

Principles and Applications of Superconducting Quantum Interference Devices (SQUIDs)

PHY 300 - Junior Physics Laboratory

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1 Abstract

In this experiment we will use a DC SQUID magnetometer to demonstrate the quantization of flux, the DC Josephson effect, detecting the superconducting phase transition and in the end use the SQUID with a FLL (Flux Lock Loop) circuit to make a sensitive DC/AC voltmeter.

2 Introduction

Some very interesting quantum phenomenon can be observed using superconductors. A superconductor is a element that loses its electrical resistance below a Curie temperature T_c . In superconductors the current is not carried by single electrons but by pairs of electrons with opposite spins called Cooper pairs. The binding energy is large compared to the thermal scattering, as a result cooper pairs propagate through the material without any resistance. Cooper paired electrons have lower energy than the Fermi energy.

There is no magnetic flux inside the superconductor and this is known as the meissner effect, this is due to screening currents flowing on the surface of the superconductor.

The reason why superconductors can be used to demonstrate quantum phenomenon is because the Cooper pairs share a common wave function. This coherence of wave function display macroscopic quantum phenomenon and we can observe quantum mechanics at a large scale.

We can use these superconductors to observe quantum tunneling. When two superconducting regions are weakly coupled, a Josephson junction (JJ) can be formed by placing a thin insulating gap between the two superconductors. Electron pairs can tunnel through this gap and a resistance less current can flow across the insulator, this is called the DC Josephson effect.

Now that we have discussed briefly the concepts to build on the background, now we will move on to SQUIDs. A Superconducting Quantum Interference Device (SQUID) uses flux quantization and the DC Josephson effect to detect extremely small magnetic fields, down to 10-15T.

The central element of a SQUID is a ring of superconducting material with one or more JJs. When a tiny magnetic field is applied, it tends to change the superconducting wave function, but the superconducting wavefunction doesnt want to change so it opposes the applied field by generating a screening current I_s and cancels out the net flux in the ring. The applied field has reduced the amount of bias current we can pass through. Now as we increase the magnetic flux, the screening current increases, but when the magnetic flux



reaches half a quantum, the junctions become momentarily resistive. The screening current changes sign when the applied flux reaches half of a flux quantum. At exactly one flux quantum, the screening current goes to zero. We measure the critical current by measuring the voltage drop across the junction as a function of total current through the device.

This method is similar to the interference of light in Young's double slit experiment. So SQUID cleverly uses interference and flux quantization to detect small magnetic fields.

3 SQUID Apparatus

Our experiment uses Mr. SQUID™, a commercial DC Superconducting Quantum Interference Device (SQUID) magnetometer, incorporating the following components,

- a high-temperature superconductor (HTS) thin-film SQUID chip,
- two feedback coils to modulate the SQUID and to couple an external signal to the SQUID
- a cryogenic probe with a removable magnetic shield
- an electronic control box containing all the circuits needed to operate the SQUID, and
- a cable to connect the probe to the electronics box.

At the heart of Mr. SQUID is a small integrated circuit chip made of yttrium barium copper oxide (YBCO) that is fashioned into a ring containing two Josephson junctions.

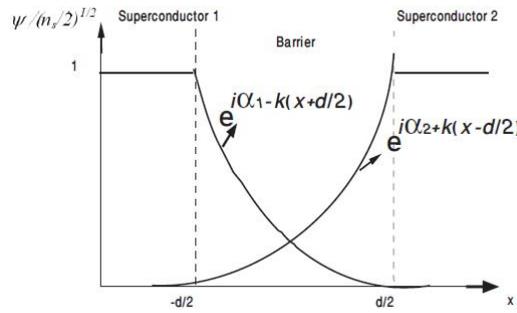


Figure 1: Tunneling of cooper pairs through the barrier

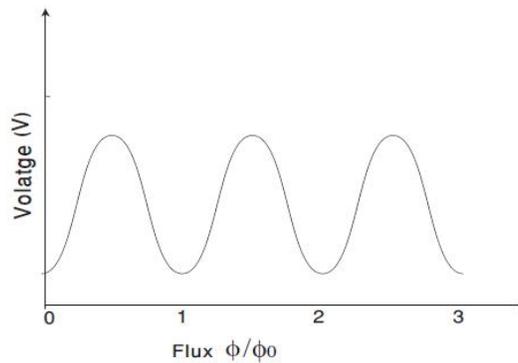


Figure 2: Voltage-Flux graph

4 Experiment

4.1 4.1 The DC Josephson effect

In this experiment we will observe the resistanceless current in the SQUID and also measure the critical current.

1. We first fill the dewar with liquid nitrogen and then lower the probe into it. The critical temperature of the YBCO is about 90K.
2. We set the oscilloscope output to V-I mode, the Bias offset is minimised and the sweep output is increased.
3. The V-I output is shown in figure 3, it shows the current flowing with almost zero voltage drop.
4. We then measure the critical current flowing through the superconductor, we take the voltage reading at the knee as shown in figure 4 and after dividing by the resistance, we extrapolate and calculate it to be $0.8\mu A$.
5. By looking at the change in voltage and current, we calculate the Normal state Resistance which is 22.2 ohms.

UNCERTAINTY : We assume internal errors due to the scope electronics to be negligible and the only uncertainty is due to the observer's limitation in reading off the screen. This is assumed to be one tenth of a large division on the screen.



Figure 3: A complete SQUID set

$$I_C = 8 \pm 0.8 \mu\text{A}$$

$$R_N = \Delta V / \Delta I = 8 \times (5 \pm 0.5) / 18 \times (0.10 \pm 0.01) = (22.20 \pm 0.5) \text{ m}\Omega$$

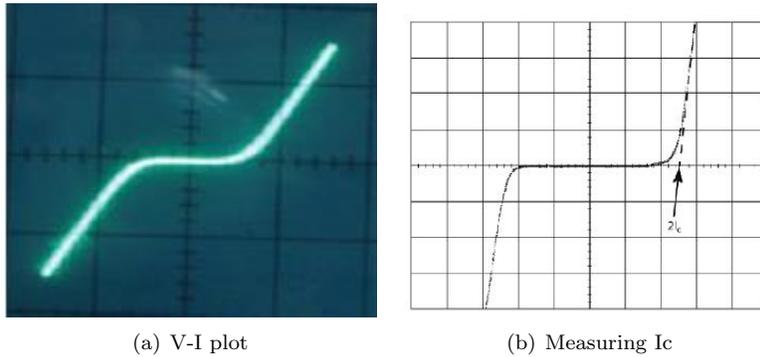


Figure 4: V-I characteristic of SQUID with CH1 at 0.1 V/div and CH 2 at 0.5 V/div

4.2 Flux quantization

This experiment investigates the quantization of flux through SQUID ring. We will observe one of the most remarkable properties of the DC SQUID: the development of a periodic voltage across it in response to an applied magnetic flux, when biased slightly above the critical current.

1. We again dip it into liquid nitrogen.
2. Bias output is adjusted to get the dot to the knee of the V-I curve.
3. Then we go into the V- mode, the flux offset and sweep output is increased to observe the periodic V-behavior as shown in figure 5.
4. The peak to peak voltage is measured, it is the modulation voltage for the squid.

$$\Delta V = 4.2 \times (50 \pm 5) \text{ mV} / 10,000 = (2.1 \pm 0.2) \times 10^{-5} \text{ mV}$$

4.3 Resistance vs. Temperature of the YBCO SQUID

This experiment helps us track the normally resistive to superconductive transition of the YBCO film in the SQUID.

1. First we construct a constant current source as shown in figure 5.
2. We now calibrate the temperature response of a silicone diode since the voltage drop across the diode increases linearly with decreasing temperature.
3. We take three sets of values for temperatures and measure the voltage drops for calibration.
4. We plot a calibration graph as shown in figure 6.
5. Now we remove the magnetic shield of the probe and bound the silicon diode with copper wires.

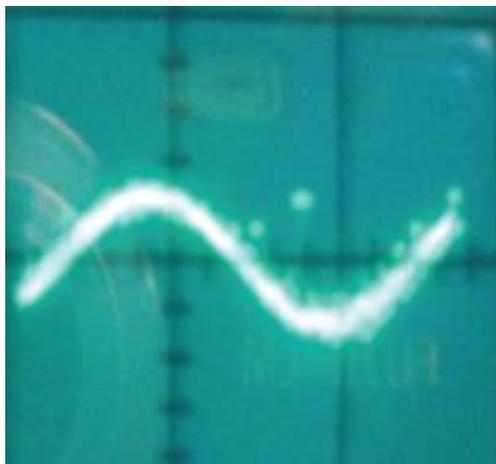


Figure 5: V-Phi curve for SQUID with CH 1 at 0.2 V/div and CH 2 at 20mV/div

Temp/K	Voltage/V
77	0.98
273	0.44
303	0.36

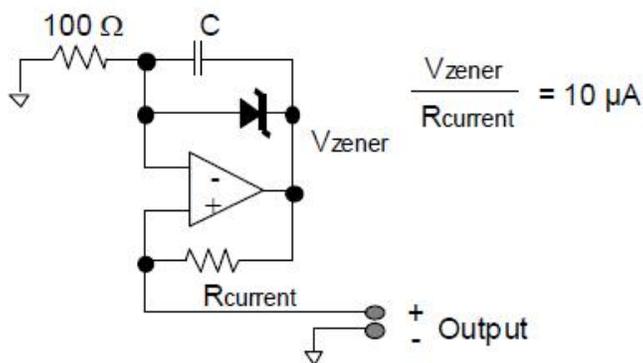


Figure 6: Constant Current Source

6. The probe is gradually lowered into the dewar using clips and the resistance is calculated by measuring the slope of the V-I curve on the CRO.
7. The table below shows the voltage and resistance readings, the temperature readings are calculated from the calibration curve above.
8. We can see from the graph that the transition occurs around 90K.

4.4 4.4 Analog Flux Locked Loop

Mr. SQUID can be used as a sensitive magnetometer when employed in the so called flux-locked loop FLL configuration. In the resistive mode we could measure up to one flux quantum but we can also measure flux

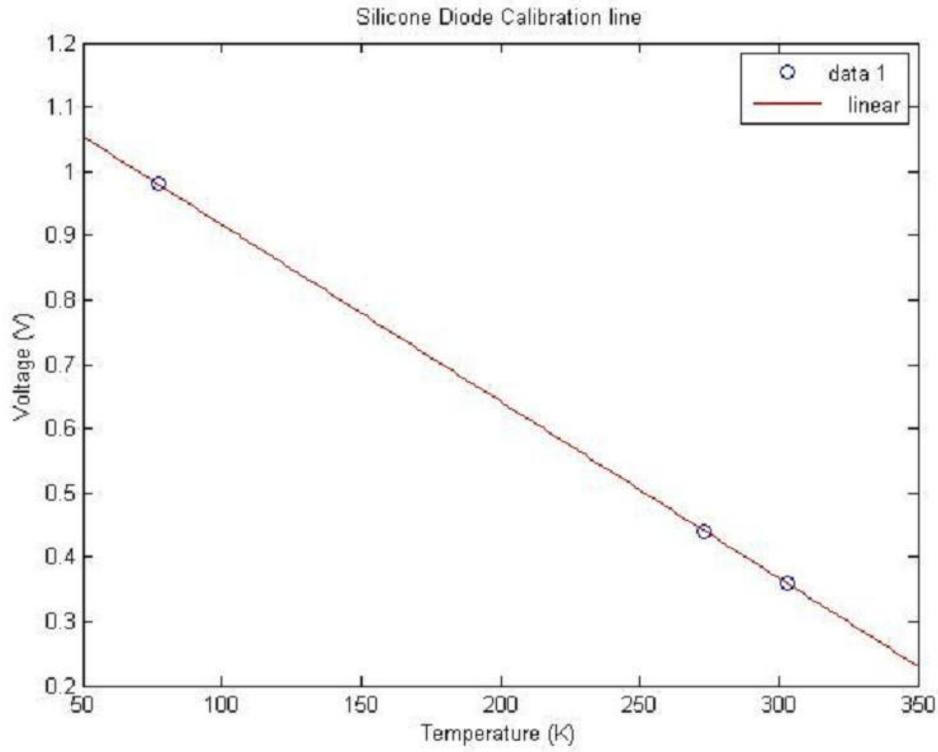


Figure 7: Calibration curve

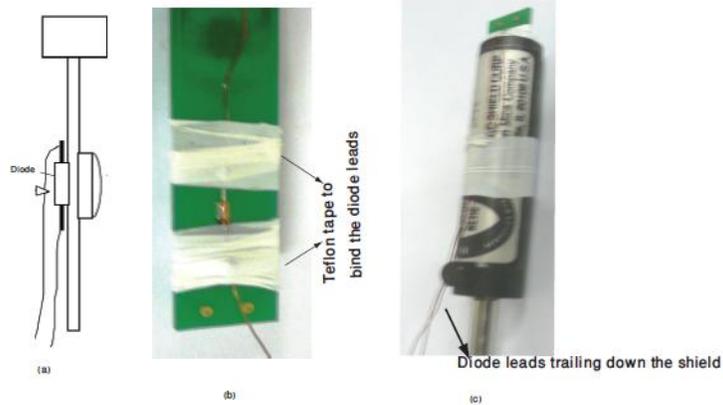


Figure 8: Attaching silicon diode to the probe

much smaller than the flux quantum.

1. We first design the circuit of the flux lock loop as shown in the figure.
2. We open up the SQUID and move the mode switch to Direct mode instead of the Buffer mode.
3. The first part of the circuit acts as an adder and the voltage across the potentiometer (ranging from -9V to 9V) is added to the signal.

S No.	Voltage/V	Temperature/K	Resistance/ Ohm
1	0.500	259.3	200.0
2	0.540	244.4	182.4
3	0.592	225.2	155.6
4	0.667	197.4	138.5
5	0.729	174.4	128.6
6	0.931	99.6	114.9
7	0.977	82.6	84.4
8	0.982	80.7	0

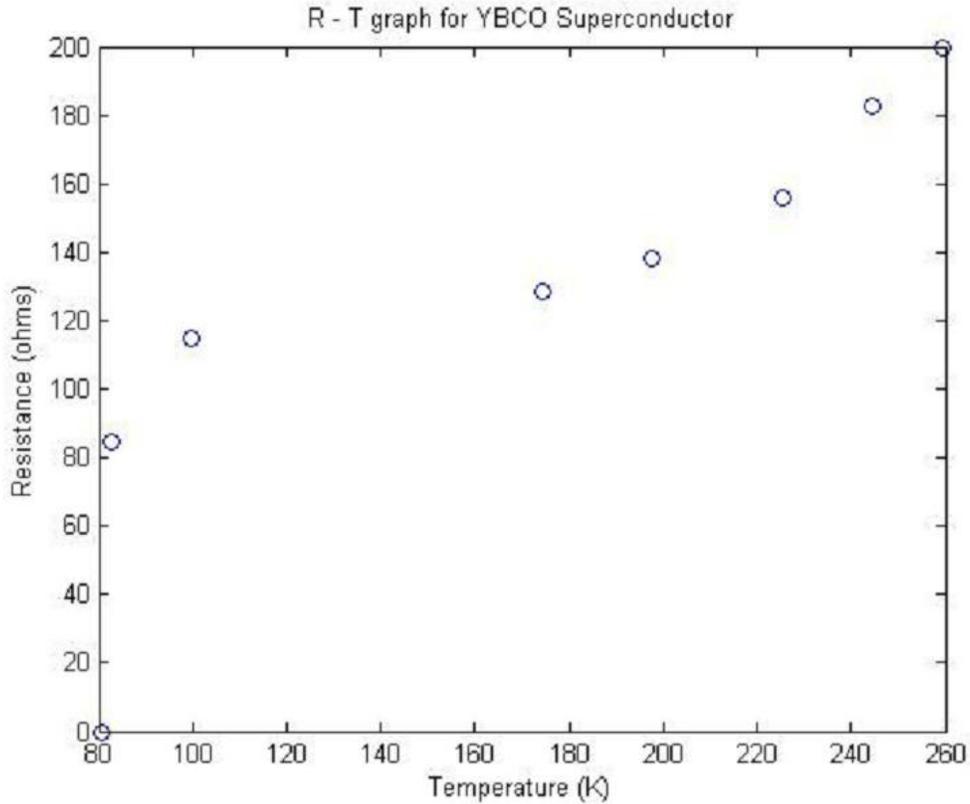


Figure 9: Graph for the superconducting phase Transition

4. This inverts the signal and also amplifies it, it goes into the electronic box of the SQUID as shown in the figure and cancels out the voltage which is producing the flux..
5. The result is shown in the figure, the curve is slightly sloped due to noise and interference.

4.5 Using the FLL as a sensitive DC/AC voltmeter

When the DC SQUID is current biased, it performs like a flux-to-voltage convertor. In order to build a voltmeter, the DC SQUID (while in the resistive mode) is connected to an electrical loop that transforms the voltage source into a magnetic flux. The schematic is shown in the figure.

Observation:

Voltage at TP1 = 7.5 Mv

Voltage at TP2 = -75 MV

Gain = -10

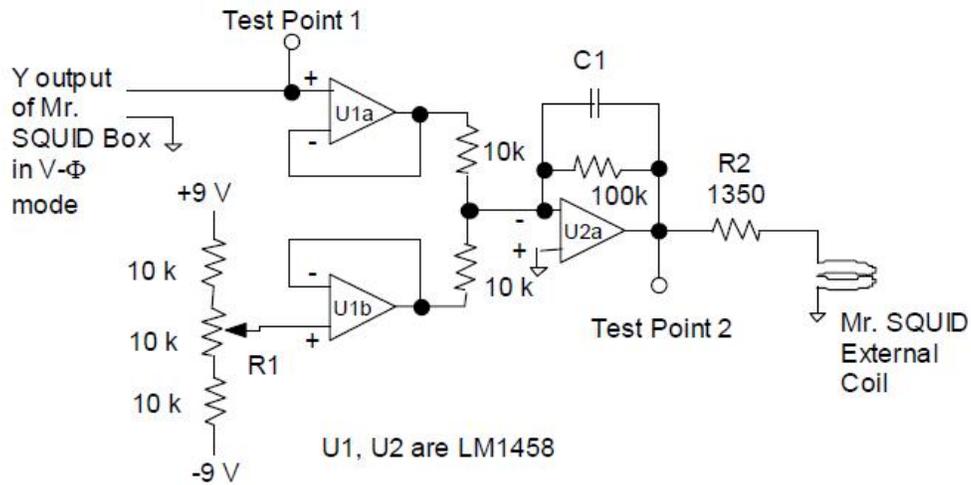


Figure 10: FLL Loop Circuit

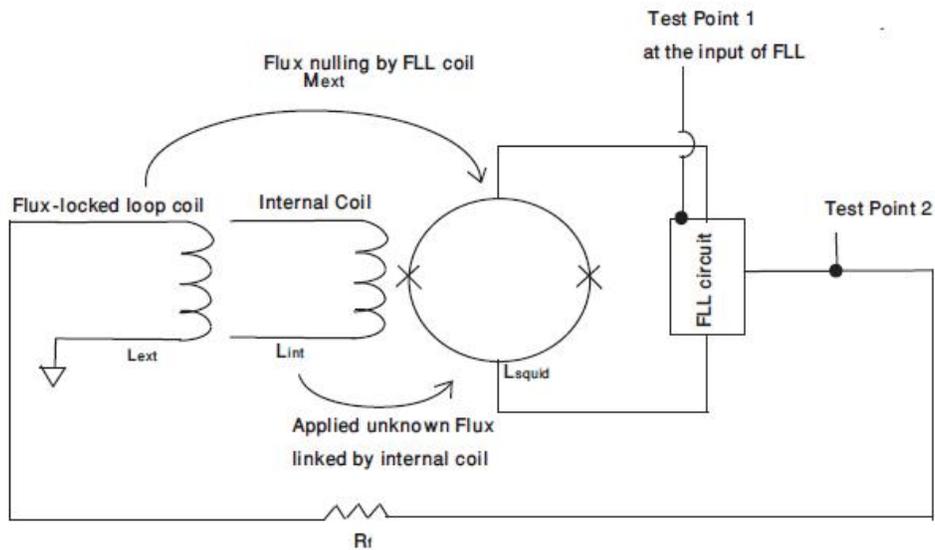


Figure 11: Flux lock loop circuit, a schematic representation

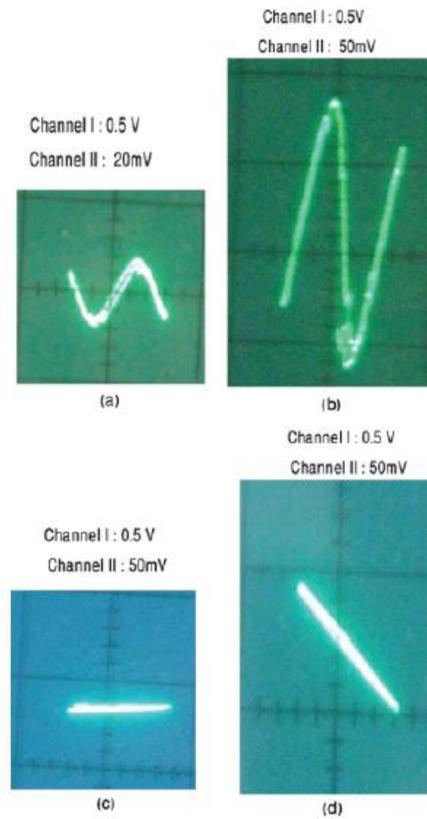


Figure 12: Scope photos of TP1 and TP2

1. First we make a voltage source for generating very small voltages.
2. We attach this to the FLL circuit we used in the previous experiment.
3. The voltage source is connected to the external coil of the SQUID probe. A small voltage is given as input, creating a magnetic flux in the SQUID. The FLL circuit tries to null out the unknown voltage and the current is measured to calculate the voltage.
4. Hence we can measure voltages down to the nano volt range very accurately.

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$$\begin{aligned}
 TP\ 2 &= (7.5 \pm 0.7)\ \text{mV} \\
 R_{set} &= 220\text{k}\Omega \\
 V_b &= (7.5 \pm 0.7)/2400 \\
 V_b &= 3.13 \pm 0.003) \times 10^{-6}
 \end{aligned}$$

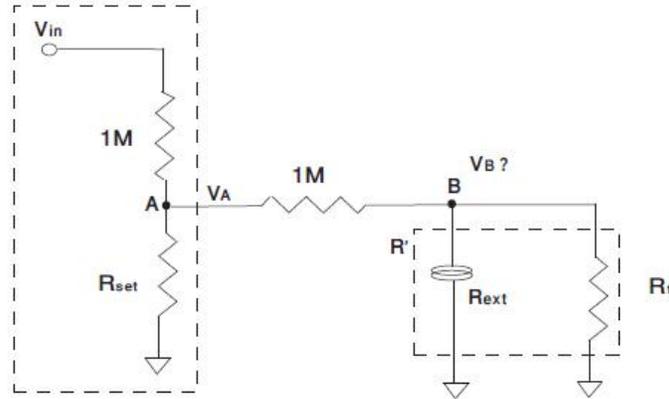


Figure 13: Voltage Source

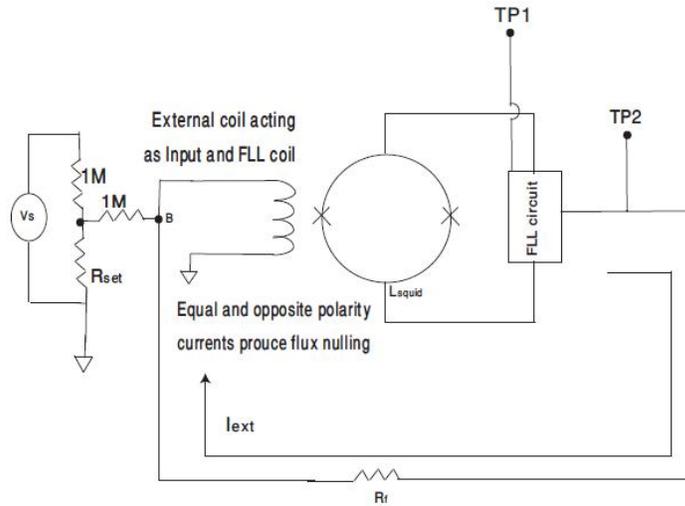


Figure 14: Flux nulling for single coil voltmeter

4.6 Conclusion

SQUID cleverly makes use of the properties of superconductors and Quantization of flux to demonstrate interesting quantum phenomenon. Using the SQUID we have seen the superconductivity of a YBCO film and have also found out the phase transition temperature. By the DC Josephson affect we have observed quantum tunneling at a macroscopic level. We used the SQUID to detect very small small quantities of magnetic flux, infact by using the Flux Lock Loop circuit we were able to detect magnetic flux well below the value of the quantised flux, hence showing how SQUIDS can be used as very sensitive magnetometers. We also demonstrated how a SQUID can be used as a very sensitive voltmeter using the flux nulling technique, we were able to measure voltages down to nano volts. It was a very interesting series of experiments that demonstrated macroscopic quantum phenomenon.