Various Power Measurements of a Microwave Tube Across a Frequency Spectrum of 139.8 to 141.2 GHz

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Abstract

NMR (Nuclear Magnetic Resonance) systems have been used for many years in polarized target applications. A microwave tube emits microwaves at a relatively narrow frequency range and these are used to polarize target material. The material can be polarized in either a negative or positive spin state while in the presence of a strong magnetic field, up to 5 Tesla. This system uses the microwave tube to send microwaves down a length of waveguide and out a horn to bathe the target material in microwaves in order to polarize it. This is all done at very low temperatures, around 1 Kelvin or -457.87 degrees Fahrenheit.

This project focused on three areas. The first was experimenting with different lengths of circular waveguide to discover which lengths and combination of lengths allowed the greatest transition of power. The second area was finding out which gasket allowed the greatest transition of power while providing an excellent vacuum seal. Lastly, the power emitted for the microwave horn was measured, or at least attempted as I will later discuss.

Introduction

Polarized targets have been around since the 1960's. They are used to study the spin structure of the nucleon, consisting of both an electron and a proton, by providing polarized nucleons. A diagram of this scattering reaction is shown below.

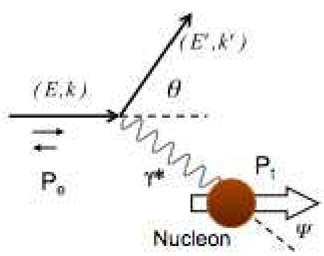

Figure 1: Nucleon cattering reaction

There are various types of polarized targets, some are gaseous and others are solid. My project is concerned with solid targets, more specifically, dynamically polarized solid targets. This type of targets uses a target material with free electrons, such as Ammonia. The material sits in a strong magnetic field, up to 5 Tesla, and low temperatures, around 1 Kelvin. With both the strong magnetic field and cold temperatures, the electrons polarize to nearly 100%. After this is done, the material is hit with microwaves to transfer this polarization to the protons. These nucleons can be polarized in virtually any direction, although they are typically polarized in either a positive or negative spin state.

All of my research will be used in the upcoming experiment, CLAS12, at Jefferson Lab. The refrigerator that will be used is approximately 10 feet in length and because of this, discovering how and where microwaves lose power is very important. A picture of the refrigerator is shown below.

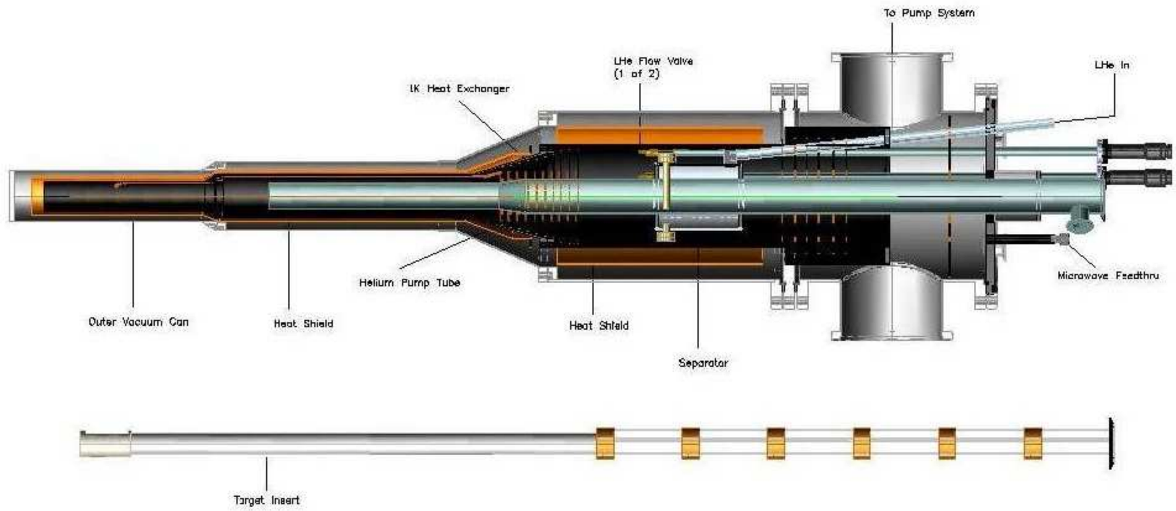

Figure 2: CLAS12 refrigerator

Placed down the middle of the refrigerator is the target insert. This is either a long rigid pipe or carbon fiber tube and houses the waveguide and horn. At the bottom of the insert the target ladder is attached and this holds the cups of target material that are polarized with the microwaves. A picture of this is shown below along with a detailed picture of the top and bottom.

Figure 3: Target insert

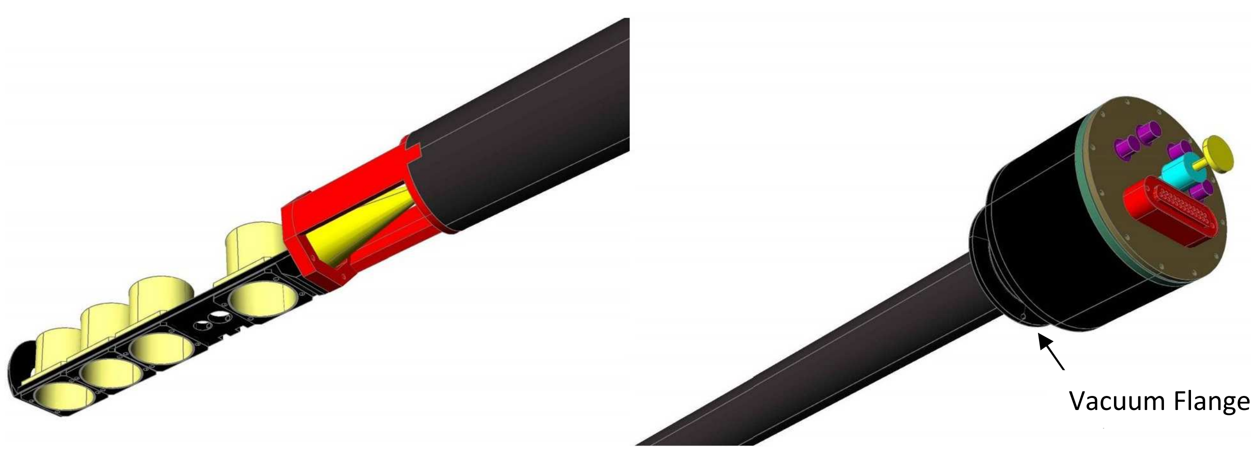

Figure 4: Insert bottom (left), Insert top (right)

The waveguide along with an attached flange is in yellow at the top of the insert. This is the position where the gasket will sit as this location is not subject to vacuum. The vacuum flange, pointed out in the picture on the right, is where the insert attaches to the target. Everything below that point is under vacuum while everything above is not. However, the entire stick along with the large black cylinder on top is hollow so it too is under vacuum. Next to the waveguide are feedthroughs, shown in red and purple. These are used as connections for various instrumentation such as thermometry. The waveguide then travels down the inside of the insert and terminates where the horn attaches, shown in yellow in the last picture. Below the horn is the target latter, colored black, and the cups, colored light yellow. These particular drawings are of the actual insert that will be used in the G2P experiment in Hall A. This insert is made of carbon fiber and all together is approximately 80 inches in length.

Microwaves systems use microwaves to polarize target material within a strong magnetic field, up to 5 Tesla, and at low temperatures, around 1 Kelvin. With such a system, the microwave tube cannot be near the target material for a few reasons such as having the tube itself exposed to high levels of radiation from the electron beam. As such, microwaves are sent down a waveguide to the target material. However, with any length of waveguide there is power lost as the transmission is not perfectly efficient. Different lengths of waveguide lose power at different rates and this is what I measured. This was important to know as future experiments can use the data I collected to better understand power loss as a function of length.

The whole system is useless if the vacuum cannot be maintained. Since the waveguide starts outside the target insert at atmospheric pressure and travels inside to just before the target cup the waveguide itself is under vacuum. However, the coupling of two microwave flanges is not enough to provide a vacuum seal. This is where gaskets come in to play. These gaskets are placed between the flanges and help maintain vacuum while allowing the microwaves to travel through. There are, however, different materials that can be used and each provides a different level of seal and allows transmission of a certain amount. I have tested different gasket materials and will further discuss their results.

The final issue addressed is that of the power emitted by the microwave horn. This horn sits at the end of the waveguide and has a conical shape to bathe the target material in microwaves while polarizing. However, because the target material sits in separate cups, not all equidistant from the horn, the power spectrum from cup to cup is different. I attempted to measure this power spectrum at various positions and distances from the horn in order to build a 3 dimensional graph of the power. This was not successful and will be explained further later on.

All three of these issues will help in the upcoming experiment for Hall B, CLAS 12. In the past, refrigerators have required waveguide approximately six feet in length. However, this refrigerator will require waveguide almost twice as long, roughly 10 feet. This presents a problem as transmitting the microwaves over such a distance results in substantial power loss. With the information I gather, the Target Group will better be able to make an informed decision on how they would like to work with such a long distance.

With the microwave horn, some is known about its power spectrum but not the exact amount of power emitted at different locations at different distances. The same holds true for the gaskets. The Target Group has classically always used FEP as their preferred material as it works well with vacuum without really testing other materials.

Description of Solution

All of my measurements were made at Jefferson Lab using the following equipment:

- Microwave tube – Emitted microwaves at a relatively narrow band of frequencies, I looked specifically at 139.8 to 141.2 GHz.
- Power Supply – Used to power the microwave tube.
- Water Chiller – Recirculated chilled water through the microwave tube to keep it cool while running.
- Frequency Meter – Measures the frequency at which the microwaves are oscillating.
- Power Meter – Basic instrument that measures the power of the microwaves at the specific point where it is attached.
- EIO Tuner – Adjusts the internal cavity length via a stepper motor on the microwave tube to change the frequency of microwaves.
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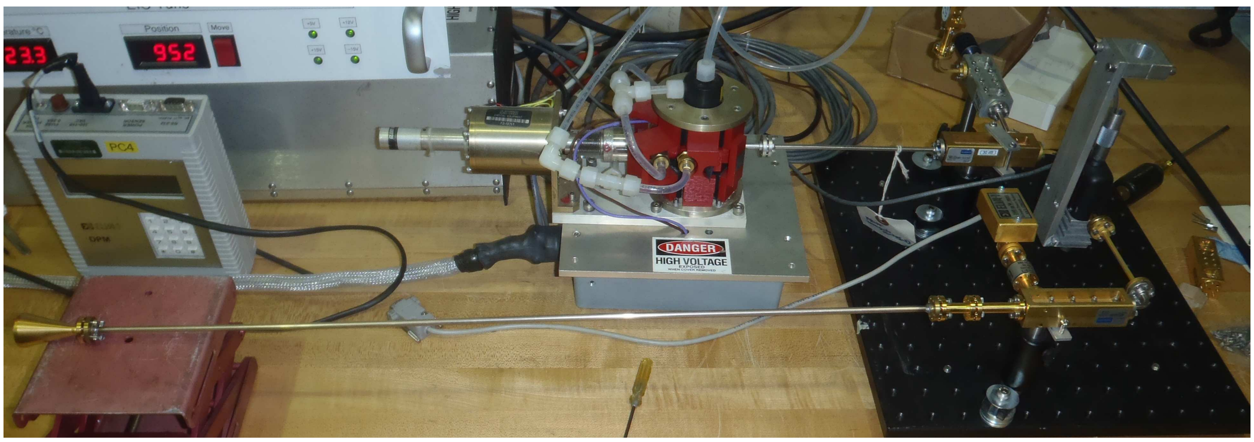

Figure 5: Microwave setup

Above is the microwave setup used for the various measurements. The tube, with water lines for recirculation, is in the middle of the picture, the main cavity of which is red. The power meter is on the left standing up on the table and the two foot piece of waveguide can be seen at the bottom of the picture. At the end of the waveguide is the horn which is where the power meter was placed for the waveguide measurements.

Measuring the power loss for various lengths of waveguide was relatively straight forward. I start with six foot lengths of copper nickel tubing with and OD (outer diameter) of 0.175” and an ID (inner diameter) of 0.167”. These lengths were cut down using a small hack saw and the tube slotted through a solid block of aluminum in order to get a perfectly perpendicular cut so the flange would sit square. A total of three sections measuring 1 foot, 2 feet, and 3 feet were cut. As the waveguide flanges were soldered onto each end they were clocked 90˚ with respect to one another. Once I was satisfied that the flanges were attached properly, both sitting square and clocked properly, each section was thoroughly cleaned. First, the inside, where the tube mated with the flange, was filed smooth so that there were no rough edges or protrusions that would affect transmission. Next, the inner wall of the tube was cleaned by running lengths of ribbon soaked in Acetone back and forth. Once the inside was cleaned of any dirt or metal filings, they were visually inspected and once each was clean, was ready to be tested.

Measurements were accomplished by hooking up the desired section(s) of waveguide to the microwave setup and recording the power transmitted. Starting off at the lowest frequency of 139.8 GHz and in approximately 100 MHz (0.1 GHz) increments, the power was recorded all the way up to roughly 141.2 GHz. Two batches of measurements were taken and the numbers were compared. What was found was not encouraging. The data was not at all consistent between each batch. This meant the measurements were not repeatable and this was unacceptable.

With the data from the first two batches not agreeing with one another, I de-soldered the flanges, cleaned the tube of solder, filed the ends smooth, and double checked to make sure the ends were cut perpendicular. Any ends that were not perpendicular were filed down in order to correct the problem. After this the flanges were re-soldered, insides filed smooth, and then everything cleaned. I then again took measurements and this time the numbers seemed to cooperate.

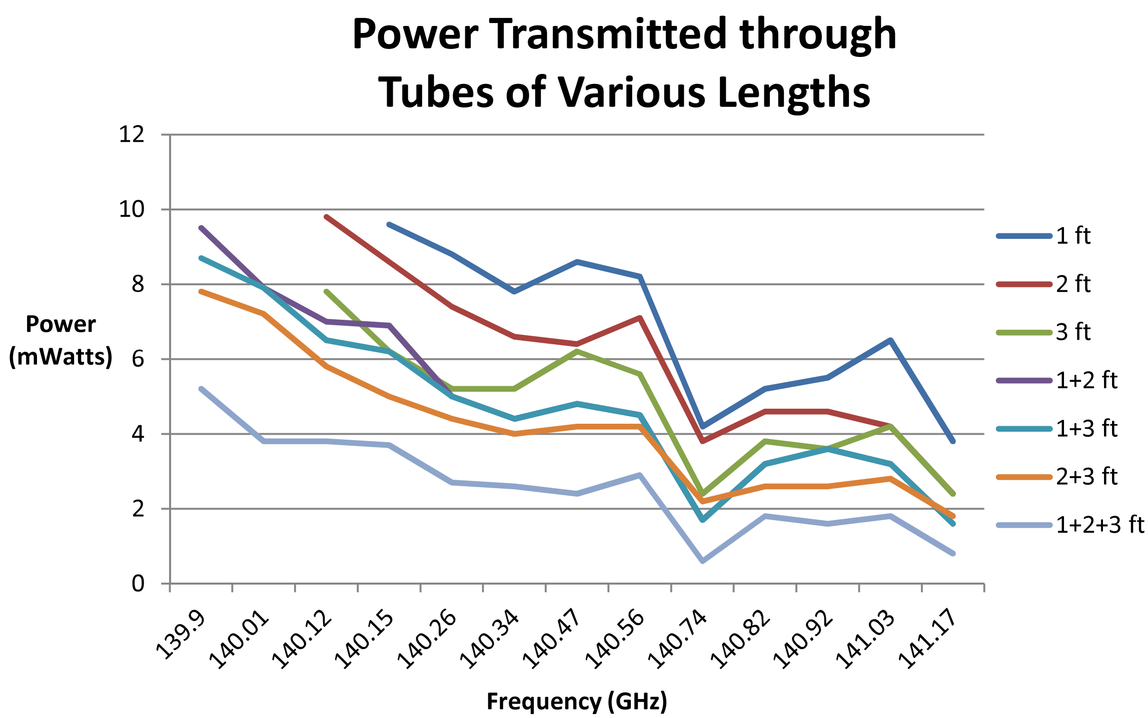

Figure 6: The power transmitted through various lengths of waveguide at varying frequencies.

As mentioned in the introduction, the entire target is useless unless vacuum can be maintained. That is where the gaskets come in to play. To start I gathered three materials of varying thicknesses. The materials, along with their thickness in inches, were as follows: Fluorinated Ethylene-Propylene (FEP) 0.002”, Kapton 0.001”, Kapton 0.003”, Kapton 0.005”, and Polyethylene (Poly) 0.0015”. These materials were taken and formed using a punch set.

Next small holes to allow the screws and pins on the flanges to pass through were punched out. The final product is shown in the picture below.

Figure 7: Gaskets

The FEP gasket is in fact there although it is nearly impossible to see. These gaskets were then placed between waveguide flanges and microwaves sent through to measure their permeability relative to microwaves. Similar to before, the frequency range was from 140 to 141 GHz. The gaskets were place just before the power meter and the data is shown below in Figure 8.

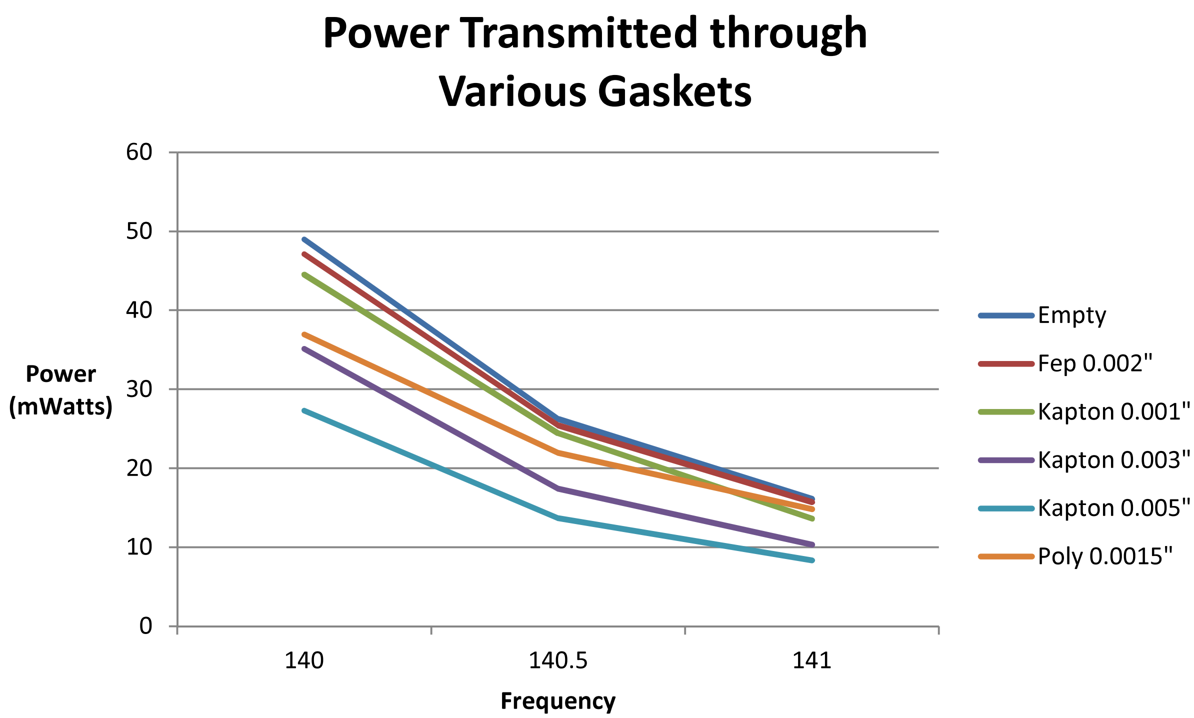

Figure 8: The power transmitted through the various materials at varying frequencies.

The final piece of my project was measuring the power output of the microwave horn. The horn scatters the microwaves in a conical shape bathing the target material while polarizing. A picture of this is can be seen below. To measure the power output, a few methods were tried. The first was an array of resistors, second was thermal paper, third was a thermal camera, and last was heat sensitive film. Each will be discussed further.

Figure 9: Microwave horn

I started by first obtaining a breadboard and approximately 16 300 Ohm resistors. Next each resistor was carefully sanded down using a file and sandpaper in order to expose the carbon on the inside. Exposing the carbon was necessary since the microwaves would simply bounce off of the outer ceramic coating and thus no change would be seen in the resistance. After sanding was complete, each was epoxied to the bread board so that there would be no movement while measurements were being taken. A total of 16 resistors were attached in a 4x4 grid, after which, two thin wires were soldered onto each lead of each resistor. This connection was then covered in heat shrink tubing in order to prevent contact between neighboring leads. At the other end of each wire a pin connector was soldered on in order to attach it to a 25 pin connector. Each of the 16 resistors had 2 leads for a total of 32 leads, each lead had two wires attached for a total of 64 wires, and each wire had a pin at the end for a total of 64 pins. After this was done the bundles of wires were zip tied together.

Each row of resistors had their own connector where the pins were inserted. This led to a total of 4 connectors with 16 pins in each. LakeShore controllers were used to read the resistances, each capable of accepting two connectors, with two controllers used. After everything was attached and the pins in their proper place in the connectors, I tested that everything worked using a LakeShore. After everything was confirmed as working, on the first try, I then had to figure out how to mount the board in order to hold it perpendicular to the horn. I accomplished this by constructing a small stand made from extruded aluminum and a custom bracket. Pictures of the final product are shown below.

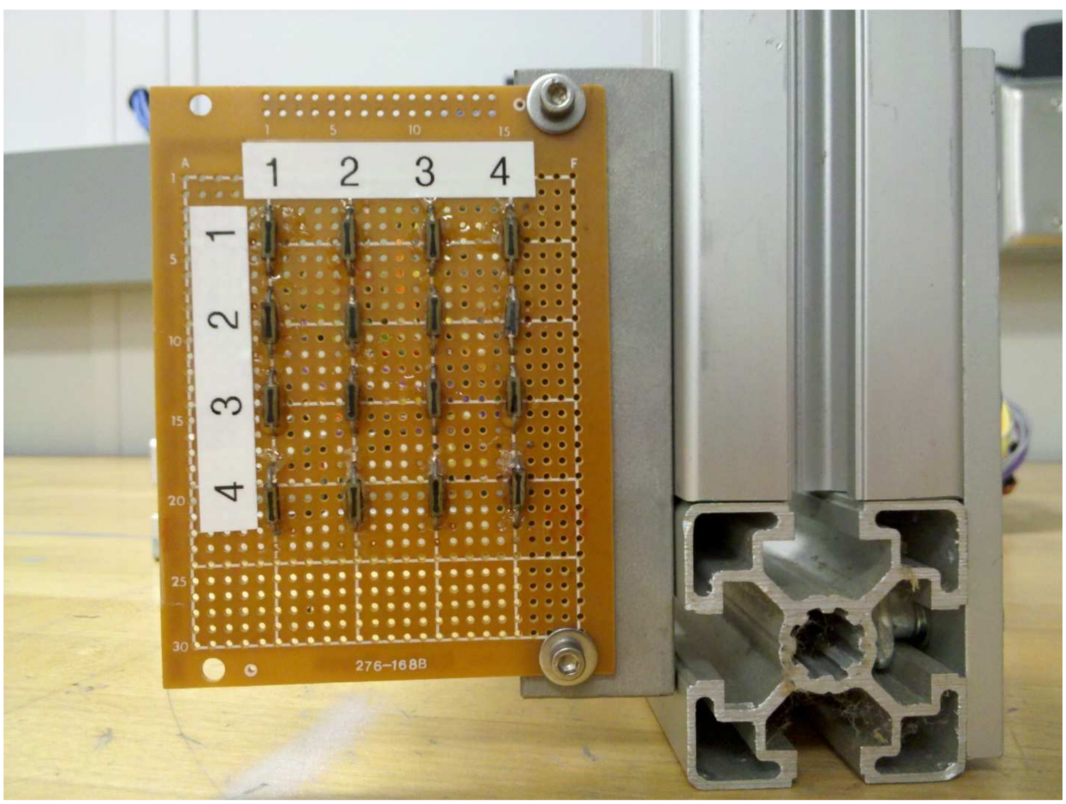

Figure 10: Resistors epoxied in place, exposed carbon is black

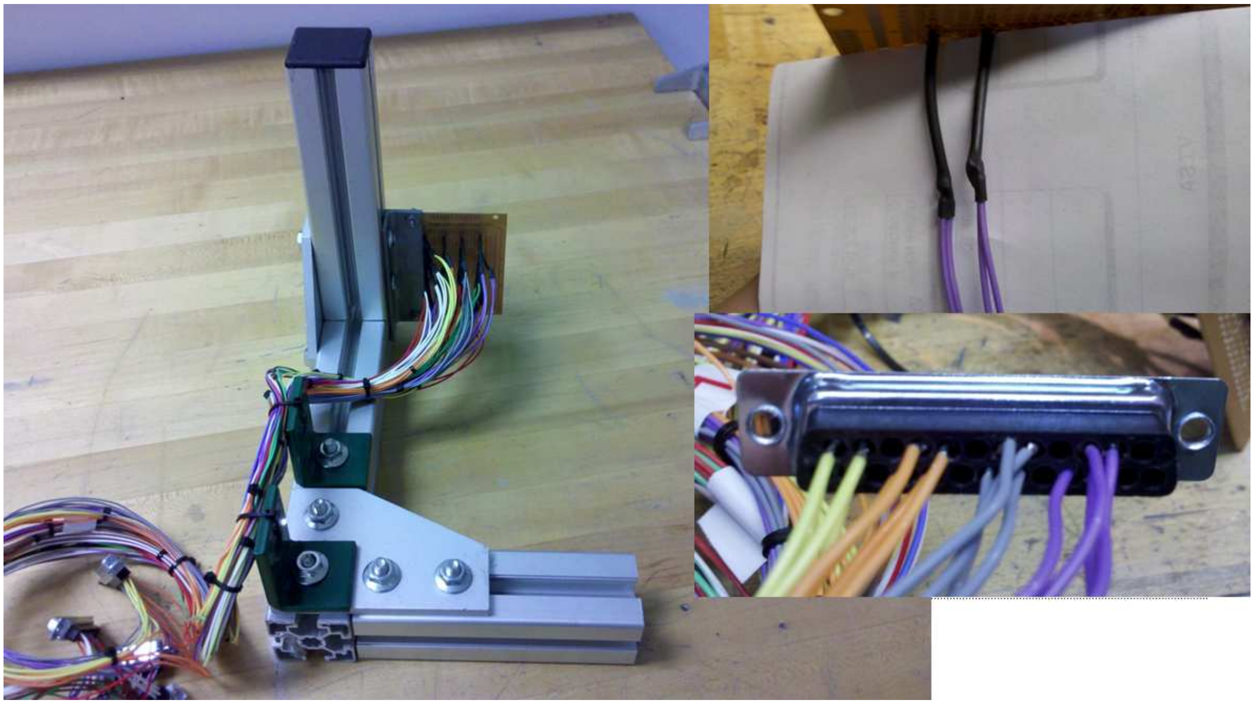

Figure 11: Final setup (left), one resistor with leads (upper right),
25 pin connector (lower right)

This assembly was then placed perpendicularly in front of the horn at a distance of one inch and barraged with microwaves. The result was not as expected. The resistances changed by incredibly small amounts, at most one ohm. One ohm was not satisfactory as such a small change would not even be noticeable once the array was moved further from the horn. With such a result, the microwave setup was analyzed to ensure that I was getting the maximum power available. With the whole setup already optimized for maximum power, the array simply did not perform as expected and another means of measurement was needed.

Next I tried thermal paper, the same paper used to print receipts, to see if the heat produced by the horn would change the color of the paper. Early testing showed the paper reacted spectacularly well to a heat gun a distance of well over a foot away and even formed concentric rings. However, the microwave tube is not a heat gun and did not produce enough heat to turn the paper black even at distance of zero inches from the horn. Again, another means of measurement was needed.

The next idea was proposed by Dr. Josh Pierce of the Target Group at Jefferson Lab. He suggested using a infrared camera to take pictures of a black screen set up in front of the horn. A camera was borrowed from Hall A and a piece of felt was placed in front of the horn, with the camera aimed at the felt. This along with the array of resistors and thermal paper, did not work. The camera was simply not sensitive enough to discern the difference of just a few degrees. However, it was not a complete was of time. I did manage to get a few pictures of the microwave setup while it was running to show how the microwaves themselves transmitted a great deal of heat in the waveguide. These are shown below.

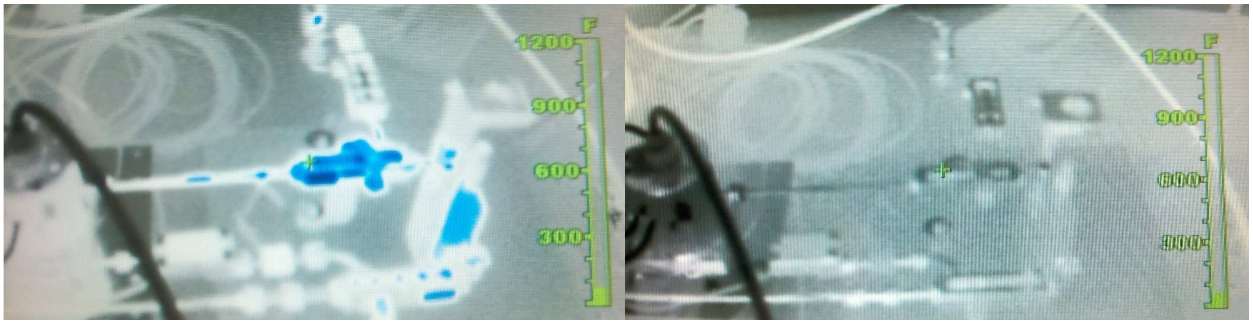

Figure 12: Setup after running for 30 minutes (left), setup before running (left)

Lastly, Dr. Pierce suggested I try heat sensitive film. This was an excellent idea as the sheets of film were very sensitive in specific ranges. Using a similar setup as the array of resistors, I attached a piece of the film to the front and mounted a digital camera behind it in order to be able to take the same picture every time. The microwave tube was set to 140.2 GHz and pictures were taken in increments of an inch.

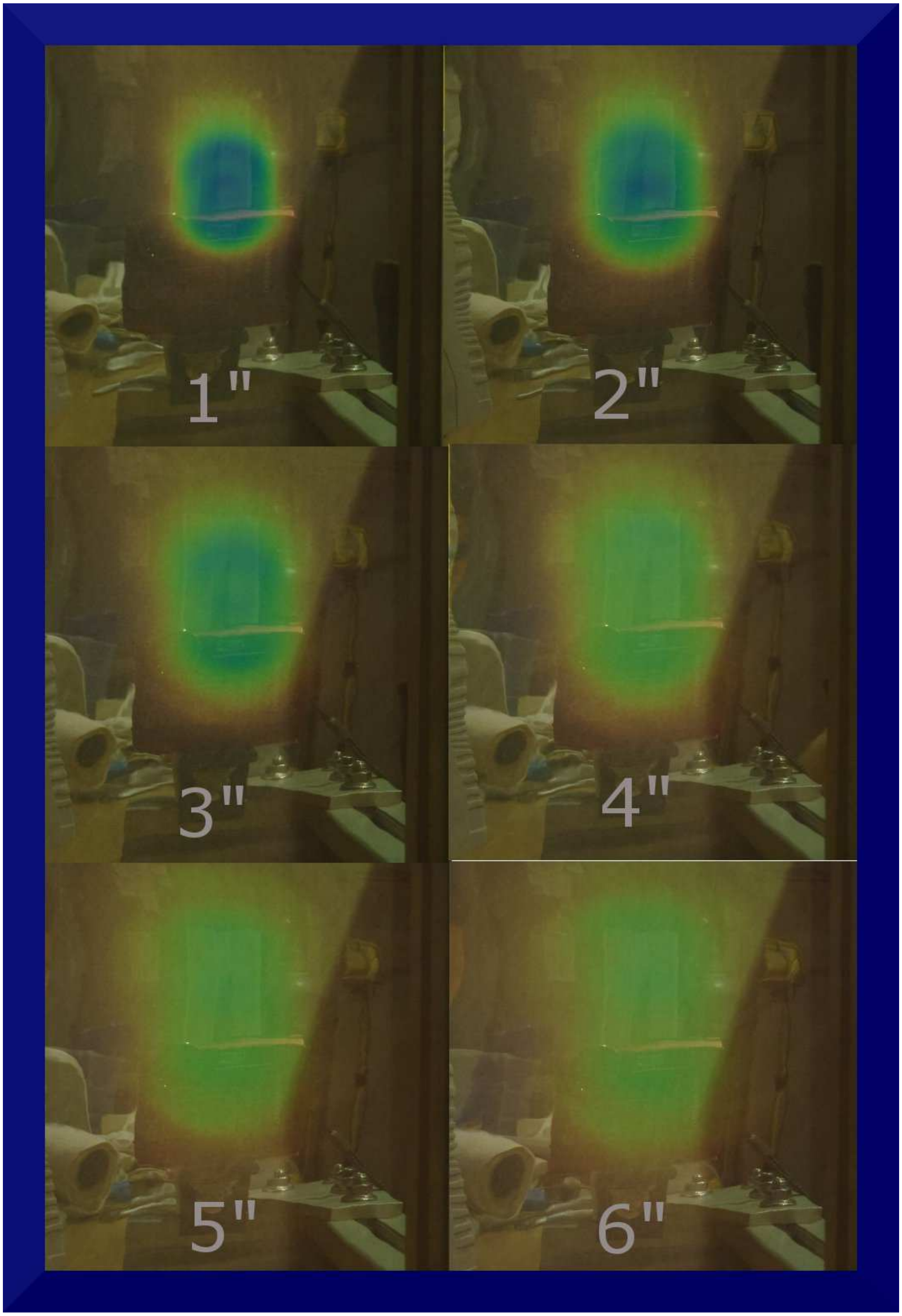

Figure 13: Power emitted from the horn at various distances

These pictures turned out well but because of the films highly reflective surface, background images can be seen. The original plan was to use photo editing software to create a 3 dimensional graph based on the color of the film. While this would have worked, the reflections in the paper completely skewed the numbers. After seeing this I came back a few days later and altered the setup. I sprayed a few sheets or cardboard with matte black paint and punched a hole for the horn and placed the first just behind the horn opening. The second was placed just in front of the camera and had a hole punched to allow pictures to be taken of the film. On this particular day it was almost eight degrees cooler inside where the test was taking place. As a result, the paper would not heat up enough to yield a good result but the pictures turned out much better than before. This was discouraging as it will not be getting warm enough to try again before semester comes to an end. A picture of the setup as well as a picture of the film on the second day is shown below.

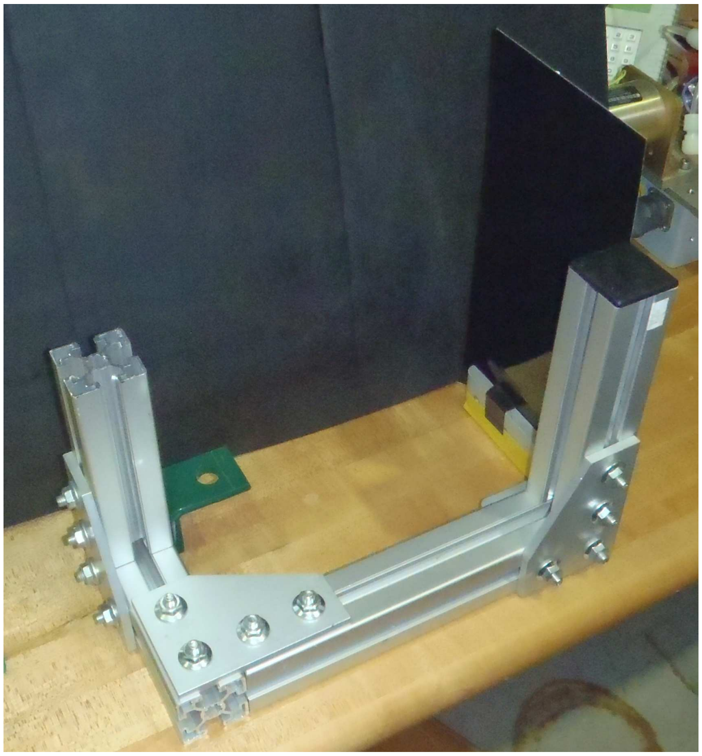

Figure 14: Heat sensitive film setup, camera attached to the green bracket on the left

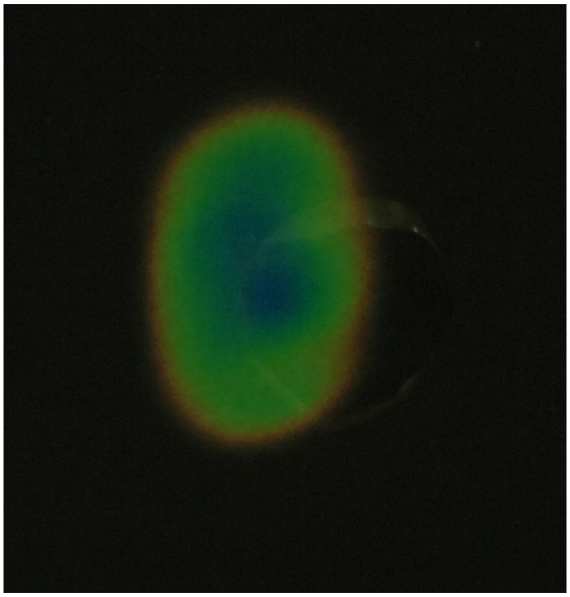

Figure 15: Second day of trying the film, the camera reflection can still be seen

Evaluation and Summary

Figure 6 shows how the lengths of waveguide reacted to the microwaves. It clearly be seen that with longer lengths of waveguide, power will be lost. There are however, areas where the numbers take a steep dive and then recover. This is because the microwave tube is not good at oscillating at certain frequencies; specifically right around 140.6 to 140.8 GHz. Swapping out the tube was not an option as I only had one available, each costs roughly $100,000, and takes upwards of a year to be manufactured. Future tests would need to be conducted to see if there is a solution to this problem. Also worth noting is that the power meter used on this particular test could not measure above 10 W so that is why the first three lengths of tube do not have any data at the beginning of the graph.

Future research could be conducted to further examine power loss of the waveguide. Various other metals could be used instead of the copper nickel tube. If possible, a different tube could be obtained to see if it is any better at oscillating through 140.7 GHz or if all of the tubes inherently don't function well in that range. With the waveguide travelling from the innermost part of the target to the outside, some of the tube is extremely cold. This could affect how the microwaves react and subsequently transmit. Testing how cold affects the power transmission is another area that could be further explored with future tests.

Classically FEP has been the material of choice and the data confirms that it is indeed the best choice. While both FEP and Kapton hold a vacuum very well, the Kapton impeded the microwaves too much to be of use. This can clearly be seen in the graph. I do not know how well the Poly holds vacuum, but since it was just mediocre at allowing the transmission of microwaves, I did not attempt to find out.

Despite the microwave measurements not going as planned, some information can still be gleaned. The power spectrum is in a conical shape, as expected, and it can be seen in the pictures that the power dissipates quickly with a distance of more than three inches. Future test would need to be conducted to get actual numbers of the power output. Possibly trying different resistors to see if the sensitivity is any better would be an option. Also, if there is some kind of carbon paper than can in some way hook up to a readout would also be something worth looking in to.

Bibliography

While I didn't use any actual books or electronic resources, I would like to thank a few people. First and foremost is my mentor and professor at Christopher Newport University, Dr. Yelena Prok. She was a great help for the duration of this project. Next I would like to thank the Target Group of Jefferson Lab as they were all helpful in various aspects of my project; James Brock, Chris Carlin, Mark Hoegral, Paul Hood, Dave Griffith, Dr. Chris Keith, and Dr. Josh Pierce. They provided the facility and equipment used during the semester.