

CRITICAL TEMPERATURE MEASUREMENT SETUP

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Abstract

The critical temperature measurement system is a means to identify a specific compound known to be more ideal for superconducting cavities, which is difficult to identify by traits other than its critical temperature. This setup makes use of the ability of superconducting materials to expel all magnetic flux by detecting the induced voltage in a solenoid that is not attached to any power source, by another solenoid on the other side of a superconducting sample. The setup currently exists as a completed Autodesk Inventor model, designed to conduct this experiment in a controlled environment.

INTRODUCTION

The ability of particle accelerators to accelerate electrons or other small particles is limited by the ability of superconducting cavities to remain in the superconducting state in the presence of magnetic fields. This trait is characteristic of any superconducting material, and cannot be changed unless the material is changed. Therefore, it is important to update the material used in cavities in order to boost their ability to accelerate particles. An important trait of a Radio Frequency (RF) cavity is its quality factor, the ratio of energy stored in the cavity to the energy lost to the oscillations of the cavity, which effectively determines the number of oscillations that will happen. The quality factor and accelerating electric field (unless a substantial amount of RF power is used) will both be much larger when the cavity is in the superconducting state than if it is conducting normally, because the electrons will be able to move with far less resistance. However, in order for the cavity to remain in the superconducting state, it must be maintained below its critical temperature and critical magnetic field. These factors, particularly the critical magnetic field, create limitations as to what can be done with RF cavities. Electric fields, which accelerate the particles, are proportional to the strength of the magnetic field inside the cavity. This effectively means that the maximum possible acceleration of the electrons in the cavity is proportional to the cavity's critical magnetic field. Therefore, achieving higher accelerating gradients requires updating the material used to make cavities to something that has a higher critical

magnetic field. A material with a higher critical magnetic field than the currently used niobium, Nb_3Sn , has already been found, but it is difficult to distinguish between it and other niobium-tin compounds, which have similar properties, but have reduced RF performance. However, Nb_3Sn can be identified from these other compounds by its characteristic critical temperature.

HYPOTHESIS

The setup works by taking advantage of a trait of superconducting materials: their ability to expel all magnetic flux. By placing solenoids on each side of a sample of a superconducting material, as in Figure 1, and driving one of the solenoids so it produces magnetic flux, it can be determined when the sample goes superconducting by the induced voltage in the receiving coil. By monitoring the temperature during this, the critical temperature can be found.

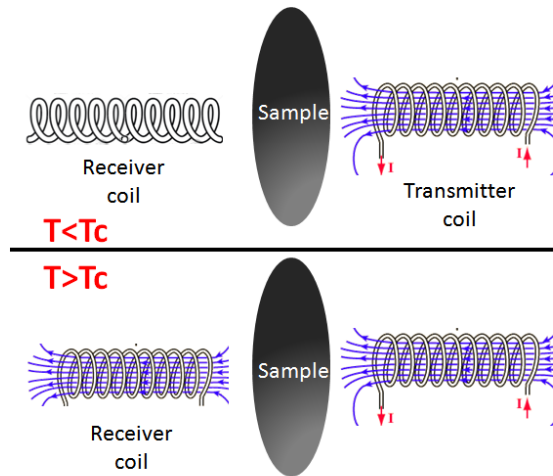


Figure 1: When the sample is below its critical temperature, it is superconducting and will expel all magnetic flux, causing the magnetic field in the undriven receiver coil to be very small. When the sample reaches T_c , the magnetic field in the receiver coil will be more comparable to that in the transmitter coil.

MAGNETIC FIELD CHANGE

According to the Biot-Savart Law, the strength of a magnetic field is inversely proportional to the square of the distance from the source of the magnetic field. Therefore, holding all other variables constant, it is possible to obtain the magnitude of the change in the strength of the magnetic field in the receiver coil by using the ratio of the lengths of the paths that the magnetic field would have to follow in normal conducting and superconducting conditions. The lengths of each path can be determined from the geometry of the superconducting sample, as shown in Figure 2. For a square sample, which is probably the most practical shape, the ratio of the path lengths for each condition can be represented by the equation:

$$\frac{d_{sc}}{d_{nc}} = \frac{2\sqrt{d^2 + \left(\frac{\sqrt{2}+1}{4}s\right)^2} + t}{2d + t}$$

where d is the distance between the sample and each of the solenoids, s is the length of each side of the sample and t is the thickness of the sample. The $\frac{\sqrt{2}+1}{4}$ factor compensates for the fact that the magnetic flux may go anywhere immediately around the sample and that it only has to go around half of the length of the side of the sample in any given direction. The ratio can also be solved, slightly more simply, for circular samples. In the case of a circular sample, the ratio can be found using this equation:

$$\frac{d_{sc}}{d_{nc}} = \frac{2\sqrt{d^2 + r^2} + t}{2d + t}$$

where r is the radius of the circle. No other factor is needed because a radius already only counts for half of the distance across the circle, and the distance between the center of the circle and its edges are constant throughout the entire circle. Since the dimensions of the sample will generally be constant, this ratio is effectively a function of the distance between the sample and the solenoids, as shown in the blue graph in Figure 3a. As the distance between the sample and solenoids approaches zero, the ratio approaches $\left(\frac{\sqrt{2}+1}{2}\right)\frac{s}{t} + 1$ for the square and $\frac{s}{t} + 1$ for the circle, whereas the limit as the distance approaches infinity is 1 for both. Therefore, it can be concluded that for large ratios for the two paths, and therefore, larger reductions in the magnetic field when it becomes superconducting, the length of the side of the sample should be dominant over its thickness and it should be as close as possible (without touching) to each of the solenoids. This equation can also be adapted for the addition of magnetic shielding (which

will be used in the setup) around the sample. For a square sample surrounded by square magnetic shielding of lesser thickness than the sample just fits inside, the equation is:

$$\frac{d_{sc}}{d_{nc}} = \frac{2\sqrt{\left(d + \frac{1}{2}(t_1 - t_2)\right)^2 + \left(\frac{\sqrt{2}+1}{4}s\right)^2} + t_2}{2d + t_1}$$

where t_1 is the thickness of the sample and t_2 is the thickness of the shielding. The percent change in the magnetic field can be obtained by solving:

$$\%change = 1 - \frac{1}{\left(\frac{d_{sc}}{d_{nc}}\right)^2}$$

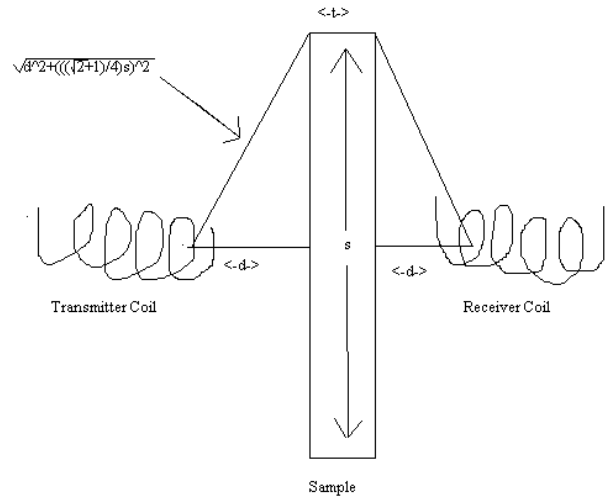


Figure 2: Representation of the paths that magnetic flux will follow under normal conducting and superconducting conditions.

Since the only variable in this equation is the ratio of the superconducting and normal conducting path lengths, which is a function of the distance between the sample and the solenoids, the percent change in magnetic field strength is also a function of this distance, as seen in the green graph in Figure 3a. When the distance is low, the ratio of the path lengths is high, causing the percent decrease in the magnetic field to be high, as well. Figure 3b is a graph obtained from a previous experiment with a similar setup to that shown in Figure 2. The graph shows a roughly 86 to 89 percent drop in the induced voltage of the receiver coil, which is directly proportional to its magnetic field strength, and while most of the actual dimensions are unknown, it is consistent with these equations for several plausible setups, such as a 1x1 in sample with solenoids between 4.25 and 5mm away.

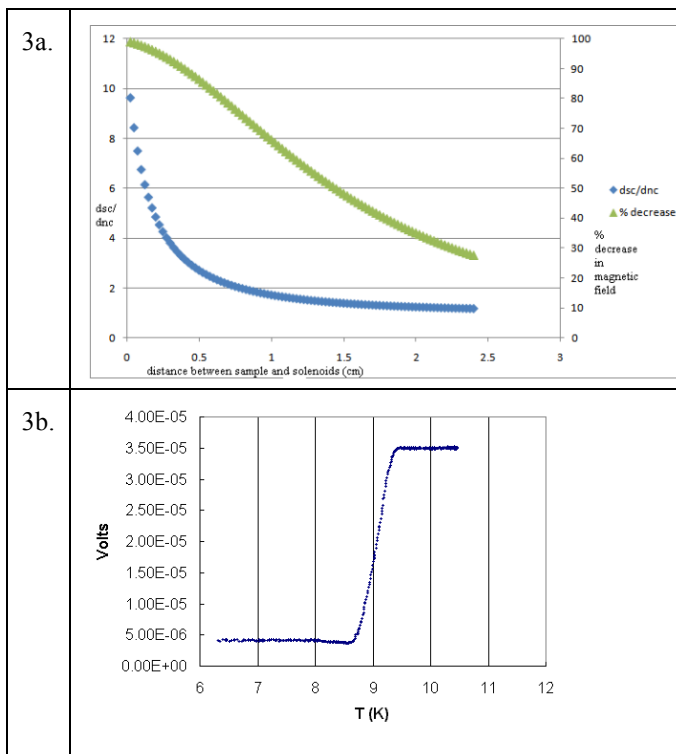


Figure 3a: Graphical estimate for percent change in magnetic field strength in receiver solenoid between normal-conducting and superconducting states as a function of the distance between the sample and each solenoid. Figure 3b: Experimentally obtained graph showing change in voltage between normal conducting and superconducting states.

THE SETUP

The critical temperature measurement setup is designed to take advantage of the fact that superconducting materials expel all magnetic flux to find the material's critical temperature in a controlled setting. Since it is easy for a superconducting material to leave the superconducting state, it is important that considerations in the design are made to prevent this from happening.

Main Assembly

The main assembly, shown in Figure 4, for this project is an insert for a Dewar, which must prevent the experiment from being significantly affected by the outside environment, while still allowing room for anything else that is needed inside the Dewar (such as wiring). Helium recovery is also a goal for this project, so several kwik flanges, as well as one conflat flange, are included in the design to accommodate this. Most of this setup will be made out of stainless steel, with the box at the bottom being made of copper.

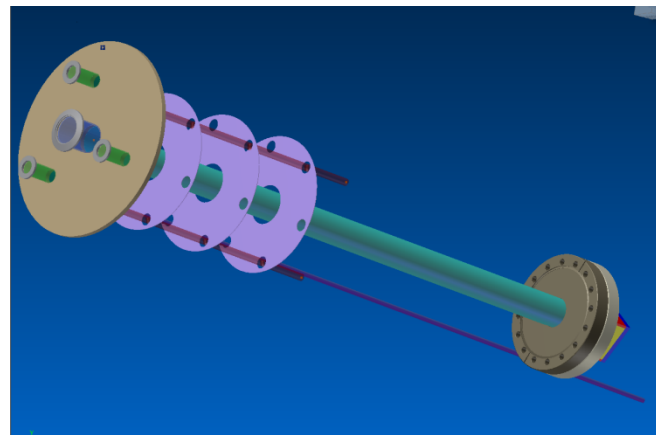


Figure 4: Main Assembly. The upper part of the insert is mainly designed to protect the experiment from the outside environment. The design includes a top plate, three heat shields, held in place by three support rods, four kwik flanges, with a tube for each, with the middle one extending down to a conflat flange, where it is connected to a copper box, which is where the experiment takes place.

Copper Box

The sample that is being studied is inside the copper box at the bottom of the insert, shown in Figure 5. The purpose of the box itself is to allow for relatively even heating and cooling of the sample of superconducting material that is being experimented on. This is important because it means that each part of the sample will, for the most part, transition between the superconducting and normal conducting states simultaneously. The box will be welded to a copper plate at the top which is designed to fit inside a 6" conflat flange, as shown in Figure 5. The setup for the experiment will be bolted to the center of the box to prevent it from moving around, keep heating relatively even, and to maintain good thermal conductivity between the box and the setup.

Experimental Setup

Inside the copper box is the setup, shown in Figure 6, where the experiment takes place. The superconducting sample (which must be square with a side length of 1" and 3mm thickness) that the experiment uses is represented by the purple square object in the model, which can be seen behind the parts that are shown in translucent colors. The hollow pink cylinders represent the solenoids that are to be used in the experiment. The sample and solenoids all have to be held in place to maintain the integrity of the experiment. For the sample, it is necessary for the container to maintain good thermal conductivity with both the sample and the copper box on the outside, so it is going to be placed inside a clamp, which will be bolted to the copper box. The solenoids will have a small part inserted inside

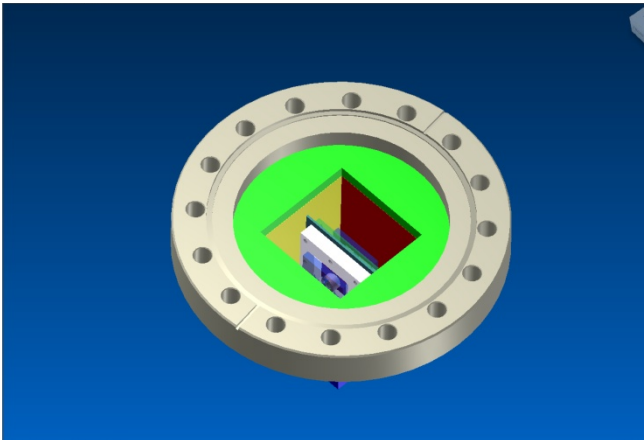


Figure 5: Copper Box. This part of the model, which can also be viewed at the bottom of Figure 4, is designed to allow for relatively even heating and cooling of the superconducting sample used in the experiment. The design includes the box itself, designed as three individual faces, the setup where the experiment takes place, a copper plate, and a conflat flange.

them, shown in light green in the model, which will be bolted into the center hole of the transparent blue part, which has five holes to allow for the possibility of probing the area around the sample for magnetic flux. This setup also uses magnetic shielding to provide a larger decrease in the magnetic field of the receiving solenoid when the sample becomes superconducting.

Other Parts

There are several parts, other than this insert, required to make the experiment work, most of which are not shown in

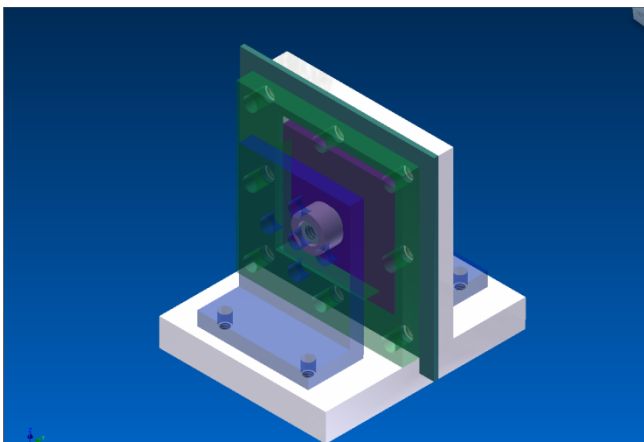


Figure 6: Experimental Setup. This part of the model represents where the experiment actually takes place. The design includes the superconducting sample, the two solenoids, with parts to hold them, and the clamp used to hold the solenoid, which is designed to maintain good thermal conductivity.

the assembly. The only such part represented in the model is the longest rod in Figure 4, which is a helium level stick, which can be used to keep track of the level of liquid helium in the Dewar by keeping track of its resistance, which is proportional to the normal conducting length of it. The parts not shown in the model are a vacuum cross, to be connected to the KF40 kwik flange located at the center of the top plate, a temperature probe that will be used to keep track of the temperature of the sample by using its resistance, several resistors, mostly along the sides of the copper box to serve as heaters for the sample, and one in the liquid helium to boil it, making gaseous helium cool the sample, the wires necessary to complete circuits for any electrical parts, the stinger that will be used to get the liquid helium into the Dewar, and any bolts, nuts, and screws needed to assemble the actual setup.

Operating Procedure

The setup is designed to be inserted into a Dewar. The sample will be hooked up to a temperature probe and the solenoids will be connected to a Lock-in Amplifier. The Dewar is then filled part way with liquid helium so that there is enough liquid helium to run the experiment, but not enough to touch the insert itself. This can be achieved by monitoring the resistance of the helium level stick, which is proportional to the length of the level stick that is still normal conducting, and is thus, above the helium level. Afterward, the Lock-in Amplifier should be activated so that a current runs through the transmitter solenoid, creating a magnetic field, and therefore an induced current and voltage in the receiving solenoid, which can be monitored by the Lock-in Amplifier. With the temperature of the sample and the voltage, and by extension, the magnetic field, of the receiving solenoid being monitored, a computer needs to plot a graph of the data, with voltage on the y-axis and temperature on the x-axis. A current should then be run through the resistor that is inside the liquid helium so that it can boil the helium, which will create helium gas, which will rise and cool the sample. The sample should be cooled this way until it either reaches 4K or until a sharp decrease in voltage occurs while the temperature decreases, which should occur at the sample's critical temperature. If another trial is needed, the process can be reversed in order to make another attempt at finding it; this time, while the sample is heated. Turn off the power to the resistor that is sitting in the liquid helium and instead turn on the ones connected to the copper box. This will heat up the copper box, the clamp, and the sample. When the sample is being heated, the critical temperature will be seen as a sharp increase in the voltage of the receiving solenoid as the temperature increases.

What Still Needs to be Done

The critical measurement setup is currently just an Autodesk Inventor model. The setup still needs to be made into an Autodesk Inventor drawing, so that the parts for it can be made. Once the parts are made, the setup can be assembled as shown in Figures 4 through 6, and the setup can be tested using the procedure previously stated. Once all of that is finished, the device can be used to measure the critical temperature of superconducting materials, which also allows it to help identify superconductors of known critical temperatures, including Nb_3Sn , which can potentially become a more viable material for the production of RF cavities, due to its higher critical temperature, and especially because of its higher critical magnetic field, which is needed to provide higher accelerating gradients in particle accelerators, in comparison with lead and niobium, which most RF cavities are made of today.

THE OLD SYSTEM

The critical temperature measurement system is not an entirely new concept. There already is a setup that has been built for the same purpose, shown in Figures 7 and 8. The old system works primarily based upon the extremely low resistance of materials that are in the superconducting state, rather than on their ability to expel magnetic flux. It uses a four-wire measurement system with the Lock-in Amplifier to monitor the potential drop across the sample as the temperature changes. This system is already operational.

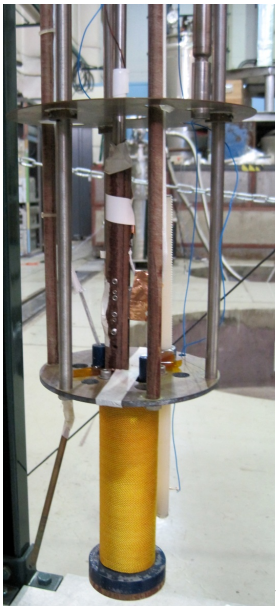


Figure 7: Photograph of the Old System. Some parts of the design of the new system have been borrowed from the old system.

Why is the New System Important?

Even though the old system is capable of measuring the critical temperature, its ability to measure it needs to be improved upon. The old system is greatly susceptible to being influenced by noise and the effects of inductive reactance, and will only accurately measure when the sample begins to become superconducting rather than the entire process, as the superconducting parts will short out the normal conducting ones, which can lead to the creation of imprecise graphs, like the one in Figure 9. By the data collected, it can be concluded that the critical temperature of the substance used in the experiment was probably somewhere around 18K, but it is possible that there were other factors in effect, which may have affected the measurement of the critical temperature, and it isn't so clear how far the resistance jumped at the critical temperature (which appears could be anywhere from 50 to 250n Ω). The new system is expected to not have as many flaws as the old system, and will hopefully produce graphs more like the one in Figure 3b.



Figure 8: Experimental Setup of the Old System. In the old system, the low resistance of superconducting materials was used to find the sample's critical temperature, rather than their ability to expel all magnetic flux.

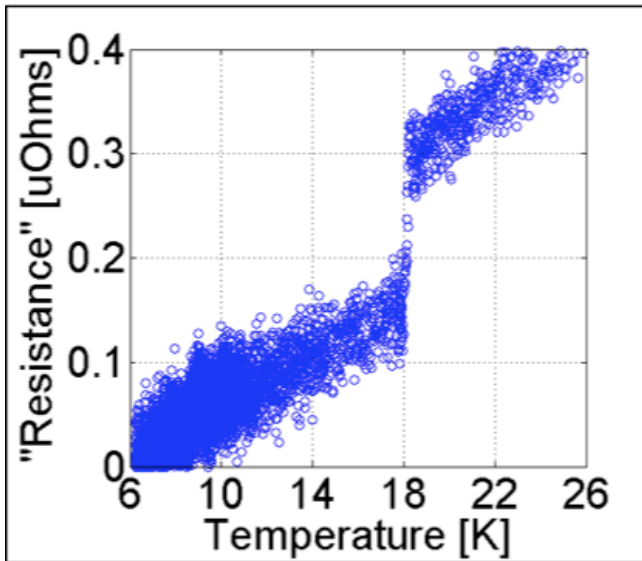


Figure 9: A graph produced by the old system, measuring the resistance of the sample against its temperature. The effects of noise and inductive reactance, neither of which will be easy to overcome, have caused the graph to become imprecise. This is vastly improved over some other graphs that it has produced, but the graphs are unlikely to get much better without replacing the system.

CONCLUSION

The critical temperature measurement system could be an important step towards advancing the field of particle accelerator physics by helping to identify materials that are more ideal for the production of RF cavities, such as Nb_3Sn , which will make cavities capable of achieving higher accelerating electric fields. By taking advantage of the ability of superconducting materials to expel all magnetic flux, rather than their low resistance, more accurate measurements of the critical temperature can be obtained, allowing more accurate identification of the superconducting materials. When utilized correctly, the critical temperature measurement system will lead to the use of better materials to make better cavities, which will be used to make better particle accelerators capable of doing more for science.