrite block(and its own eddy resistance), their function is to realize a LC couple in order to minimize the loss current produced by the amplifier obtaining the resonance between the inductance of the block and capacitors. Using two amperometers and one volltmeter, it's possible to measure current produced by the amplifier (only the part passing through the LC couple), current and voltage between block terminals (ignoring the voltage between eddy resistance terminals).
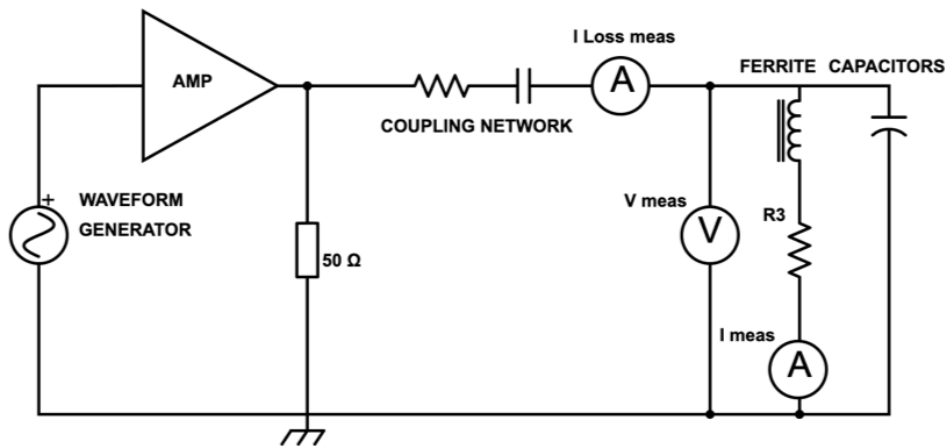
Figure 9: Measurement circuit in Dipole mode

During the project, the measurement environment changed. In the new one, because of availability issues, measures are done without the 50 Ω resistance and the coupling network, this didn't produce considerable changes in results.

5.4 Measures

The goal of the measurement process is to evaluate magnetic field and losses at different excitation levels but at a fixed frequency. To increase the magnetic field induced in the block, it's necessary just to increase the amplitude of the wave produced by the waveform generator, considering that amplifier has a fixed gain.

Figure 10: Signals measured by oscilloscope
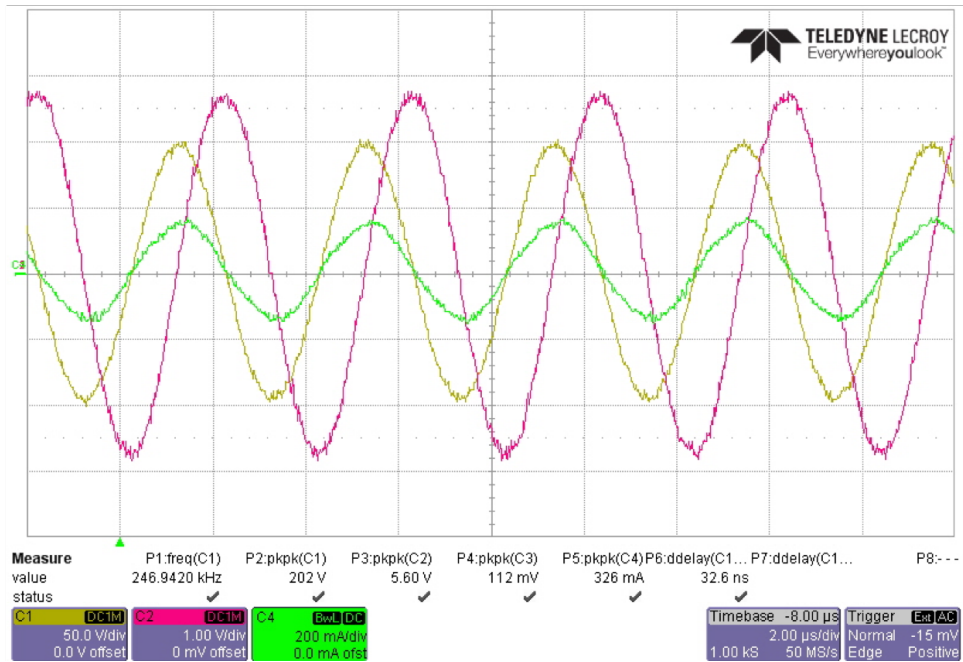
An example of signals measured by the oscilloscope at a certain excitation level is shown in Figure 10. Yellow and pink traces represent respectively voltage and current at the terminals of the inductor. The green one shows the current produced by the amplifier that passes through the LC couple, this is called Loss current because it's the responsible of losses in ferrite. Yellow and pink traces has a phase delay of 90° because of the inductor law, while loss current and voltage have a null phase delay because in the right resonant frequency, condition in which loss current is as lower as possible.

5.5 Data recording

Using a simple worksheet, it's possible to calculate the inductance and the power losses of the block. In Figure 11, an example of measures and subsequent elaborations is shown.

	meas	1/(2*freq)	meas	Vc/2	meas	(Vc*I1/2)/loss	
	freq	sec	Vc	OneTurn V	I1	Q	L (H)
							Vc/(2*pi*freq*I1)
CMD10	[Hz]		[pk-volts]	[pk-volts]	[pk-amps]	[pk-volts]	
"50V"	2.532E+05	1.974E-06	24.2	12.1	0.70100	45.56	2.166E-05
"100V"	2.494E+05	2.005E-06	49.9	25.0	1.44000	28.86	2.213E-05
"200V"	2.469E+05	2.025E-06	101.0	50.5	2.80000	20.26	2.326E-05
"500V"	2.533E+05	1.974E-06	251.0	125.5	5.89000	8.69	2.679E-05
5005							
"50V"	2.433E+05	2.055E-06	25.0	12.5	0.26500	14.35	6.163E-05
"100V"	2.477E+05	2.019E-06	49.6	24.8	0.48950	9.45	6.514E-05
"200V"	2.537E+05	1.971E-06	99.0	49.5	0.89500	6.82	6.942E-05
"300V"	2.488E+05	2.009E-06	152.0	76.0	1.57000	6.41	6.196E-05
"500V"	2.528E+05	1.978E-06	253.0	126.5	2.37000	4.34	6.725E-05

	Vc/1.571	meas	Vcav*(T/2)/N*area	(Vc*I_R)/2	Point-to-Point		B-Loop
	V av	I R meas	delB	Loss	Loss	loss/m*m*m	delB
CMD10	[volts]	[pk amps]	[Gauss pk-pk]	[watts]	[watts]	[watts]	[Gauss_pk-pk]
"50V"	15.374	0.025	30	0.3	0.18578341	71	30
"100V"	31.767	0.058	62	1.4	1.24471	477	62
"200V"	64.299	0.163	128	8.2	6.97767	2,676	128
"500V"	159.792	0.698	309	87.5	85.10816	32,638	309
5005							
"50V"	15.884	0.023	32	0.3	0.23043	88	32
"100V"	31.576	0.060	62	1.5	1.28470	493	62
"200V"	63.025	0.147	122	7.3	6.49149	2,489	122
"300V"	96.766	0.269	191	20.4	18.61279	7,138	191
"500V"	161.065	0.583	312	73.7	69.14820	26,518	312

			Core Parameters			
		N	core area	Path length	Core volume	Resonant
		turns	[m*m]	[m]	[m*m*m]	Capacitance
	"1.2cm"	2	5.10E-03		0.00261	

Figure 11: Example of worksheet with measures

Since the signals are sinusoidal waves, voltage and current amplitudes are related by the inductance of the block: indeed it's possible to obtain the inductance having voltage and current measured by the next formula.

$$\frac{V_{peak}}{I_{peak}} = 2\pi f L \tag{7}$$

To gauge losses in ferrite block, it's possible to average the product of current loss and voltage measured on a period as written in the next formula.

$$P_{loss} = \frac{1}{T} \int_T V_c \, I_{loss} \, \mathrm{d}t \tag{8}$$

These measures will be useful to model the magnetic permeability of blocks.

6 Modelling ferrite bricks

Once blocks are measured, it's useful to obtain a model for real and imaginary part of magnetic permeability in order to simulate the behavior of ferrite in conditions different from the measured ones.

6.1 Comsol MultiPhysics environment

Comsol Multiphysics is a finite elements simulation software. Defining the geometry and placing the constitutive equations of electromagnetism, software simulates the situation defined by the user in a virtual environment and obtains interesting results like the magnetic field distribution within the material.
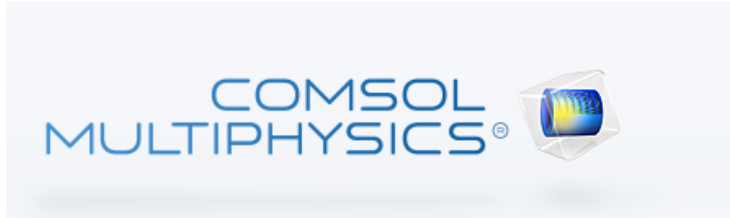

Figure 12: Comsol Multiphysics logo

6.2 Relation between B and μ

The main concept of this work is the relation between B and μ. As written in the previous paragraphs, the real part of **magnetic permeability has a strong dependence on magnetic field** amplitude. The issue is that, by the magnetic induction formula, **magnetic field amplitude depends on magnetic permeability**. This dependence "circle" doesn't allow an easy reconstruction of material's magnetic permeability.

6.3 Obtaining μ from measures

By measuring ferrite blocks and applying the 7, the block's inductance is calculated. This is a measure of the total magnetic flux through the ferrite. This calculation contains a precious information but not enough to obtain the complete function of the real part of magnetic permeability depending on magnetic field. As said before, the real part of magnetic permeability is the ability of a material to produce a magnetic field within itself but the value is not constant in the volume because of the different local values of magnetic field. **To obtain a model of real part of magnetic permeability, the way used is to estimate a likely function of μ depending on B (firstly using function present in fabric data), simulate the geometry on Comsol with this model and adjust finely this function in order to fit the measures previously obtained.** Inserting in Comsol the model of μ depending on B,

the software is able to calculate magnetic field amplitude point to point in the whole volume: simply integrating the magnetic flux through a section of the block it's obtained the simulated induction of the block that must coincide with the measured one.

The imaginary part of magnetic permeability, instead, takes account of the power losses within the material depending on the magnetic field amplitude. Therefore, after the determination of magnetic flux point to point, it's possible using the same method expained before (simplified because in this case there is not a dependence circle: an increase in losses doesn't affect the magnetic flux). An example of magnetic field distribution obtained using Comsol Multiphysics is shown in Figure 13.
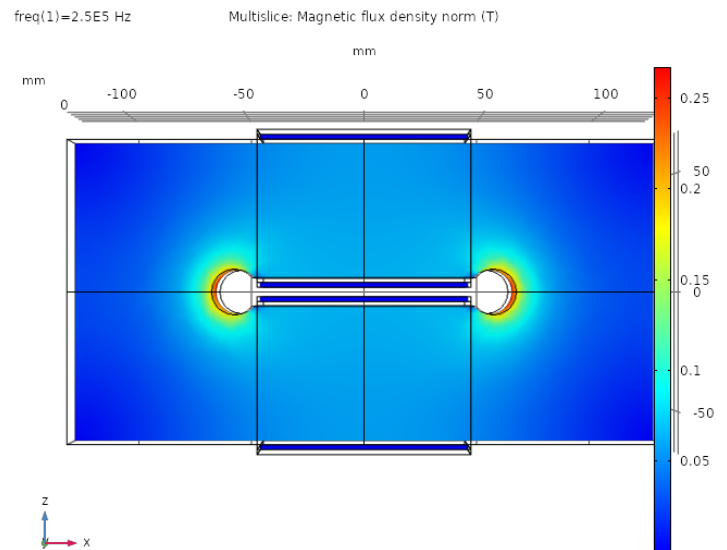

Figure 13: example of magnetic field distribution in the block

As said before, magnetic flux is concentrated around the two circular gaps in the block's shape. magnetic field amplitude increases from blue to red in Figure 13.

6.4 Iterative method

To model μ it's used an iterative method. Starting with very low excitation measures it's possible to determinate the almost constant value of μ at very low level of B. Increasing step by step the excitation voltage, total magnetic flux increases and in the regions near the external surface, where magnetic flux is more concentrated, the value of μ is the correct continuation of the μ characteristic for higher B. To simplify this method, it's possible to approximate

μ with a low grade polynomial function. Using this method the parameters to set are only grade and coefficients of the polynomial that can vary in order to fit the measures. The same method was applied to model the imaginary part of μ and fit the power losses measures previously obtained.

6.5 Resulting model

During the measured, the maximum magnetic field amplitude reached was 2700 Gauss (0.27 T), therefore the model of μ obtained fits measures and has sense only until this limit. The model obtained are shown in the next figures.
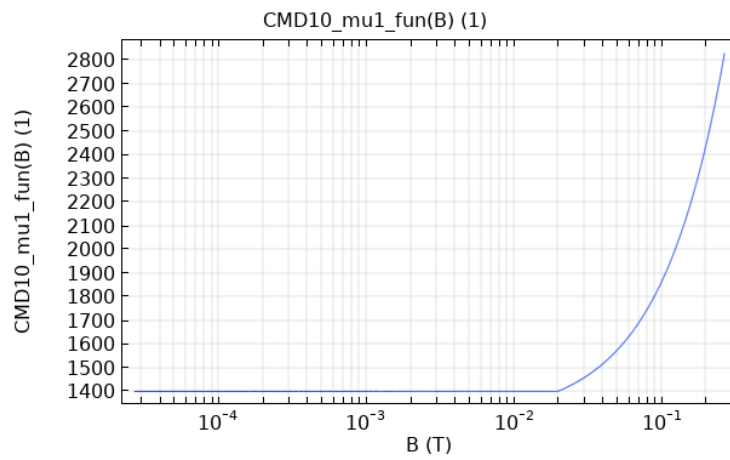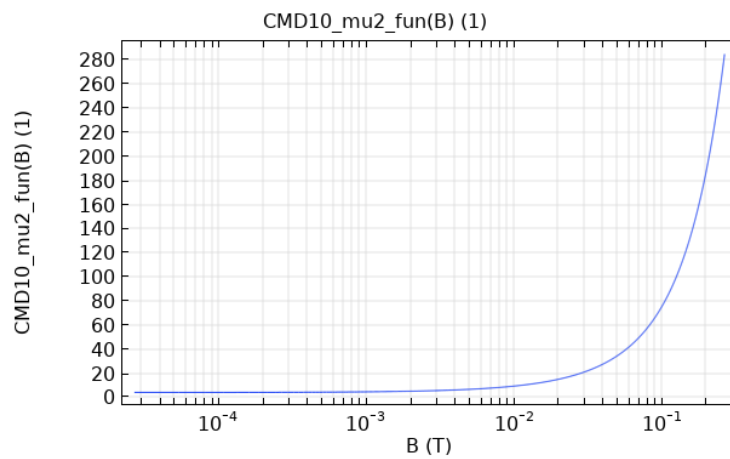
Figure 14: Model of real part of μ

Figure 15: Model of imaginary part of μ

In these two graphs, it's shown the strong dependence of magnetic permeability μ on magnetic field amplitude. The model obtained is linear for the real part and quadratic for the imaginary part of μ. To give an idea, inductance and power losses simulated using these models have a maximum difference from the measured ones less than 10%.

7 Further steps

Models presented in the previous paragraph are not an arrival point. There is the need to extend the model until the maximum magnetic field required for the correct functioning of AC-Dipole magnet (about 0.6 T) using the same procedure presented in this article.

7.1 Obtain acceptable boundaries

The previous analysis has as a second aim: obtaining acceptable boundaries for real and imaginary part of μ in order to give to the fabric specific parameters to meet to satisfy requirements for AC-Dipole magnet. These boundaries can be obtained manipulating the models until the power losses simulated are less than the maximum affordable by power supplier and cooling system.

7.2 Simulation using the model

Once obtained a complete and working model for the material, the behavior of each single block can be simulated and a specific order in the series of blocks in the AC-Dipole magnet can be decided to obtain better performance.