IMPROVED MAGNETIC SENSOR FOR OIL AND NATURAL GAS WELL LOGGING APPLICATIONS

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Project Summary

The purpose of this project is to produce a low field magnetic sensor that has a high signal to noise ratio and that can eliminate unwanted resonances brought about by losses in the measurement system. The sensor in question will be utilized for logging down-hole oil and gas reservoirs so it has to be accurate. The sensor component which will be modified is the magnetic core. It will be used along with a coil as an antenna to send radio frequency (RF) pulses used to characterize underground formations. Hence, the magnetic core will be improved on in order to reduce hysteresis losses, eddy current losses and anomalous losses. In addition, a uniform external magnetic field generator will be designed for the measurement setup to accurately analyze the antenna's response. Besides this, other sources of noise or interference may be investigated. Finally, a user defined interface to operate the measurement setup and, a program to detect and plot resonant frequencies will be implemented.

Introduction

Nuclear Magnetic Resonance (NMR) spectroscopy is used in multiple different industries such as medical and chemical. A key application of this technology is in the oil and gas industry where, it is used to acquire information about underground rock formations. This is done by embedding a Low Field NMR sensor into a drill tool used for down-hole drilling. The key component of the magnetic sensor, an inductive RF antenna which surrounds the magnet as shown in figure 1.

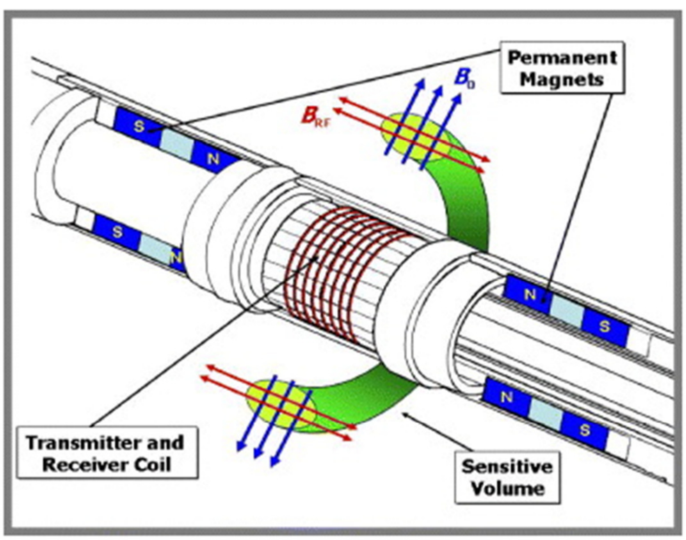


Figure 1. NMR schematic [1].

If a permanent magnet induces a static magnetic field, this in turn magnetizes the materials in the underground formation and produces a small amount of spin polarization in the particles of the formation. Figure 1 demonstrates the effect of adding a permanent external magnetic field. If a perturbing field is applied orthogonal to the external field as shown in figure 2 it can disturb the magnetic equilibrium causing a complete or partial inversion of the spin states depending on the length of time the RF field is applied [2].

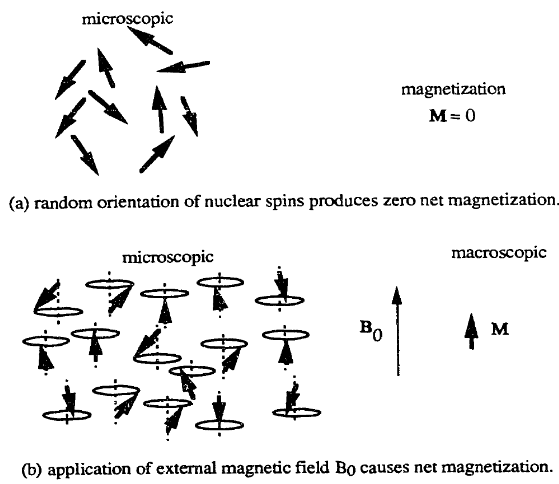


Figure 2.Distribution of nuclear magnetic fields without (a or with (b an external magnetic field [2].

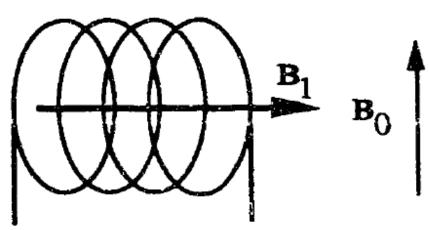


Figure 3.Perturbing field vs. external field direction [2].

When the perturbing field is removed, the spin states return to equilibrium. This change is governed by the chemical and magnetic properties of the formations [2]. When an inductive antenna transmits into the surrounding earth formation a timed RF signal in the form of an oscillating magnetic field at the proper resonant frequency, it induces a transition between the spin states. This transition causes some of the spins to go into a higher energy state. When the RF signal is turned off, it causes the relaxation of the spins to their lower energy state producing a measurable RF signal at the resonant frequency of the spin flip. This frequency is also called the Larmor frequency. The Larmor frequency ω_0, is the frequency of precession of the external field B_0 as shown in equation 1.

$$\omega_0 = \gamma B_0 (1)$$

Where B_0 is the external field and γ is the ratio of the magnetic moment to angular momentum. The gyromagnetic ratio γ is a function of the material type [2].

In between the bursts, the antenna “listens” to the free induction decay (FID) or echo of the decaying signal from the hydrogen protons which are in resonance with the field induced by the inductive field. The magnetic core of the antenna therefore has to be easily magnetized and demagnetized in order for it to work. Therefore, the core has to be made from a soft ferromagnet. These tend to have low coercivity and low remanence therefore, they have very narrow hysteresis loops as shown in figure 4.

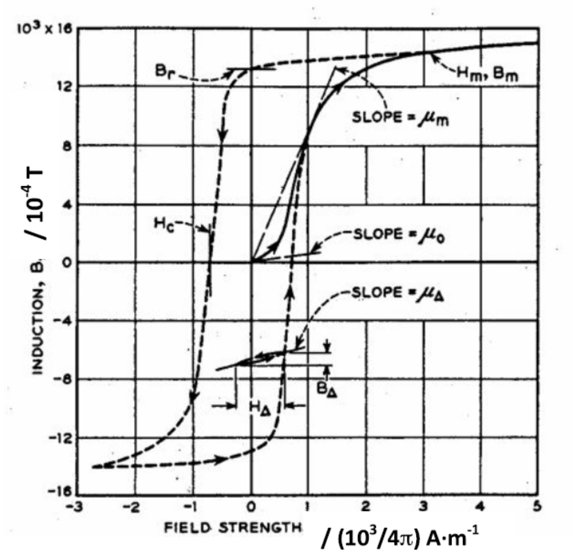


Figure 4.Typical hysteresis graph for a soft ferromagnet [3].

In this project since the client is interested in understanding the response of the sensor and not the response from the underground formation, the polarizing magnet will be outside of the antenna and not inside. Therefore, the measurement set-up will look more like an MRI system and not an NMR.

Project Requirements/Specifications

Functional requirements for the magnetic core:

- Soft magnetic material.
- Coercivity should be low.
- Permeability should be high.
- Remanence should be low.
- Rod-like geometry.
- Non-corrosive.
- Magnetorestriction should be low.

Software Requirements:

- Graph returning signal in frequency domain. Find max amplitude from frequency spectrum.
- Find Full Width Half Maximum (FWHM).
- Put all measurements of a single material onto a single plot or record all the resonances on a similar scale.
- Have a graphical user interface to accomplish this.
- Have a second graphical user interface to run the previously mentioned one on multiple materials

Functional requirements for the uniform field:

- A magnetic field of uniform flux density existing throughout the magnetic core.
- Rapid increase of magnetic flux density inside the core for maximum uniformity.
- Shielding to create uniformity of magnetic flux.
- Shielding to prevent any extraneous potential resonances from effecting frequency domain readings.

Project Goals

- Eliminate additional potential resonances by designing a uniform permanent magnetic field.
- Eliminating possible sources of interference or noise or, identifying the causes of noise in the system such as circuit resonances or material phenomena.
- Identifying a suitable candidate for the soft magnetic core in the inductive RF antenna from the existing samples provided by the client. Reduction of unwanted acoustics introduced by the soft magnetic core of the RF antenna is desirable. The core material needs to have high relative permeability, low Q factor and small coercivity.
- Investigating the signal spectrum and streamlining the processing of signal recording from antenna.
- Creating graphical user interface for simpler user operation.

System Description

The measurement system of the NMR sensor shown in Figure 5 below comprises of three parts. There is the uniform static magnetic field and the RF antenna with a spectrometer, transmitter and receiver attached to it. Finally, there is power matching between the components.

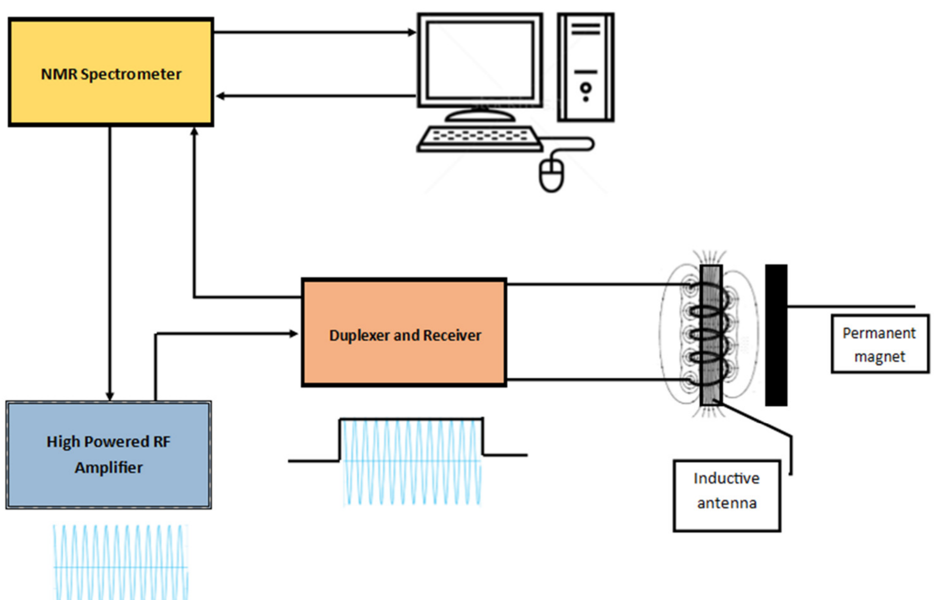


Figure 5.Measurement system setup schematic.

To perform the measurement, a low power pulsed RF signal with a resonant frequency between 0.1-1.2 MHz is generated by the user and sent to the NMR spectrometer. The signal is then sent to a high powered RF amplifier where it may be amplified to a maximum of 4000 W. The signal is then sent to the duplexer which acts as a filter allowing only certain frequencies to pass onto the inductive load. Once the pulse is sent, the spectrometer "listens" to the echo of the signal sent to the inductive load. This signal is then sent to the spectrometer where it is processed and the frequency spectrum is produced for analysis.

Design, Production and Testing

The suitable magnetic core material will be provided by our client. Currently, the samples are ferrite alloys which include manganese or nickel zinc ferrites. We began characterization of existing samples already in the lab using the hysteresis graph measurement system. The preliminary results were inconclusive because there was no magnetic saturation in the B field. New samples will be characterized using the hysteresis graph measurements to find the coercivity and remanence of the materials. The candidates suitable for this application will have the lowest coercivity and remanence, from the samples provided by the client, after optimizing the sample preparation method. Core materials will be investigated based on their potential coercivity. Below is a graph showing the relationship between various materials, their grain size and their coercivity.

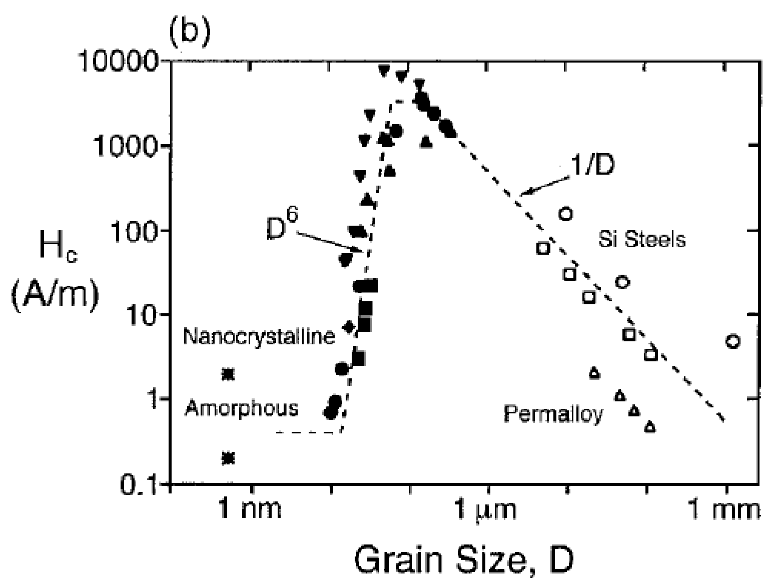


Figure 6. Coercivity vs Grain size [4].

New samples composed of the alloys of the samples previously provided by the client, will be created at Ames National Lab by our graduate student advisor. Currently, we are trying to create Mn-Zn ferrites, $Mn_xZn_{1\_x}Fe_2O_4$ (with x varying from 0.2 to 0.8), where M is either Mn or Ni. The samples are created by mixing the various constituent powders of the alloy, and ball milling them. This is followed by a calcination process to increase bonding between the particles. Additional ball milling and calcination is done one more time. An additional ball milling is done after the final stage of calcination. The final stages are sieving and sintering (annealing). After the final stages, the sample will be mixed with epoxy. The amount of epoxy to sample ratio will be 20/80, 40/60, 60/40 and 80/20. For the first batch of samples, the sintering process is omitted. The other sample made on site by the client will be a commercial Ferrite epoxy. It will be made by mixing a commercial as prepared Ni-Zn Ferrite powder with epoxy in the ratios described above.

A low coercivity and high permeability is desired for the core material. Hence, smaller hysteresis loop losses. Therefore, the commercial ferrite alloys as shown in figure 7 will suffice for this project.

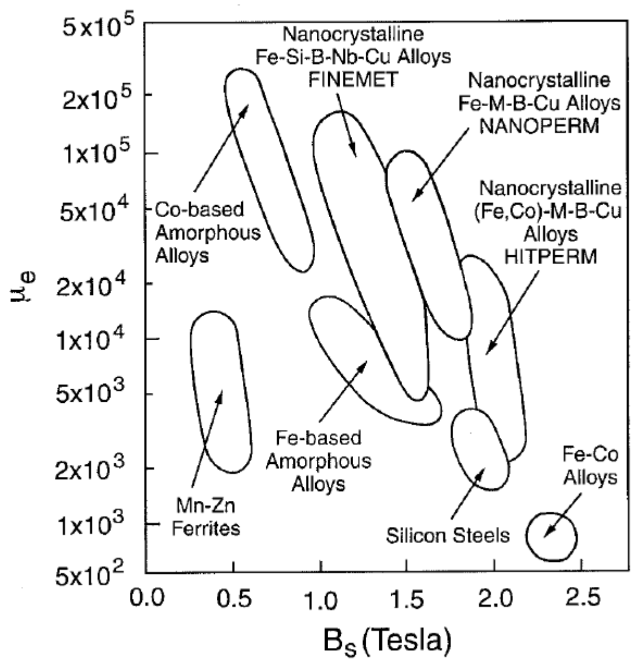


Figure 7.Permeability vs. Saturation of Flux [2].

To reduce core losses, annealing will be performed on the sample in a vacuum or in inert gas atmosphere. The annealing temperature will have to be chosen very carefully to prevent the sample from displaying anisotropy i.e. preferential direction for magnetization. Lower temperatures starting from 500^{o}C will be used at first. Measurements will be done to see if the samples magnetic properties have improved. So long as the microstructure is random, it will be easily magnetized regardless of the direction of the applied field.

Other losses not covered in the project specification which will affect system performance include the effect of eddy currents and anisotropy on the atomic level. Eddy currents can be minimized by decreasing the electrical conductivity of the material [4]. This will be addressed by picking the optimal epoxy to sample ratio.

Measurement of existing and new samples will be done using the new measurement setup which has a more uniform permanent magnetic field. Further testing will look at trying to define the sensor's noise and identifying sources of noise from the mechanical setup. These may be due to the nature of the RLC measurement circuit or mechanical vibrations coming from the machines. Defining the sensor's noise will be important in order to properly calibrate it. This semester, testing has been performed in an enclosed Aluminum box and this led to increased resolution in the test results. That is, more peaks can be identified. The effects of reflection due to a mismatch between the transmission and the inductive load will also be investigated. Also, natural circuit resonances will be investigated.

Simulation using COMSOL is well underway for simulating the permanent magnet solution. Considerations being made are the increase and decrease slope of the magnetic flux density inside both air and a core material with high permeability to simulate the material being created. Using real world data obtained from a reliable distributor [7], I can more accurately simulate the magnetic flux density. Uniformity along the greater axis is designed. This will be accomplished using some measure of shielding. Nickel or mill steel alloys can absorb the flux lines from the neodymium boron magnets. This creates a more uniform flux density field inside the core material. Consideration is being given to a material with high permeability, good attenuation, and high saturation. The higher saturation is required for permanent magnets [7].

The GUI and processing software will be written in MATLAB. The code operates on 3 levels as shown in figure 8. There is a primary GUI that takes in a folder path from the user. This primary GUI then calls an instance of the sub-GUI for each material folder contained in the folder that the user has given. The sub-GUI then calls three functions to process the data for the files it contains and plots them. The Fast Fourier Transform (*fft)* function will be used to find the signal in the frequency domain for this processing. The data processing and plots will be tested using old data and comparing the results provided by the new software with the ones obtained previously.

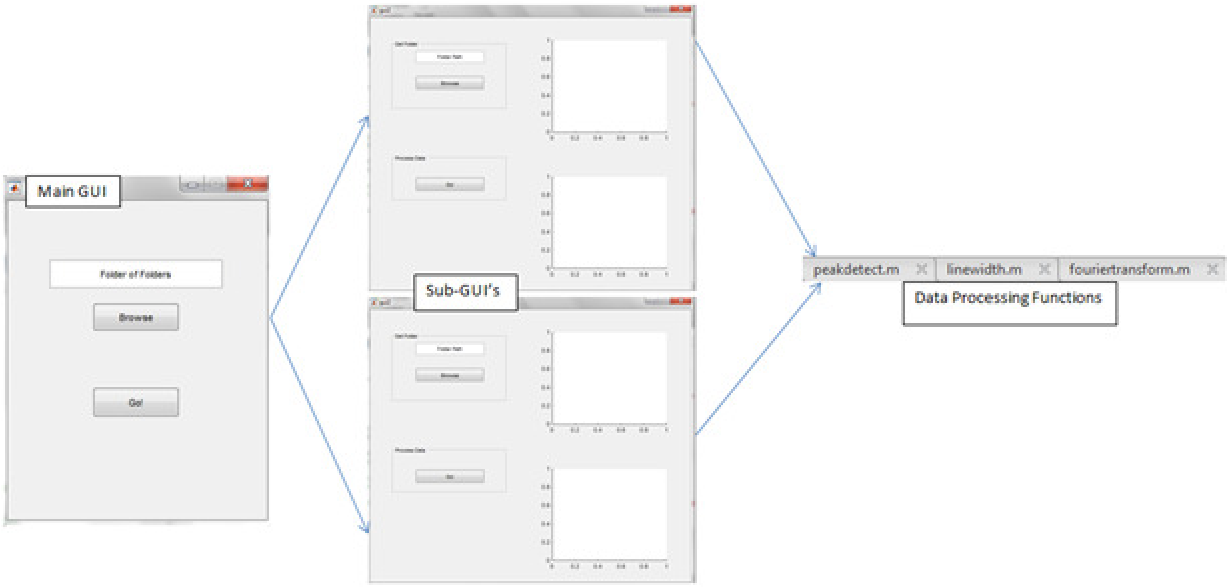


Figure 8. Code design.

Limitations and Risk

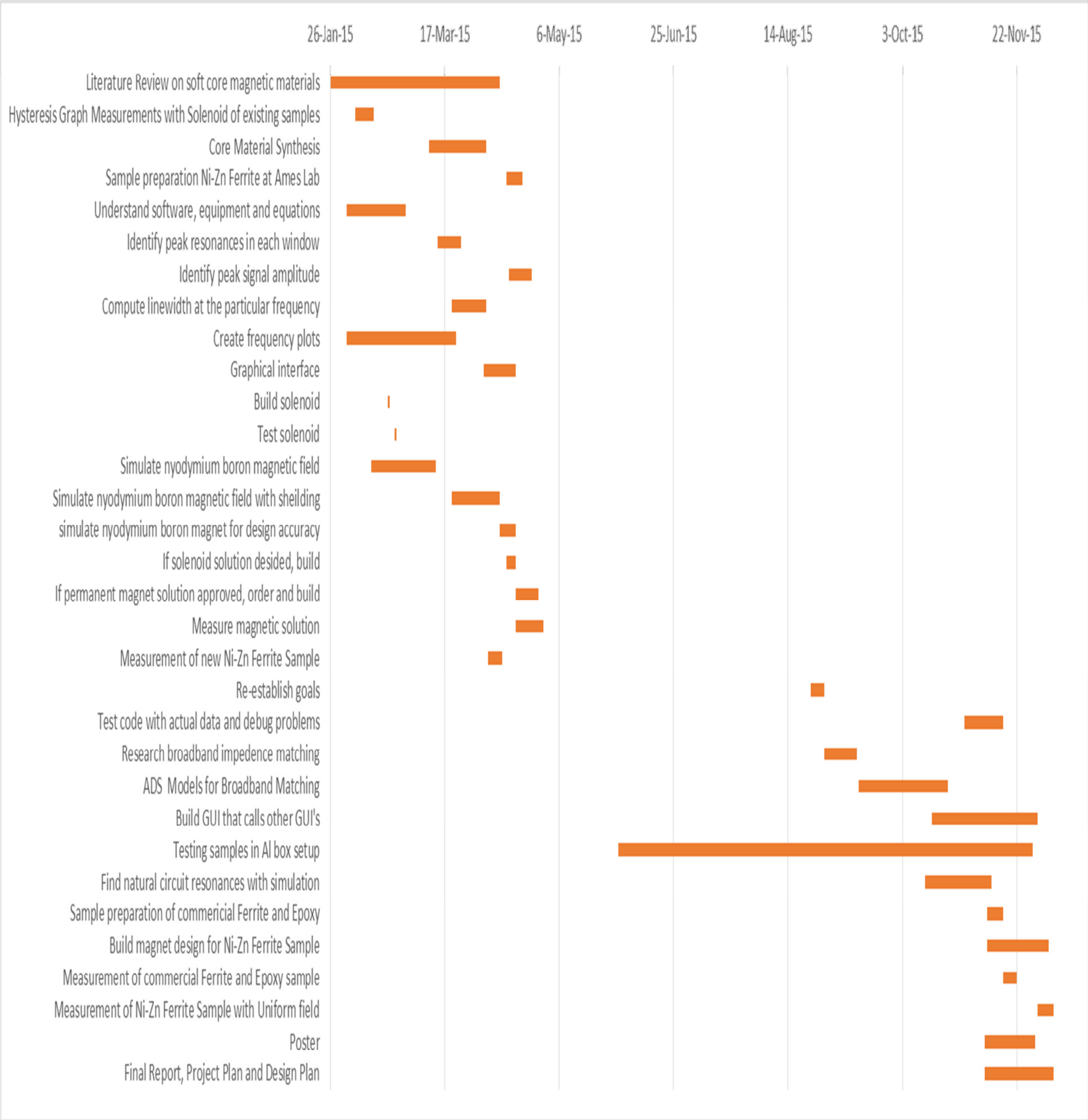
The limitations that could arise when creating the magnetic core is that even though the theoretical properties of the material are good for this application, the synthesis process has to be optimized so as not to alter the material's properties. A mismatch between the load and line could create reflections that interfere with the results.

The most apparent limitation using permanent magnets is cost. Neodymium boron magnets are expensive at this size. The shielding required to absorb the magnetic flux lines with a high saturation is costly as well. Simulations already performed have had good results. The geometry has not yet been decided.

The potential problems with the software are as follows. We are currently unsure whether we need to look at the complex, the real or both data inputs. Since this GUI processes real data it may be difficult to tell whether results are just unexpected or there is an error in the processing process.

Tasks & Schedule

Task	Start Date	End Date	Duration
Literature Review on soft core magnetic materials	26-Jan-15	10-Apr-15	74
Hysteresis Graph Measurements with Solenoid of existing samples	6-Feb-15	13-Feb-15	8
Core Material Synthesis	10-Mar-15	3-Apr-15	25
Sample preparation Ni-Zn Ferrite at Ames Lab	13-Apr-15	20-Apr-15	7
Understand software, equipment and equations	2-Feb-15	28-Feb-15	26
Identify peak resonances in each window	14-Mar-15	24-Apr-15	10
Identify peak signal amplitude	14-Apr-15	24-Apr-15	10
Compute linewidth at the particular frequency	20-Mar-15	3-Apr-15	15
Create frequency plots	2-Feb-15	20-Mar-15	48
Graphical interface	3-Apr-15	17-Apr-15	14
Build solenoid	20-Feb-15	20-Feb-15	1
Test solenoid	23-Feb-15	23-Feb-15	1
Simulate nyodymium boron magnetic field	13-Feb-15	13-Mar-15	28
Simulate nyodymium boron magnetic field with sheilding	20-Mar-15	10-Apr-15	21
simulate nyodymium boron magnet for design accuracy	10-Apr-15	17-Apr-15	7
If solenoid solution desided, build	13-Apr-15	17-Apr-15	4
If permanent magnet solution approved, order and build	17-Apr-15	27-Apr-15	10
Measure magnetic solution	17-Apr-15	29-Apr-15	12
Measurement of new Ni-Zn Ferrite Sample	5-Apr-15	10-Apr-15	6
Re-establish goals	24-Aug-15	30-Aug-15	6
Test code with actual data and debug problems	30-Oct-15	16-Nov-15	17
Research broadband impedence matching	30-Aug-15	13-Sep-15	14
ADS Models for Broadband Matching	14-Sep-15	23-Oct-15	39
Build GUI that calls other GUI's	16-Oct-15	1-Dec-15	46
Testing samples in Al box setup	1-Jun-15	1-Dec-15	181
Find natural circuit resonances with simulation	13-Oct-15	14-Nov-15	29
Sample preparation of commericial Ferrite and Epoxy	9-Nov-15	16-Nov-15	7
Build magnet design for Ni-Zn Ferrite Sample	9-Nov-15	8-Dec-15	27
Measurement of commercial Ferrite and Epoxy sample	16-Nov-15	20-Nov-15	6
Measurement of Ni-Zn Ferrite Sample with Uniform field	1-Dec-15	8-Dec-15	7
Poster	8-Nov-15	1-Dec-15	22
Final Report, Project Plan and Design Plan	8-Nov-15	8-Dec-15	30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Final Report, Project Plan and Design Plan

Work Plan

Name/Role	Task
Marion Okoth (Team Leader)	Coordinate between group members and advisors, research of magnetic core material, circuit simulations, and sometimes assists with signal processing code, perform measurements.
Elizabeth Clarkin (Webmaster)	Build and maintain website, produce GUI, write signal processing program, broadband impedance matching.
Matthew Mulloy (Reporting)	Design and build a constant, uniform magnetic field, assist with GUI, write weekly reports. Assist with measurements once material is ready.

Deliverables

Fall 2015

At the end of this semester we will provide the client with a redesigned measurement setup that includes a uniform magnetic field. The RF antenna will have a suitable magnetic core material chosen from candidates supplied by the client after extensive testing of all samples provided. Included will be a MATLAB program that processes the data. Also included will be a graphical user interface created for MATLAB software that processes the data.

References

1. K. Pourabdollah, B. Mokhtari, Magn.Reson.Chem 50,(2012) 208-215
2. S.Sgobba, Proceedings-CERN Yellow Report, CERN-2010-004 39-63
3. R.M. Bozorth, Ferromagnetism, Van Nostrand, New York, 1951
4. M.E. McHenry et al., Progress in Material Science 44 (1999) 291-433
5. K&J Magnetics: Neodymium Ring Magnets. N.p., n.d. Web. 31 Mar. 2015
6. K&J Magnetics: Magnetics Blog. N.p., n.d. Web. 31 Mar. 2015
7. L.Long et. al, 2008 2nd IEEE International Nanoelectronics Conference (INEC 2008)