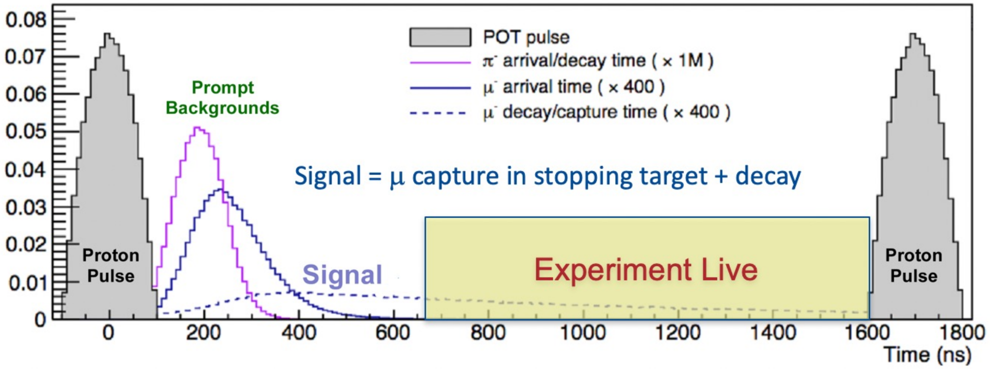
# Ferrites analysis for the AC-Dipole magnet

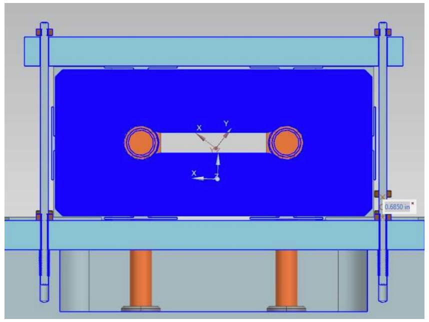
Corrado Comino
Summer Internship Final Presentation
09 / 25 / 2019

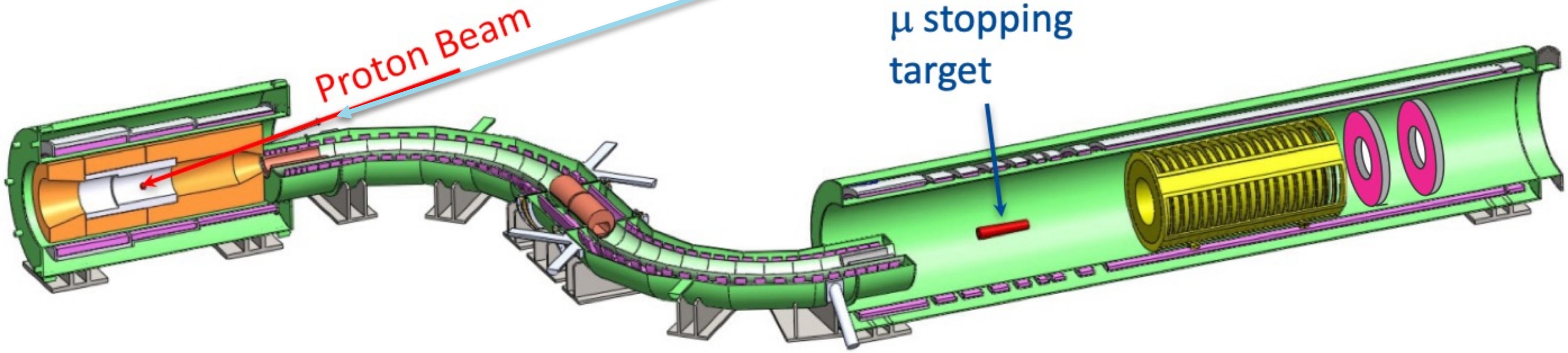
# Mu2e Experiment

The first part of mu2e experiment needs a low noise pulsed proton beam: AC – Dipole magnet is made to satisfy this requirement.



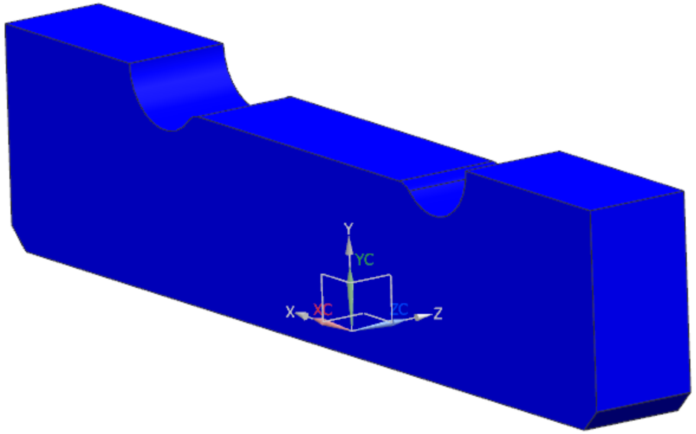
AC - Dipole

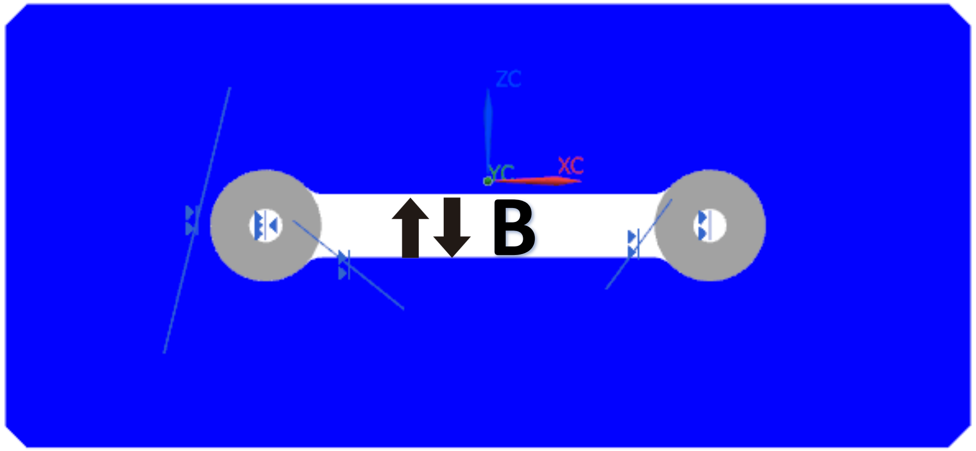




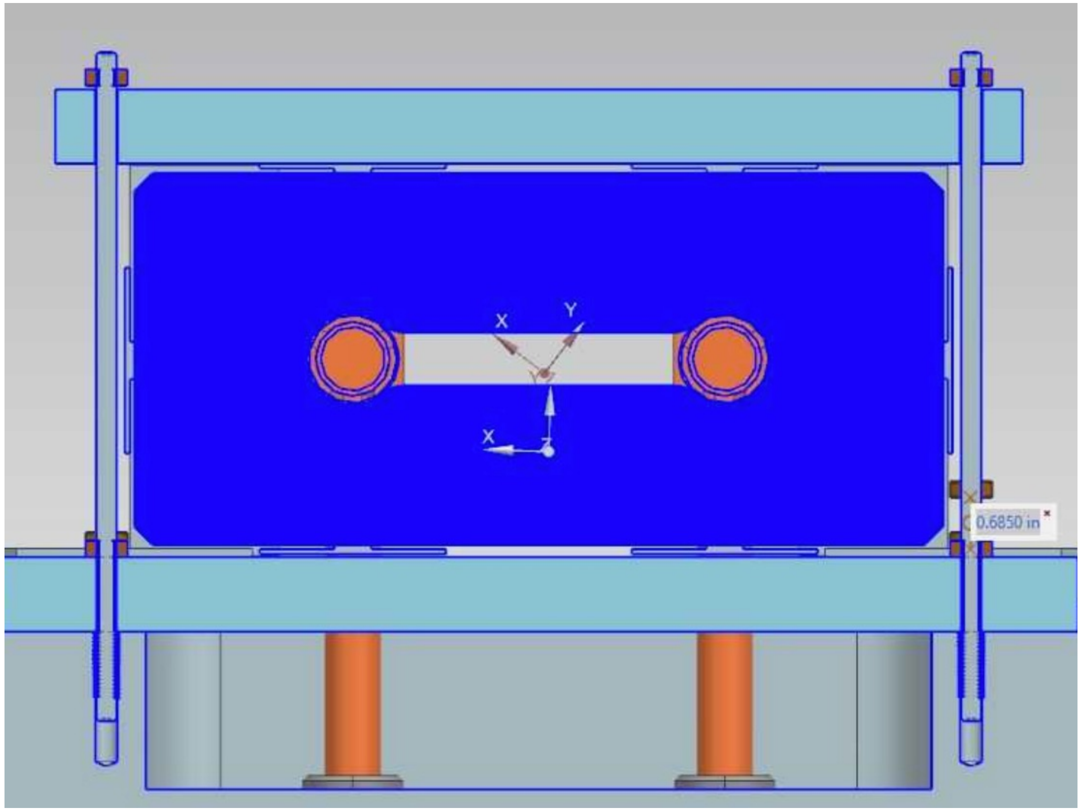
# AC-Dipole magnet

- AC- Dipole magnet is made by a row of bricks of ferrite (ferromagnetic material)
- Coil: single turn of copper tube
- Periodic magnetic field induced by the current through the tube
- AC-Dipole magnet steers the beam periodically to a collimator (a small opening)

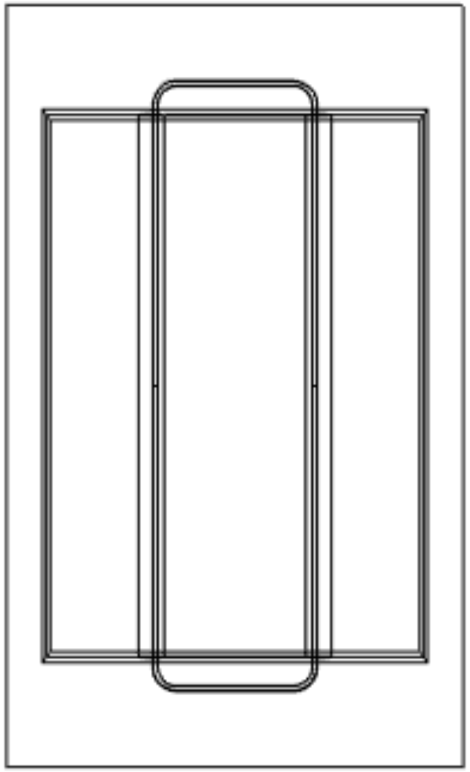




# AC-Dipole magnet



Cross section



Top view

# Magnetic Permeability

The magnetic permeability is the measure of the ability of a material to support the formation of a magnetic field within itself.

$$\boldsymbol{B} = \mu \boldsymbol{H}$$

While at low frequencies this is a linear relationship, at high frequencies there is a phase delay between *B* and *H*.
Writing as a phasors:

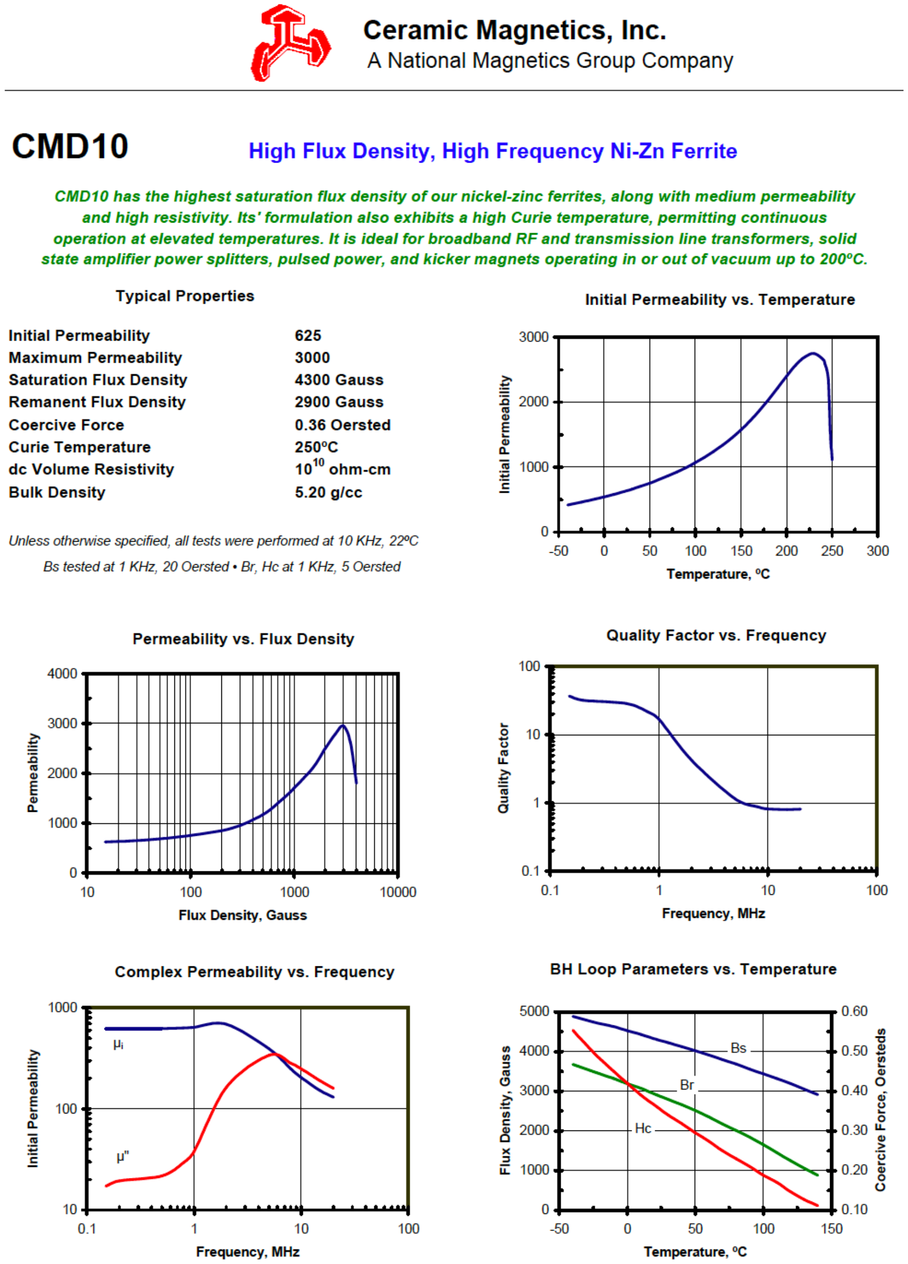
$$\boldsymbol{B} = B_0 e^{j\omega t} \qquad \boldsymbol{H} = H_0 e^{j(\omega t - \delta)}$$

The phase displacement is the responsible of losses. The imaginary part of the magnetic permeability takes account of this phenomenon:

$$\mu = \mu' - j\mu''$$

# Issues

- CMD10: high resistivity and low losses ferrite
- Different batches have different behaviour of ferrites
- Factory data don't fit the measures (fornitors use a small ring to evaluate $\mu$)
- $\mu \propto B, f$



**Ceramic Magnetics, Inc.**
A National Magnetics Group Company

## CMD10

**High Flux Density, High Frequency Ni-Zn Ferrite**

***CMD10 has the highest saturation flux density of our nickel-zinc ferrites, along with medium permeability and high resistivity. Its' formulation also exhibits a high Curie temperature, permitting continuous operation at elevated temperatures. It is ideal for broadband RF and transmission line transformers, solid state amplifier power splitters, pulsed power, and kicker magnets operating in or out of vacuum up to 200ºC.***

**Typical Properties**

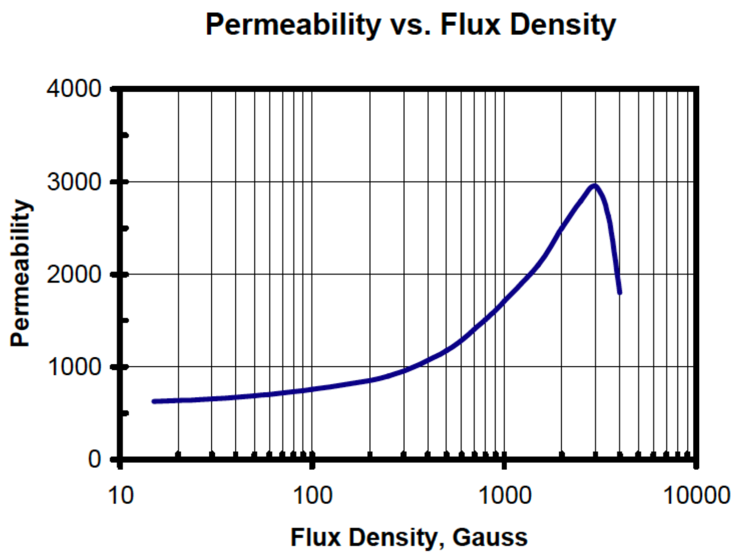
| | |
|---|---|
| **Initial Permeability** | **625** |
| **Maximum Permeability** | **3000** |
| **Saturation Flux Density** | **4300 Gauss** |
| **Remanent Flux Density** | **2900 Gauss** |
| **Coercive Force** | **0.36 Oersted** |
| **Curie Temperature** | **250ºC** |
| **dc Volume Resistivity** | **$10^{10}$ ohm-cm** |
| **Bulk Density** | **5.20 g/cc** |

*Unless otherwise specified, all tests were performed at 10 KHz, 22ºC*

*Bs tested at 1 KHz, 20 Oersted • Br, Hc at 1 KHz, 5 Oersted*

# Ferrites Parameters

- ❑ Low excitation permeability $\mu$



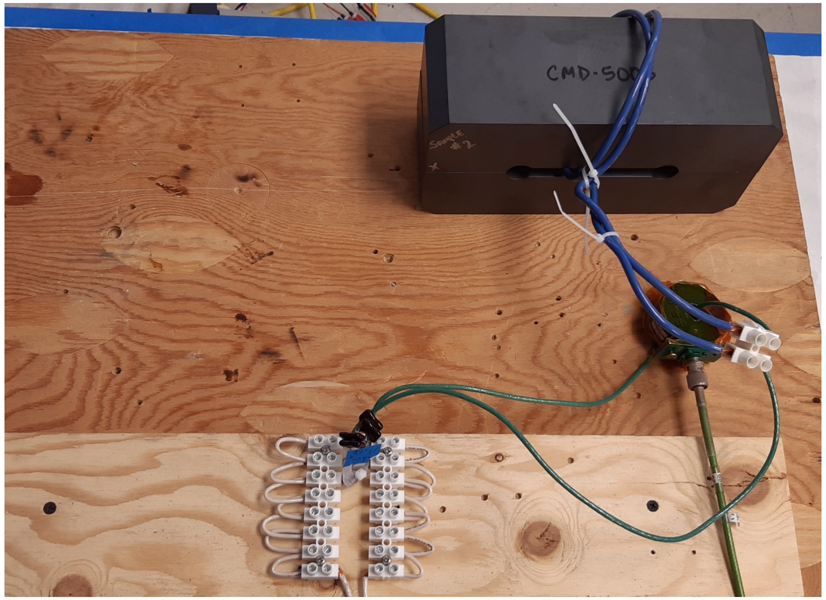
**Mostly interested in losses**

- ❑ Low excitation quality factor $Q$
- ❑ Quality Factor at 1000 Gauss

$$Q = \frac{stored\ energy}{energy\ loss}$$

# Work steps

- Measure ferrites
- Model the magnetic permeability $\mu$ of bricks
- Define acceptability boundaries for brick's power loss and magnetic field



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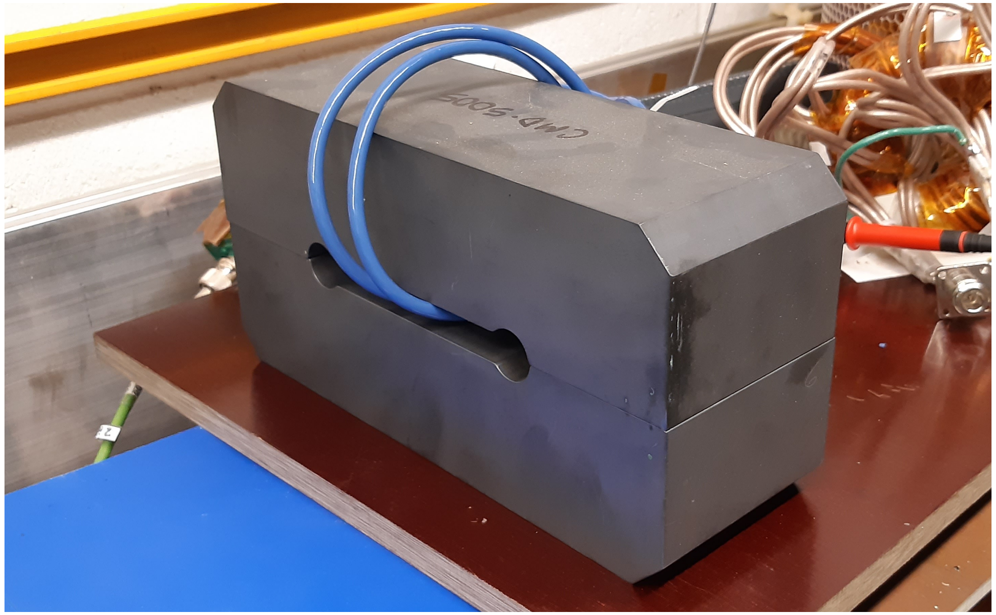
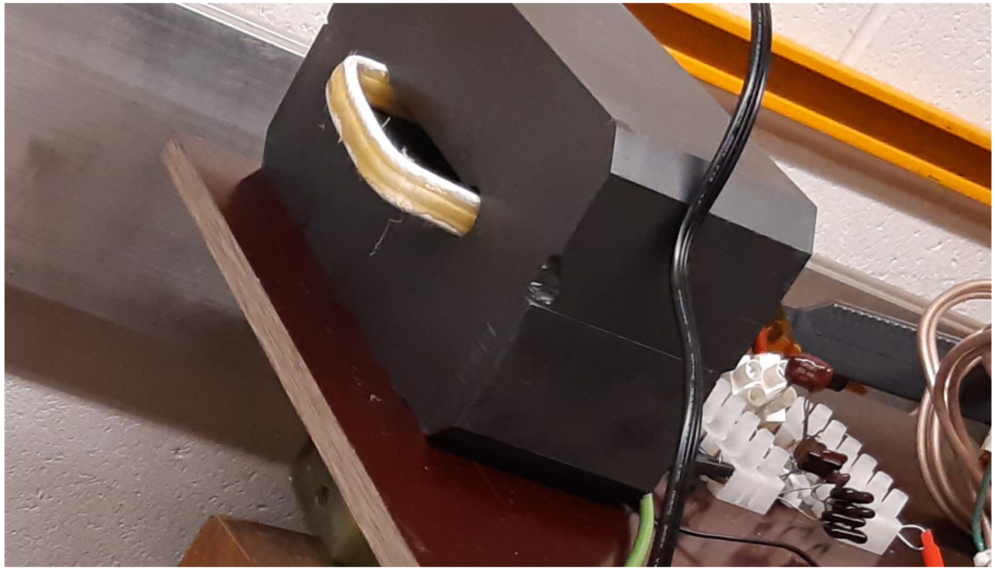
# Measurement Circuit

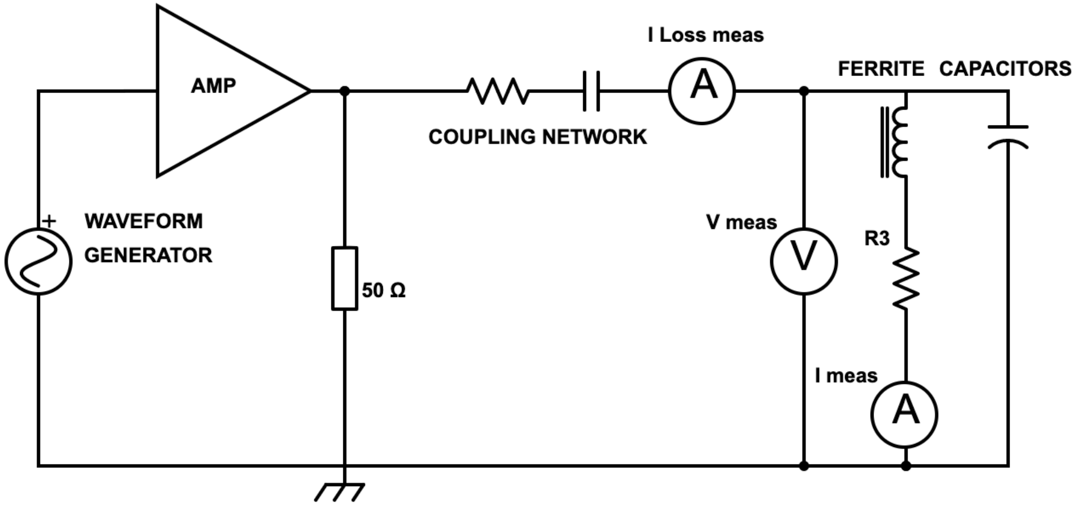


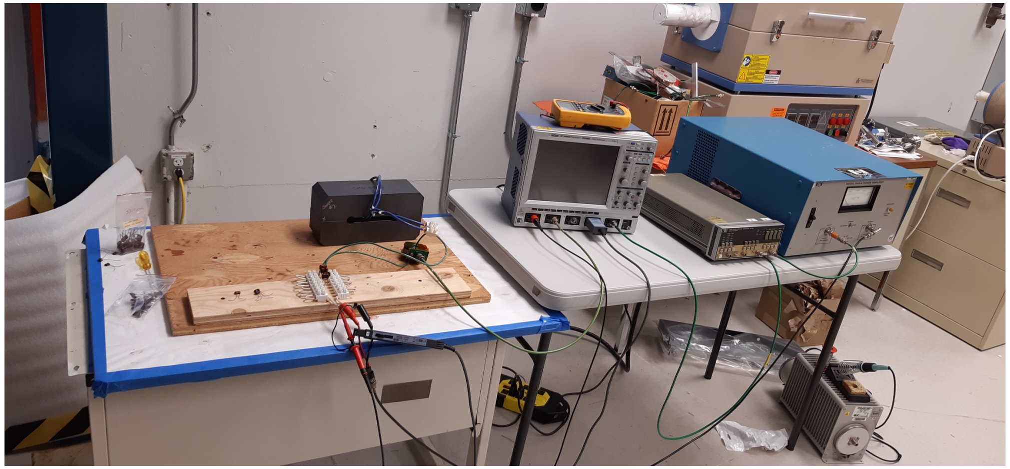


- Dipole Mode vs Toroidal Mode
- Toroidal Mode (no gap measure) to obtain measures to model
- Dipole Mode to verify the model $\mu$

# Measurement Circuit

- ❑ Capacitors to obtain resonance with ferrites
- ❑ Measures taken in resonant condition
- ❑ $I_{meas}$ current inducing the magnetic field
- ❑ $V_{meas}$ voltage at the ferrite terminals
- ❑ $I_{loss}$ current producing power loss



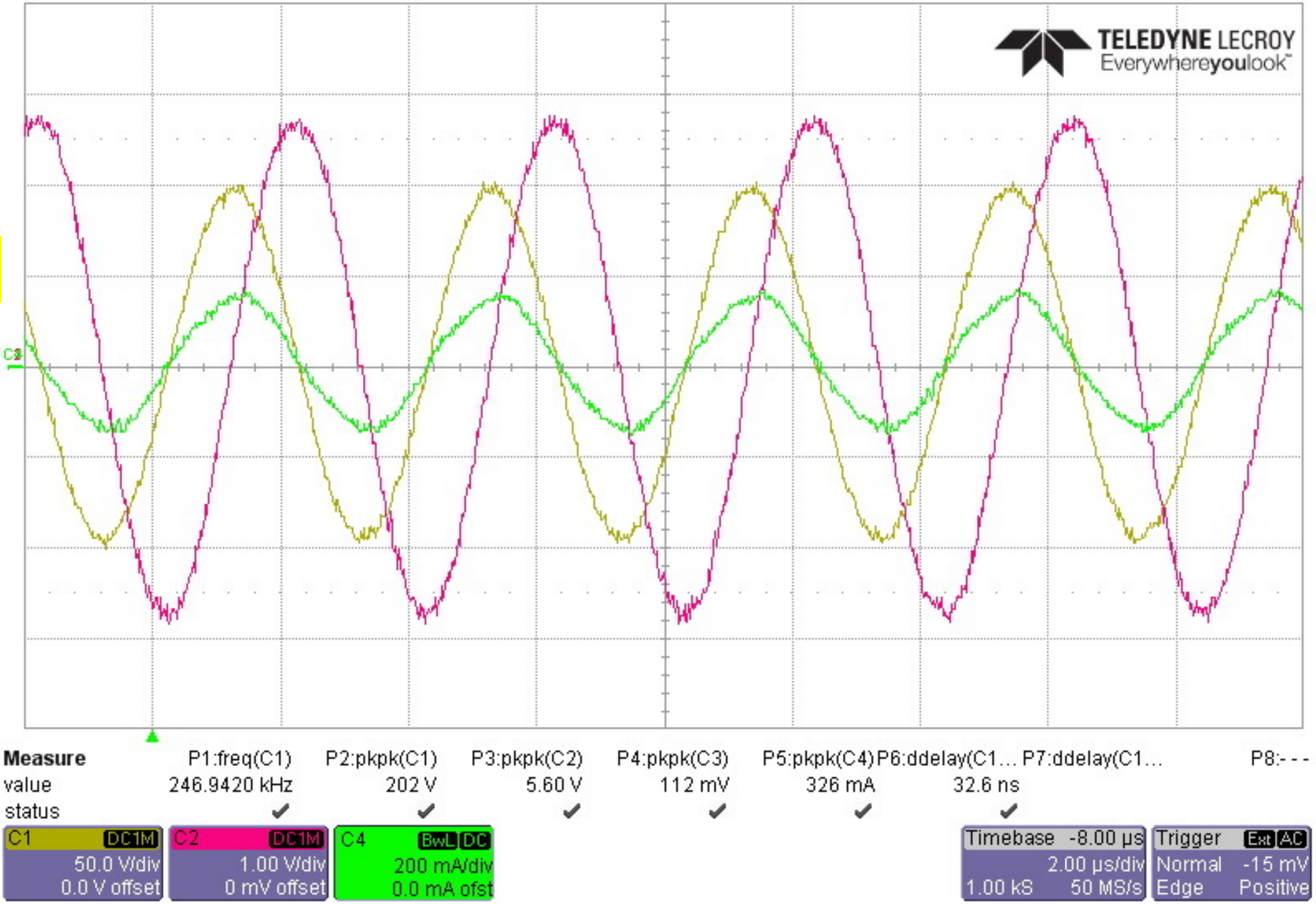


# Measures

$V_{meas}$

$I_{meas}$

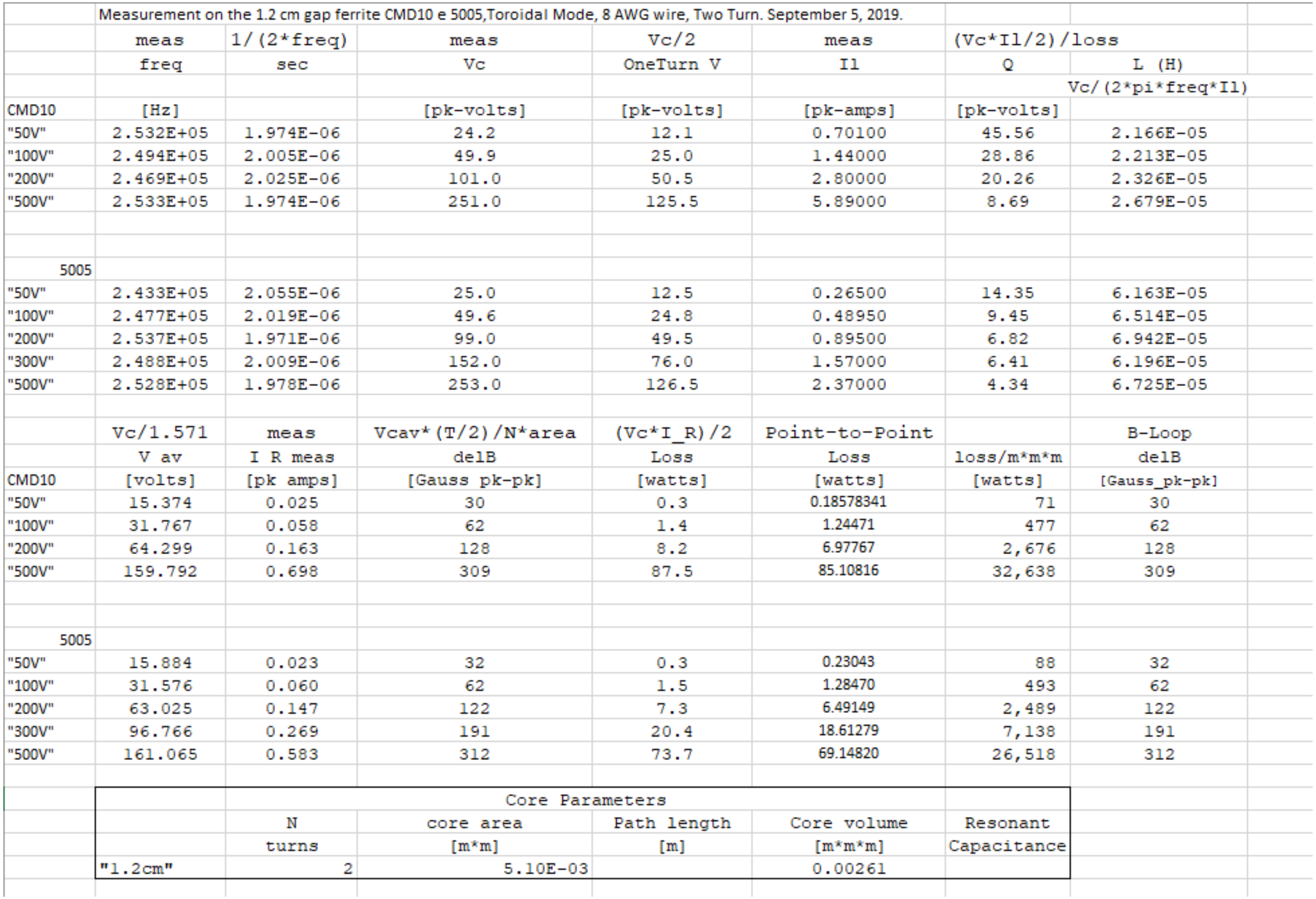
$I_{loss}$



```
Measure      P1:freq(C1)   P2:pkpk(C1)   P3:pkpk(C2)   P4:pkpk(C3)   P5:pkpk(C4) P6:ddelay(C1... P7:ddelay(C1...        P8:- - -
value        246.9420 kHz        202 V        5.60 V        112 mV        326 mA        32.6 ns
status                  ✓             ✓             ✓             ✓             ✓             ✓
```

```
C1       DC1M    C2       DC1M    C4       BwL DC        Timebase   -8.00 µs   Trigger     Ext AC
    50.0 V/div       1.00 V/div       200 mA/div                  2.00 µs/div   Normal    -15 mV
   0.0 V offset      0 mV offset      0.0 mA ofst        1.00 kS     50 MS/s    Edge     Positive
```

# Measures



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Measurement on the 1.2 cm gap ferrite CMD10 e 5005,Toroidal Mode, 8 AWG wire, Two Turn. September 5, 2019. | | | | | | |
| | 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 | |

# Model $\mu$

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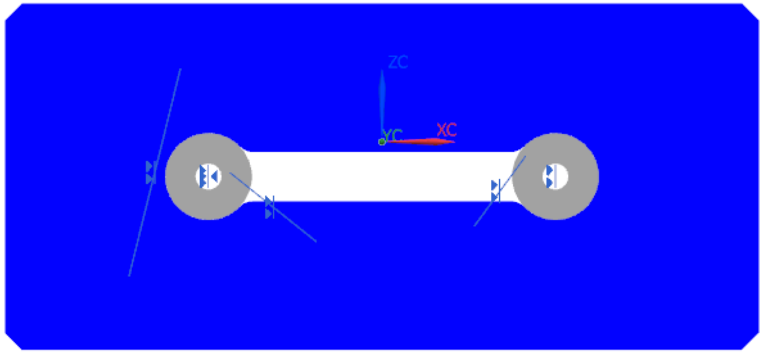
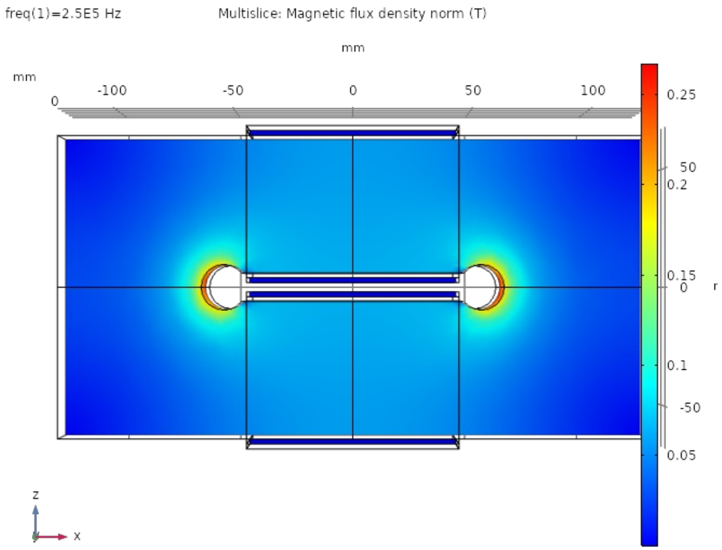
- ❑ COMSOL Multiphysics
- ❑ Design of ferrite bricks
- ❑ Simulation of magnetic field within the brick varying current through the coil





# Model $\mu$

- Iterative method: modelling $\mu$’ and $\mu$’’ in order to fit measures
- Small measures steps to finely track the magnetic permeability behaviour
- Increasing $\mu$’, magnetic flux increases
- Increasing $\mu$’’, power loss increases

Low excitation ($B_{max}$ 200G)

↓

$\mu$’ and $\mu$’’ until 200G (almost constant)

↓

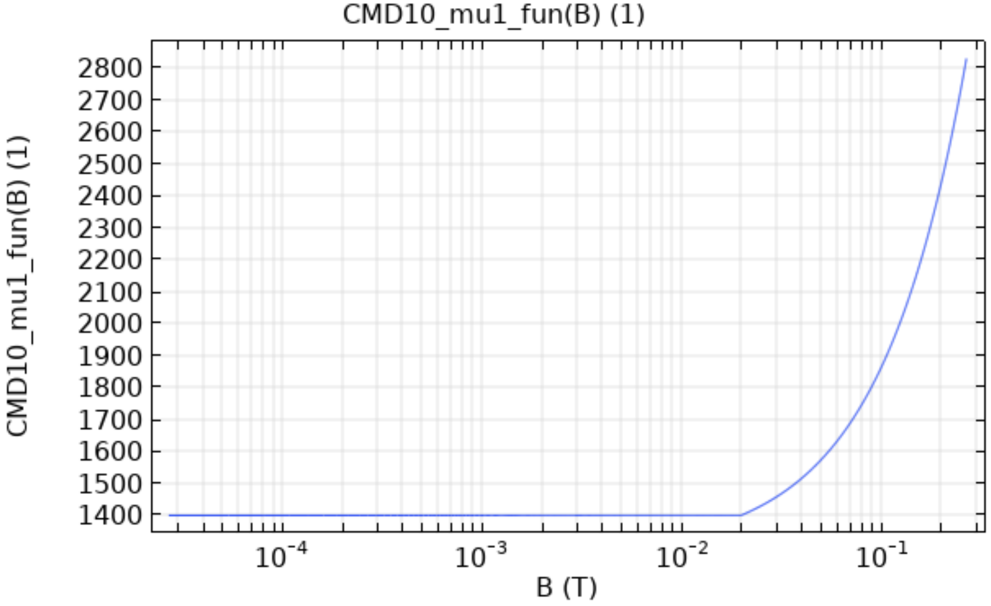
Slowly increasing B

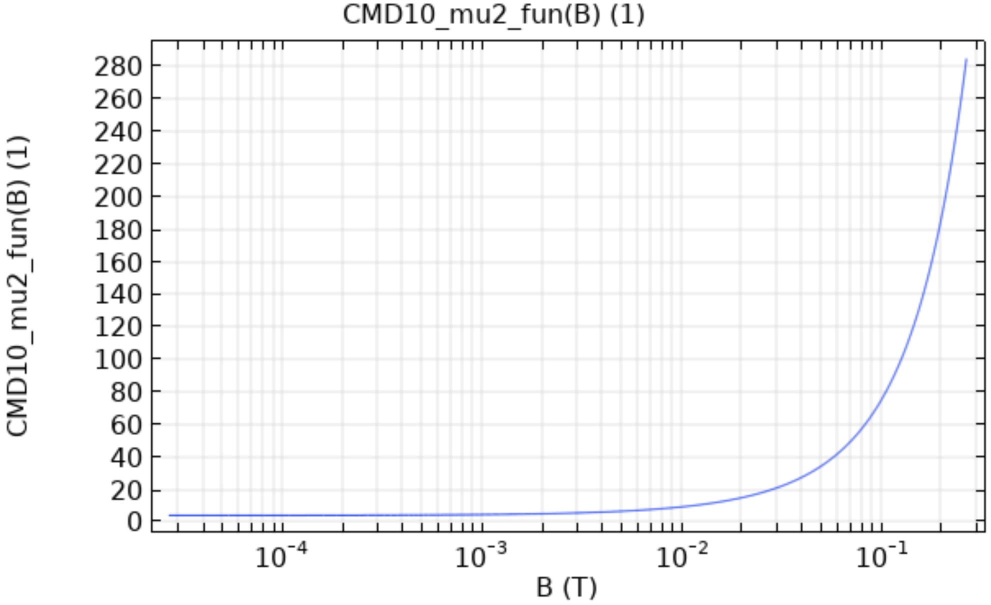
↓

Refine $\mu$’ and $\mu$’’ to fit the measures

# Resulting Model

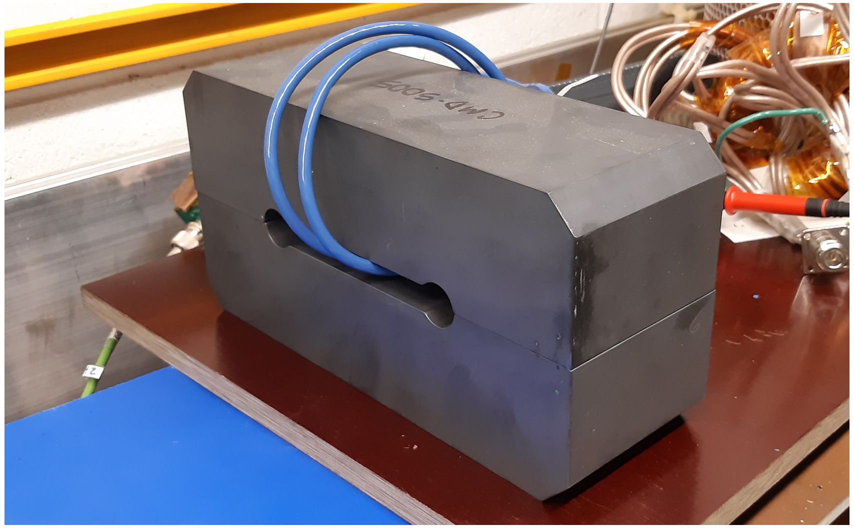
- The maximum magnetic field measured is 2700G (equal to 0.27 T)
- $\mu'$ modelled with a linear function of B under $B_{max}$
- $\mu''$ modelled with a quadratic function of B under $B_{max}$
- These models fit magnetic field and losses measures with less than 10% of error



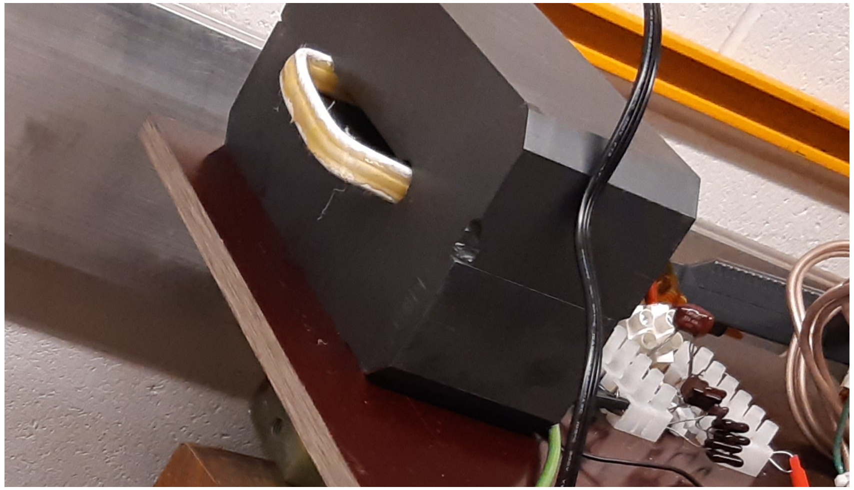


# Using the model

- Fringe Effect evaluation



- Dipole Mode behaviour



# Thank you for your attention

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