Post Mortem for the

Portable MRI Scanner

by

MRI SOLUTIONS

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1. Introduction

MRI uses magnetic fields to magnetize hydrogen protons in the human body. Then a radio frequency pulse is used to excite the protons. When the radio frequency pulse is turned off, hydrogen protons will relax back into a lower energy state by emitting radio frequency waves. Conventional MRI uses Fourier imaging method to encode these signals and create tissue contrast images. But Fourier imaging requires linear encoding magnetic field to describe the position and frequency of detected signals.

To produce linear encoding magnetic fields, a conventional MRI uses the superposition of a very homogenous field pattern and a linear gradient. However, it is extremely challenging to design a permanent magnet or electromagnet system that has a good field homogeneity and a reasonable field strength. The homogeneity constraint results in very heavy and power hungry MRI. A conventional MRI relies on superconducting magnets and gradient coils to produce a strong homogenous field and a linear gradient. This is why a conventional MRI is expensive and not portable. An MRI machine can cost over $3 million USD and requires more than $1 million USD in yearly maintenance. In Canada, there are only 6 MRI machines per million population and the average waiting time is between 12 and 18 months [1]. The cost of an MRI machine severely limits access to MRI scans. Besides that, MRI machines are also not portable and are usually installed in a highly specialized facility.

We proposed an imaging technique based on a rotating spatial encoding magnetic field to solve these problems. Our design is inspired by the method outlined in [2]. We will use the rotation of magnet system to encode spatial information at different angle to reproduce the 2D image by back projection.This unique technique allows us to build a cost-effective and portable MRI using permanent magnets. The objective of this research project is to prove the concept of this imaging technique.

At MRI Solutions, we have designed a magnet and radiofrequency system for MRI. The design is primarily centered around cost-effectiveness, portability, safety and scalability. We have successfully tested and integrated all system. However, we have been unable to observe magnetic resonance response as of this writing. This may be due to various the challenges that we have faced throughout the project. Dr. Andrew Rawicz has graciously provided us with a two week extension and the permission to use his shielded room for further testing and system improvement. We are also grateful for the tremendous support from Dr. Rodney Vaughan and his lab. With their support, we hope to improve our system and observe resonance response by January 8th 2016.

2. Project Overview

Our MRI design consists of a rotating magnet system and a radio frequency (RF) system. The magnet system consists of several permanent magnets arranged in a Halbach array as shown in Figure 1. Compared to other arrangements, Halbach array produces a stronger and more homogenous magnetic field within a larger working space. The radio frequency system can be divided into a transmission and a receiving chain. A microcontroller is used to program RF pulses and a Direct Digital Synthesizer (DDS) is used to generate high frequency sine waves. This signal is then amplified and sent to a solenoidal coil, which generates a magnetic field perpendicular to the magnet's magnetic field that tips the proton by 90 degrees. When the pulse is removed, the proton will relax back to a lower energy state by emitting a response. A separate receiving coil is used to pick up this response. During receiving, the T/R switch couples the low noise amplifier to the receiving coil. The T/R switch provides isolation during transmission to protect the low noise amplifier from any damages. The response signal is generally very weak in the range of microvolts. A low noise amplifier is used to amplify the signal without introducing distortion. The signal is then filtered using a low pass filter and digitized using an Analog to Digital Converter (ADC). The microcontroller can be used to send the signal to a computer for signal processing and image reconstruction.

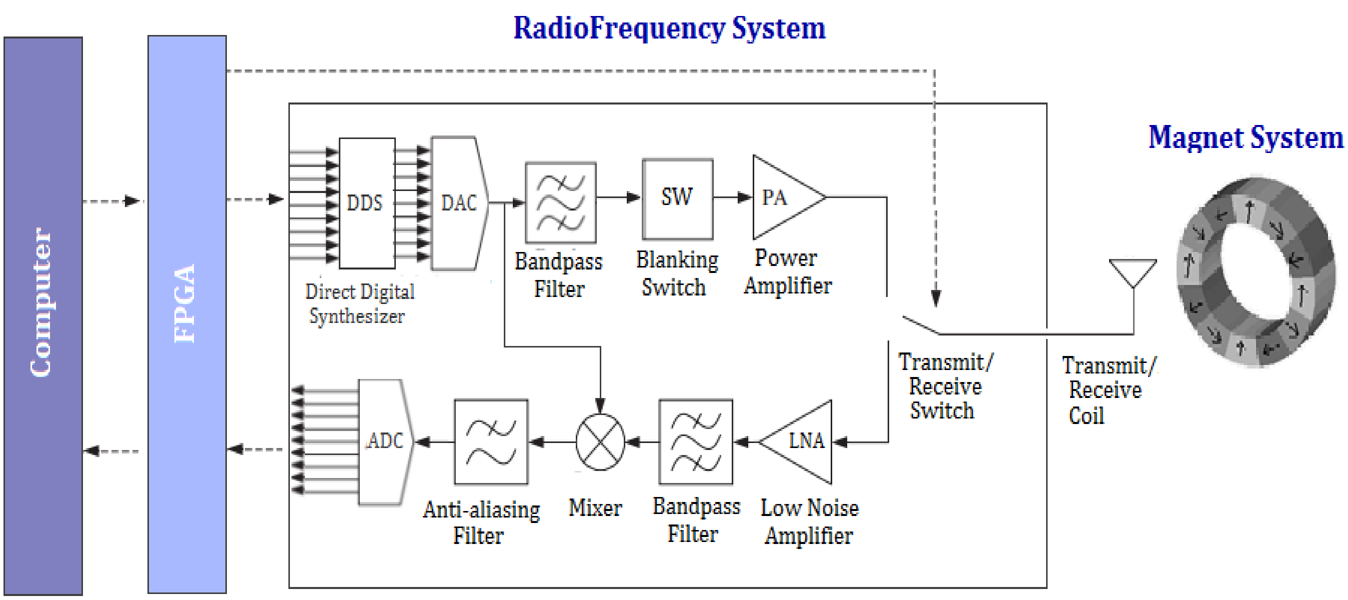

Figure 1: System Overview

3. Project Challenges

Our original proposal was very ambitious. We underestimated the complexity and difficulty of our project. This caused prolonged research and we spent many hours meeting with professors who are knowledgeable in the fields related to our project. Due to the challenges described below, we revised our scope from 2D imaging to 1D signal acquisition.

Our limited experience working with high frequency components was another factor that was overlooked. High frequency systems presented unique challenges that are not present in the low frequency electronics that our team had experience working with. High frequency electronics require wide paths for signal flow and to account for skin effects. Besides that, component leads have to be as short as possible to prevent the leads from acting as antennas. Interference from the environment and other lab equipment is a serious issue and this introduced significant noise. The components used at high frequency are also very sensitive. A slight readjustment of the wires in the transmitting or receiving coils can result in different parameters.

Another major challenge is the lack of proper equipment for testing high frequency electronics. Radiofrequency electronics need to be matched to 50 ohm for maximum power transfer and performance. However, the oscilloscopes in lab 1 only have high impedance probes which also cause significant capacitive loading. To work around this issue, we built 50 ohm adapter for the probes. This allowed us to make voltage measurements at high frequency. However, lab 1 has no equipment that that guarantees or provides information about impedance matching. Dr. Rodney Vaughan has generously provided us with access to a network analyzer that allows match the impedance of our circuit to 50 ohm and tune our circuit to 9 MHz.

The T/R switch is also a challenging part of the project. The main function of the T/R switch is to protect the low noise amplifier from any damage during the high power transmission pulses and prevent it from oversaturating. Commercially available T/R switches are either rated for low power or rated for very high frequency (in GHz). So the team decided to build a T/R switch. After 3 revisions and different designs, we built a T/R switch that is capable of providing good isolation for voltages below 15 V. This helped prevent the low noise amplifier from oversaturating.

Noise level proved to be a significant challenge in our receiving line. Since the sample response was expected to be only in the order of few millivolts (after 60 db amplification), it was likely buried under the noise. To reduce noise, we built a Faraday cage and installed our receiving chain inside the Faraday cage. We also designed a bandpass filter to further remove unwanted signal and noise. To improve signal-to-noise ratio, we modified our design to use separate coils for transmitting and receiving. This allowed our receiving coil to be as close as possible to the sample, thus increasing our signal-to-noise ratio.

4. Proposed Schedule vs Actual Schedule

The comparison between our initial proposed schedule and our actual schedule is shown in Figure 1. The individual systems required more research than initially expected. The team performed extensive research to fully understand the principle behind MRI and design our magnet and radiofrequency systems accordingly. This was the primary reason for falling behind the schedule. Delay in magnet system design further delayed radiofrequency system design since radiofrequency system design depends on knowledge of field map of the magnet system. The team decided to build many components instead of purchasing components, due to high market price and power requirements. This added to the time and complexity of the project. Also, due to lack of access to high frequency devices in engineering labs, the team has had to come up with innovative methods to test the performance of high frequency circuits. These factors have contributed in delaying the project by approximately two weeks.

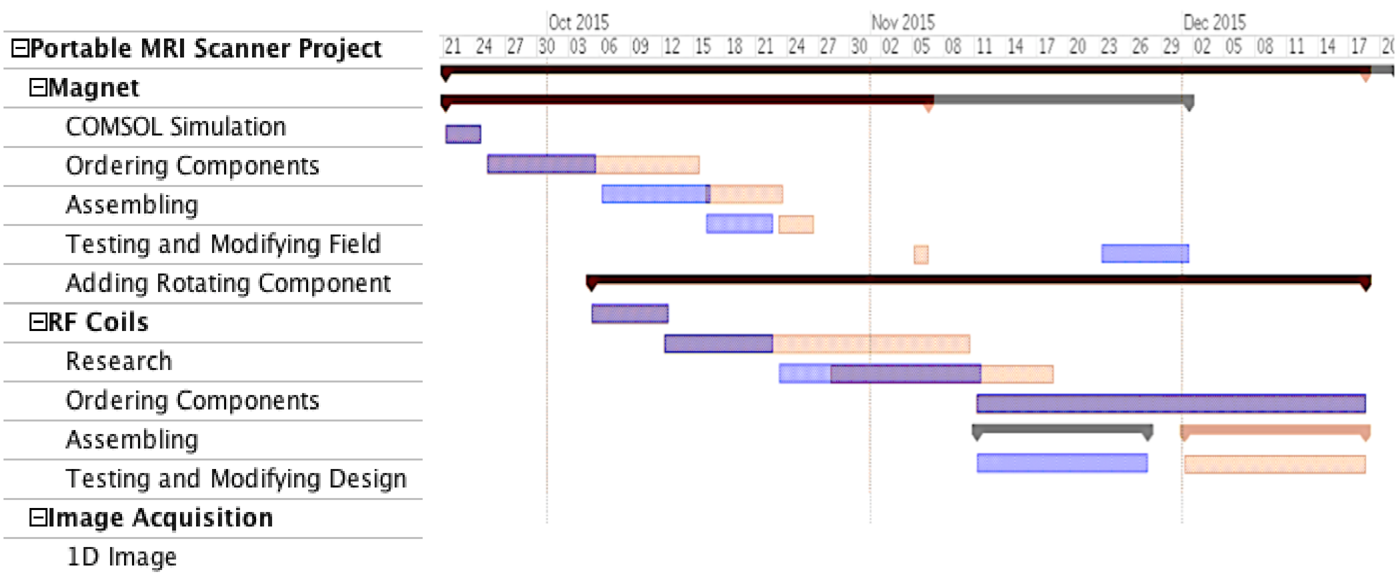

Figure 1: Proposed Schedule versus Actual Schedule (Proposed Schedule Tasks shown in blue, and Actual Schedule Tasks shown in Red)

5. Proposed Budget vs Actual Cost

The total cost for the project exceeds the proposed budget by approximately $300. Table 1 summarizes all the incurred cost and the difference between the estimated and actual cost. The primary reason for exceeding the proposed budget is due to changes in design of the radiofrequency system and underestimation of the components' prices. We were able to reduce the costs by requesting sample components from Analog Devices, Linear Technology and Mini Circuits. Furthermore, we used our own FPGA boards, Arduino boards and tested components using equipment in lab1 and the Sierra Wireless lab at SFU.

ESSEF funding has contributed $500 to the project, which is insufficient to cover all the incurred expenses. The remaining $1203.34 has been covered by team members in equal contributions. MRI solutions will apply to the Wighton fund in December to cover the exceeded cost.

Table 1: Comparison of Estimated and Actual cost

Equipment	Estimated Cost	Actual Cost	Difference
24 Neodymium permanent magnets	$600.00	$729.62	-$129.62
Fibreglass square tube	$50.00	$21.00	+$29.00
Magnet mount	$50.00	$32.98	+$17.02
Epoxy Adhesive	$60.00	$35.74	+$24.26
Magnetometer	$50.00	-	-
RF Tx & Rx coils	$10.00	$31.15	-$21.15
Arduino Uno	$40.00	-	-
Direct Digital Synthesizer (DDS)	$100.00	-	+$100.00
Analog-to-Digital Converter (ADC)	$100.00	$50.77	+$49.23
Power Amplifier	$100.00	$129.15	-$29.15
T/R switch	$10.00	$166.79	-$156.79
Filter(s)	-	$78.42	-
Low Noise Amplifier	-	$29.52	-
FPGA	-	-	-
SMA Cables	-	$133.60	-
Miscellaneous electronics and boards	-	$264.60	-
Contingency (20%)	$234.00	-	-
Total Cost	**$1404.00**	**$1703.34**	**-$299.34**

6. Group Dynamics

MRI Solutions consists of 5 determined, brilliant and compassionate senior engineering students: Anterpal Singh Sandhu, Barry Yim, Evangeline Yee, Gagandeep Kaur, and Robin Wisniewski. Each team member brings their own unique set of technical skills and personality to the company.

Status update meetings were held weekly for 1-2 hours. During the status meetings, decisions were made and any issues or concerns were addressed. Furthermore, the team members met 1-2 times within the week for reporting and information-oriented meetings as well. Also, the team members were available cross-platform mobile messaging application.

There were no serious problems while working as a team. Equal distribution of workload and frequent communication between team members helped in avoiding any problems during the project. Despite giving a leadership role to one member in individual components, all of the members working on the component were treated on the same level. However, there was a conflict of opinion a few times, but team discussions helped in resolving it in a civilized manner.

7. Workload Distribution

The workload was distributed evenly among the team members aligning with their interests and area of expertise. The team ensured that all technical tasks were done by more than one person. This is because in the case of an emergency there would be at least one person who is able to continue with the design and testing of the components. Table 2 provides precise information about the roles played by all the team members in building and testing different components.

- Responsible (R) : The person was the authority in the execution of this area. The person is responsible for meeting the weekly goals and any delays in the component.
- Assisting (A) : The person executed significant work in this area. Their workload could be equal to that of the responsible, but they would not be responsible for making any crucial decisions.
- Contributor (C): The person provided valuable contribution in planning, design or execution at times but was generally less than the responsible or assisting.

Table 2: Workload Distribution Chart

Task	Anterpal	Barry	Evangeline	Gagan	Robin
Research	C	C	C	C	C
Magnet Assembly	R			A	R
Field Mapping			R		
Rotation of Magnet	A				R
FPGA programming		A	R		
DDS		R	A		C
Blanking Switch			R		
Power Amplifier	R		R		
Matching & Tuning circuit	R			R	
Filter(s)				R	
T/R Switch		R	A		
Low Noise Amplifier	C		A	R	
ADC		A		R	R
System Testing	R	A	R		A
Documentation	C	C	C	C	C

8. Personal Reflections

Evangeline Yee (CEO, *MRI Solutions Inc*)

When we first started researching into MRI scanner, we initially planned to do a small scaled conventional MRI. We soon realized that it is incredibly difficult to build a MRI the conventional way and there is no value in doing so since we are not solving a problem. With this in mind, we did further research to look for alternatives and creative ways to address the issue of cost that is associated with MRI scanner. We eventually stumbled upon some recent research in projection-based MRI. This was an incredibly valuable experience for me especially as an biomedical engineer to learn how to take a real-world problem and find a solution that is both simple and effective.

Prior to this capstone project, I had very little experience in magnet and radiofrequency design. I have spent countless hours in the first two months of the semester reading research papers and textbooks just to figure out the magnet and radiofrequency designs that others have built for MRI. Having built our hardware and circuits from scratch, I feel absolutely confident in tackling any problem that I might not have expertise or previous experience in. This project has definitely helped me develop as an engineer. Throughout this project, I was also able to utilize the programming skills and knowledge that I have gained from previous courses and Co-op. My interest in FPGA and signal processing allowed me to quickly develop a platform for controlling our radiofrequency design. This project helped me expand my skills and provided me with an opportunity to learn how to integrate my skills and knowledge.

Unlike most teams, our team was not entirely formed based on friendship. We had to learn quickly how to work with each other and work in a good dynamic. It has been an absolute pleasure to work with my fellow teammates. They have taught me so much in terms of interpersonal and communication skills. Each of them has their own strengths and they inspire me to be a better version of myself. I have learned to communicate more effectively and I gained valuable experience in project management. We wanted this project to be a highlight of our undergraduate career, something we can look back on and be proud of. I hope with our remaining two weeks extension, we can end our project in a high note and achieve our goal of observing magnetic resonance response

Anterpal Singh Sandhu (CFO, *MRI Solutions Inc*)

This project gave me a chance to work independently with my fellow students towards achieving a goal mimicking the real world scenario. By the end of term, I am confident enough to take any challenges in industry or research. I have developed an attitude, which will help me in solving any problem even if I have no knowledge about it.

Overall, this project gave me an exposure to the working of an MRI scanner. I have been mainly responsible for working on designing of the magnet system. I researched into different magnet arrangements that can be used to produce a magnetic field of desired strength and homogeneity. I had productive discussions with many professors in Physics and Engineering department, who have experience working with MRI scanners. This enhanced my understanding of the concepts and phenomenon used in this imaging technique. Being a biomedical student and having designed a scanner myself, I believe that I will have a competitive edge over others while applying for biomedical imaging jobs related in MRI field.

Also, I have worked on transmission and receiving line. This helped me explore the world of high frequency (HF) electronics. Coming from negligible experience in HF, this project gave me an introduction to design in HF, which will be very helpful if I plan to pursue a career in telecommunications. I got my hands on tools like network analyzer and designed HF circuits on copper clad boards. It involved working with surface mount components and polished my soldering skills.

I learned that anything that seems straightforward as a concept and works perfectly in theory could have an unpredictable response in practice. Especially working with hardware can be very tricky, since changing only the placement of one tiny component or one improper connection can give you redundant outcome or might blow up the entire circuit. For majority of the time, our team members worked in parallel on different components. I understood that efficient communication between team members is the key in integrating individual work into a final system. Overall, the project was a success and I am very happy that I was able to work with an excellent team of engineering students.

Barry Yim (CTO, *MRI Solutions Inc*)

In the initial stages of deciding on our capstone project, we wanted to do something that will be the highlight of our undergrad career here at Simon Fraser University. This lead us to create a company called MRI Solutions, and we ultimately decided to design a small scale MRI, capable of imaging a finger. After further research, we found that conventional MRI uses the superposition of a homogenous field pattern and linear gradient. However, homogeneity is an enormous constraint, due to the fact that it is essentially the main reason why conventional MRI is expensive and not portable. We decided to go in an unconventional route. We found that by using inherent inhomogeneous field pattern of permanent magnet for spatial encoding, along with an project-based imaging technique we can achieve our goal.

As the CTO of MRI Solutions, I was able to apply skills that I have learnt over the past four years in school to this project while picking up new skills along the way. "Life is either a daring adventure or nothing at all" is a great quote by Helen Keller. I would have never thought that studying the physics regarding MRI and ultimately attempting to design a MRI would be my daring adventure. My main focus on the project was the FPGA Programming with DDS and ADC, and also the construction with the TR Switch. Working on the FPGA programming for the Direct Digital Synthesizer and ADC has allowed me to apply the skills that I have gained from previous circuitry and system design courses. However, I was unable to carry out my approach to the FPGA/DDS programming as I believed that I initially would. In hindsight, I felt that my approach was inflexible, and quite ambitious. This experience has led me to continuously have a broader perspective with the whole picture. More importantly, I have gain a better sense of how I work under pressure and given time constraint. I will not over-think, and be confident in my approach in the future. I truly believe that this learning experience will be impactful when I graduate and start working in the industry.

I would sincerely like to thank Anterpal, Gagan, Evangeline, and Robin for their immense contributions to the team. I am fortunate to be able to work with these four outstanding engineers and I will definitely consider working with them again in the future. It has truly been an awarding four months!

Gagandeep Kaur (CCO, *MRI Solutions Inc*)

I started this project with no knowledge about MRIs. During the course of this project, I got to learn about conventional and non conventional MRIs as well as various imaging techniques. I also got the opportunity to design and create prototypes of high frequency circuits on copper clad board.

This project was very ambitious from the beginning but we did not expect to encounter as many problems as we did. I learnt from my teammates how to simplify a complicated design by dividing it into several smaller problems and solving them individually. It makes me believe that any problem can be solved by following the same methodology. I also learnt the importance of paying attention to small details to avoid problems in future, to keep trying different ways to figure out how to solve a problem, and to think of innovative ways to solve present issues. Having no previous knowledge of high frequency or copper clad prototyping, I learnt how to make a good circuit after making several errors and faulty circuits.

We worked as a team while researching and divided goals and tasks appropriately amongst each other. Out of the tasks given to me, some I was able to accomplish, while there were few I was not completely successful at. This is because as we go to high frequencies, circuits start behaving differently and sensitivity becomes really important.

The teamwork required in this project not only helped me in improving my communication skills but also provided me with experience in multitasking, resolving conflicts, working on a time limit and handling stress. Also, working on the technical documents as a team improved my written and documentation skills a lot.

In all, working with this team was very rewarding and I learnt many things from my team members that will help me in future.

Robin Wisniewski (CPO, *MRI Solutions Inc*)

Over the last four months, I have been lucky enough to work with the talented MRI Solutions team on a low cost portable MRI. Acting as the CPO, I gained valuable experience working as a group as we encountered problems and worked hard to solve them, as well as, the daily challenges faced when the project wasn't progressing as quickly as some members would hope.

A the beginning the project, I had no knowledge of MRI scanners aside from the fact it used a very strong magnetic field. By spending countless hours reading textbooks and scientific papers, I was able to slowly unravel the complex science that allows the MRI machine to function. Throughout these 4 months, I have gained knowledge and experience in magnetism, signal processing, analog to digital conversion and various filtering methods. Adding to my knowledge and gaining hands on experience, my skills in these categories have been increased and refined.

As the project wrapped up, communication has turned out to be one of the most important aspects of this project. When communication gaps emerged, it usually resulted in group members butting heads. Experiencing those frustrations has forced me to improve my communication skills as a team needs to be able to function smoothly otherwise progress will suffer. I don't believe anyone was perfect in communicating issues or progress but I feel we all put in a strong effort to keep everyone up to date with the latest information.

Overall, I am happy with my experience with the MRI Solutions team. I have gained a tremendous amount of knowledge of MRI's and I believe my experience with various aspects of the project will benefit me in the future as I enter industry. I would like to thank the MRI Solutions team and the professors at SFU for the opportunity to work on this capstone project. There were also many professors who took time out of their busy schedule to help out our team, I would also like to thank them for their valuable contributions to the project as we would not have finished nearly as much without them.

9. Conclusion & Future Work

We outlined our final progress towards the making of an unconventional MRI scanner. This semester has been a very challenging and yet a rewarding experience for the MRI Solutions team. Over the course of this project, we have successfully designed a Halbach magnet system and a radiofrequency system. Although we encountered many challenges during the implementation and testing phase, we were able to improvise and make design changes to resolve these issues. Due to time constraint and underestimation of the complexity of this project, we have changed our scope from 2D imaging to observing 1D resonance response. We will continue to push on and further improve our system for 1D signal acquisition. Pending successful observation of 1D free induction decay response, the next goal will be to produce a 2D image from the received signals. A stepper motor will be used to rotate the magnet system in synchronicity with the data acquisition at different angles. Thereafter, an image can be produced using a backprojection technique from data acquired at various projection angles.

10. References

[1] MRI Scans: Waiting for Public Health Care vs. Paying for a Private MRI Clinic, 2010. [Online]. Available: http://www.bcliving.ca/health/mri-scans-waiting-for-public-health-care- vs- paying-for-a-private-mri-clinic. [Accessed: 27-Sep-2015]

[2] Cooley, C.Z., et al. (2015). Two-Dimensional Imaging in a Lightweight Portable MRI Scanner without Gradient Coils. Magnetic Resonance in Medicine, 73, 872-883.

APPENDIX: MEETING MINUTES

MRI Solutions
AGENDA

September 13, 2015
1500-1700 hrs
WAC Bennett Library Room 2112

Purpose of Meeting: Initial Meeting, discuss on project idea, and discuss upon initial research on "Portable MRI Scanner"

Items for Discussion:

- Discussed possible ideas for capstone project
- Scope of the project
- Our aim for the project
- Possible Design solutions
- Roles and Responsibility

MRI Solutions

MINUTES

September 20, 2015
1500-1700 hrs
WAC Bennett Library Room 2112

Present: Anterpal, Gagan, Barry, Evangeline, Robin

Absent: None

Purpose of Meeting: Initial Meeting, discuss on project idea, and discuss upon initial research on "Portable MRI Scanner"

Minutes by: Barry

A. Discussion of project ideas

Discussion:
Ideas that were discussed:

1. Portable MRI Scanner
2. Fingerprint Sensor on keyboard cover
3. Cell phone wireless charging through Wifi Router
4. Portable Vein finder and Ultrasound Scanner

Most possible option will be to make a portable MRI Scanner

1. What is the optimal magnetic field needed for a MRI of a finger?

B. Actions and Deadlines

1. Do more research regarding magnetic fields, specifically how to generate homogeneous field for MRI imaging.
2. Meet with Andrew Rawicz tomorrow at 1:30pm, ask about "Portable MRI Scanner", and his thoughts on it. Also, ask about our other ideas if need be.
3. Set up a whatsapp group for frequent communication.

C. Next Meeting Date

The next meeting was arranged for September 20, 2015 at 1500-1700 hrs. .

D. Meeting End

Meeting was adjourned at 1700 hrs.

MRI Solutions
AGENDA

September 20, 2015
1500-1700 hrs
WAC Bennett Library Room 2112

Purpose of Meeting: To discuss initial research on "Portable MRI Scanner"

Items for Discussion:

- Finalize the design and subsystems in the prototype
- Deadlines for each subsystem
- How far should the project aim at achieving?
- Budget and apply for funding options

MRI Solutions
MINUTES

September 20, 2015
1500-1700 hrs
WAC Bennett Library Room 2112

Present: Anterpal, Gagan, Barry, Evangeline, Robin

Absent: None

Purpose of Meeting: To discuss initial research on "Portable MRI Scanner"

Minutes by: Barry

A. Discussion

1. Halbach Design for the magnet system and simulations using QuickField
2. Neodymium magnets will be used
3. What should be a realistic ending point for the project
4. Refer to papers uploaded on dropbox folder for RF system components design
5. Discuss the budget for the project

B. Actions and Deadlines

1. Look at simulations for the magnet assembly before ordering
2. Talk to Dr Mike Hayden, the MRI expert in Physics department, about possible problems
3. Email various suppliers for quotes about the Magnet prices
4. Look for funding options

C. Next Meeting Date

The next meeting was arranged for September 27, 2015 at 1500-1700 hrs.

D. Other Business

None.

E. Meeting End

Meeting was adjourned at 1700 hrs.

MRI Solutions
AGENDA

September 27, 2015
1500-1700 hrs
Lab 1 Sunny Room

Purpose of Meeting: Magnet system and housing design

Items for Discussion:

- Ordering Magnet
- Discuss housing component for magnet, materials needed etc.
- RF System components, when to order and what specifically to order
- Setting specific deadlines for the RF system- for all the components
- ESSS funding update
- Set weekly deliveries (ie. goals for this week and individual assignments)

MRI Solutions
MINUTES

September 27, 2015
1500-1700 hrs
Lab 1 Sunny Room

Present: Anterpal, Gagan, Barry, Evangeline, Robin

Purpose of Meeting: Magnet system and housing design

Minutes by: Barry

A. Discussion

Magnet system

1. In terms of Halbach design, I think we're set, we just need to place the order. Anter, do you want to do this?
2. For housing
   a. We decided on using fiberglass. We'll need to place an order as well
   b. Need to get glue. We can get this from homedepot. Not urgent
   c. Wooden frame can also be easily sourced, so let's just wait till we get the magnets and fiberglass first
3. Let's do transmitter part first. After this, hopefully we'll have a 1D imaging system ready. Then we'll move on to RF receiver and motor system for 2D imaging.

B. Actions and Deadlines

Sept 29 - Oct 4 TO-DO List	Details/Comments	Assigned to
Order magnet		Anter
Order fiberglass		Anter
Research RF coils	equations, impedance matching, coil material to use/buy, coil size, plastic tube to wrap coil around … etc	Everyone
Email ESSS about parts	from their website..	Awesome! We can do this on Sunday!

C. Next Meeting Date

The next meeting was arranged for October 4, 2015 at 1500-1700 hrs.

MRI Solutions
AGENDA

October 4, 2015
1500-1700 hrs
ENSC Lab 1

Purpose of Meeting: Discussion about RF System

Items for Discussion:

- Surface and volume coils
- Impedance matching
- Research about components used in RF System
- Ordering of components
- Matching and tuning

MRI Solutions
MINUTES

October 4, 2015
1500-1700 hrs
ENSC Lab 1

Present: Anterpal, Gagan, Barry, Evangeline, Robin

Absent: None

Purpose of Meeting: Discussion about RF system

Minutes by: Barry

A. Discussion

Radio Frequency System

1. Constructing the surface and volume coils

- the easiest part is to design the volume coils first
- the simplest design looks like this. Tuning frequency is easy, w=1/sqrt(LC).
- Figuring out how to match impedance.
- Match all our circuits to 50 ohm cause most coaxial cable is matched to that as well.
- On that note, we'll probably need coaxial cables http://www.digikey.ca/product-search/en/cable-assemblies/coaxial-cables-rf/1573243?k=coaxial%20cable) for our RF.
- We'll need a plastic tube to wrap our coil in. This should be easy to find.
- The RF system has to be shielded to stop interference for Radio frequencies

Ordering the components

Look into the RF System and see what components we need to order, that could be our assignment for the week. We can assign one component to each person? During Sunday's Meeting we can meet and discuss?

All of us could have 2 goals each such that there are two people researching on the same thing. That way we can compare 2 ideas?

B. Actions and Deadlines

Oct 4 - Oct 11 TO-DO List	Details/Comments	Assigned to
Research RF coils	equations, impedance matching, coil material to use/buy, coil size, plastic tube to wrap coil around ... etc	Gagan, Anter
Research microcontroller	That we need to program the pulses, send and receive RF waves, generate square wave to turn RF on/off	Barry, Gagan
Research DDS	model, specs, how to use it, how to interface this with microcontroller, filter, and amps, check if ADC is included	Barry, Anter
Research Low pass filter	design one? pretty sure we can build one	Evangeline
Research power amp	criterias? gain, bandwidth etc do we need to buy this? can we source/build one?	Robin, Evangeline
Research gating switch	This is to modulate output from DDS (ie combine the square wave (on/off) from microcontroller with the sine wave from DDS). Can do this using op-amp with enable pin or microcontroller or an actual switch	Robin

C. Next Meeting Date

The next meeting was arranged for October 11, 2015 at 1500-1700 hrs.

D. Other Business

None.

E. Meeting End

Meeting was adjourned at 1700 hrs.

MRI SOLUTIONS

MRI Solutions
AGENDA

October 11, 2015
1500-1700 hrs
WAC Bennett Library Room 2103

Purpose of Meeting: To discuss the design of Power Amplifier, Bandpass Filter and component matching

Items for Discussion:

- How much power do we need for our circuit
- How much magnetic field required to tip the protons
- Determining the pulse time, current and size of the transmitting and receiving coils
- Design of bandpass filter
- Matching and Tuning of coils
- Order a DDS

MRI Solutions
MINUTES

October 11, 2015
1500-1700 hrs
WAC Bennett Library Room 2103

Present: Anterpal, Gagan, Barry, Evangeline, Robin

Absent: None

Purpose of Meeting: Discuss the requirements and calculations for power amplifier, how to get one, bandpass filter

Minutes by: Robin

A. Discussion

1. Power Amplifier: How much power do we need? Emailed Shawn Stapleton (recommended by Rodney Vaughn)
2. How much magnetic field is required to tip protons by 90 degrees
3. Bandpass Filter: Not available in the market for our frequency range. Study the design of bandpass filter: discuss the final design with Rodney on Thursday
4. How to match and tune the rf coils: Study the possible circuits
5. Where to look for an amplifier: a 300W amplifier is very expensive
6. FPGA Altera DE1 will be used to control the DDS
7. Waterjet cutting will be used to cut the plywood for magnet system

RF coil

1. Use the same coil for receiving and transmitting would reduce our power and current requirements. (Decreasing the diameter of the T/R coil)
2. Use two T/R switches

B. Actions and Deadlines

1. Come up with a design for Bandpass filter until thursday and discuss with Rodney
2. Start on the magnet design by the end of this week
3. Robin will email Analog devices to request a sample for DDS
4. Order magnets and Fiberglass tube
5. Come up with ideas to minimize our power requirements

C. Next Meeting Date

The next meeting was arranged for October 18, 2015 at 1500-1700 hrs.

MRI Solutions
AGENDA

October 18, 2015
1500-1700 hrs
ENSC Lab 1

Purpose of Meeting: Design for Magnet assembly and transmitting system

Items for Discussion:

- Populating the magnets to make the Halbach arrangement
- Components for transmitting circuit
- Filter Design in high frequency
- Minimize the power requirements

MRI Solutions
MINUTES

October 18, 2015
1500-1700 hrs
ENSC Lab 1

Present: Anterpal, Gagan, Barry, Evangeline, Robin

Absent: None

Purpose of Meeting: Design for Magnet assembly and transmitting system

Minutes by: Barry

A. Discussion

1. DDS sample has been received from Analog devices
2. Magnets and Fiberglass has been received
3. The DXF file for waterjet cutting has been sent to BCIT
4. The magnet populating will start by the end of week
5. Transmitting circuit components such as solenoid, band pass filter will be made on copper clad
6. Minimize power by using tightly wound wire. The wire diameter will determine the current passing through the coil

B. Actions and Deadlines

1. Search for clamps required to populate the magnets
2. Buy epoxy strong enough to glue two magnet pieces together
3. Buy copper clad board
4. Gagan will be researching on filter design in high frequency

C. Next Meeting Date

The next meeting was arranged for October 25, 2015 at 1500-1700 hrs.

D. Other Business

None.

E. Meeting End

Meeting was adjourned at 1700 hrs.

MRI Solutions
AGENDA

October 25, 2015
1500-1700 hrs
ENSC Lab 1

Purpose of Meeting: Start on magnet system and finish calculations for transmission line

Items for Discussion:

- Time period of frequency pulse
- Minimize power requirements by decreasing the current required
- Spin echo trains

MRI Solutions
MINUTES

October 25, 2015
1500-1700 hrs
ENSC Lab 1

Present: Anterpal, Gagan, Barry, Evangeline, Robin

Absent: None

Purpose of Meeting:

Minutes by: Barry

A. Discussion

1. Magnets and Fiberglass has been received. Fiberglass can be cut and prepare housing
2. Strong clamps to hold magnets together and bond them using epoxy
3. Revise deadlines
4. Spin echo train
5. What should be the Quality factor and Time period of the pulse?
6. Current should be minimized and n should be increased in coil to consume less power

B. Actions and Deadlines

1. Magnet assembly should be assembled by next weekend
2. Robin can arrange for clamps which are strong
3. Do research on spin echo train

C. Next Meeting Date

The next meeting was arranged for November 1, 2015 at 1500-1700 hrs.

D. Other Business

None.

E. Meeting End

Meeting was adjourned at 1700 hrs.

MRI SOLUTIONS

MRI Solutions
AGENDA

November 1, 2015
1500-1700 hrs
ENSC Lab 1 Sunny Room

Purpose of Meeting: Discuss and find the components for transmitting and receiving channel

Items for Discussion:

- Field mapping for Halbach array
- Receiving channel components
- Calculate values for all the design components
- Cables for the components
- Components for circuits

MRI Solutions
MINUTES

November 1, 2015
1500-1700 hrs
ENSC Lab 1 Sunny Room

Present: Anterpal, Gagan, Barry, Evangeline, Robin

Absent: None

Purpose of Meeting: Discuss and find the components for transmitting and receiving channel

Minutes by: Barry

A. Discussion

1. Halbach array is prepared and all the magnets are fixed.
2. Hall probe sensor will be used to make a circuit so that magnetic field is mapped.
3. The inhomogeneity is expected to be less than 1%
4. The components in the receiving channel should be LNA, Bandpass filter followed by ADC or Mixer+ADC.
5. Should aim to use one kind of cables for consistency. SMA cables, since DDS comes with SMA cables. Also, they are easy to find.

B. Actions and Deadlines

1. Order components for Low noise amplifier and a mixer for a backup.
2. Request an ADC from Analog devices
3. Designworks drawings for the design specs
4. Finalize all the values for every components so that Design Specs document can be prepared
5. Order T/R switches, AWG 20 wire and
6. Order SMA male to male cables and female connector pins for the components

C. Next Meeting Date

The next meeting was arranged for November 8, 2015 at 1500-1700 hrs.

D. Other Business

None.

E. Meeting End

Meeting was adjourned at 1700 hrs.

MRI Solutions
AGENDA

November 8, 2015
1500-1700 hrs
ENSC Lab 1

Purpose of Meeting: Finalise the values for every component to prepare Design Specs

Items for Discussion:

- Final Design for Design specs
- Magnet system rotation
- Values for all the design
- Components for Receiving channel
- Request samples from Mini circuits
- Reassign the duties

MRI Solutions
MINUTES

November 8, 2015
1500-1700 hrs
ENSC Lab 1

Present: Anterpal, Gagan, Barry, Evangeline, Robin

Absent: None

Purpose of Meeting: Finalise the values for every component to prepare Design Specs

Minutes by: Barry

A. Discussion

1. Magnet system is completed and field is mapped, which is very good. A sample size is decided to be 1 cm.
2. The center frequency is 9 MHz
3. Maximize the Q and calculate the respective resistance value
4. Calculate the values for tuning and matching capacitor
5. Calculate the current and finalize the turns for our transmitting coil
6. The time period for the pulse is increased so that power requirements can be decreased
7. Anterpal and Robin move to other components of the transmitting circuit

B. Actions and Deadlines

1. Order variable capacitors for the matching and tuning circuits
2. Order resistor with a power rating of 10 W for matching and tuning circuit
3. Request samples of mixer, Low Noise Amplifier from mini circuits

C. Next Meeting Date

The next meeting was arranged for November 15, 2015 at 1500-1700 hrs.

D. Other Business

None.

E. Meeting End

Meeting was adjourned at 1700 hrs.

MRI Solutions
AGENDA

November 15, 2015
1500-1700 hrs
ENSC Lab 1

Purpose of Meeting: To discuss the problems with FPGA part, finalise the RF design

Items for Discussion:

- Order new amplifier(5W)
- Discuss the design of bandpass filter and matching circuit
- Discuss the problems with FPGA
- How to design the pulse programmer

MRI SOLUTIONS

MRI Solutions
MINUTES

November 15, 2015
1500-1700 hrs
ENSC Lab 1

Present: Anterpal, Gagan, Barry, Evangeline

Absent: Robin

Purpose of Meeting: To discuss the problems with FPGA part, finalise the RF design

Minutes by: Gagan

A. Discussion

The transmitting coil has been designed and the inductance is calculated to be 25.9 uH and n=1080. The values for matching and tuning capacitors has been calculated.

RF Design

1. Ordered 5W power amplifier: Anter confirmed that maximum power required by the circuit does not exceed 3W
2. Design of bandpass filter: 3rd order butterworth filter, using surface mount instead of through holes
3. Matching circuit: making islands on copper clad board by scraping off some part of the copper

FPGA Design

FPGA programming: 2 options

a. embedded programing in fpga to program the dds
b. using the evaluation software for dds

Spin Echo Pulse

Setting up the different parameters for spin echo pulse.

B. Actions and Deadlines

1. Gagan will Finalise the design of bandpass filter with Lucky and order parts from digikey.
2. Evangeline is working on the evaluation software, looking for a parallel to usb port to connect it to the computer. Barry is working on the embedded program.
3. Set up a google document to discuss the values and the physics behind Spin echo pulse.

4. Buy the components from Lee’s electronics and make the matching and tuning circuits.

C. Next Meeting Date

The next meeting was arranged for November 22, 2015 at 1500-1700 hrs.

D. Other Business

None.

E. Meeting End

Meeting was adjourned at 1700 hrs.

MRI Solutions
AGENDA

November 22, 2015
1500-1700 hrs
ENSC Lab 1

Purpose of Meeting: To finish the transmission stage and speed up the project

Items for Discussion:

- T/R switch
- Test BPF and matching and tuning circuit on network analyzer
- ADC and Mixer
- Order components from Digikey

MRI SOLUTIONS

MRI Solutions
MINUTES

November 22, 2015
1500-1700 hrs
ENSC Lab 1

Present: Anterpal, Gagan, Barry, Evangeline, Robin

Absent: None

Purpose of Meeting: To finish the transmission stage and speed up the project

Minutes by: Gagan

A. Discussion

1. Tuning and matching has been built. One set of BPF has also been built. We will use Network Analyzer to test both
2. FPGA has been controlling the DDS now. The output of the DDS is about 10 mA
3. Power amplifier has been received and testing with power amplifier and resonating circuit has begun
4. Work together on Tuesday and Thursday from 12 pm-late night
5. T/R switch does not meet power requirements. May need to built it ourselves

B. Actions and Deadlines

1. Rotation platform should be designed soon
2. Pick Swivel plate and cables from US mailbox
3. Talk to Rodney to get hands on network analyzer
4. Order a new T/R switch
5. Order ADC and Mixer

C. Next Meeting Date

The next meeting was arranged for November 29, 2015 at 1500-1700 hrs.

D. Other Business

None.

E. Meeting End

Meeting was adjourned at 1700 hrs.

MRI Solutions
AGENDA

November 29, 2015
1500-1700 hrs
ENSC Lab 1

Purpose of Meeting: To test the transmission line and start building components for receiving line

Items for Discussion:

- ADC, clock, Low noise Amplifier testing
- Transmission line is almost finished
- Test the transmission line
- Build components for receiving line
- Written Progress report
- Test plan

MRI Solutions
MINUTES

November 29, 2015
1500-1700 hrs
ENSC Lab 1

Present: Anterpal, Gagan, Barry, Evangeline, Robin

Absent: None

Purpose of Meeting: To test the transmission line and start building components for receiving line

Minutes by: Gagan

A. Discussion

1. Components from digikey, cables and swivel plate for rotation has been received.
2. ADC and clock is built
3. Matching and tuning circuit is tuned to 9 MHz and matched to about 40 ohm
4. DDS, Power amplifier and matching and tuning circuit has working together and current measured is 240 mA
5. T/R switch has been constructed, testing pending
6. Low Noise amplifier has been built, testing pending
7. Written progress report and test plan

B. Actions and Deadlines

1. Test the T/R switch, Low Noise Amplifier
2. Test the sample with magnet and transmission system together
3. Access Network Analyzer and measure the impedance of our matching and tuning circuit
4. Buy more SMA connectors for the circuit.

C. Next Meeting Date

The next meeting was arranged for December 6, 2015 at 1500-1700 hrs.

D. Other Business

None.

E. Meeting End

Meeting was adjourned at 1700 hrs.

MRI SOLUTIONS

MRI Solutions
AGENDA

December 6, 2015
1500-1600 hrs
ENSC Lab 1

Purpose of Meeting: To test the transmission line and start building components for receiving line

Items for Discussion:

- ADC testing, Bandpass filter modification and TR switch
- Fix Low Noise amplifier
- 1 D signal testing
- Final exams and lab closure

MRI Solutions
MINUTES

December 6, 2015
1500-1600 hrs
ENSC Lab 1

Present: Anterpal, Gagan, Barry, Evangeline, Robin

Absent: None

Purpose of Meeting: To test the transmission line and obtain 1 D signal

Minutes by: Gagan

A. Discussion

1. TR switch has been working and being implemented on copper clad board or in extreme case, use blanking switch on receiving channel
2. Fix Bandpass filter and we need a low pass filter for testing purposes
3. Shielding for our magnet system to avoid high frequency noise
4. Low noise amplifier: only one stage is working, fix the second stage to improve gain
5. Final exams and lab closure: sent email to Andrew about permission for access to labs after 20th December.

B. Actions and Deadlines

1. Run testing of system to obtain 1 D signal
2. Finish bandpass filter by Monday
3. Test ADC on FPGA

C. Next Meeting Date

The next meeting will be arranged if required and the team members will be informed.

D. Other Business

None.

E. Meeting End

Meeting was adjourned at 1600 hrs.

MRI Solutions
AGENDA

December 13, 2015
1500-1600 hrs
ENSC Lab 1

Purpose of Meeting: To test the entire system

Items for Discussion:

- DDS broken and use function generator for pulsing
- Stable assembly for coil and tuning and matching circuit
- 1 D signal testing
- Post Mortem, presentation and demo

MRI Solutions
MINUTES

December 13, 2015
1500-1600 hrs
ENSC Lab 1

Present: Anterpal, Gagan, Barry, Evangeline, Robin

Absent: None

Purpose of Meeting: To test the entire system and obtain 1D signal

Minutes by: Gagan

A. Discussion

1. DDS is broken and replacement will be a function generator, pulsing will continue to happen from FPGA
2. Low Noise Amplifier has arrived with a gain of 60 dB
3. Make the magnet system stable and rotate it . Fine tune using the network Analyzer
4. T/R switch work has been ongoing. The back up plan is to use a voltage cut off chip to save low noise amplifier from high power during transmission.

B. Actions and Deadlines

1. The assembly should be stable and finished by Monday
2. Finish T/R switch as soon as possible
3. Post Mortem and presentation by December 20,2015

C. Next Meeting Date

The next meeting will be arranged if required and the team members will be informed. If everything goes well, there will not be a meeting required.

D. Other Business

None.

E. Meeting End

Meeting was adjourned at 1600 hrs.

Post-Mortem Analysis for

Portable MRI Scanner

by

MRI SOLUTIONS

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Revision: 1.0

Introduction

We modified our design and made various improvements over the past 5 weeks. Unfortunately, we are still not able to observe the free induction decay (FID) for our sample. We believe that there are two main reasons for this. First, there may be problems in our transmission line which affect the excitation of protons. In this case, the net magnetization may not be completely tipped onto the transverse plane so the FID signal may be too small to detect. Second, our transmission line may be working as expected but our receiving line may be introducing too much noise to the extent of drowning the FID signal. We are confident that our transmission line is working properly and that it is providing sufficient power at the Larmor frequency to energize and tip the protons. Our experimentations lead us to believe that the problem lies in our receiving line. This paper outlines our analysis of each subsystems: magnet, transmission and receiving to show how we arrived at this conclusion.

Analysis 1: Magnet System

We measured the 1D static field in the center plane of our Halbach magnet and assumed that the static field is perfectly orthogonal to the cylindrical axis of our Halbach magnet. However, the static field could be at an angle to the cylindrical axis due to error in our manufacturing process. Since our Halbach magnet and our transmission/receiving (T/R) coil are concentric, this would cause tipping of protons at less than 90 degrees angle and thus the FID signal would be much smaller. Future work would be to perform a 3D mapping of the static field. Additionally, we can reposition the magnets within a circle of smaller radius. This will increase the static field strength, net magnetization of protons and amplitude of FID signal.

Analysis 2: Transmission Line

We need a large amount of Radiofrequency (RF) energy to excite and tip the protons within a short time frame. This is because if we use lower power and transmit the RF waves for longer period of time the precessing protons can dephase quickly due to field inhomogeneity. So the maximum pulse length that can be used is limited by our field inhomogeneity. In our case, the maximum pulse length is 17μs corresponding to a field inhomogeneity of $1mT/cm^2$. This shorter pulse length increases our power requirement so we built a 3W power amplifier rated at our Larmor frequency (8.94 MHz). We also modified our tuning and matching circuit to increase the impedance matching to 95% thereby reducing power reflection. Our calculations show that a 1μs pulse is sufficient to provide enough RF energy to tip the protons by 90 degrees. This pulse length is 15 times smaller than the maximum length which gives us room to increase our pulse length during trials.

The static field at the center of our Halbach magnet is 210 mT and this corresponds to a Larmor frequency of 8.94 MHz. However, due to field inhomogeneity the protons are precessing at slightly different frequencies. Thus the RF pulse needs to cover a larger bandwidth. In order to increase the excitation bandwidth, we reduced the quality factor of our T/R coil to 81. This corresponds to 110 kHz bandwidth centered at 8.94 MHz. Considering that our sample has a volume of 1 cm^3, this bandwidth is sufficient to excite all the protons in our sample. This allows us to perform a frequency sweep and run signal averaging at different frequencies. To increase our signal-to-noise ratio (SNR), we also repositioned our T/R coil to be as close as possible to our sample. We measured the current in the T/R coil during transmission and our measurements lead us to believe that our transmission line is working as expected. Future work could involve using smaller pulse length and this would require higher power.

Analysis 3: Receiving Line

We strongly believe that the problem lies in our receiving line. Initially, we bought an active T/R switch which couples the T/R coil to the transmission or receiving line depending on the programmable input pins. Upon further investigation, we determined that the T/R switch caused an artifact which also had the same exponential profile as FID signal. When the receiving input pin turned on, it reflected into the receiving line causing an exponential decay response. So we built a passive T/R switch that does not require any trigger inputs and it couples the T/R coil and transmission/receiving line depending on the power of the RF signal. With this passive T/R switch, we no longer observed those artifacts.

To amplify the signal, we bought a 60 dB low noise amplifier (LNA). This gain was insufficient so we built a 25 dB LNA using GALI-74. However, when the two amplifiers are cascaded there were serious oscillations between them causing artifacts and dead time. This was resolved by replacing the 60 dB LNA with a low noise op amp circuit based on a design that was previously done for Nuclear Magnetic Resonance (NMR) experiments. Unfortunately, we still could not observe the FID. This is likely due to hum from the power supplies and other environment noise that may be drowning the FID signal. We built a bandpass filter to remove these noise but it degrades the signal by 3 dB. In addition, our amplifiers are cascaded using coaxial cable which may cause further signal loss.

We also tested the sensitivity of our T/R coil using a pickup coil. We placed the pickup coil inside our magnet and passed a very small current on the order of micro Amp oscillating at our Larmor frequency. Our T/R coil was able to detect the small magnetic flux produced by the pickup coil and the voltage developed across our T/R coil was at the Larmor frequency. This shows that our T/R coil and receiving line are capable of detecting signal of microVolt range. So we believe that the FID signal is in the nanoVolt range which is also the range where the noise from the op amp resides in.

The most critical future work would be to improve our receiving line. A high performance LNA is incredibly tricky to design so it will be wise to purchase one. Note that at the beginning we tried to buy a LNA specifically designed for NMR (AU-1547) but it costs $500 and has a 3 month delivery time. If we had more time, we could afford to buy one.

Conclusion

Although we have not managed to achieve our goal of observing a FID signal, the process we went through over the past 5 weeks in continuously analyzing our systems, eliminating any source of problems and making incremental improvements has been a tremendous learning experience. It also showed us the rigor, determination and expertise required to conduct good research.