Heat Transfer in Fast Ferrite Phase Shifters

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Abstract

The Linear Accelerator at Fermilab accelerators negative Hydrogen ions to the Booster. In order to facilitate the acceleration process, Radio Frequency energy is used and is produced by Klystrons. Each RF cavity has its own Klystron to provide this source of energy. However, a cheaper alternative to the current design is being investigated where there will be one large klystron source, and at each particular RF cavity a device called a Vector Modulator will be put in place to modify the amplitude and phase of the RF wave from there. This paper deals primarily with the heat transfer tests on phase shifters which are found within the Vector Modulator.

Introduction

Fermi National Accelerator Laboratory (Fermilab) is a research laboratory dedicated to the study of high energy physics with the view to understand the fundamental nature of matter. Towards this end, they have constructed what is currently the world's largest particle accelerator called the Tevatron. This accelerator collides protons and anti – protons at speeds close to the speed of light and the resulting collisions are studied.

<u>The LINAC</u>

A Linear Accelerator (LINAC) is a device used to accelerate particles. These are more generally known for their use in creating high energy radiation to treat cancer. At Fermilab the LINAC is used to accelerate a beam of H- ions, from a 25 KeV source, from an energy of 750 KeV to 400 MeV for injection to the booster. It is the second part of the acceleration process. Fermilab's LINAC provides (shown in Figure 1) beam to the booster at a frequency of 15 Hz. Additionally, every week the LINAC also provides 66 MeV protons to the Neutron Therapy center for use in the treatment of cancer.

Accelerators often use Klystrons to provide the Radio Frequency (RF) energy needed to accelerate the particles. The Klystron drives a resonant RF cavity to produce the desired accelerating voltage. Each RF cavity has its own Klystron to allow individual adjustment of the amplitude and phase shift of the accelerating field.

The negative Hydrogen ions are accelerated as follows:

- Gaseous Hydrogen is taken and injected into an ion source and negatively charged ions are made.

- These ions are then are then extracted from the source at about 18 KeV

Figure 1: The LINAC at Fermilab

- It is transferred to the Pre Accelerator to gain a final kinetic energy of 750 KeV

- It is then transferred via two 750 KeV transfer lines to the first of 5 large tanks containing 201 MHz drift tubes that are held in a vacuum. These are powered by tubes.

- It is then compressed through a 4m RF transition section to match the 201 MHz beam into the 805 MHz RF structure, and change the transverse focusing.
- And finally through seven 804.996 MHz side-coupled cavity structures to the final energy of 401.5 MeV.

Klystrons at Fermilab

The Linac at Fermilab contains side-coupled RF cavities that are powered by klystrons similar to that shown in Figure 2. There are 10 klystrons that are used for the LINAC at Fermilab to help the acceleration process. In layman's terms, the klystrons act like a large power source. Accelerators usually use Klystrons in order to produce Radio Frequency (RF) energy in order to control the amplitude and precise power and phase shift needed to accelerate the particle in question.

Figure 2: Klystron at Fermilab's Linac

In a klystron**:**

- The electrons are sent to bunching cavities

- These cavities regulate the speed of the electrons so that they arrive in bunches at the output cavity.
- The bunches of electrons excite microwaves in the output cavity of the klystron.
- The microwaves flow into the waveguide, which transports them to the accelerator.
- The electrons are absorbed in the beam stop.

Klystrons are built to be long lasting and work for extended periods of time. Thus, such devices, when they fall into need of repair, often are quite expensive to upkeep. Hence the need for a new more cost effective design.

The New Design

Fermilab is currently in the process of constructing a new Linear Accelerator that has a different design from the one currently in use. This set up will have one large 325 MHz Klystron at 2.5 MW with a 4 millisecond pulse. Through the process previously described, the microwaves are produced. They are sent along the waveguide into the Vector Modulator to the phase shifter for phase modification. From there they go into the accelerator RF cavities. The entire process is shown in drawing in Figure 3 below.

The Phase Shifter

Phase shifters, are twin-ported devices that change the phase of an input signal in response to an external signal. Variable phase shifters change the output signal phase by applying a variable control signal. There are basically two common types of variable phase shifters: analog and digital. Analog phase shifters change the output phase with a continuous signal, usually voltage, to change the output signal. An important specification to consider in phase shifter is the phase shift change itself.

The Phase shifters used within the Vector Modulator are made from copper coaxial transmission lines filled with garnet. When an electromagnetic wave propagates (through the coaxial line) through the ferrite, it will experience a change in velocity of wave propagation and if a magnetic bias field is applied and changed in the direction of the wave propagation, the effective permeability of the material changes. This causes a change in the amplitude and phase of the input signal. One phase shifter in the new design can change the phase by about 60 °± at 325 MHz.

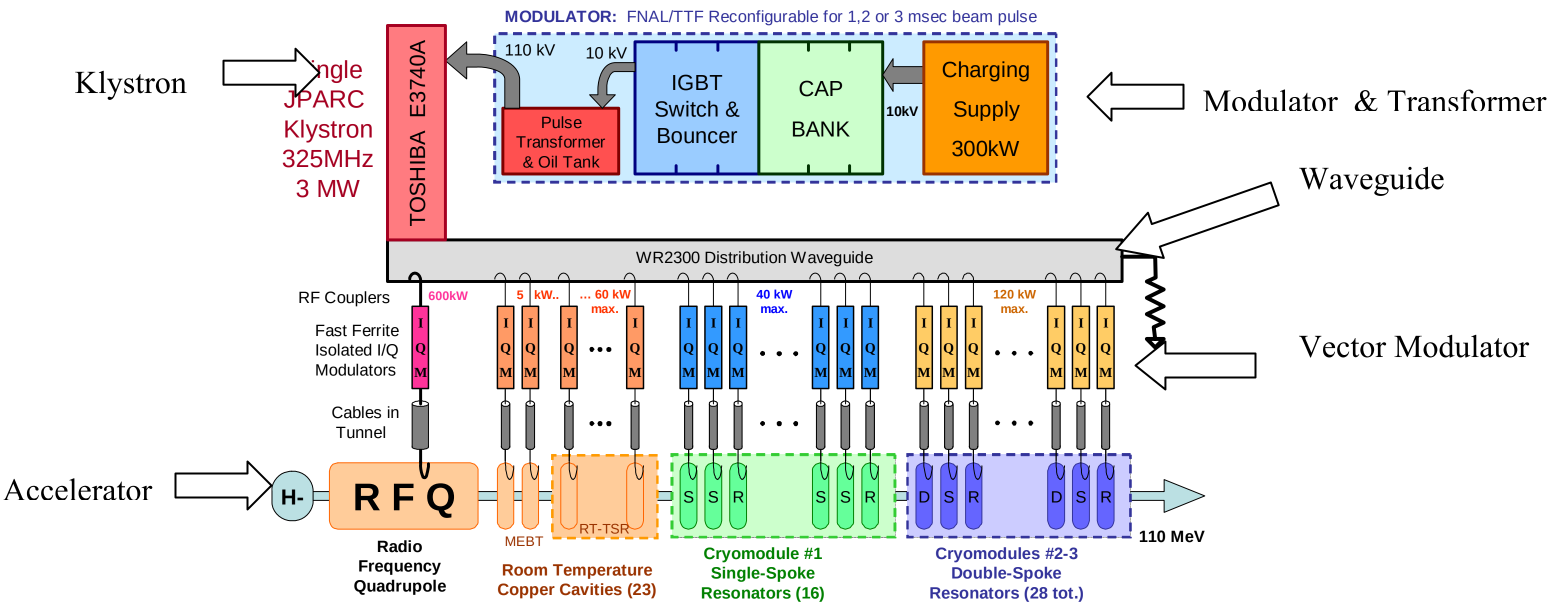

Figure 3: The Process for the new Linear Accelerator

In order for the phase shifter to correctly function it must not exceed the Curie temperature of 130º C. If the phase shifter gets too hot it affects its magnetism and eventually its ability to change shift and amplitude.

Phase Shifter and Heat Transfer

In order to ensure that the phase shifter does not overheat, tests need to be carried out in order to determine how hot the phase shifter (shown in Figure 4) will get when it receives the microwaves from the waveguide. To test this, one has to simulate the conditions that the phase shifter will be in. However, some theoretical work was still to be done in. By using the various pertinent heat transfer equations, one can get an estimate of the temperature change and the rate of heat transfer from the phase shifter to the surrounding environment.

Figure 4: Fast Ferrite Phase Shifter

Some Heat Transfer Basics

Heat Transfer is basically the flow of heat from one substance to another and is usually achieved through conduction, convection and radiation. Each method has its own particular set of pertinent equations. In the case of the phase shifter to be examined, heat transfer will take place via all three modes, thus this gives rise to the need of an amalgamated equation that will give the total heat transfer. In order to determine this change in temperature two methods were employed. First, the phase shifters were placed into conditions where there was exposure to a certain number of watts, and the temperature was taken over a period of time until it reached thermal equilibrium. Then, the resulting temperature difference was used in the appropriate heat transfer equation in order find out the rate of heat transfer. This figure should be close to the amount of watts used in the experiment and thus determine its accuracy.

Heat Transfer Testing

Equipment:

Thermocouple

A thermocouple is a junction formed with two dissimilar metals. One is at a reference temperature, and the other at a temperature to be measured. A difference in temperature will cause a temperature dependent voltage to develop.

Thermocouple Readout (digital voltmeter)

Figure 5: Thermocouple Readout

Figure 5 is an electronic instrument used to measure the temperature detected by the thermocouples. At the very top of this device, there are slots to accommodate the two prongs of the thermal couples. Once activated, the temperature is displayed in its LCD screen and can be shown in Fahrenheit or Celsius.

Signal Generator

Figure 6 shows a signal generator, an electronic device that generates a sine wave output that can be varied in frequency and amplitude.

Figure 6: Signal Generator

RF Amplifier

This is a device that receives and amplifies RF signals. The unit in Figure 7 has a maximum output of 500Watts and has Frequency range from 10Khz to 100 Mhz

Figure 7: RF Amplifier

The Setup

- A thermocouple was attached to the surface of the phase shifter in each of the locations, indicated by the arrows in the figures below. They labeled 1 and 2 respectively.

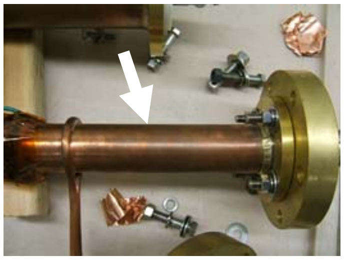

Figure 8: Thermocouple 1

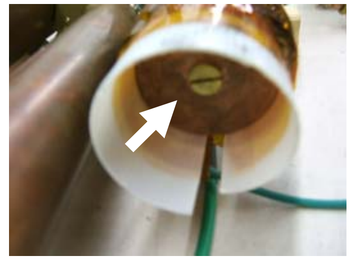

Figure 9: Thermocouple 2

- The signal generator was set to produce an RF signal of 95 MHz at 0 dBm, since the maximum for the RF Amplifier was 100 Mhz a little less was put in place

- The RF amplifier gain was set to 100%

- Two attenuators were placed at the input of the amplifier to give a net reduction of the signal amplitude of 20 dB.

- The output of the amplifier was then connected to the end of the phase shifter indicated in the figure below by a short coaxial cable in order to minimize loss of input.

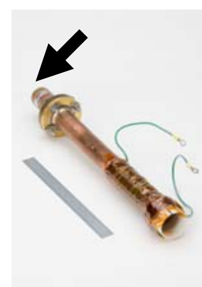

Figure 10: Point where coaxial cable was connected to phase shifter

- The initial temperature of the Phase Shifter was taken as well as the room temperature

- A reading from each Thermocouple was taken until the system reached Thermal Equilibrium.

Table 1 displays the readings from each Thermocouple along with the time. One should note the following things:

- Around 16:45 the system began to approach thermal equilibrium, as the temperature showed little or no change subsequent to this time.

- Thermocouple 2 was in an area less exposed to the environment than Thermocouple 1 thus the temperature is higher. This is because of there is more ferrite concentrated at that end and it has a higher thermal conductivity.

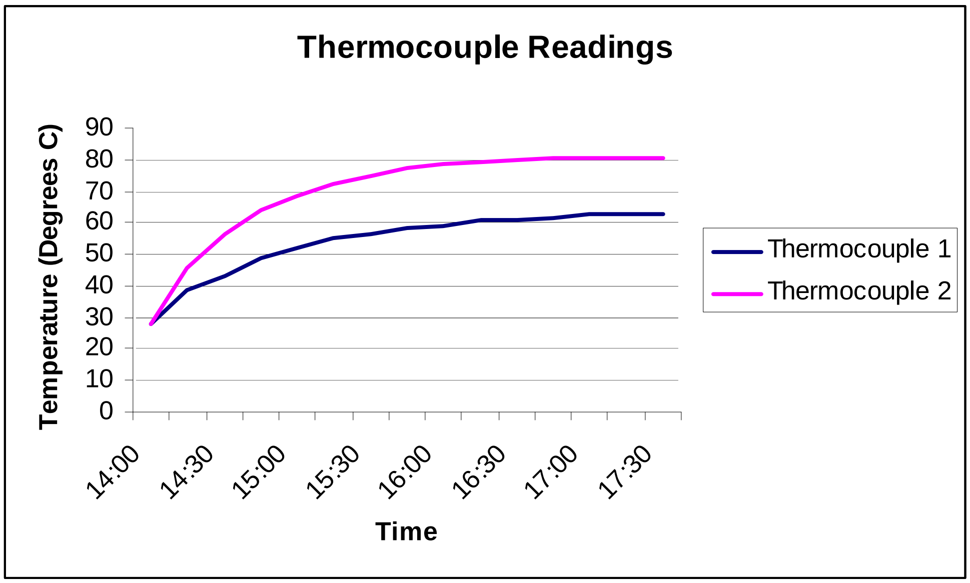

Table 1: Graphical representation of the Thermocouple Readings at 40 Watts

Finding the Correct Power Figure

In order to strive to get the correct reading of the power input into the phase shifter a Bird Meter was used. This is a device that isolates and displays RF power in terms of watts. At the conclusion of the experiment the coaxial cable was removed from the phase shifter and connected to the bird meter. This however, gave power reading of 40 Watts, which does not agree with the values of the RF amplifier which had a reading of approximately

32 Watts. Which then was the correct reading? From the bird meter there was also a reading of a peak to peak voltage of 2.

Thus, knowing that there was a resistance of 20 dB, one can simply use Ohm's law to come up with a value of 40 watts. This makes the bird meter's reading more accurate.

The system reached thermal equilibrium at 65 ºC at thermocouple 1.

The entire experiment was repeated with a power of 20 Watts and the results are shown in Table 2 below.

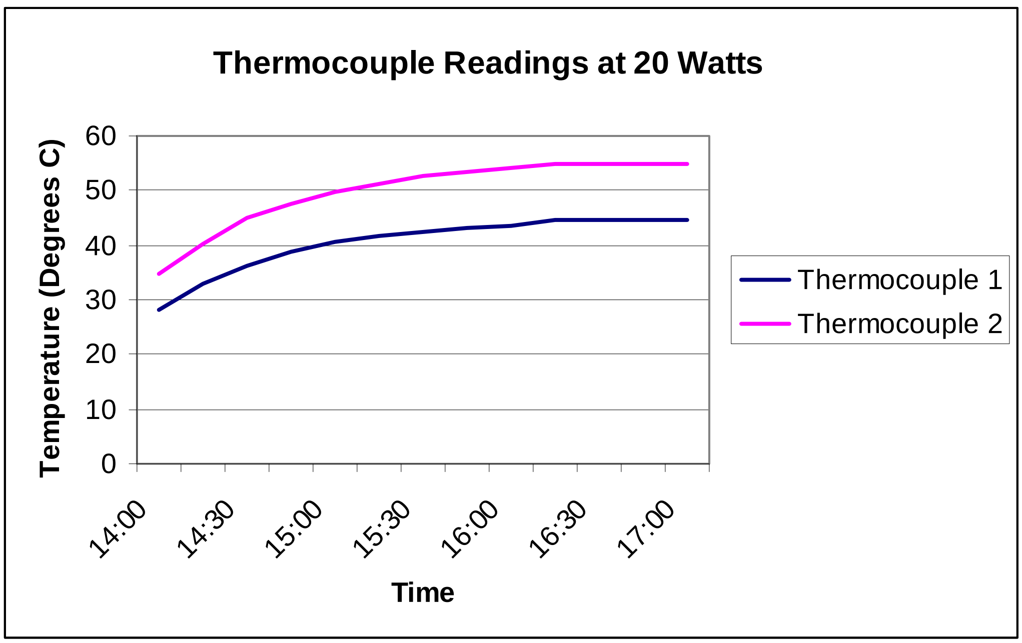

Table 2: Graphical representation of the Thermocouple Readings at 20 Watts

<u>Checking the Results</u>

Having received the initial and final temperature from the experiment one can then input these figures into a heat transfer equation and see if one comes up with a rate of heat transfer that closely resembles the 40 watt input.

In calculating the change in temperature (ΔT) the following characteristics of the Phase Shifter was taken into consideration.

- Its dimensions, length, diameter etc.
- The material from which it is made. In this case copper.
- It's initial Temperature
- The Temperature of it's environment

The following assumptions must also be made:

- The surface area is small compared to surroundings
- Room air is quiescent
- Radiation exchange is between a small grey surface and large isothermal surroundings
- Constant properties

Equations Used

Properties:

Length = 0.381m   Diameter: 0.0413m

Surface Temperature = 65 º C or 338 K

Temperature of Environment = 23 ºC or 296 K (here one assumes that the environment is room temperature)

The copper (material that the phase shifter is made of) has an emissivity (ε) of 0.78.

The film temperature (Surface Temperature – Environment Temperature) / 2 = 317 K

The properties of air at 317 K are as follows:

k = 0.0263 W/m.K   Cp = 1.007   v = 15.89 e-6 Pr = 0.707

β= 1/317 = 0.0031545 ά = 22.5 e-6

The equation for total heat transfer per unit length:

$$q' = q'conv + q'rad = \bar{h}\pi DL(T_s - T_\infty) + \in \pi D\sigma L(T_s^4 - T_\infty^4)$$

This is measured in W/m

L is the length of the phase shifter

Where σ is the Stefan-Boltzmann constant: $5.670 \times 10^{-8} W/m^2 \cdot K$

D is the diameter of the phase shifter, and ($\bar{h}$) is the free convection coefficient measured in $W/m^2 \cdot K$.

Now in order to make these calculations one must first determine the free convection coefficient ($\bar{h}$) via the Churchill-Chu correlation:

$$\overline{Nu_D} = \left\{0.60 + \frac{0.387 Ra_D^{\ 1/16}}{\left[1 + (0.559/\Pr)^{9/16}\right]^{8/27}}\right\}^2$$

The necessary Rayleigh number (Ra_D) can be found using: $Ra_D = \dfrac{g\beta(T_s - T_\infty)D^3}{v\alpha}$

Where g represents gravity in m/s.

Both the Rayleigh number and the Churchill-Chu correlation result are dimensionless and thus have no units.

Substituting back into the Churchill-Chu correlation gives the Nusselt number. One can thus calculate the free convection coefficient using this formula:

$$\bar{h} = \frac{k}{D}\overline{Nu_D}$$

This gives a figure of 13.078 for the free convection coefficient.

Inputting this figure into the equation for total heat transfer one receives a figure of 38.754 which is fairly consistent with the amount of wattage per unit length used in testing.

Cooling the System

The phase shifter was then tested under the condition that it was subjected to constant cooling by Low Conductivity Water supply at 35°C. The water flowed at a constant rate through tubing that was wrapped around the phase shifter 8 inches from one end. As shown in the figure below.

The water was managed through a flow meter, which is an instrument to measure volume or mass flow of a fluid in a pipe or channel. Having made this one change to the phase shifter, the experiment was repeated with the same setup and equipment as before and yielded the following results.

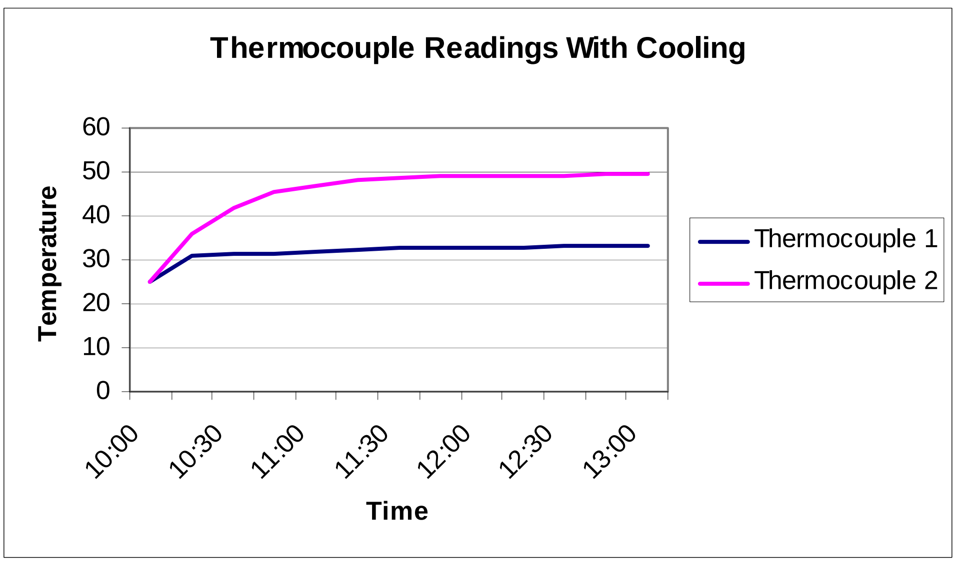

Table 3: Graphical representation of the Thermocouple Readings at with cooling

What is noteworthy about these results is that the final temperature of the Thermocouple at the shorted end (Thermocouple 2) showed a final temperature close to 50 degrees. This means that with cooling the system should reach thermal equilibrium at a temperature not much higher than that of the cooling agent.

Conclusions

The Phase Shifter is a device that is partially temperature reliant for correct function. The tests carried out show that at 20 and 40 Watt inputs will not seriously affect the performance of the device. The implication is, of course, that higher wattages will produce higher temperatures. However, with the introduction of a system of cooling, and maintaining the temperature of the device at a specific temperature overheating can be avoided. The system can be maintained and thus the temperature may not exceed the curie temperature of 130 degrees Celsius.

References:

Moran, Michael. Introduction to Thermal Systems Engineering: Thermodynamics, Fluid Mechanics and Heat Transfer. John Wiley & Sons, 2003.

http://www.fnal.gov

Numerous one on one supervisor counseling.

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