Temperature Dependence of the Critical Current in the YBCO Superconducting Quantum Interference Device

By Jordan Raisher and Philip Thomas

Abstract:
Using the Cryoeletronics Mr. SQUID® YBCO-SQUID apparatus, we establish a temperature curve of the resistance and voltage of the SQUID itself. Through this, we also examine the temperature range through which the SQUID progresses from a high temperature-normally conducting regime to a low temperature-superconducting regime. To assess the validity of this curve, we also explore the physical properties of the SQUID at 77K including the properties of microwave radiation in subduing the superconducting critical current in an attempt at producing Shapiro steps.

I. Introduction

Few phenomena in the world of physics have as many immediate industrial, theoretical, and practical applications as that of superconductivity. This is the phenomenon by which the electrical resistance of a material is reduced to zero allowing the passage of current with no energy loss.

Superconductivity was first discovered in the Netherlands in 1911 when a sample of Mercury was cooled to 4K. Then, in 1934 Meissner and Ochsenfeld discovered the ability of superconductor to expel magnetic fields, which was called the Meissner effect. The expulsion of magnetic fields from loops of superconducting wire is caused by the production of induced currents within the superconductor. These phenomena were made even easier to study in 1986 with the discovery of relatively high temperature superconductors. These discoveries laid the groundwork for and augmented the development of Superconducting Quantum Interference Devices (SQUIDs) in the 1960's with the discovery of a Josephson junction.

Josephson junctions are a characteristic component of many superconducting electronic circuits. By creating a gap in the superconducting wire, filling the gap with one of several non-superconducting materials, the wire exhibits quantum effects. Up to a certain critical current (I_c), the electrons of the current can actually tunnel through the gap, maintaining the supercurrent. However, above this current, the gaps display characteristic "normal" resistance (R_N).

Most SQUIDs are constructed of a single loop of high-temperature superconductor, such as ours made of Yttrium Barium Copper Oxide (YBCO), with two symmetric Josephson Junctions at the center of the loop (Figure 1). When no magnetic field is passing through the loop, the current will be

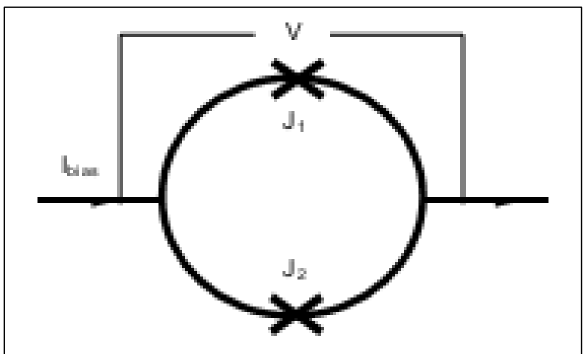


Figure 1: A voltage, V, is applied across this loop, creating two currents, J_1 and J_2 which pass through the Josephson Junctions, symbolized by X's

symmetrically divided between the two pathways.

If, however, a magnetic field is applied to the loop, creating a flux, there will be a secondary current applied in going around the loop in accordance with Faraday's Law (Figure 2). The portion of the loop carrying the induced current in the same direction as the applied voltage will have a higher current than the portion of the loop carrying the induced current against the applied current. This means that at a certain magnetic field strength, one of the junctions will surpass the critical current and lose its superconductivity or "go normal". At this point, the entire current, taking the path of least resistance, will be directed toward the opposite junction, forcing it to go normal as well. In this brief moment that the junctions both go normal, the Meissner effect, which only holds for superconductors, allows a specific amount of flux to be established in the loop. This reduces the amount of current necessary to counteract the external flux through the loop, allowing superconductance to be restored.

The amount of flux allowed into the loop is a universal constant known as the fluxon

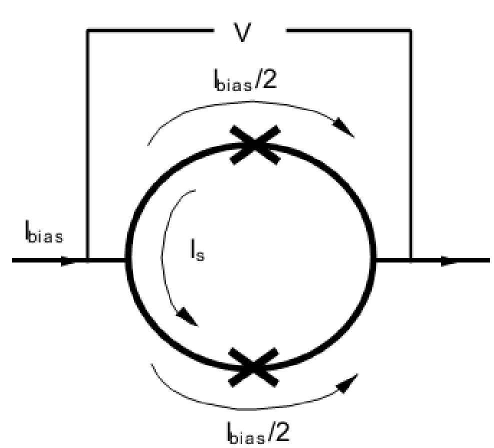


Figure 2: In the presence of an external magnetic field, a second current, labeled I_S, is induced in the wire.

(Φ_o) which has been calculated in previous experiments to be equal to Planck's constant divided by twice the fundamental charge (h/2e) or $2.07\text{x}10^{-15}$Wb. As such, a SQUID can be used to measure very small magnetic fields.

The focus of this research project has been divided into three overarching concepts. The first is a verification of the accuracy of the YBCO-SQUID probe which we were using by comparing several measured and calculated values to the literature values given. The second is an examination of the phenomena of Microwave-Induced (Shapiro) Steps in the V-I curve (Voltage plotted against current) using two different containers to assess the effects of standing wave modes on the prevalence of the steps. The third test presents an examination of the critical current and superconducting properties through a range of temperatures surrounding the superconducting transitional temperature.

II. Methods and Procedure

Apparatus

For all of our experiments, we used the STAR Cryoelectronics Mr. SQUID® YBCO-SQUID to take all of our measurements. Most of our measurements took place in the provided 1L, 33.7cm tall, silvered-glass vacuum dewar (Figure 3). The one exception to this is the measurements of Shapiro steps which took place both inside the dewar and a Styrofoam container, modified to account for the probe connections.

The SQUID probe was controlled using the included Mr. SQUID® control box (Figure 3). This box converted the signals from the SQUID probe into signals compatible with a digital oscilloscope. This

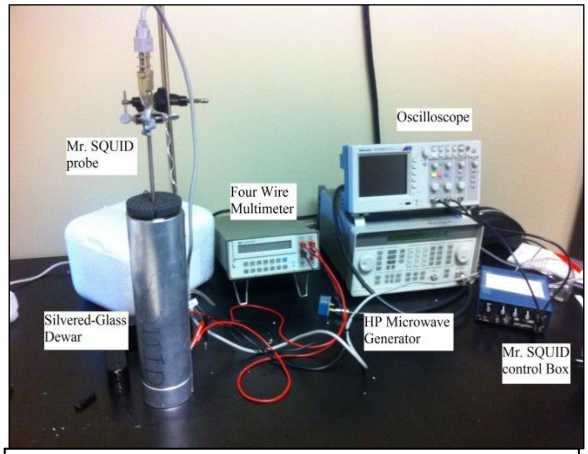


Figure 3: The experimental setup including the dewar, control box, multimeter, oscilloscope, and microwave generator.

control box was also able to modulate several aspects of the SQUID including the flux bias, the current bias, the current amplitude and the mode of measurement.

All of our SQUID readings were taken automatically using a Tektronix digital Oscilloscope with a USB compatible port (Figure 3). The data was recorded digitally and saved to an external USB drive to decrease any unaccounted for time dependent effects in our measurements.

A platinum resistor was used in conjunction with a digital, 4-wire, multimeter to provide accurate temperature measurements at very low temperatures (Figure 3). The resistance of the platinum wire varied linearly with respect to temperature in the regime of this experiment which, as measured by the digital multimeter, allowed us to measure temperature.

Basic Procedure

All measurements were taken based on the following specific procedure with slight variations according to which experiment was being run.

At the start of a research period, the dewar was filled, to approximately 5cm below the top of the dewar, with liquid nitrogen (LN_2). The dewar was allowed to cool and refilled based on the amount of LN_2 which had boiled off during cooling. The SQUID probe was lowered into the cooled dewar. In order to prevent flux trapping as directed by the Mr. SQUID® user's manual, the probe was not plugged into the control box while the probe was cooling.

The control box was then used to set up a V-I or V-Φ (Voltage plotted against magnetic flux) curve which was displayed on the oscilloscope (Figure 4). The USB writing function on the oscilloscope was only supported in YT mode as opposed to XY mode on the oscilloscope which means that our digitally recorded data was scaled accordingly to match the XY voltage readings.

Vacuum Cooling

In order to test the critical current at temperatures below standard LN_2 (77K), a vacuum pump was employed. By creating a low pressure area above the surface of the LN_2, the higher energy LN_2 molecules were vaporized, lowering the overall energy, and thus temperature of the LN_2. A rubber gasket was affixed to the top of the dewar

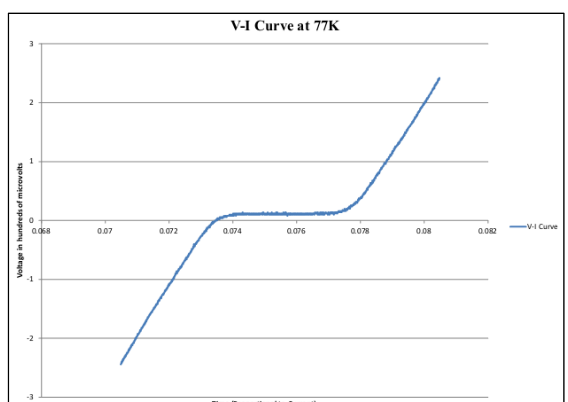


Figure 4: A characteristic V-I curve at 77K with a flattened knee where the wire becomes superconducting.

and a mechanical vacuum pump was used to lower the temperature of the LN_2 inside for between 15 and 20 minutes. At this point, due to evaporative losses, additional LN_2 at 77K was added to the cooled LN_2 and the mixture was pumped again. This procedure occasionally produced solidified nitrogen at the bottom of the dewar which provided stabilized lower temperatures at the bottom of the dewar.

During the pumping, the SQUID probe was inserted into a second container of LN_2 to reduce the temperature difference between the SQUID and the cooled LN_2. This reduced the equilibrium temperature of the system when the SQUID probe was inserted into the cooled LN_2.

Two methods were used to vary the temperature of the probe in the cooled LN_2 experiments. First, the probe could be raised and lowered since the frozen nitrogen and the cooler LN_2 sank to the bottom of the dewar. Second, due to exposure to the room, the temperature of the dewar and LN_2 slowly rose again toward 77K. The time in which the temperature rose, however, was slow enough to allow for quazistable temperatures at which to take measurements.

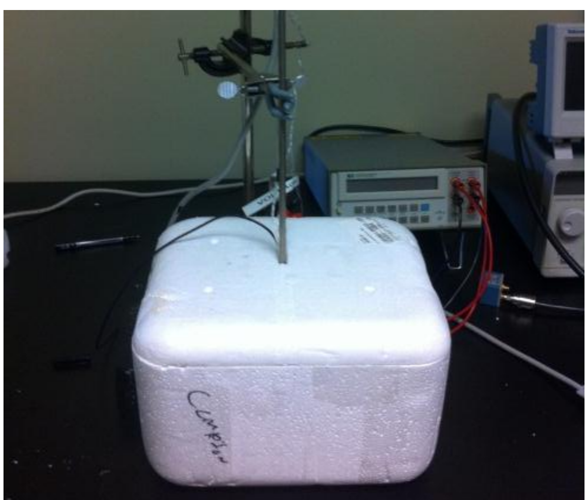


Figure 5: The Styrofoam container in which some of the Shapiro Step experiments were performed.

Microwave Induced Shapiro Steps

An HP microwave source generator was used in this portion of the experiment to generate up to 2GHz low amplitude microwaves through probes which were affixed to the end of the SQUID probe. The oscillating electromagnetic waves subdue the critical current in the dc SQUID, creating small discontinuities in the V-I curve at higher voltages and currents than expected creating a step-like pattern referred to as Shapiro Steps.

The SQUID was prepared as specified earlier, cooled to around 77K and verifying a normal V-I curve before testing. Then, using the microwave generator, with a strength of between 350 and 500 mV (approximately half power), various frequencies were identified in which the critical current was completely subdued. The amplitude was then lowered to recover a small critical region and the frequency was varied to attempt to "tune in" to a frequency which created Shapiro steps. However, no combination of frequencies or amplitudes supported Shapiro steps.

The same procedure was repeated using the modified Styrofoam container (Figure 5). This was to examine any frequencies which were different between the two containers to determine what, if any effect the aluminum and silver coatings on the dewar would have in Shapiro step readings.

High Temperature Readings

Due to the 77K temperature of LN_2, which exists below the superconducting temperature of the YBCO-SQUID, a normal LN_2 submersion could not be used to examine the superconducting transition of the SQUID which existed above 77K. A lower level of LN_2 was added to the dewar such that the SQUID could be inserted into the dewar without coming in contact with the LN_2. Sealing the dewar with the foam cap allowed a temperature gradient to be established between the near-room-temperature foam cap and the 77K LN_2 lower in the dewar. The SQUID probe was then lowered through the temperature gradient as readings were made periodically based on temperature readings from the platinum resistor. In order to keep the data self-consistent, readings were only made while the SQUID was descending rather than ascending.

III. Results

Basic SQUID Parameters

The basic parameters of the SQUID were recorded at approximately 77 K using several relations recorded by the oscilloscope. The measurements were also taken without any current of magnetic bias.

The critical current is measured by examining the flat “knee” of the V-I curve. The oscillation of the current across zero means that the magnitude of the current will be half of the flattened region. Furthermore, since the current was divided symmetrically between the two junctions, the critical current for a single junction is equal to a quarter of the current width at the “knee” of the V-I curve. The output of the SQUID control box corresponding to the current was recorded in voltage by passing the current through a 10 kΩ resistor. This gives a current, as calculated by Ohm’s Law (Equation 1)

$$I = \frac{V}{R} \qquad (1)$$

Similarly , using Ohm’s law, the normal mode resistance can be found by finding the slope of the V-I curve as in Equation 2.

$$R = \frac{V}{I} \qquad (2)$$

Using these equations, the critical current (I_c) was found to be 21.35±0.05 μA and the normal mode resistance (R_N) was found to be 3.64±0.07Ω.

The voltage difference caused by the breakdown of the Meissner effect can be measured directly from the V-Φ curve as the height of the sinusoidal curve. From this, we measure the voltage difference (ΔV) to be 31.2±0.02μV.

From these three values, the characteristic value of β_L can be calculated using equation 3-2 from the Mr. SQUID® user’s manual (Equation 3).

$$\beta_L = \frac{4I_cR_N}{\pi\Delta V} - 1 \qquad (3)$$

This expression, relating the normal mode resistance, the critical current, and the voltage drop, yields a characteristic value for β_L of 2.2±0.2.

These values all fell within the suggested ranges of the literature.

Furthermore, the period of the sinusoidal V-Φ curve can be used to determine the magnitude of the fluxon (Φ_o) (Figure 6). The period of the V-Φ curve gives a current which can be equated to the fluxon using

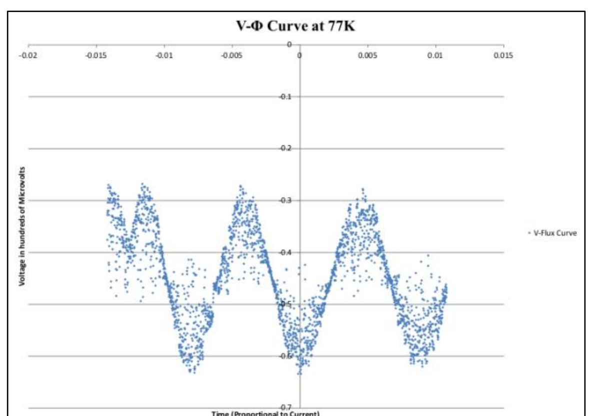


Figure 6: The Period of the Sine wave of this V-Φ curve is the current difference correlated to one fluxon.

equation 3-4 using the literature value for the mutual inductance (M) of 37pH (Equation 4).

$$M = \frac{\Phi_o}{\Delta I} \qquad (4)$$

This gives a value of the fluxon (Φ_o) to be approximately 3.33×10^{-15}Wb. The inductance (L) of the SQUID can then be calculated by using the value of the fluxon through equation 3-1 (Equation 5).

$$\beta_L = \frac{2 I_c L}{\Phi_o} \qquad (5)$$

Using the literature value of 2.07×10^{-15} Wb yields an inductance of 1.052pH. Using the calculated value of 3.33×10^{-15}Wb yields an inductance of 169pH. Both of these measurements are between a factor of 1.5 and 3 away from the given literature value of 60pH.

As suggested by the Mr.SQUID® user's manual, the inductance and mutual inductance of the SQUID is based on several qualities which can change over time. Most importantly could be the change of the ring shape or size due to continued use or size fluctuations due to temperature changes.

From the first set of SQUID characteristics, it appears that the superconducting qualities of the SQUID are to be as expected. However, examining the magnetic qualities of the SQUID indicated that the SQUID's geometry, and thus its inductance, has changed from literature values.

Microwave Suppressed Critical Current

The first step of demonstrating Shapiro steps is to suppress the critical current by passing electromagnetic waves through the SQUID. This project challenges the previous assumptions that Shapiro step

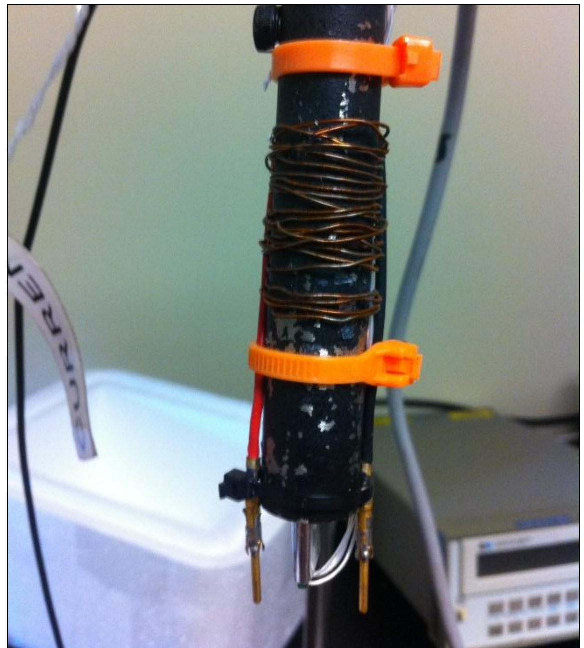


Figure 7: The microwave probes (red and black) on either side of the SQUID probe.

measurements can only be made in a Styrofoam container.

The suppression of the critical current was carried out in both the Styrofoam and in the dewar with the microwave emitters affixed to the end of the SQUID probe fixed to either side of the probe base using plastic ties (Figure 7).

The microwave generator was attached

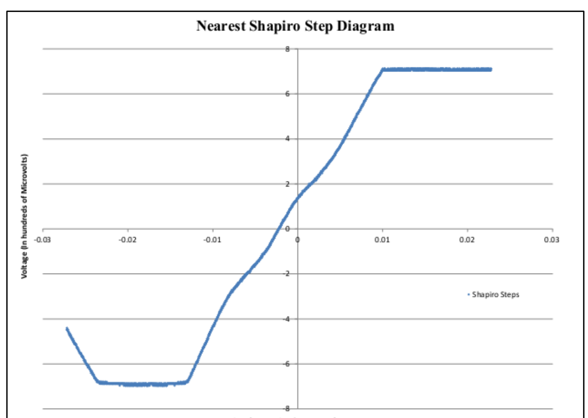


Figure 8: This is an example of the V-I graph with an applied Microwave field. Small Shapiro steps are visible and the central knee is diminished.

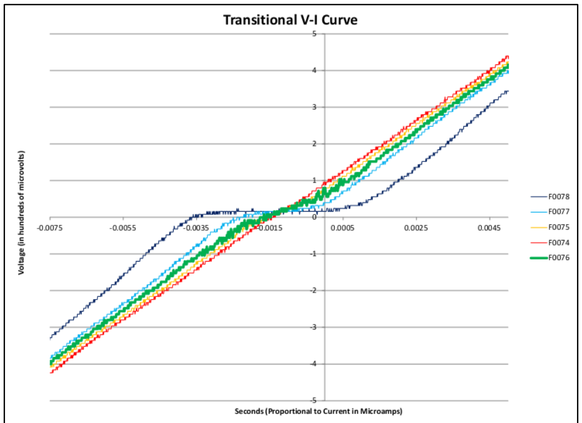
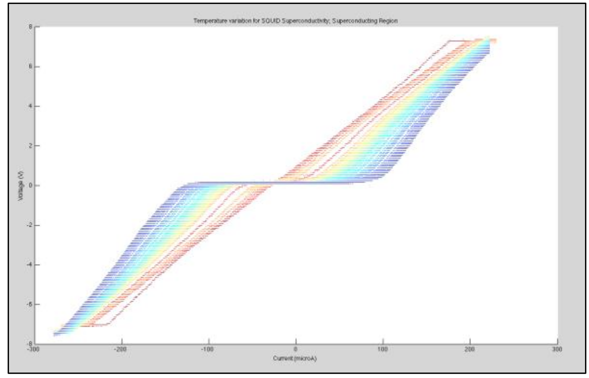


Figure9: This diagram displays five different curves ranging between 77K and 80K. Here, the green line represents the limit at which the SQUID becomes superconducting.

to a frequency doubling apparatus which boosted the maximum frequency output of the generator from 1GHz to 2GHz.

In the Styrofoam container, between 350μV and 500μV intensity, frequencies of 138, 208, 298, 344, 390, 412, 420, 490, 592, 626, 660, 702, 830, 854, 916, 986, 1040, 1132, 1482, and 1972 MHz demonstrated the suppression of critical current. In the dewar, also between 350μV and 500μV, frequencies of 298, 408, 422, 552, 582, 882, 1046, 1072, 1106, 1124, 1404, 1120, 1958 MHz all demonstrated the suppression of critical current. While some lower frequency signals available in the Styrofoam are not available in the dewar, most of the frequencies, specifically 298, ~410, ~420, ~587, ~1043, ~1128, ~1964.

This indicates that there are certain frequencies which are characteristic of the orientation of the probes to the SQUID which are similar between the two. In each vessel, there are frequencies which are characteristic to the vessel as well. In further studies, based on these common frequencies, Shapiro steps are likely to be observed at these frequencies. However,



based on the Mr. SQUID® user's guide, Shapiro steps are likely to occur above 1GHz. Due to the images which were recorded, higher frequencies appear necessary to excite more "knees" in the V-I curve (Figure 8).

Figure 10: This figure displays the transition of the V-I Curve from high temperatures (red) to low temperatures (blue).

Superconducting Transition and Vacuum Cooling

By lowering the probe gradually, the temperature of the probe was lowered in a very controlled manner. Starting at 273K, the temperature was gradually lowered to 77K with images taken throughout the process, with more readings per temperature span near the superconducting transition.

The transition between normal conductance and superconductance took place between 79.7K and 78.1K which departs slightly from literature values of 93K for YBCO (figure 9). This could be due to deviation from previous calibrations of the platinum wire, or because of the temperature deviation from the platinum wire to the SQUID.

As the temperature was lowered even further, the critical current (I_C) also decreased to from 21.35μA at 77K to 37.36μA at 71K. This demonstrates the effect of the temperature on the critical current demonstrating an approximately linear relationship between the critical current and the temperature between 71 and 79K of -2.67μA/K (Figure 10).

IV. Conclusion

Through the use of the rapid data acquisition of the USB port on the Oscilloscope, a complete cooling curve was able to be created for the YBCO SQUID. This includes, in proportionally greater detail, the transitional range between 78K and 80K.

The validity of this cooling curve is supported by the confirmation of expected values of critical currents and normal resistances. This indicates that this cooling curve is valid for any YBCO grain-junction SQUIDs.

Additional and more accurate cooling curves could be made by taking an even large amount of quazistable measurements by allowing the cooled LN_2 to slowly warm and then evaporate to create an even more stable temperature through the probe.

However, the difference between the calculated fluxon and inductance values and the predicted literature values indicates that the calibration of this specific SQUID to small magnetic fields is less accurate than the user's manual predicts. In future research projects, the specific errors and deviations in magnetic measurement can be further studied in more detail.

As calculated, we have also found that there are two classes of microwave frequencies which subdued the supercurrent. The first of which is characteristic of the geometric relation between the probes and the SQUID, the second, reflective of the geometry of the container in which the SQUID is placed. Although no Shapiro steps were directly observed, any future research projects using this apparatus are more likely to be successful at those frequencies which were shared by both containers.

Further magnetic errors and deviations may be caused by the orientation of the SQUID with respect both to the earth's magnetic field and with respect to local electronics.

V. References

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