DESIGNING AND TESTING A QUENCH HEATER FOR A 16 T CIC DIPOLE

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Designing and Testing a Quench Heater for a 6T CIC Dipole

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The purpose of this project is to create and design a quench heater for the 16 T Cable-in-Conduit (CIC) superconducting magnet. This magnet will be used to create stronger and more cost-effective particle accelerators. The quench heater is a device that is designed to protect the magnet from an unexpected quench. In order to achieve this, the quench heater must be able to produce enough heat to heat the superconducting wires in the CIC cable to approximately 9K over the course of 10 ms. To design a quench heater in this way, it is required to find the dimensions needed using simulations. After finding the required dimensions, a Computer Assisted Design (CAD) file was created so the design could be machined to the exact specifications. Then, using liquid helium and one cable, we tested if the heater would properly heat the cable. Thermocouple wires were integrated into the cable to measure the temperature of the wires during the experiment. This physical experiment has not yet been conducted and thus the results are still unknown. It is expected that the quench heater will be able to properly heat the cable over the 10 ms timeframe. If this experiment is successful, this design for a quench heater will be used for the 16 T CIC cable.

NOMENCLATURE

CIC	Cable-in-Conduit
K	Kelvin
T	Tesla
CAD	Computer Assisted Design
LHC	Large Hadron Collider
EDM	Electrical Discharge Machine

CHAPTER I

INTRODUCTION

This project involves the development and testing of a quench heater design for the 16 T CIC superconducting dipole magnet. The predecessor to this magnet is the 3 T CIC dipole superconducting magnet. The 16 T magnet will improve upon the design by allowing a second layer of wire in the cable and utilize better superconductors. The creation of this magnet will allow the production of higher energy and more cost-effective particle accelerators.

The LHC is currently the world's strongest particle accelerator, producing collisions at an energy of 13 TeV. Currently, the dipoles used at the LHC are 8.3 T. This particle accelerator allowed for the discovery of the Higgs-Boson particle (CERN) This new magnet would allow for the construction of a particle accelerator that could produce collision an order of magnitude greater. This theoretical particle accelerator could allow for new discoveries to be made similar to those made from the LHC.

The Role of a Quench Heater

The Quench Heater serves a very important role in a superconducting magnet. In the event of an unexpected quench in a magnet, the quench heater will fire off, saving the magnet from the quench. A quench is a term used to describe when a superconductor transitions out of the superconducting phase. The superconducting phase occurs when the resistivity of a material drops to a near zero value. The transition results in a jump in the resistance of the material. The following equation shows the relationship between power and resistance.

$$P = IR^2$$

In a superconducting magnet, the current is so great that when only a small part of the magnet quenches, the area may be severely damaged and could make the magnet non-operational. In order to prevent this, quench heaters will be utilized to cause the rest of the magnet to quench. This distributes the power over the entire magnet and prevents damage.

The three quench catalysts in a magnet are the temperature, current, and the magnetic field. The quench heater that is discussed in this paper uses temperature to heat the magnet. By using the same formula shown above, a resistor heater can be created. By knowing the resistance of the heater, we can pulse a current through the resistor to heat the magnet to the desired temperature.

We know when to activate the heaters by constantly measuring the voltage across the entire magnet. Since the magnet is superconducting, the voltage across the magnet will be close to zero. Once the voltage reaches a certain threshold, we will know that part of the magnet has quenched. At this point, the heaters are activated.

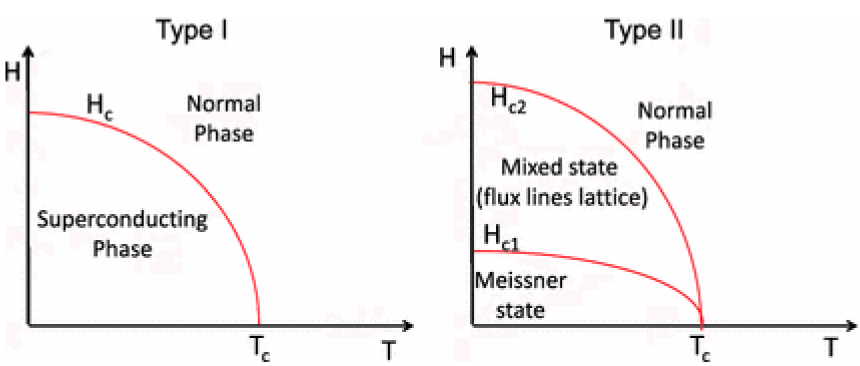

Figure 1: Above shows the superconducting phase for a Type I and Type II superconductor. This shows the relationship between the magnetic field and temperature for the superconducting state (Rigamonti).

Previous Designs of Quench Heaters and Alternatives

The design of this quench heater takes inspiration from a similarly designed quench heater made at the same lab. This quench heater was for the 3 T CIC superconducting dipole.

While the designs for the two heaters are very similar, the 16 T heaters must be able to heat a much larger cable over the same time period that the 3 T heaters were able to.

An alternative to using a quench heater is using a Capacitive Limiting of Current (CLIQ). These work in a similar manner to a quench heater, however, rather than using temperature to quench a magnet, these devices use current. Stored current is released into the magnet when the magnet reaches a certain voltage. This current causes the superconductor to quench, and then has the same effect that the quench heater has. A CLIQ was not considered for this project since it has no major benefits and is harder to implement into a magnet.

CHAPTER II

METHODS

In order to construct the quench heater, we ran simulations to find the dimension for the quench heater. We then needed to construct a CAD file to produce the physical heater. This physical heater can now be used in a test to validate our simulation. The simulations are still enough on their own to get the results desired, even without completion of the physical test.

Comsol Simulations

The first step in designing the quench heater was constructing the simulation. For this process, I used the Comsol Multiphysics 4.3a simulation program. Using symmetry within the design of the cable, I designed a geometric model of the cable and the quench heater. After running this simulation multiple times, I was able to find the resistance and current needed for the quench heater.

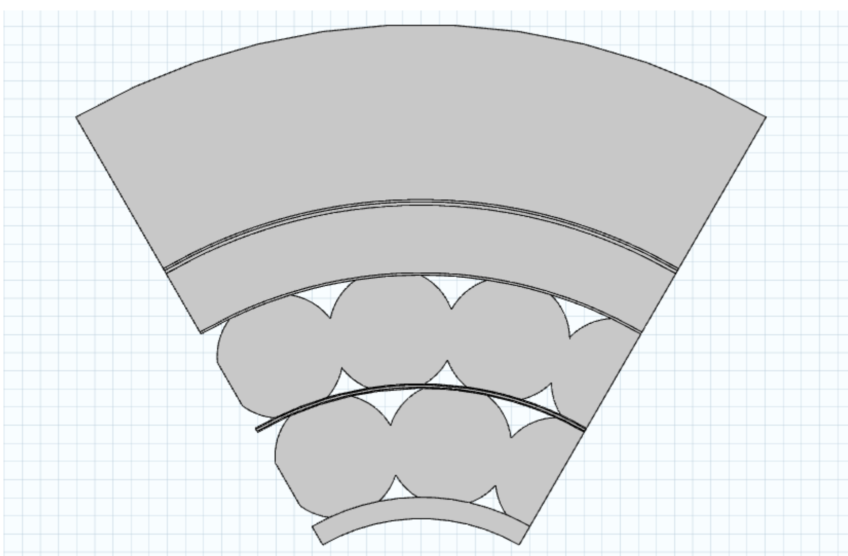

Figure 2: 2-D Model of 2 Layer CIC cable. The overlap between wires in the cable were measured from a sample of cable we made.

First, a 2-D model was designed. Next, we took into consideration the symmetries in the design of the cable. The cable has 21 wires on the outer layer and 15 wires on the inner wire. The greatest common divisor of 21 and 15 is 3. Knowing that that the wire has symmetry with itself, it is clear to see that the cable can be divided into 6 symmetric parts. This design can be seen in Figure 1.

The 2-D model was extruded multiple times to produce a 3-D model. The thin extrusions represent the gaps in the quench heater. We used a 2.5-inch section to represent the lead ends of the cable. Each section in the design was assigned different material properties based on what they represented in the experiment. Since the heater has symmetry of its own, the 3-D model only represents half of the heater.

When designing the quench heater, we worked with two changeable variables. These variables are the width of the strips and the width of the gaps. There is a restriction on the width of the strips and the gaps in the heater. This is that the total width of the quench heater must be under 4 inches. The other variables are being limited by each other. The resistance of the heater is determined by the widths of the quench heater, the width of the gaps, and the length of the quench heater. The pulse of the magnet must occur in over 40 ms. This adds further restrictions to our parameters since 40 ms must take place over 2-time constants for an RC circuit.

$$\tau = RC$$

In the above equation, τ represents the time constant of an RC circuit. The RC must be equal to 20ms given this equation. So, when finding the gap width and the strip widths, the voltage and the capacitance must give values for capacitors that are obtainable for the experiment. We found that the width of the strip would need to be 11/32 inches and the width of the gap has to be 5/32 inches.

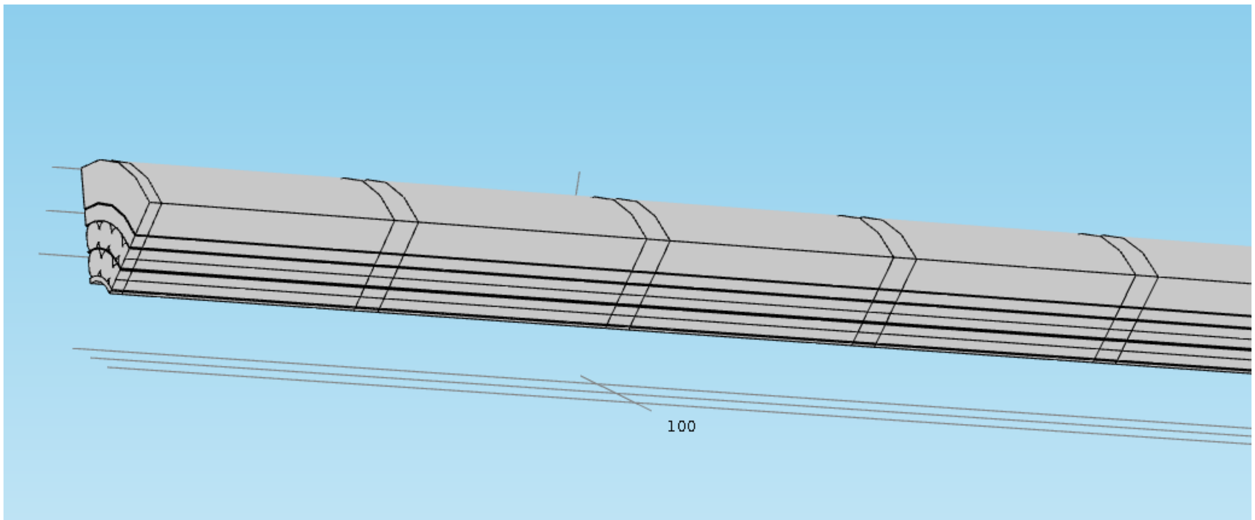

Figure 3: 3-D Model of the 2 Layer CIC cable used in the simulations to find the design of the quench heater.

CAD

Using the specifications found in the simulation, the exact width of the stainless-steel strips for the quench heater could be determined. Utilizing the width of the stainless steel, a CAD file was created to match this design. The CAD file allows precise machining of the heater. This machining will be done by an EDM.

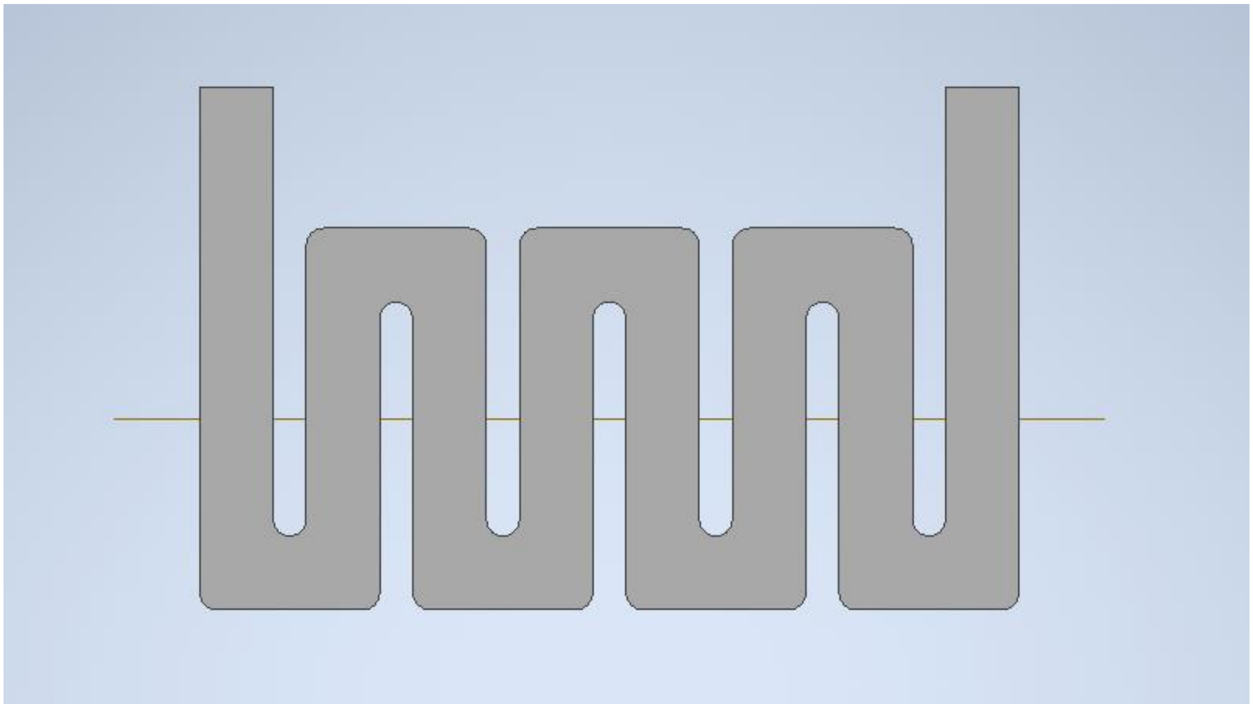

Figure 4 CAD file of the quench heater

Quench Heaters Design

The quench heater is designed as a serpentine piece of stainless-steel foil placed between two layers of Kapton. Kapton is ideal for this purpose because it has high temperature conductivity, but low electric conductivity. This means that the heat generated from the quench heater will easily pass through the Kapton, but the current used to heat the heater will not.

One of the sheets of Kapton has heat-activated adhesive which ensures that the quench heater does not come apart. In order to activate the adhesive, a T-Shirt press was used. This was able to achieve the desired heat of 400 K need to activate the adhesive. The adhesive would have to remain at this temperature for roughly 30 mins before becoming fully bonded. The soft surface of the T-Shirt press ensured that when the quench heater was being pressed together, no air bubbles would remain.

When making the final product to use in the actual magnet, the EDM will be used. Unfortunately, the EDM malfunctioned when attempting to produce the test heater. Note that in Figure 4, the corners of the heater are rounded while in Figure 5, they are sharp. This is due to the change which occurred from the loss of the EDM.

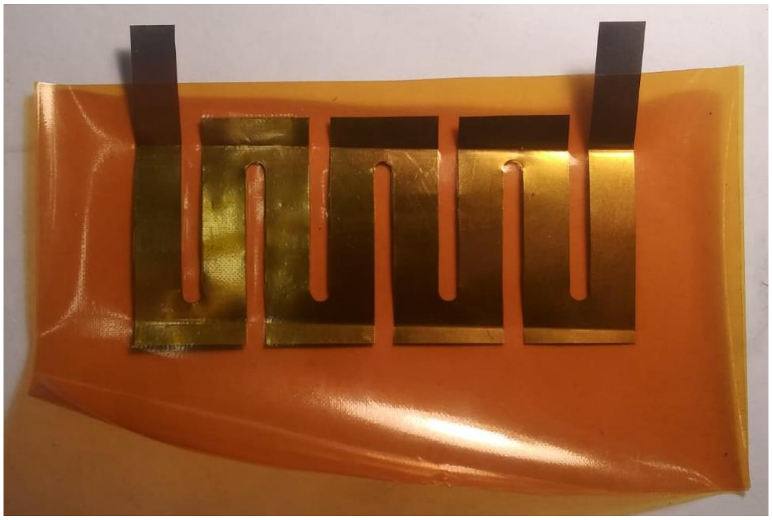

Figure 5: This is the quench heater designed for the physical test. This heater was cut by hand resulting in the sharp corners instead of the curved corners whoen in the CAD file.

Future Testing and Measurements

In future testing, we can validate the design of the quench heater. The preparation for the physical test has already begun but has not yet been completed. For the test, we created a quench heater and cable specially designed for an experiment. The design of test quench heater varied from the quench heater for the magnet because the test quench heater was only heating a single cable. This results in a smaller quench heater that has less resistance and needs a much larger current to heat the cable.

The cable used for the experiment needed to be specially designed for this experiment. In order to record the temperature inside the cable, we needed to have thermocouples inside the cable with the wires. To accomplish this, we used hypodermic stainless-steel tubing. After placing the thermocouples inside the tubing, we vacuum impregnated the tubing with epoxy to ensure that the thermocouples would not move around inside of the tubing. We then used the tubing as a surrogate for the wire in a standard handmade design of the CIC cable. We used three thermocouples in this design. One is located at the center of the cable on in the inner layer, the second one is located at the edge of the heater in the inner layer, and the final one is located at the center of the cable on the outer layer.

We utilize capacitors in order to simulate the pulse that will occur in the quench heater. We can easily find the time constant of the RC circuit created for this experiment. Using this, we can find the power discharged over 2-time constants.

The results are found by placing the cable and heater into liquid helium. Using the thermocouples from the cable, we can acquire a real time read of the temperature inside the cable as the heater is activated. Finally, we can compare these to the results found in the simulations to verify the accuracy of the simulation.

CHAPTER III

RESULTS

The physical test has not yet been conducted. The outer layer reaches a much higher temperature than the inner layer, as expected. The inner layer reaches the temperature we desired in an appropriate amount of time. The results from the simulations are shown in Figure 6. From the results, we can see that the strips of foil heat up the fastest. This is seen from the bumps in temperature along the flat line. These bumps are much more pronounced in the outer layer than the inner layer. This fits with our expectations since the temperature should be much more dispersed on the inner layer. Only the four inches covered by the heater are heated from the quench heater, but this will be enough to protect the magnet. From the results shown below we see that the inner layer of the cable is heated to ~10 K in 50 ms. This meets requirements we placed on the quench heater.

When compared with the simulations for the earlier quench heater, very similar results are found. This gives us confidence in our results. In the results, the x-axis is shown as an arc length, so it has no comparable units. 100 represents the center of the quench heater and 0 represents the start of the lead. There for 100 is approximately 4.5 inches. The end of the heater will be around 55. This is reflected by the drop off seen in the results.

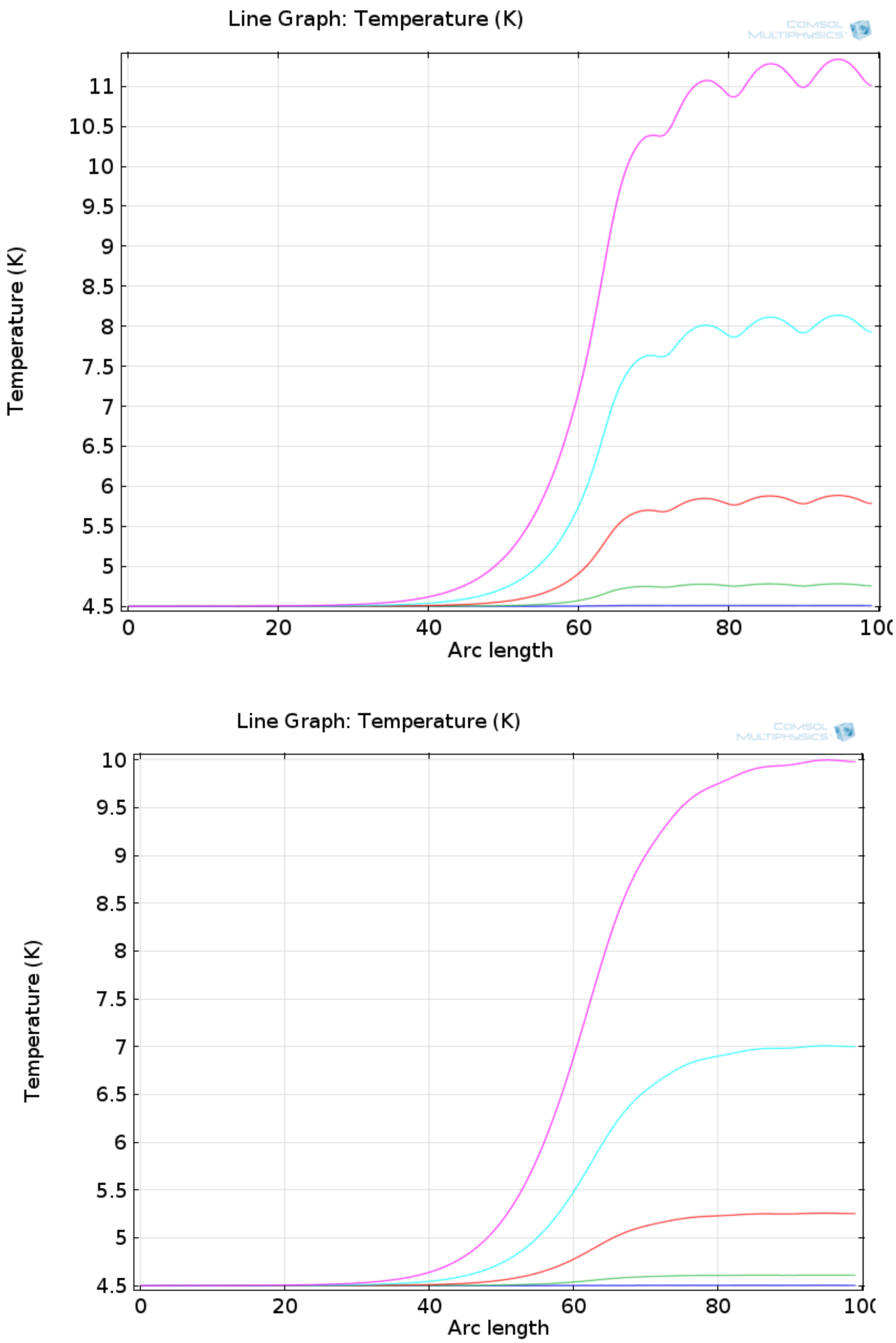

Figure 6: The figures above show the results from the simulation. The figure above shows the results for the outer layer and the figure below shows the results for the inner layer. Each line indicates a time step of 0.01 seconds with the final time step being 0.05 seconds.

CHAPTER IV

CONCLUSION

From what we have seen from the simulated results, we can construct a heater to protect the 16 T magnet. We were able to see that the test heater could quench the cable used in the test. The test has more steep requirements to quench the cable since resistance of the heater must be smaller than that for the entire magnet.

The physical test of this experiment will be carried out and hopefully confirm the results found in the simulations. This confirmation will increase confidence in our quench protection. Once the physical test is complete, we will be able to finalize the design of the heater to be used in the magnet.

The creation of the quench protection is an important step in the development of the 16 T dipole magnet. The development of this magnet will allow for the creation of stronger and more cost-effective particle accelerators. It is estimated that a 16 T dipole magnet would allow the creation of a particle accelerator that can produce higher energy particle of an order of magnitude higher than the LHC can currently produce.

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