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Magnetic Field Measurements in a Transmission Line Kicker Magnet

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Abstract

Kicker Mangets are a very specific class of Magnet. They are pulsed dipole magnet with a very fast rise time. In this report Magnetic Field measurements of a RKA0003 Kicker Magnet will be reported and further analysis will be presented.

Contents

Chapter 1

Kicker Magnet

In the last two decades of Particle Physics, accelerator had the main role in the scene, as with them thousands of scientists and engineers could look inside matter. In particular circular accelerator became one of the biggest machine which human kind has ever built. In this type of accelerator particle has to be steared and in order to do that we have to supply high intensity magneti field. At the end of the picture magnets have an essential role: dipole, quadrupole, octupole and so on...
In an accelerator periodic refilings of particles are needed in order to reach high energy. These are obtained by beam transfer, in and out the machine. One specific class of magnet are *kicker magnet.* They could perform several differents actions: beam injection, beam extraction and beam clearing.

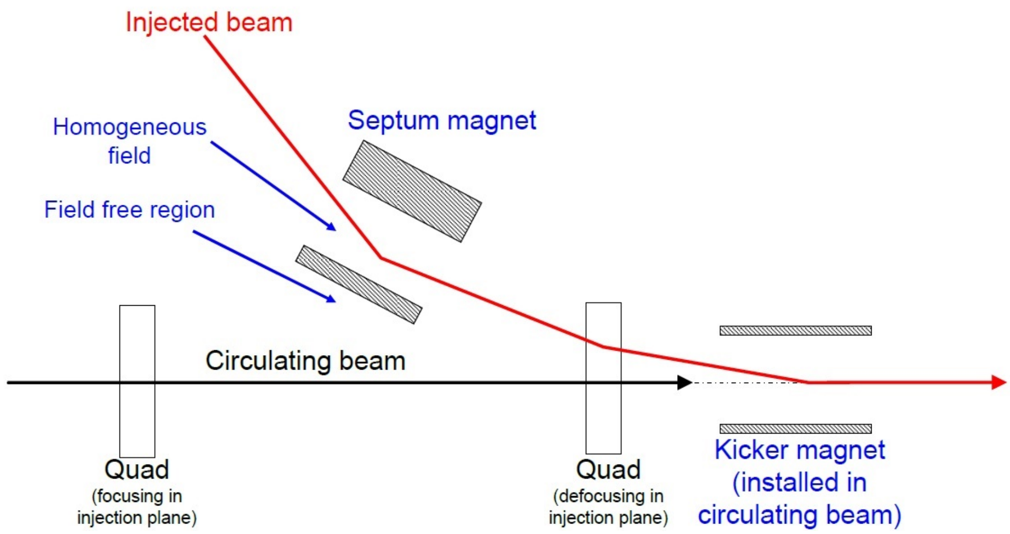


Figure 1.1: Injection Kicker Magnet [6]

As shown in Figure (1.1) the Kicker Magnet is placed in the circulating

beam and it has to give a small angular deviation on the order of $10^{-1} \rightarrow 10^{0}$ mrad. It derives his name from the fact that it gives particles a small "kick" in order to deflect them just a bit. Furthermore it is clearly, from Figure (1.1), that the kicker does not have to interact with the circulating beam, so its magnetic field should rise only for the time of the injected beam.
In general a Kicker Magnet is a pulsed dipole magnet with very fast rise and/or fall time (typicallt 10 ns → 100 ns). The kicker magnetic field must rise and fall within the time period between the beam bunches. In addition, the magnetic field must not significantly deviate from the flat top of the pulse or from the zero between pulses.

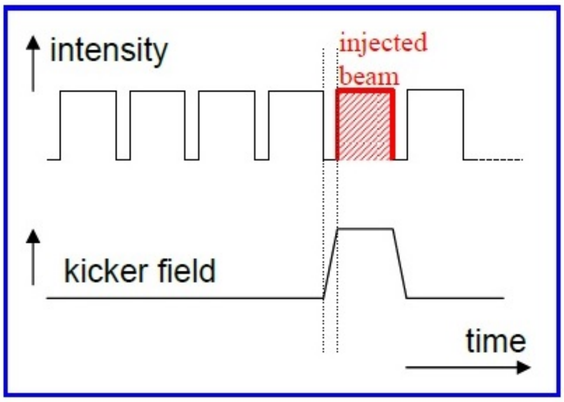


Figure 1.2: Kicker Magnet Field Timing [6]

As we could see from Figure (1.2) Kicker Field should meet several requirements:

- Fast rise and fall time
- Low ripple
- Flat Field Shape

Since the velocity of the particles of the beam is very close to c, different particles woud "see" different sections of the pulse, and they would be kicked by different amount of angles. So it is very important to meet all the requirements in order not to have offsets in the closed orbit.

1.1 Gap Clearing Kicker Magnet

In our case we have a *Gap Clearing Kicker Magnet*. It has usually been use as a clearing magnet, however in this case it has been used as an injector. In our sperimental setup we are not going to consider high voltage measurements as it is in the real enviroment. We would suppy a test pulse of just $5 \rightarrow 6$ V. We generate our pulse we a Pulse Generator by Berkeley Nucleonics, it is Model 6040 [1]. The signal that we usually input in our system is:

$$x(t) = A \cdot \mathrm{rect}(\frac{t}{T_0}) \tag{1.1}$$

where T_0 is the width of the pulse, with $T_0 \in [150 \text{ ns}, 300 \text{ ns}]$.

Our Kicker is a Transmission Line Kicker Magnet. Its internal structure resemble the structure of a Transmission Line in order to behave as a coaxial cable. It is formed by 28 cells of C-cores Ferrite and High Voltage Capacitance Plates sandwiched togheter.

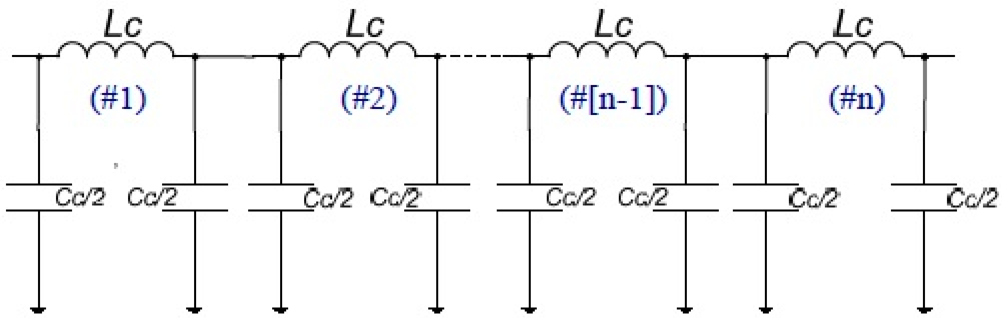


Figure 1.3: Kicker Magnet Schematic

L_c are the C-core Ferrite and C_c are the High Voltage Capacitance Plate. From the reference literature [4] we evaluated that:

- $L_c = 46.8$ nH
- $C_c = 22.85$ pF

In the Magnet two main buses are present: one is the ground bus, where are connected all the capaticance, and the other is the high voltage bus, where all the inductor are in series. From Figure (1.3) we could spot both the Ferrite and the Capacitance Plate.

In order to input the pulse inside the magnet and to get the signal out from the magnet itself we have to mount high voltage input and output cups. We did not have the exact model for the part that we used, so we estimated and collected data from similar magnet. We used the following schematic for input and outuput cups:

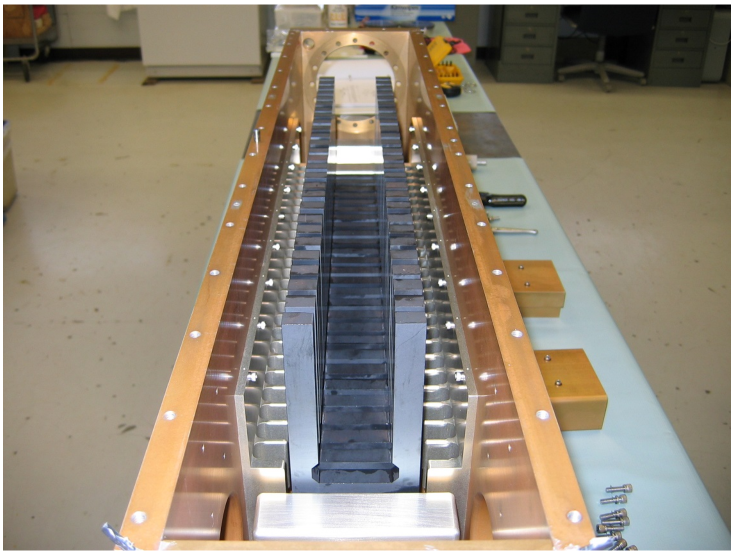
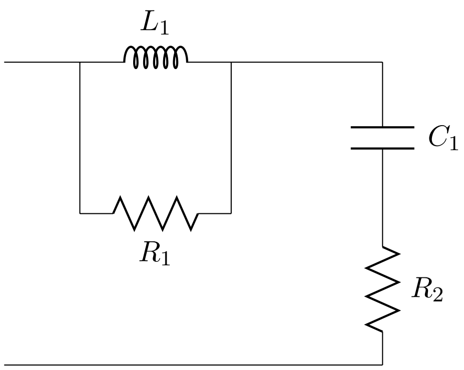


Figure 1.4: Kikcer Top View

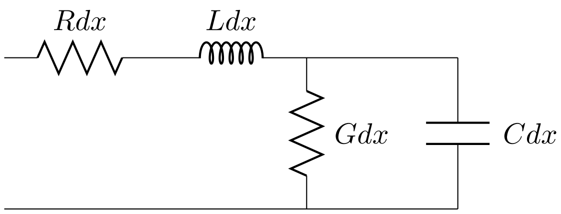


We used $L_1 = 95$ nH, $C_1 = 30$pF, $R_1 = 200\ \Omega$ and $R_2 = 10\ \Omega$. These will be key parameters in order to have a dettailed understanding of the magnet.

1.2 Transmission Line

At the start of this project I had no previous background on RF or Transmission Line Theory, so I had to get my hands on it. In this section I will explain very shortly what a Transmission Line is.

Transmission Line is a particular structure designed to carry AC signal of Radio Frequency, they are usually made up by two conductors. Coaxial Cables or Kicker Magnet coud be Transmission Line. Transmission line could be modeled by an infinite series of two-port elementary components, each representing an infinitesimally short segment of the itself.



From this model we could derive two equations for $V(x)$ and $I(x)$.

$$\frac{\partial V(x)}{\partial x} = -(R + j\omega L)I(x) \tag{1.2a}$$

$$\frac{\partial I(x)}{\partial x} = -(G + j\omega C)V(x) \tag{1.2b}$$

If we solve this system of partial differential equations we get wave like solutions

$$V(x) = V^{+}e^{-\alpha x} + V^{-}e^{\alpha x} \tag{1.3a}$$

$$I(x) = \frac{1}{Z_0}(V^{+}e^{-\alpha x} + V^{-}e^{\alpha x}) \tag{1.3b}$$

Where

$$Z_0 = \sqrt{\frac{R + jL}{G + jC}} \tag{1.4}$$

and

$$\alpha = \sqrt{(R + jwL)(G + jwC)} \tag{1.5}$$

Z_0 is Characteristic Impedance of the Line and α is the loosy coefficent.

1.2.1 Impedance Matching

When we are dealing with Transmisison Line we have to deal with System of Transmission Line. In a system different Line are placed togheter and it is vital to obtain the rigth match between these lines. Let us consider, Figure (1.5), the simplest system that we could think of.

A the end of the Transmission Line a Load Impedance has been placed in order to terminate the Line. Indeed reflections could occur at the end of the Line. From Eq. (1.3) we could evaluate the reflection coefficent

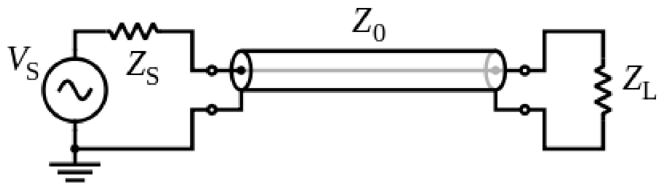


Figure 1.5: Transmission Line System

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{1.6}$$

From Eq. (1.6) we could say that in order not to have reflections at the end of the line we should have $Z_L = Z_0$.

Chapter 2

Preliminary Measurements

The Kicker has been used in the NOvA experiment in 2009. Since that period we do not have any kind of updated measure. Hence the first measuremets that we took were impedance measuremts. In order to obtain this kind of measurements and to compare with the old one we had to recreate the same experimental setup. High Voltage Cups and vacuum beam had to be removed from the magnet. After this process ended we could hooked up our impedance analyzer to the magnet through the cups and custom made contacts. We used an HP Agilent 4194A [3].

2.1 Impedance Measurements

We performed an AC Sweep betwenn 5 KHz to 5 MHz and we setted the instrument to do a 32 averaging of the samples. After the initial calibration we performed our analysis. We repeated the measurements and averaged the data. Here Capacitance and Inductance data are present:

Impedance Analysis - C and G		
Frequency (KHz)	Capacitance (pF)	Conductance (nS)
10	704.1	16.4
40	702.9	287.8
100	702.6	579.2
400	703.0	3370.0
1000	712.1	9804.0
2000	748.1	27018.0

Impedance Analysis - L and R		
Frequency (KHz)	Inductance (nH)	Resistance (mΩ)
10	1.759	6.24
40	1.738	8.59
100	1.730	11.95
400	1.729	21.24
1000	1.750	41.92
2000	1.845	100.49

These are only some of the various measurements that we took. We obtained:

- C = 703.7 $\pm$ 0.5 pF
- L = 1.73 $\pm$ 0.08 μH

Secondly we would like to know the Characteristic Impedance of the Line and the Propagation Time, which is time difference between the time when the pulse has propagated through all the magnet and the time when the pulse is entering into the magnet.

In order to acquire these values we hooked up the pulse generator to the magnet and we measured the input pulse and the output pulse with two oscilloscope probes. All the data has been collected with a LeCroy WaveRunner 204MXi Oscilloscope [2]. The Oscilloscope has been setted to do a 32 average of all the samples.

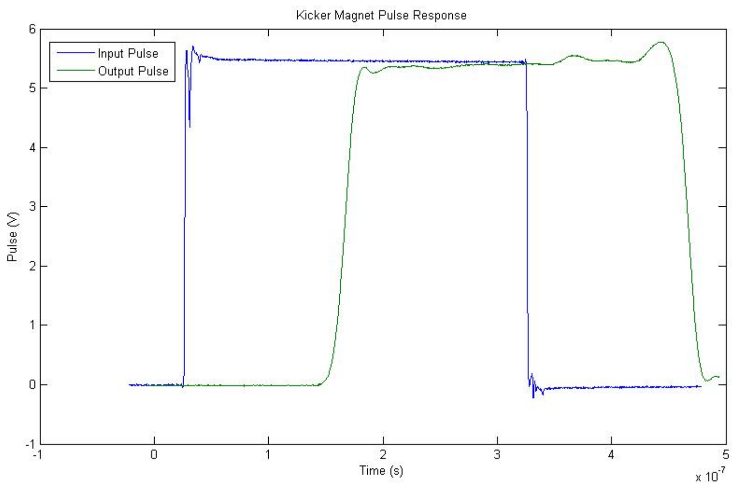


Figure 2.1: Magnet Response

We evaluated the Characteristic Impedance $Z_0 = 51.6\ \Omega$ and the Propagation Time $T_D = 15.7$ ns.

2.2 Kicker Analysis

Prior to the actual Magnetic Field Measurements we performed a SPICE Simulation and a Fourier Analysis of the Kicker.

2.2.1 Kicker Simulation

We worked out our SPICE Magnet simulation with the model found in previous paper [4]. Figure 2.2 shows two cell of the whole Magnet. It is made by 28 of them.

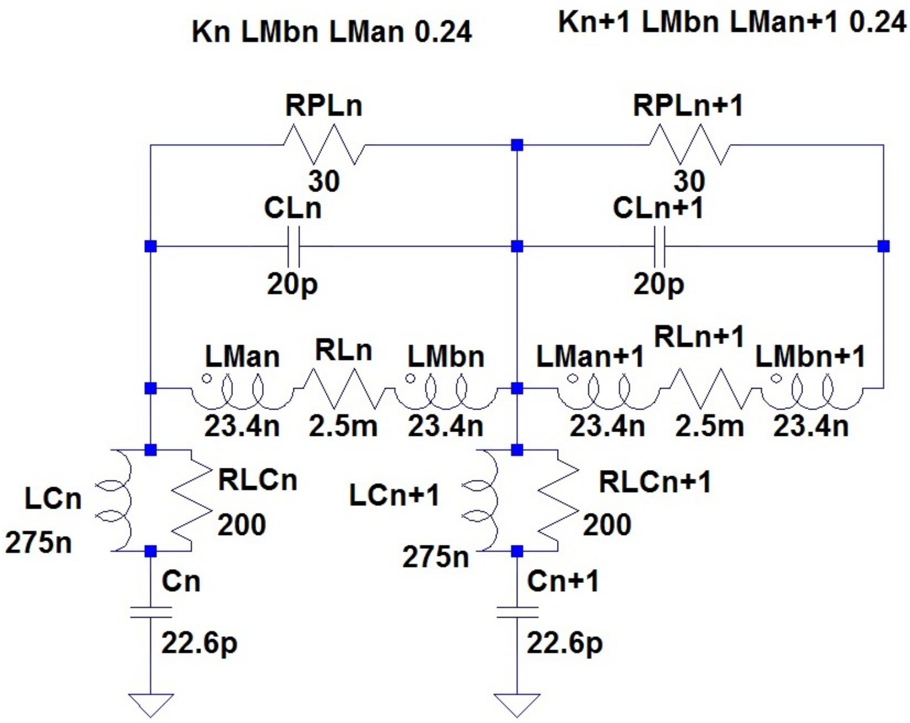


Figure 2.2: SPICE Magnet Model

Where

- $C_{L_n} = 20$ pF

- $R_{PL_n} = 30\ \Omega$
- $L_{Ma_n} = 23.4$ nH
- $L_{Mb_n} = 23.4$ nH
- $R_{L_n} = 2.5\ \text{m}\Omega$
- $L_{C_n} = 275$ nH
- $R_{LC_n} = 200\ \Omega$
- $C_n = 22.6$ pF

and where the coupling coefficent between $L_{Ma_{n+1}}$ and L_{Mb_n} is 0.24. As previously said we do not have an accurate model of the couplings of the magnet, this had result in a not precise simulation.

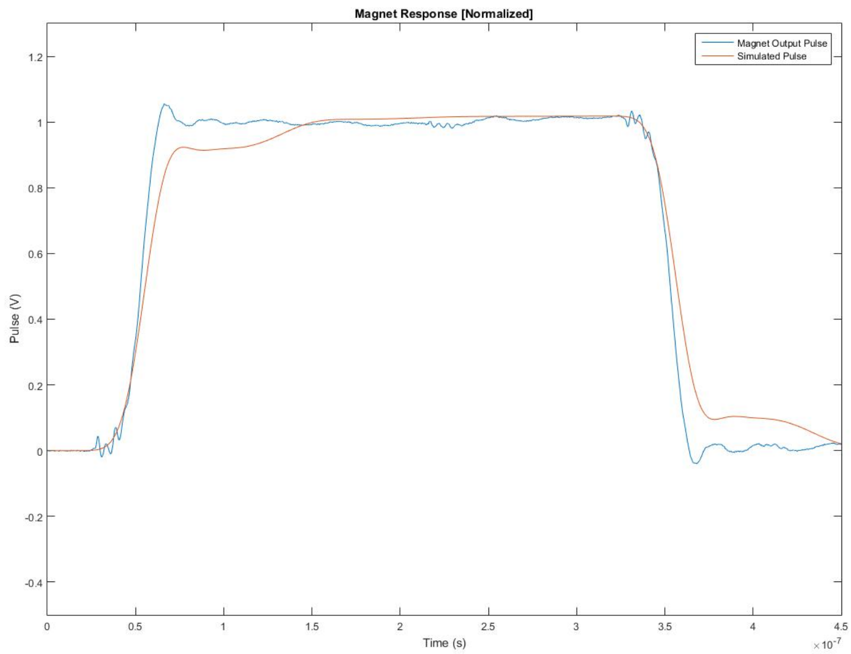


Figure 2.3: SPICE Simulation

We could see from the Normalized Plot that the overall shape of the Simulated Pulse, in red, quite matches the real pulse into the magnet, in blue. However there are still some adjustment to do:

- The magnet has been designed in order to have a first overshoot which could be seen in the magnet signal, instead the simulated one do not present this kind of shape

- The rise time of the simulated one is slower than the real one, indeed we have $t_{rise_{real}} = 40.4$ ns and $t_{rise_{simulated}} = 48.8$ ns
- At 376.5 ns we could see from the plot that some kind of reflections occur due to not perfectly matched termination

2.2.2 Fourier Analysis

Fourier Analysis is one of the most important analysis in signal processing due to the fact that could give us essential information about the system that we are looking at. In order to perform this kind of analysis we sended a fast pulse, 150 ns width, into the magnet and we looked at the output pulse. We evaluated the spectrum of this two signal by performing FFT (Fast Fourier Transform) and we worked out the ratio of them.

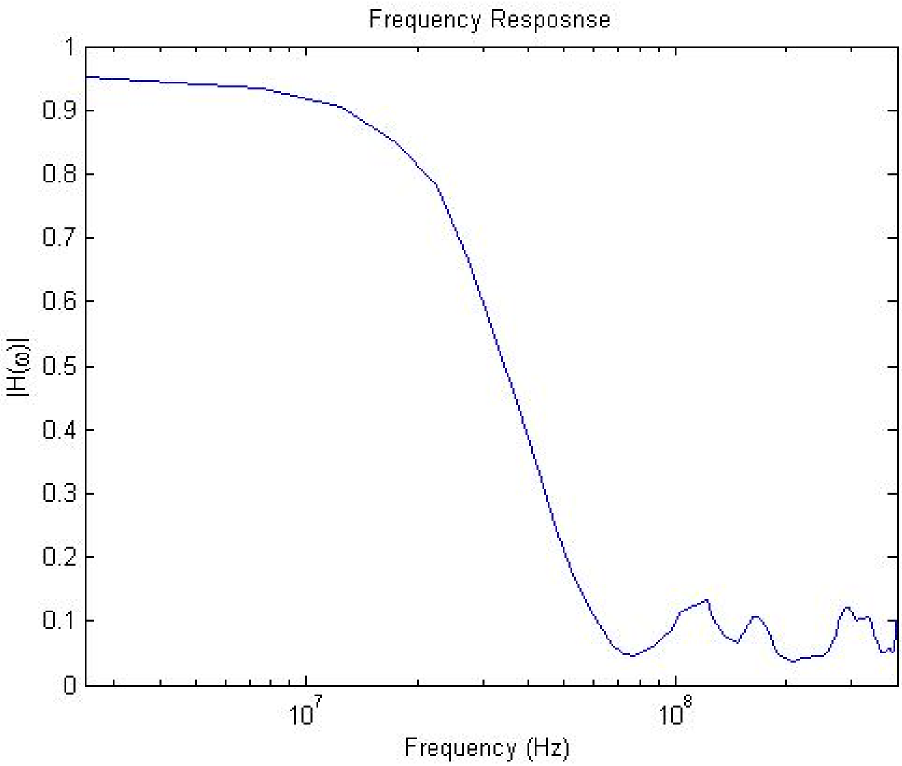
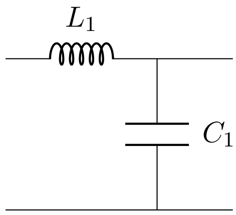


Figure 2.4: Magnet Frequency Response

From Figure (2.4) we could see that it behaves as a Low-Pass Filter, and more in particular as a LC Low-Pass Filter. In fact all the magnet could be seen as in the following schematic



With MATLAB we evaluated the Cut-Off Frequency of the system, $f_{cut-off}$ = 27 MHz.

Chapter 3

Field in the Magnet

In order to evaluate the Kicker Mangnet Field we use the model of a Ferrite C-core, so we get

$$|\mathbf{B(x,t)}| = \mu_0 \cdot \frac{\mathbf{N \cdot I(t)}}{\mathbf{V_{ap}}}, \mathbf{N} \approx \mathbf{1} \tag{3.1}$$

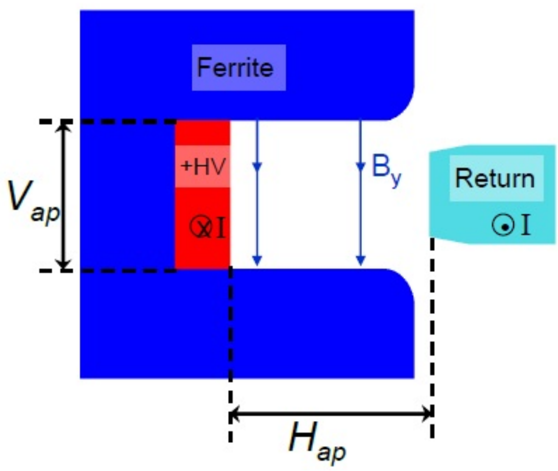


Figure 3.1: Ferrite C-core Field

In out case $N \approx 1$ and the Magnetic Aperture is 11 cm x 5.3 cm. When we think of a beam moving through the magnet, the beam would see the integrated magnetic field, that is the integration along the z axis of the magnetic field. In fact the total kick would be

$$\Theta = \frac{0.3}{p} \int_0^L B_y dx = \frac{0.3}{p} \cdot l_{eff} \cdot |B_y| \tag{3.2}$$

where p is the beam momentum and l_{eff} is the effective length. The effective length of the magnet is not the length of the whole magnet, but we have to consider the air gaps which are present. We defined:

$$l_{eff} = \frac{1}{B_0} \int \mathbf{B} \cdot \mathbf{dl} \tag{3.3}$$

where B_0 is the flat field intensity.

Chapter 4

Probes

For the measurements of the magnetic field inside the Magnet we used a coil probe. Coil Probe would catch $\frac{\partial \Phi}{\partial t}$ and produce a signal proportional to it.

4.1 Old Probe

Our first probe was a rectangular shape coaxial cable probe.

It has been made by allign togheter two coaxial cable and soldered them at one end of it. The cables has been placed in a solid support of G10 and two metallic BNC connectors has been placed at the other end of the probe in order to connect a BNC cable.

The probe has a Length of 67.5 cm and an Heigth of 16.05 mm. The Heigth has been measured between the two internal conductors of the coaxial cables. We have performed Transmission Line analysis on the probe with the Pulse Generator and the Oscilloscope. By collecting all the data with MATLAB we obtained

- $Z_0 = 52.5 \pm 0.5\ \Omega$
- $T_D = 6.6$ ns

4.2 New Probe

During the project we came up with the idea that another probe had to be built. The reasons for this will be explained in the Results Chapter.

There are two main requirements that the new probe had to satisfy:

- The length should be the same as the length of the magnet
- The probe's area should be defined in a more precise way

The overall shape and the constitutive idea are the same, so we had another rectangular shape coaxial cable probe. CAD Schematic has been drawn and the Probe has been realized by the Systems and Automation Staff.

Figure 4.1: New Probe

In order to have a defined area into the probe we close the two coaxial cables with a Protoboard. On the other end of the probe in order to have an ideal L shape we placed a short piece of coaxial cable in the middle of the two.

This new probe has a Length of 106.934 cm and an Heigth of 20.863 mm. We performed the same analysis that we had perform on the old probe and we obtained:

- $Z_0 = 46.7 \pm 0.5\ \Omega$
- $T_D = 26.6$ ns

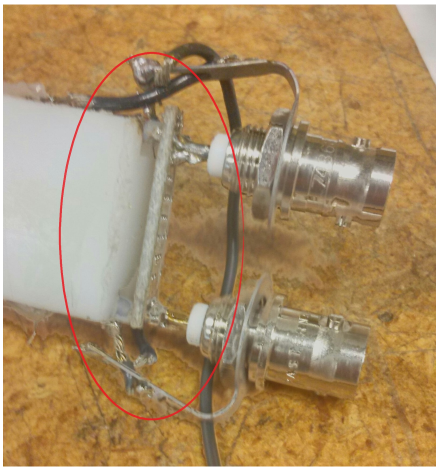


Figure 4.2: Probe's End

For this new probe the Characteric Impedance has been evaluated also from geometric measuremets, in fact we measured a small piece of cable sample. Figure (4.3) is the section of the cable.

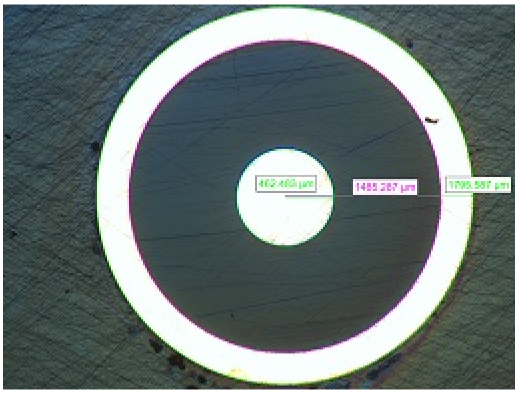


Figure 4.3: Cable's Section

From the measuremetns and the following equation

$$Z_0 = \frac{138}{\sqrt{\mu_r \epsilon_r}} \cdot log(\frac{r_{external}}{r_{internal}}) \tag{4.1}$$

we could evaluate the Z_0. The geometrical theoretical value is $Z_0 = 46.6$ Ω with $\epsilon_r = 2.25$.

4.3 Magnetic Induction

Both of these two probe work thanks to Electromagnetic Induction. *Electromagnetic Induction* is the production of an electromotive force across a conductor when it is exposed to a time varying magnetic flux.

In our case the conductor is the coaxial cable and the flux is calculated on the area's probe.

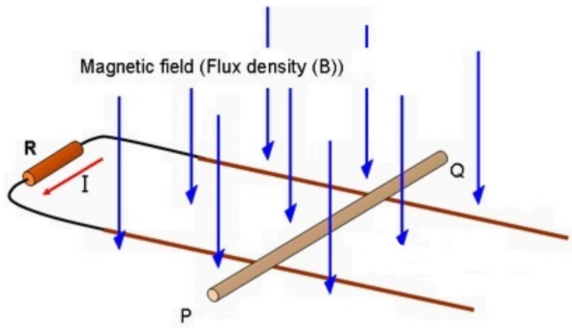


Figure 4.4: Electromagnetic Induction

By recalling the third Maxwell's Equation

$$\oint \mathbf{E} \cdot \mathbf{dl} = -\frac{\partial}{\partial t} \int_S \mathbf{B} \cdot \mathbf{dS} \tag{4.2}$$

we get that the signal probe should be

$$\xi(t) = -\frac{\partial \Phi}{\partial t} \tag{4.3}$$

where the flux is calculated on the probe's area.

This is what we expected at first. But we have to take in account that the magnetic pulse is propagating through the magnet, so the electromagnetic induction would produce a rising pulse through the whole probe.

Chapter 5

Results

With MATLAB we performed all our data collection and our analysis. We came up with the following results.

5.1 Original Guess

Our initial guess was that we expected to see a signal that soulded be proportional to the time derivative of the flux, so

$$\xi(t) = -\frac{A_{magnet}}{A_{probe}} \cdot \frac{\partial \Phi}{\partial t} \propto -\frac{A_{magnet}}{A_{probe}} \frac{\partial V}{\partial t} \tag{5.1}$$

We considered the ratio of the two area as the two fluxes are evaluated upon different areas.

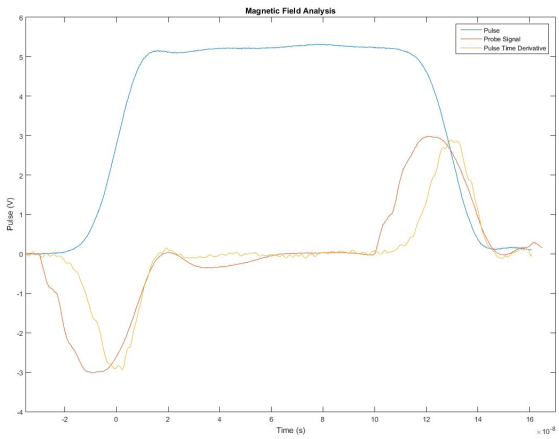


Figure 5.1: Magnetic Field Analysis

From Figure 5.1 we could see that the expected signal and the measured signal are mismatched. The overall shape is quite similar but the measured pulse is larger than the expected one.

5.2 Results

Given the fact of the previous section we had to reconsider what we were looking at. From literature [5] we came up with a new idea: we could think out whole transmission line as a big inductor. This assumption is true for a lossless Transmission Line, in fact for a Transmission Line where for each cell

$$i_C << i_L \tag{5.2}$$

The Capacitance do not have any kind of part in the system. By recalling the constitutive equation of an inductor

$$V_{in} - V_{out} = L \cdot \frac{\partial i}{\partial t} \tag{5.3a}$$

$$\Phi = L \cdot i \tag{5.3b}$$

We get that

$$V_{in} - V_{out} = -\xi(t) \cdot \frac{A_{magnet}}{A_{probe}} \tag{5.4}$$

We obtained

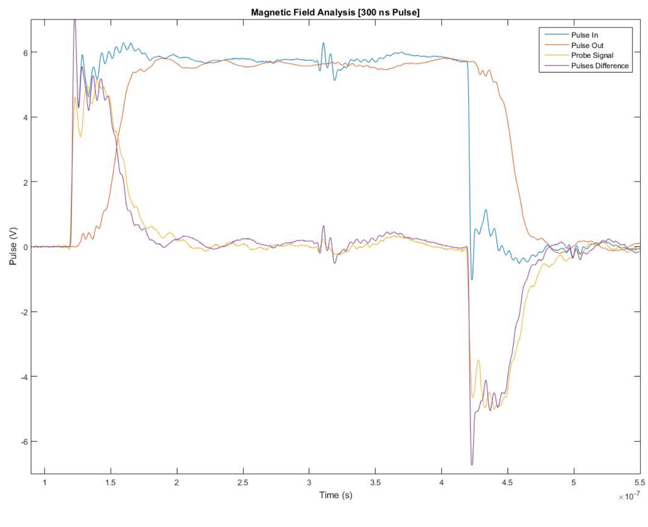


Figure 5.2: Magnetic Fiedl Analysis

From Figure (5.2) we could see that the expceted signal and the measured signal quite match. However there are still some adjustment that has to be done in order to have a clearer signal:

- The Probe itself behaves as a Low-Pass Filter, so High Frequency part of the Spectrum of the signal could not be evaluated
- Ripple arises due to the fact that probe inside the manget changes the overall magnet impedance, so the pulse would see a different impedance from the one that it has been designed to see
- The amplitude of the signal is not the one that we expected to be, infact we had to apply a "normalization coefficent" of 1.14 in order to match the two signals

5.3 Flux

The most important measure that we are interested in is the magnetic flux. It is linked to the total deviation angle that the particles see. From the previous equation we get that

$$\Phi = -\frac{A_{magnet}}{A_{probe}} \int (V_{in} - V_{out}) dt \tag{5.5}$$

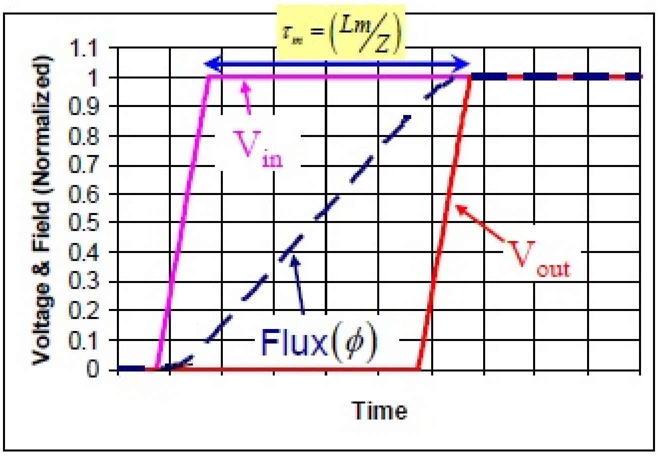


Figure 5.3: Magnetic Flux

We obtained

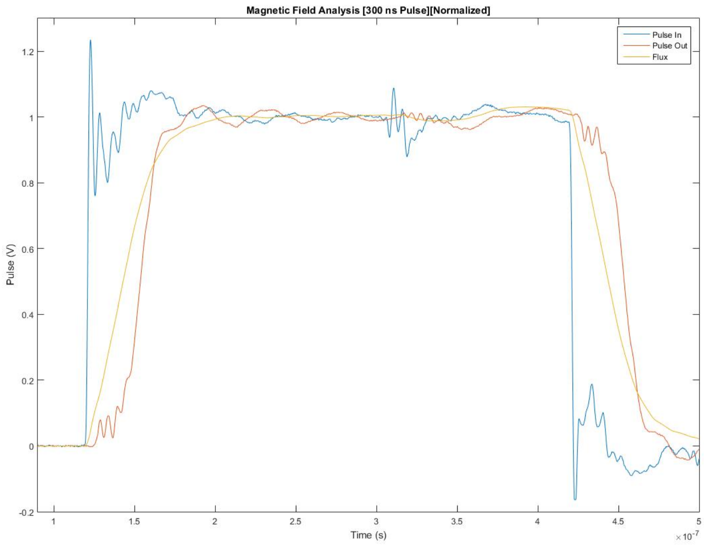


Figure 5.4: Magnetic Fiedl Analysis

The above results are the normalized plot of the input pulse, output pulse and magnetic flux. We could observe that

- A voltage drift is present in the signal as we are dealing with a time integral, indeed error would sum up
- The first overshoot of the pulse is not present in the flux signal, this coud be due to the fact that the probe behaves as a low-pass filter

Further analysis has to be conducted in order to better understand these various behaviours.

Chapter 6

Further Develpments and Conclusion

It is possibile to built on to this project. In here we outline possible developments:

- Measure and Model the various couplings of the magnet
- Model and Simulate the rising signal through the probe
- Design and Built a new Two Cell long Probe in order to model the Field Cell by Cell
- Perform the High Voltage Measurements (25 kV)
- Design and Built a new Probe with a reduced area, e.g. with a factor of 10, in order to perform High Voltage Measurements

It is possible to directly measure the magnetic field with an ad hoc probe. This work achieves the addressed result directly measuring the magnetic field profile and strength of a fast injection kicker magnet throught a custom design probe.
Interpretation of many of the specific phenomena has been given considerable effort and have been understood and described. Further developments is needed to achieve a full understading of the profile of the Field utilizing this technique. I would like to thank:

- Luciano Elementi
- Chris Jensen
- Iouri Terechkine
- All the Technical Division Staff for this opportunity and all the help kindly received

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