A Garnet Tuner for the NOvA Recycler 52.809 MHz RF Cavity

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Abstract

We describe the function of an yttrium-iron garnet tuner and a radio frequency cavity. This experiment is on the subject of particle acceleration and the role the tuner and cavity play in such. This paper will show the data we received while working with RG 58 coaxial cable models and higher Q transmission line models of the RF cavity and tuner, as well as data from the prototype cavity and the tuner using an adjustable short.

1. Introduction

One of the many research programs currently in place at Fermi National Accelerator Laboratory (Fermilab) is a particle study of neutrinos. Radio frequency (RF) cavities[1] are the preferred means of accelerating these particles. The RF cavities use an electromagnetic standing wave with a set frequency so that it particles accelerate as they pass through. For example, if a series of electron bunches are being accelerated then the sign of the wave will change from positive to negative as the bunch passes through the cavity, switching back to positive as the next bunch arrives. The project to be described in this paper describes the research conducted using a garnet tuner and studying its effects on the RF cavity.

A tuner is a transmission line that is shorted at one end and loop-coupled to the cavity at the other. In this project the tuner is a half-wavelength (λ/2) and the cavity is a quarter-wavelength (λ/4) long. This tuner was used to ensure that the temperature variations, RF power levels, and the proton beam intensity stay within a specific range, and do not reach levels that could potentially alter the cavity's results. The tuner maintains the suitable ranges by altering its own electrical length.

A cavity is a coaxial quarter wave resonator with one open end, and the other short-circuited (shorted). The RF cavity and tuner are strongly bonded; as a result, the size of the cavity must be taken into consideration when doing tests. The size of a cavity is related to the frequency of the standing wave so that there will be an integer number of nodes throughout the cavity.

During this project, coupled electrical circuits and coupled mechanical circuits were tested and used to model the RF tuner. When given a driving force both the coupled mechanical circuit and the coupled electrical circuit reached the same conclusion. While experimenting with this set-up, it was noted that, as the tuner electrical length varied, the frequency, inductance, and capacitance changed as well. When the mutual inductance (m) of the aforementioned cavity/tuner system was equal to zero, there was no coupling. As a result all of the information that could be attained from the tuner was excluded.

[1] The prototype radio frequency cavity that will continue to be discussed throughout the entirety of the following paper: 

All of the above experimentation has been and continues to be conducted at Fermilab. Fermilab is a national laboratory that works under the federal United States Department of Energy and is dedicated towards the advancement of the understanding of the elementary nature of matter and energy. In order to do so, Fermilab provides leadership roles and resources for skilled researchers to perform basic methodical investigations at the frontiers of high energy physics and similar disciplines of work. Fermilab is located in Batavia, Illinois and is affiliated with other large scale laboratories, including the European Organization for Nuclear Research (CERN). Fermilab is an advanced laboratory committed to many different forms of scientific research, ranging from environmental science to particle acceleration and much more.

Within the various particle acceleration programs at Fermilab, the particle study of neutrinos is what I focused on this summer. A neutrino is a member of the Standard Model, a theory concerning the electromagnetic, weak, and strong nuclear interactions describing the universe in terms of matter (fermions) and force (bosons), belonging to a class of particles known as leptons, elementary particles. In the past, many scientists and researchers were led to believe that neutrinos had no mass and retained the ability to move at the speed of light. However, further studies have led to the conclusion that neutrinos do indeed possess a miniscule mass of approximately 0.1 eV. With this new understanding, the theory that neutrinos move at the speed of light is proved false as a result of Einstein's theory of special relativity: $\mathrm{E}_{\mathrm{Total}} = \gamma \mathrm{m}_0 \mathrm{c}^2 = \frac{1}{\sqrt{1-\frac{\mathrm{v}^2}{\mathrm{c}^2}}} \mathrm{m}_0 \mathrm{c}^2$. This formula states that an object can only authentically reach the speed of light if it is free of mass. Photons, for example, are the particles which transport light and are free of mass, therefore retaining the ability to travel at the speed of light. In relation to the total energy needed to transport particles, the energy must be equal to $\gamma m_0 c^2$, which means that velocity cannot be equal to the speed of light. If velocity were to become equal to the speed of light, Einstein's theory of special relativity states that energy would become infinite; which, in turn, is truly impossible.

Neutrinos have also been found to possess neither a positive nor negative charge, to have an angular momentum of ½, and have been proven to be stable particles. Because neutrinos belong to the lepton class, they always have a charged particle partner; the electron, the muon, or the tau. Coinciding with the particle study of neutrinos, Fermilab possesses large and precise detectors sensitive enough to detect the neutrinos when they interact with matter; which seldom occurs. In order to promote an interaction with matter, intense beams are used to encourage the neutrinos to travel towards the detectors. This is done through the storage of protons, changing those protons into muons, and therefore resulting in the creation of neutrinos.

Another neutrino experiment being conducted at Fermilab, the Main Injector Neutrino Oscillation Search (MINOS) is designed to study neutrino oscillations. The experiment uses a beam of neutrino particles produced by the Neutrinos at the Main Injector (NuMI) beamline facility. The beam of neutrinos is sent from the MINOS near detector at Fermi National Accelerator Laboratory in Batavia, Illinois to the MINOS far detector at the Soudan Underground Mine State Park in Tower, Minnesota, a 450 mile distance. At Fermilab there are many experiments and projects constantly developing, but the one we are going to acknowledge today is a part of the NOvA (NuMI Off-Axis Electron neutrino Appearance) experiment and focuses on an RF cavity and an yttrium-iron garnet tuner.

2. Materials and Methods

i. *Equipment Used*

a. Network Analyzer[2]
   A network analyzer is a scientific instrument used to measure the network parameters of electrical networks; they commonly measure the s-parameters (reflection and transmission) of electrical networks.
b. Oscilloscope[3]
   An oscilloscope is an electronic test instrument that enables the observation of constantly shifting voltage signals. Oscilloscopes are typically used to observe the precise wave shape of an electrical signal, its amplitude, distortion, frequency, pulse width and rise time, and the relative timing of two related signals.
c. High Frequency Probe[4]
   The high frequency probe we used was an Agilent 85024A probe. The high frequency probe provides passive probing of high impedance circuits.

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[2] The network analyzer we used for measurements with the model set-ups:  [10]

[3] The type of oscilloscope we used in early set-ups:  [11]

[4] The high frequency probe used in model set-ups:  [12]

d. Coaxial Cables[5] and Elbows[6]

The coaxial cables and elbows were used in experimentation when measuring the difference they made in frequency, loss, and Q. The coaxial cables used in our experimentation were RG 58 cables, and can be defined as an electrical cable with an inner conductor surrounded by a tubular insulating layer, surrounded by a tubular conducting shield. A coaxial cable is used as a transmission line for RF signals and has a characteristic impedance of 50 ohms. On the other hand, an elbow is a short section of a 50 ohm coaxial cable with a 90 degree angle used to connect different segments of the λ/2 component of our model set-ups.

e. Adjustable Short[7]

For the adjustable short we used a copper covered piece of stainless steel. This adjustable short was used to help measure the different frequencies associated with the tuner and the RF cavity.

ii. ***Cavity Dimensions***

In order to calculate the inner and outer radii the power available, the desired center frequency, and the voltage across the gap needs to be formerly identified. For this specific resonant frequency cavity the power available is 150 kW, center frequency is 52.809 MHz, and the voltage across the gap is 150 kV. The maximum power available to the RF cavity once installed, along with the desired gap voltage determines the shunt impedance (R_{sh}).

To calculate the dimensions of the cavity first you must implement the formula; $\lambda = \frac{v}{f}$[8], which will result in the detection of the full wavelength, furthermore allowing us to calculate the dimensions of the tuner (λ/2) and the cavity (λ/4). In this case v is equal to the speed of light, $c = 2.998 \times 10^8 \frac{m}{s}$, and f is equal to 52.809MHz. Because we want to

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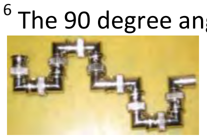
[5] The coaxial cables we used for the model set-ups: 

[6] The 90 degree angle elbows that were used during the construction of the cavity and tuner models:



[7] The adjustable short used during experimentation inside of a portion of the tuner:  The adjustable short is in the center, between the wide, outer radius, yet outside of the smaller copper radius.

[8] The notation in this formula: λ is wavelength, v is velocity, and f is frequency.

ascertain the length of the cavity we must take the full wavelength and divide it by four. The wavelength, being equal to 5.677 meters, led us to the result, $\frac{\lambda}{4} = \frac{5.677\text{m}}{4} = 1.419\text{m} = 56.7\text{in}$, providing us with 56.7 inches as the length of the cavity.

iii. *Electric Field*

In the conduction of this project, a section of it required for us to calculate the electric field between the inner and outer cavity when $V = 150kV$[9]. In order to do so we used the formula $V = \int E \cdot dr = \int E(r)\hat{r} \cdot d\hat{r}$, keeping in mind that $E(r) = \frac{E_0}{r} = 882.35\frac{kV}{m}$. After going through the different calculations we came to the conclusion that the electric field between the inner and outer cavity is $E(r,\theta) = \left[\frac{882.35\frac{kV}{m}}{r}\right] \cdot [\sin(\theta)]$.

3. Results

i. *Frequency Graphs*

The following graphs and figures illustrate the different models of the cavity/tuner system and the frequencies received from the models through the use of RG 58 coaxial cables.

Graph 1 illustrates the resonant frequency measured from a λ/4 (quarter wavelength) transmission line model set-up as shown in Figure 1.

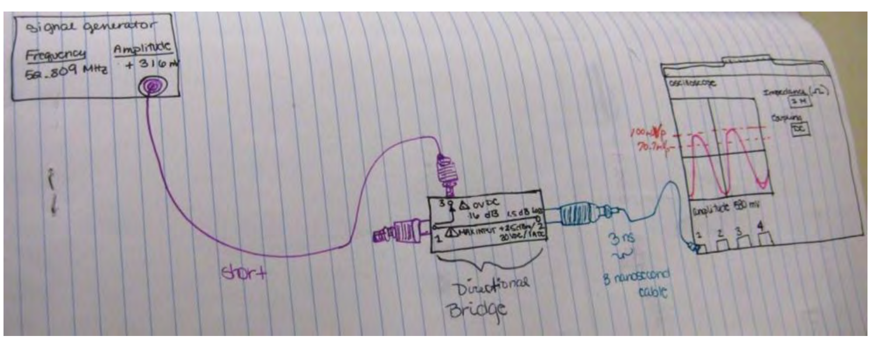
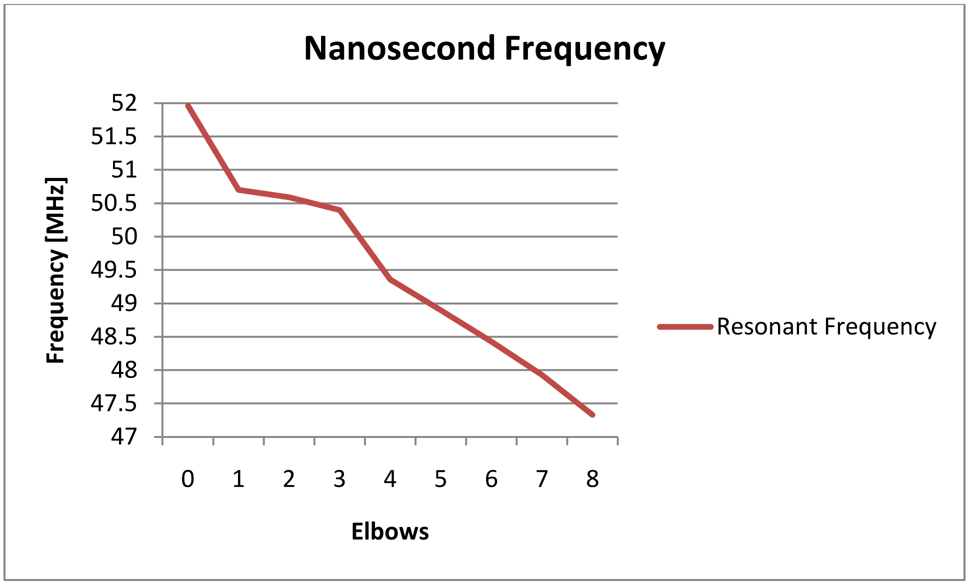


Figure 1

[9] This formula's notation is: V is voltage, and 150 kV is equal to 150 kilovolts.



Graph 1

Graph 2 shows the measured resonant frequencies taken from two different model set ups. One of the set-ups is reflective of the cavity (Figure 2) and the other is reflective of the tuner (Figure 3).

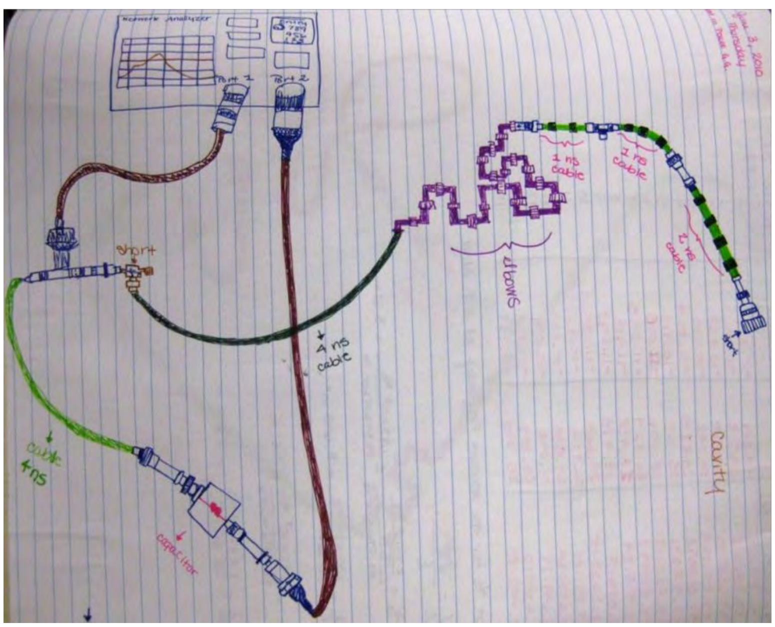


Figure 2

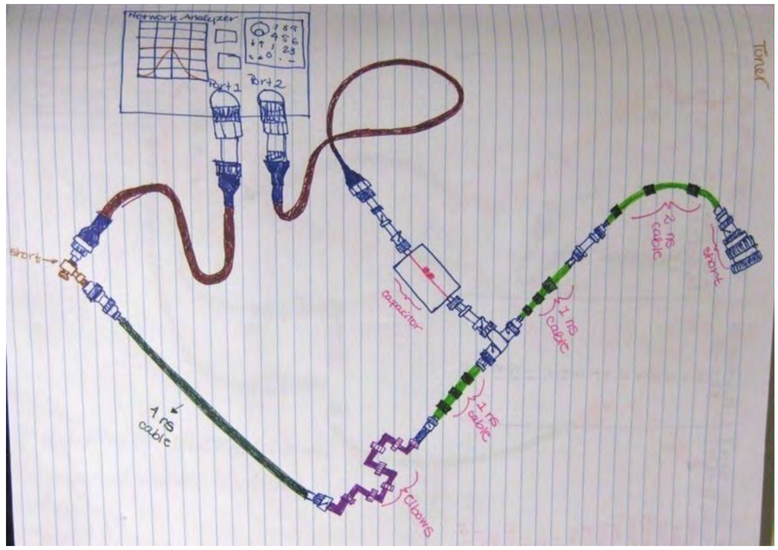
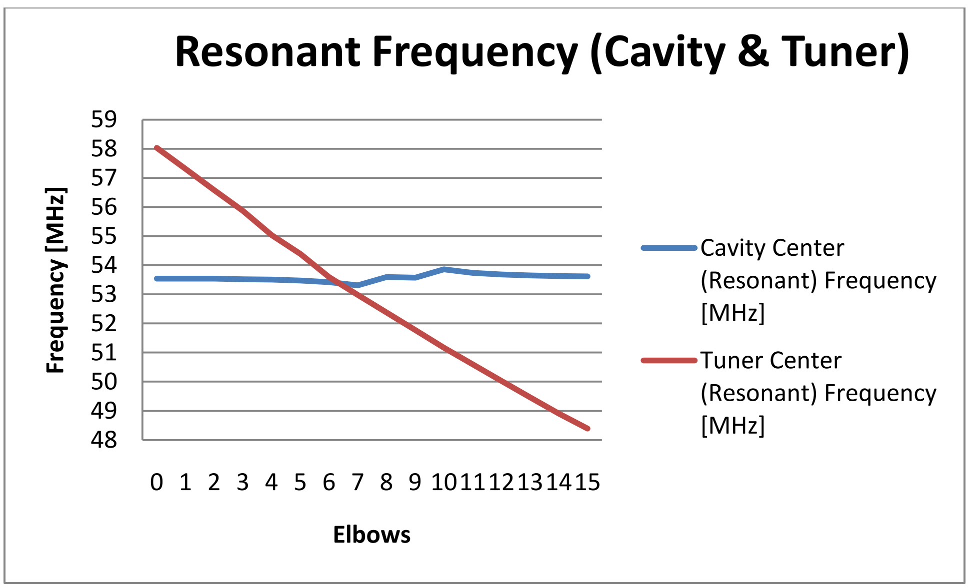


Figure 3



Graph 2

Here is where the set-up transition is made from the use of RG 58 coaxial cables to the use of higher Q transmission lines.

In the following set-up we used the Agilent 85024A high frequency probe, shorts, coaxial cables, elbows, and a network analyzer as is displayed in Figure 4. Graph 3 is representative of the resonant frequency measurements as a function of the number of elbows in circuit sections ① and ②.

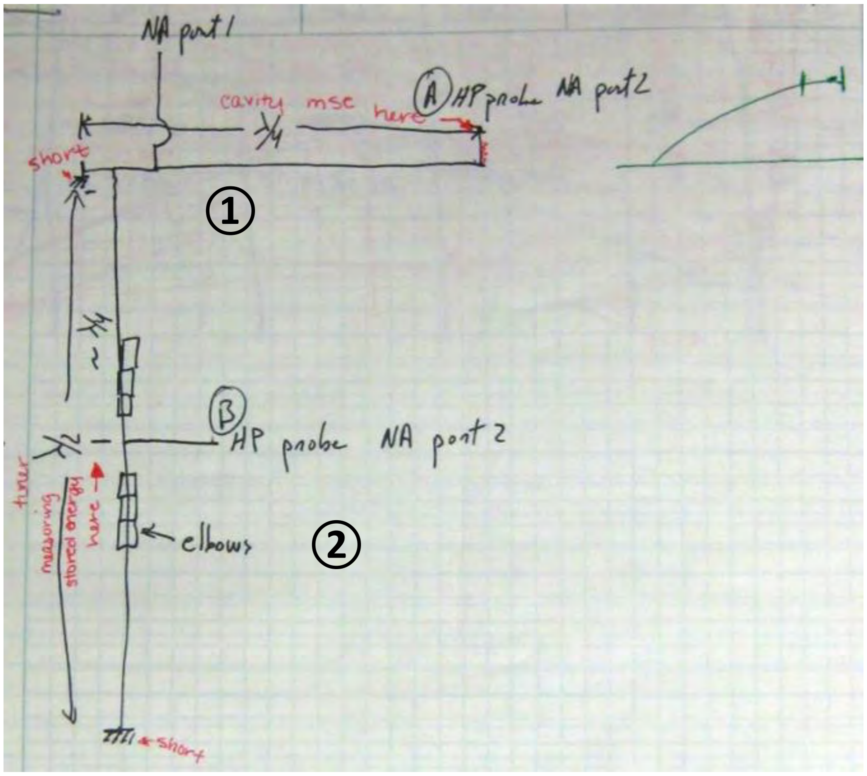
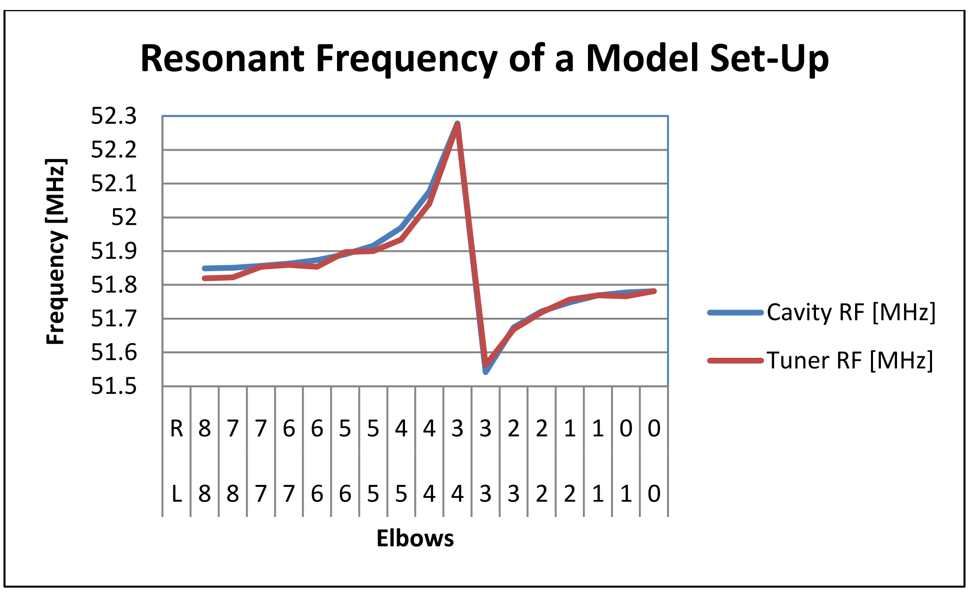


Figure 4



Graph 3

This set-up is the same set up as before; however, there is an extra tee positioned between two four nanosecond cables. This action worked to position the short further away from the network analyzer on the λ/2 (half wavelength) section, resulting in a slightly different resonant frequency range due to a change in the loop coupling to the tuner. Graph 4 reflects the resonant frequency measurements from the point when there were 16 total elbows, 8 to the left and 8 to the right of the high frequency probe, to when there was a total of 0 total elbows, 0 to the left and 0 to the right.

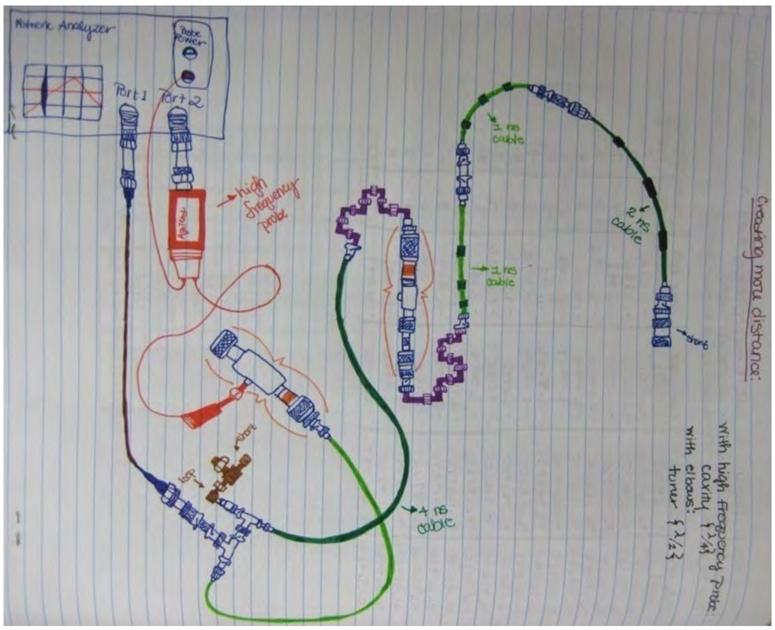
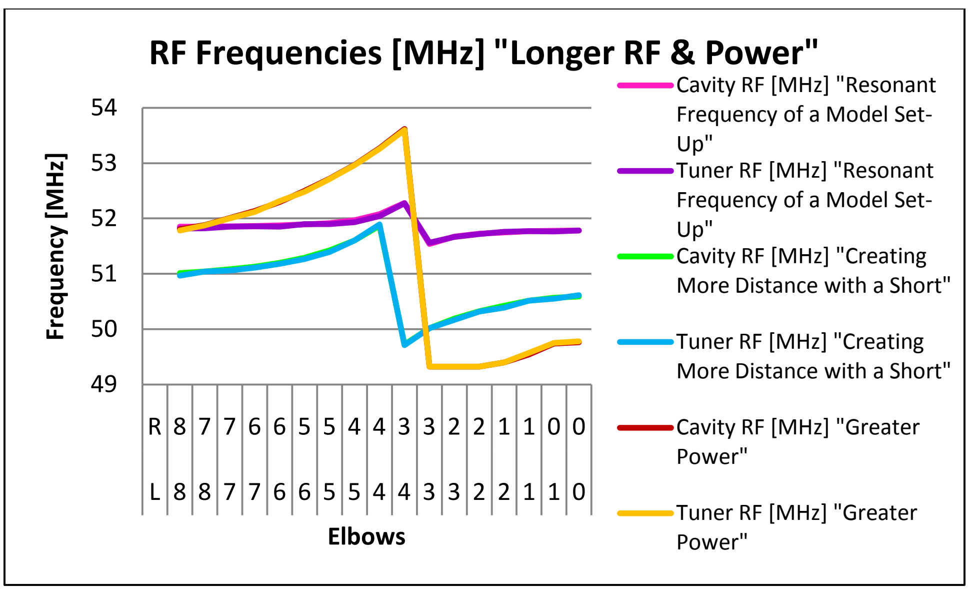


Figure 5

Graph 4

Graph 5 displays measurement taken with the previous set-ups associated with Figures 4 and 5, as well as "Greater Power." Graph 5 portrays the differences from seemingly minor changes made in model cavity/tuner system set-up.



Graph 5

In the following figures and graphs we make the change from cavity/tuner model tests using higher Q transmission lines to the prototype cavity/tuner model tests. The following graphs show the frequencies received from measuring frequencies with the prototype cavity, a 3'/8" EIA transmission line tuner, and an adjustable short.

In the Cable-Model Cavity set-up (Figure 6) we used the network analyzer to provide us with the frequency among other things. The Prototype RF Cavity set-up (Figure 7) uses the actual prototype cavity and tests the frequency just the same as was done with the Cable-Model Cavity. Graph 6 is the comparison of the resonant frequency shift measured using the cavity/tuner model (using higher Q transmission lines) and the actual prototype RF cavity with a 3'/8" EIA transmission line tuner with an adjustable short.

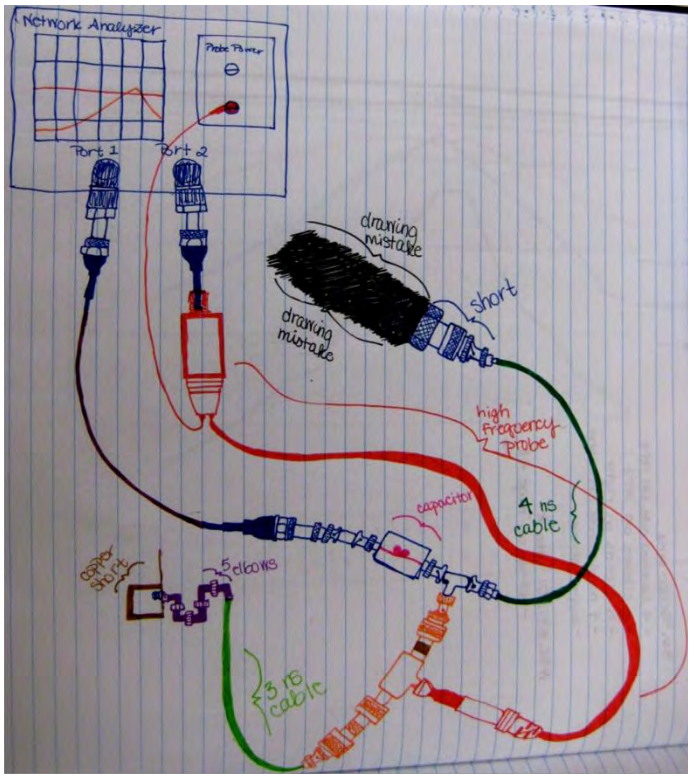


Figure 6

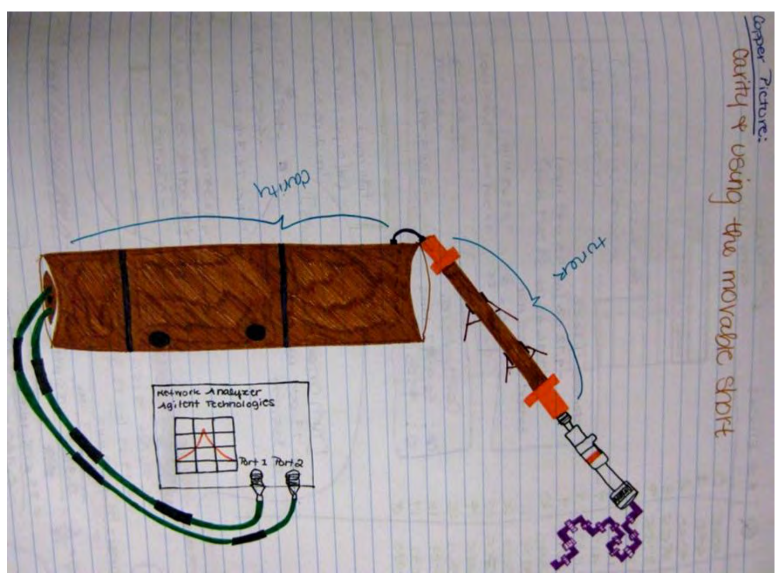
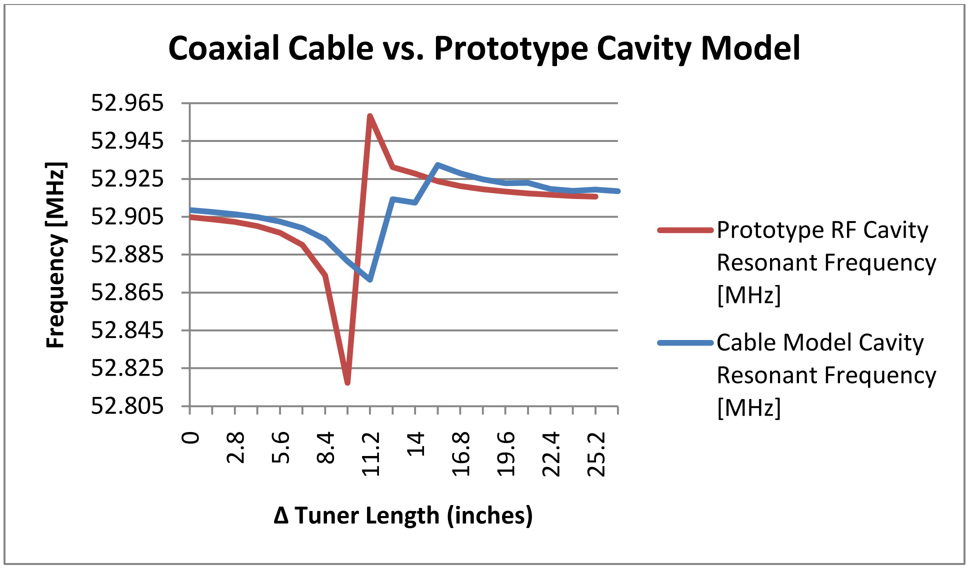
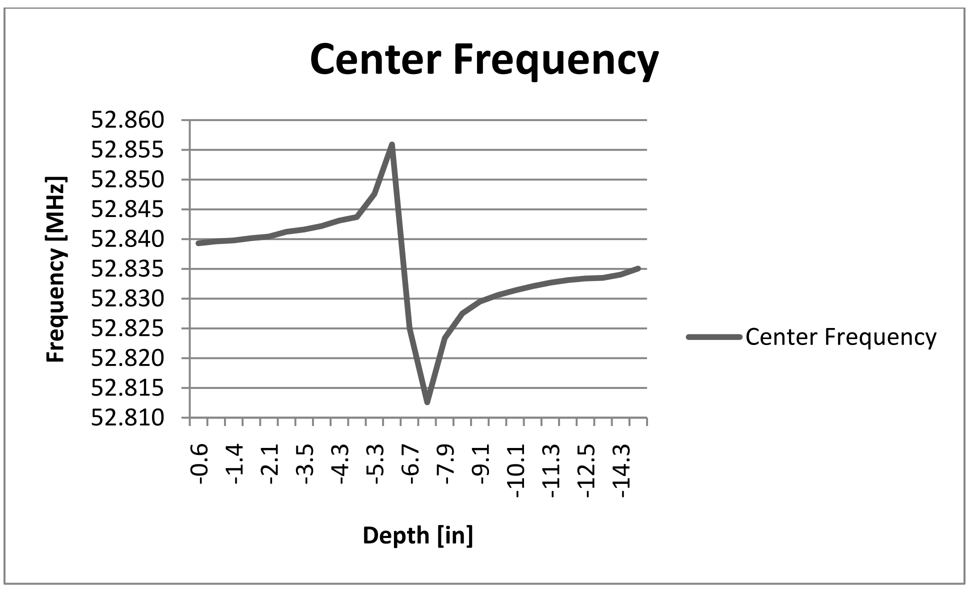


Figure 7



Graph 6

In this setup the tuner loop was rotated into a different set position than in the preceding graph, providing different readings of the center frequency.



Graph 7

The following set-up displays the frequencies reached once ω_1 and ω_2 were solved. Figure 8 is the display of the beginning steps of the set-up used to receive the information for the frequencies displayed in Graph 8.

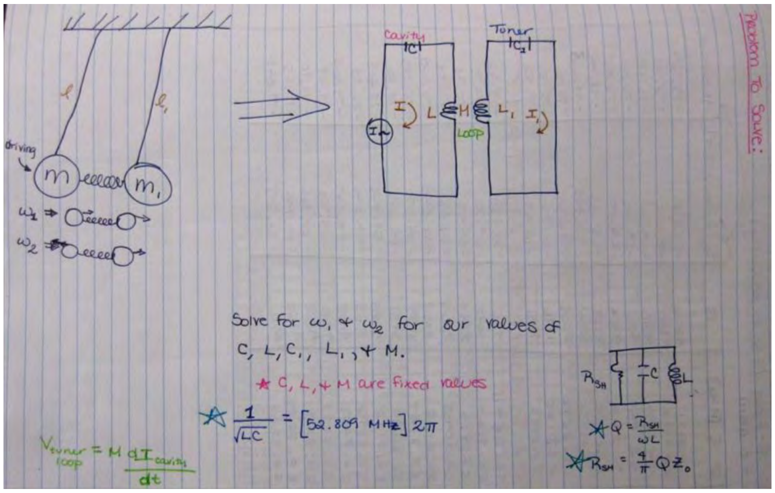
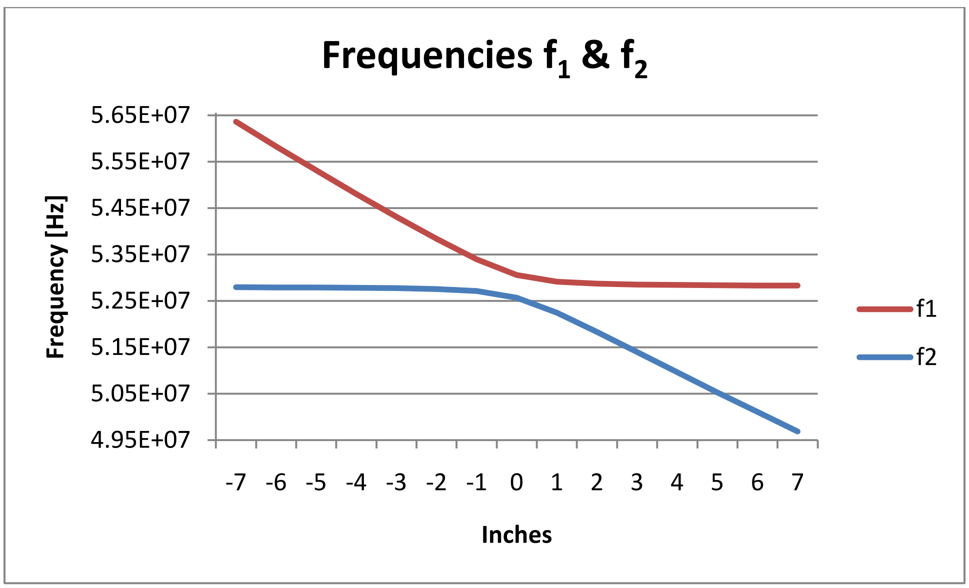
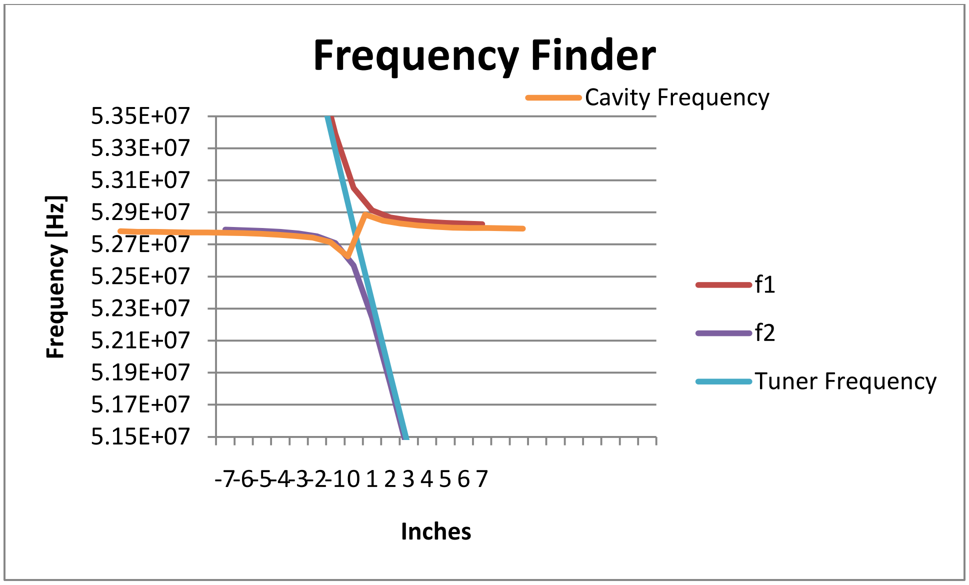


Figure 8



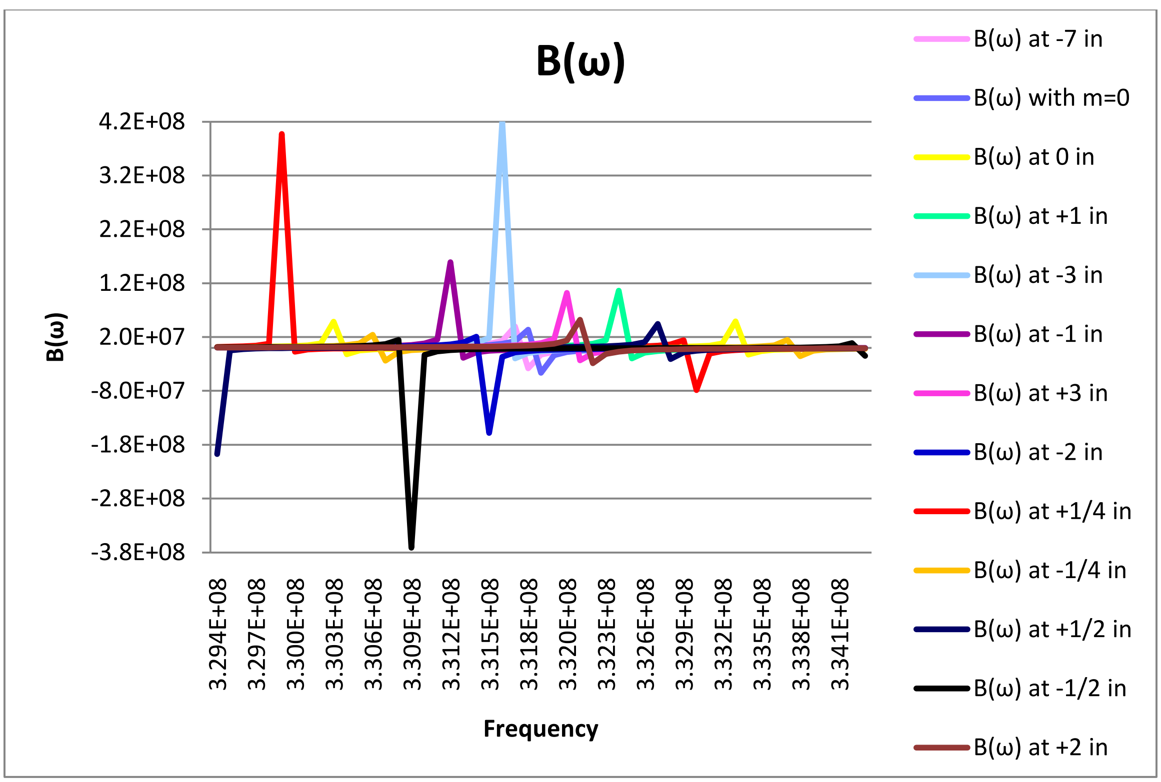
Graph 8

This graph includes the frequencies, f_1 and f_2 from Graph 8 along with the graphs of the resonant frequencies of the tuner and the cavity once we came to a conclusion of the formulas displayed in Figure 8.



Graph 9

Graph 10 is the combination of all of the B(ω) graphs. We came to receive B(ω) from the former formulas when solving for $I = Acos(\omega t) + Bsin(\omega t)$, when solving for B(ω) at several different lengths.



Graph 10

ii. *3 Graphs with respect to $I_{monitor}$ (Amps)/the Solenoid Bias Current*

a. *Frequency*

In this graph we measured frequency [MHz] as a function of the monitors' current [Amps]. This graph was used to determine loss [dB] and where the loss is the least.

b. *Phase Shift*

This graph measures the phase shift [ϕ] of the cavity when the tuner was connected as a function of the monitors' current [Amps] while it examines the changing of the bias of the solenoid. This graph measures the variance of the voltage and amperes.

c. *Amplitude*

This graph measures the amplitude [dB] of the 52.809 MHz cavity over a tuning range of 5-10 kHz as a function of the monitors' current [Amps]. This graph was based off of a logarithmic magnitude graph and changes with the initial variance of voltage and amperes.

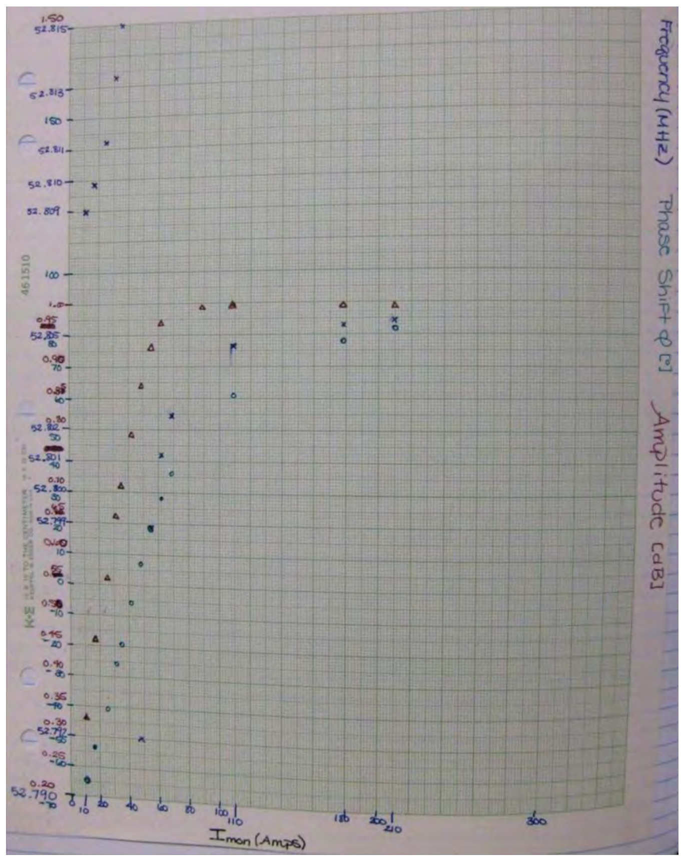


Figure 9

4. Discussion

Models of the cavity and tuner using RG 58 coaxial cables were made, as well as models using higher Q transmission lines. Tests using both the prototype cavity and the tuner were also performed. In performing each of these actions information of resonant frequencies, different Q's, and loss was received.

When work began with the RG 58 coaxial cable models I learned how to use a network analyzer and the importance, as well as the function of an RF cavity and tuner. The models gave me a sense of what was yet to come.

After working with solely the RG 58 coaxial cables, I began to use high Q transmission lines and a high frequency probe. This led to explanations about ports, calibration, and power. Once these models became significant enough I began to go to Meson to work with the prototype cavity, the tuner, and the adjustable short.

Once the tests progressed to Meson, work with the actual prototype cavity and tuner began to commence. While working with these there was a better opportunity to understand the garnet tuner for the NOvA recycler. The tests we performed with the cavity and the tuner in Meson were to determine which specific set-up would provide the right frequency that we were looking for.

5. Conclusion

We have run tests with the prototype resonant frequency cavity with a garnet tuner to show how the resonant frequency, the Q, and tuner loss change with different set-ups and tuner lengths. Many tests were run during the past eleven weeks and throughout their execution advantageous results were attained as well. It would be beneficial if more tests are performed, as is planned, in order to receive more accurate results and to learn more of the garnet tuner and the cavity.

6. Acknowledgments

This research was conducted at Fermi National Accelerator Laboratory in Batavia, Illinois. I thank Dianne Engram, Jamieson Olsen, Linda Diepholz, Sandra Charles, and the rest of the SIST committee for the opportunity to participate in such a prestigious internship. I also thank them for their open-door policies and being of great assistance to me whenever I was in need. With genuine gratitude I would also like to thank my supervisor, Dave Wildman, for having such patience and leading me through each process so that I could emerge from this program with a greater knowledge of physics and one of its many detailed applications. I would also like to thank my assistant supervisor, Robyn Madrak, for also being there to help me through this process and for helping to explain some concepts in more detail when it took me a little longer to understand.

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And in conclusion, I would like to thank the Almighty for watching over me and guiding me along the road of life.

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