Experimental Analysis of Superconductivity and Quantum Interference

Emaan Sohail, Muhammad Shiraz Ahmad and Muhammad Sabieh Anwar*
Syed Babar Ali School of Science and Engineering, LUMS

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Josephson effect is the flow of current without a potential drop across an insulator, with the ability to expel magnetic flux from its region. Superconducting QUantum Interference Devices (SQUIDs) are based on this effect to take sensitive measurements at quantum level. In this experiment, we study the variation of current, voltage and magnetic flux using a High–Temperature SQUID (HTS) in different configurations. We aim to observe the DC and AC Josephson and Meissner effects, study the temperature–resistance relation of the SQUID, and use the SQUID as a flux detector via flux locked loop circuits.

KEYWORDS:

Superconductivity · Josephson Effect · Flux Quantization · Critical Current · Flux Locked Loop · Meissner effect ·

Contents

1 Theoretical Introduction

This section provides theoretical details for the underlying phenomena on the basis of which the experiments are performed.

1.1 Superconductivity

Superconductivity is the phenomena when electrical resistance of a conductor is zero, and the conductor is capable of eliminating magnetic flux from its region.

1.1.1 Cooper Pairs and Tunneling

Certain materials exhibit the property of conducting electricity in resistance–less environments when cooled down below certain temperature ranges. This effect comes about as the result of pairing up of electrons in the material, which possess opposite spins and directions of motion, but the same speed. The movement of both electrons create a disturbance in the positive lattice of the material. The displacement caused by either electron becomes a cause of attraction for the other. This results in coupling between them into a pair. This development of attraction can also be depicted as the exchange of a *"phonon"* [1] between the pair (see Figure 1). Cooper pairs are named after the phenomenon's discoverer, Leonard Cooper[2]. Since the electrons in a pair show a coherence in their state, they share a common wave–function.

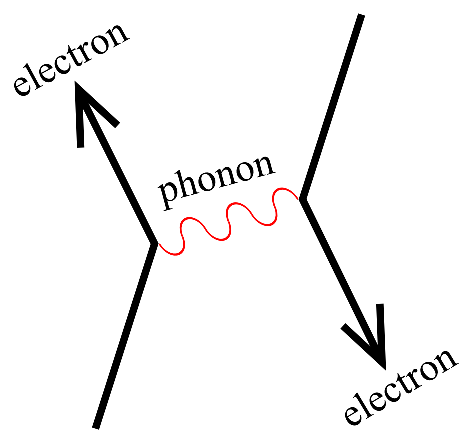


Figure 1: Feynman Diagram for Electron Coupling

The aspect which makes these Cooper pairs even more peculiar, is their ability to tunnel through high potential energy barriers, keeping the current flow alive, unlike the electrical conductivity at non–cryogenic temperatures[3].

[1] Quantum of vibrational mechanical energy[1].

1.1.2 Flux Quantization

In quantum mechanics, a *fluxon* or ϕ_o is the quantum unit for magnetic flux. One fluxon has the value of approximately 2.07×10^{-15} Wb. Magnetic flux can exist in the `SQUID` as multiples of magnetic flux quantum, as long as it is in a superconducting state. The reaction of the superconducting phase to applied magnetic field (described in Section 1.2.1), manages to cause the expulsion of the extra magnetic flux (Meissner Effect).

1.1.3 Josephson Junctions

Josephson Junctions can be categorized into four types (see Figure 2). Namely, tunnel junction, separated by an insulting layer, proximity junction, separated by a normal metal, micro–bridge, with a constriction between two phases, and point contact junctions[10].

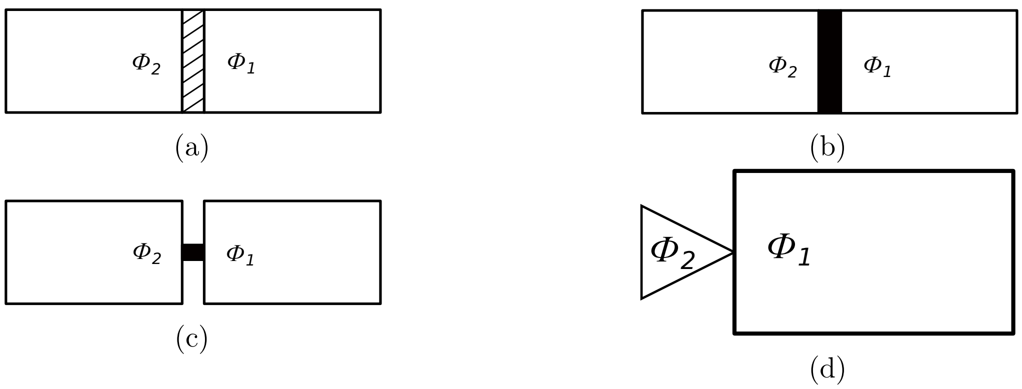


Figure 2: Types of Josephson Junctions showing (a) Insulating barrier of grain boundary or metallic compound, (b) Metal barrier, (c) Micro–junction, (d) Point Contact Junction. ϕ_1 and ϕ_2 are the wave–functions describing the different phases of the two superconductors, which do not differ in superconductive state.

However, the junction under discussion in the light of the `SQUID` is the insulating tunnel junction. This insulation can be a grain boundary [2]. The gap between the two superconductors in the junction ranges from a distance of 10 Å to 50 Å. This configuration ensures lower energy ground state, which results in superconductivity. ϕ_1 and ϕ_2 in Figure 2a represent the respective phases on either side of the barrier. Below the critical temperature T_C, the temperature at which electrons enter a superconducting state, the resistance becomes zero and electrons flow with infinite conductivity. The maximum current which is allowed to flow without any resistance is known as the critical current I_C. Above the critical current, the junction becomes resistive.

The magnitude of the current through the tunnel depends on the phase difference between the junctions,

$$I = I_C \sin \Delta\phi, \quad (1)$$

[2]Grain boundary is a boundary between crystalline groups which inhibit electrical conductivity [12]

where I is the current through the junction, and $\Delta\phi$ is the difference between the two phases on either side of the junction. Since the two phases are coupled in the superconducting state, the difference in their time–dependent phases becomes zero,

$$\frac{d}{dt}\Delta\phi = 0,$$

making the current through the junction constant,

$$I = I_C.$$

This is known as the DC Josephson effect.

Looking through Josephson's second equation,

$$\frac{d}{dt}\Delta\phi = \frac{2e}{\hbar}V, \tag{2}$$

substituting equation 2 in equation 1 by taking the integral of equation 2, we get,

$$I = I_C \ \sin\left[\phi(0) - \left(\frac{4\pi eVt}{h}\right)\right], \tag{3}$$

where $\phi(0)$ is the superconducting phase at time $t = 0$. This tells us that with a fixed value of V, the I through the Josephson junction oscillates with the frequency,

$$f = \frac{2eV}{h}. \tag{4}$$

This oscillation of current at a fixed biased voltage is known as the AC Josephson effect.

1.2 Operation of the SQUID

The `SQUID` is a device which takes the advantage of quantum mechanical effects to act as a detector. It operates with a framework of coils in its chip. Thus, it is important to look at the design of the Josephson junctions.

1.2.1 Framework of Josephson Junctions–The Meissner Effect

The `SQUID` comprises of a loop with usually two Josephson Junctions, parallel to one another. Either of the junctions is equipped with capacitors and resistors as shown in Figure 3. The shunt resistances across the junctions facilitate controlled flow of current. There are two coils located outside the loop, which are responsible for application of magnetic flux on the `SQUID` when current passes through them (see Figure 3). I_{bias} is the applied current to the circuit, which divides into half when passing through each side of the loop. If $I_{bias} < I_C$, then the voltage V and the magnetic flux produced by it remain zero.

Once the current is raised above I_C, potential drop takes place across the junction. The quantum state of the system prefers to remain unchanged. Thus, in opposition to the magnetic field produced by the development of potential drop, an induced current known as the *screening* *current* (I_S) is generated, which flows in a direction which favours the production of magnetic field needed to cancel out the initially generated flux (See Figure 3). This expulsion of the magnetic field is known as the Meissner effect.

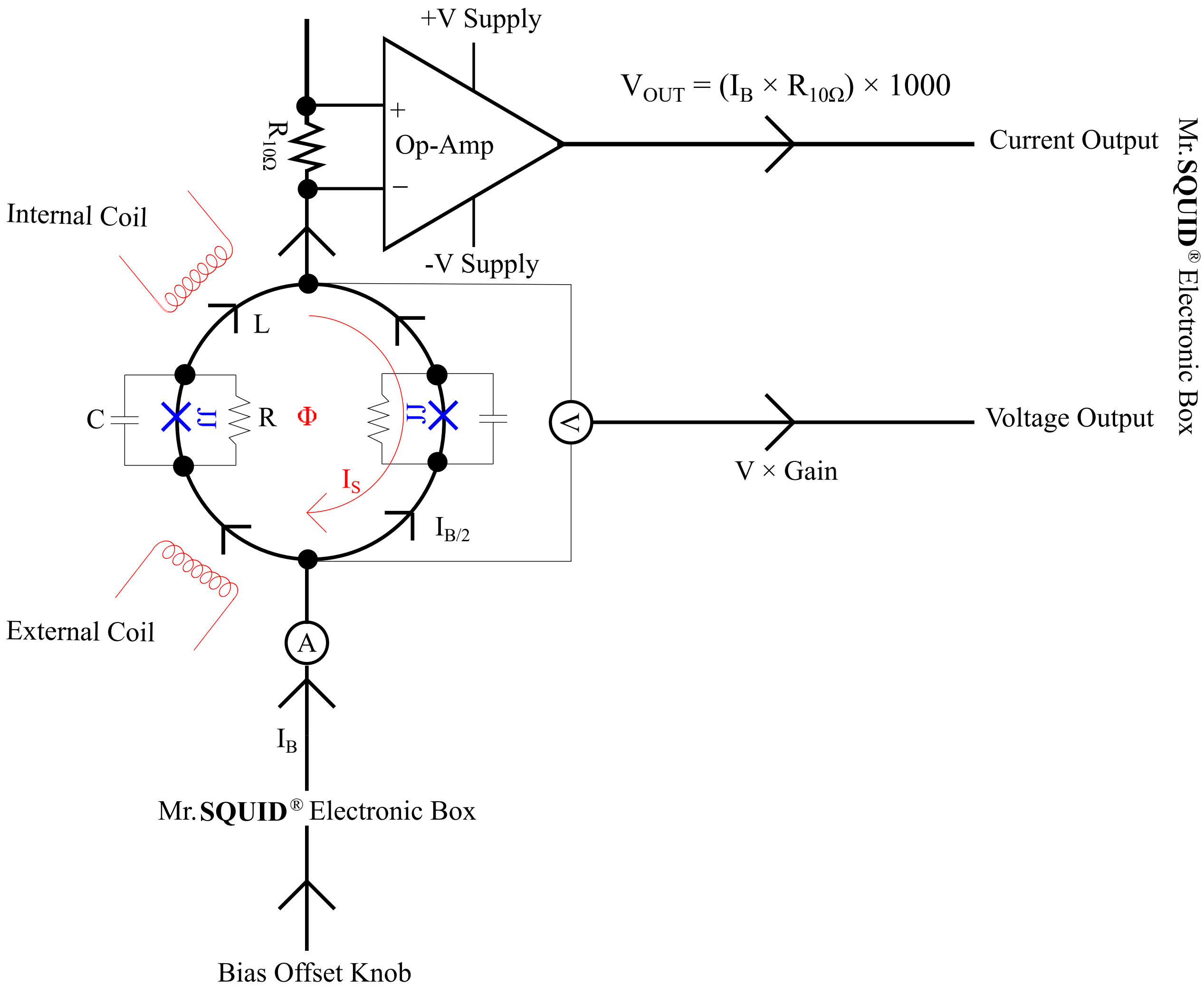
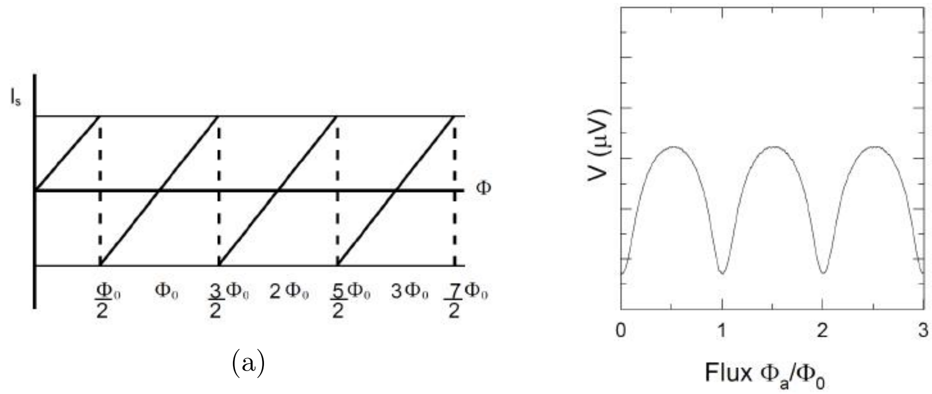


Figure 3: `SQUID` loop showing the two parallel Josephson Junctions (JJ), with capacitors (C), and resistors (R) across them. I_B is the biased current which divides into half ($I_{B/2}$) in either of the junctions. Internal and external modulation coils apply magnetic flux (ϕ), inducing the screening current (I_S). The self inductance of the loop (L) also contributes to the total flux (ϕ). An ammeter (A) in series and voltmeter (V) in parallel monitor the biased current and the voltage across a junction respectively. The output current is read as voltage across a resistor ($R_{10\Omega}$), which has been amplified by an operational amplifier (Op–Amp) by a factor of 1000.

Increasing the flux, increases the screening current in the loop, until half fluxon is reached. At this point, the screening current can not increase further, as it would increase the net current in the superconducting loop greater than the I_C, which would pull the system to a normal state. The energy state of the quantum system does not allow this, as expelling $\phi_o/2$ of flux is more energy consuming than keeping that flux in, and working to expel the extra flux following with the increase of magnetic field strength being applied. Consequently, the screening current begins to decrease until it becomes zero. In order to remove the successive flux, it increases again, but in the opposite direction (See Figure 4a.).

Throughout this operation, the current through the `SQUID` remains constant, while the voltage varies with the applied flux periodically.



(a)

(b)

Figure 4: Behaviour of the current and voltage in the presence of magnetic field can be observed through these graphs. (a) Shows the rise and fall of screening current through the loop and resultant quantization of flux. (b) Shows the variation of voltage with applied magnetic flux at a constant biased current.

1.2.2 Quantum Interference

The passage of Cooper pairs through the gap, is analogous to the passage of coherent light waves through the double slits of Young's optical interference experiment. The wave–functions of the two light beams interfere on the screen, with periodic regions of high intensity light, and low intensity light. Likewise, when the wave-function of two superconductors interferes with current flow, the maxima and minima of the screening current depicts the interference pattern.

2 Apparatus and Functioning of the SQUID

In our experiments, we are using Mr.SQUID® device to study applications of the Josephson effect. The `SQUID` probe is equipped with an integrated circuit on which the Josephson junctions are embedded. For the High Temperature SQUID (HTS), Yttrium barium copper oxide ($YBa_2Cu_3O_7$) film is used to make the `SQUID` chip.

2.1 Probe

The chip of HTS is located on a probe, available with a DB–9 M/M connection at one end.

Figure 5: Mr.SQUID® probe.

2.2 Functionality of Mr.SQUID® electronic box

The current and voltages through the `SQUID` can be controlled using a control box which has various functions.

(a)

(b)

Figure 6: (a) Electronic box front view showing control knobs. (b) Back view displaying the connection pots.

Bias Offset Knob: Supplies DC current through the `SQUID`. Rotating the knob in either direction would trace out the current value at respective setting.
Sweep Output Knob: Supplies current through the `SQUID` back and forth about the DC offset value, which automates the manual function performed by the bias offset knob. Tuning

this knob clockwise traces out the Voltage–Current graph in the V–I (see Figure 6a) mode. Whereas, in the V–ϕ mode, it applies oscillating magnetic field on the SQUID by passing current through the internal modulation coil.

Flux Bias Control Knob: In the V–I mode, this knob applies magnetic field across the SQUID, by passing current through the internal modulation coil. Since the field is static, turning the knob periodically in either directions would trace out a curve in the V–I mode. On the other hand, in the V–ϕ mode, it applies static magnetic field, which moves the V–ϕ curve right or left.

The following table summarizes the control knobs' functions in either mode:

Control/Output	***V-I Mode***	***V-Φ Mode***
Sweep Output	Sends current back and forth about a fixed DC value, through the SQUID loop. Sets the amplitude of the wave test signal.	Sends current through the internal modulation coil, producing oscillating magnetic field. Sets the amplitude of the wave test signal.
Bias Offset	Sets a DC value for the current in the SQUID loop.	Sets a DC value for the current in the SQUID loop.
Flux Offset	Sends DC current through the internal modulation coil, which generates flux applied to the SQUID loop.	Sets a DC value for the current in the internal modulation coil. This sets the static value for the applied magnetic flux.
Current Output on Mr. SQUID® electronic box	Total current through the SQUID loop.	Current through the internal modulation coil.
Voltage Output	Voltage across SQUID loop.	Voltage across SQUID loop.

Figure 7: Controls and outputs of Mr.SQUID® electronic box.

3 Experiments Performed using the SQUID

This section provides the details and outcomes of the experiments performed by availing the superconducting properties of the JJ junctions.

3.1 Calculating Resistance of the SQUID at room temperature

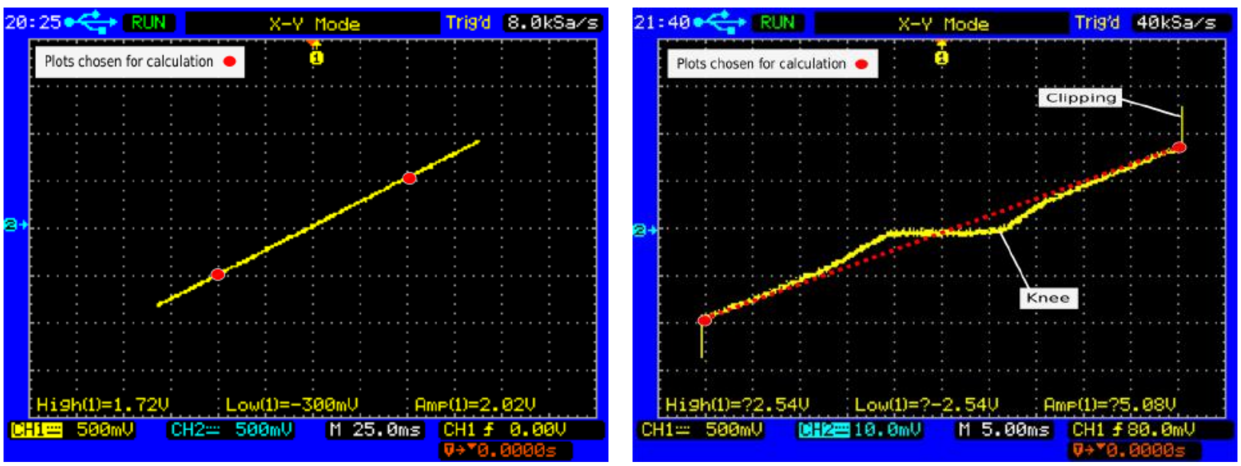
To conduct the experiment, SQUID probe is connected to the control box with a DB–9 M/M connector, to measure the resistance of the SQUID at room temperature (24 °C), from the slope of the V–I curve.

The oscilloscope settings are configured to produce a linear V–I curve, whose slope is determined to find the value of resistance. Refer to appendix (4) for the detailed procedure. The calculated resistance is 50 Ω (See Figure 8a).

3.2 Observing the DC Josephson Effect

In this section, we observe the superconducting state of Josephson Junctions by placing the SQUID probe in liquid nitrogen (−196 °C), in an insulated dewar. After the phase transition, the critical current of the SQUID and its normal state resistance is calculated.

The apparatus is set with the probe connected to the electronic box and placed in liquid nitrogen. The opening of the dewar is blocked with a stuffed foam cover to inhibit the rapid evaporation of liquid nitrogen. The gradient of the V–I graph falls rapidly until the resistance becomes zero during the cooling of the SQUID [3]. Once adjustments are made on the scope, with both channels DC coupled, a graph showing the superconducting state of the SQUID is obtained (See Figure 8b). The horizontal line represents the current in the SQUID which flows without voltage (vertical shift zero). Once the horizontal line picks up gradient, it indicates the transition to normal state as a potential drop develops in the SQUID. The critical current is shown at the "knee" (Figure 8b). This critical current is maximized, by tuning the flux offset knob. The curve may have a vertical offset, which is characterized by horizontal region



(a) (b)

Figure 8: Drop of resistance to zero with drop in temperature. (a) Shows the V–I trace at room temperature in contrast to (b)'s curve showing a region of resistance–less current at 77 K. Horizontal line is the current which passes without a potential difference. The point on the "knee" shown, is the critical current above which normal state begins. The $R_N/2$ can be calculated by the slope of dotted red line shown.

not crossing the origin. This offset can be removed by adjusting the amplifier offset pot on the amplifier board inside the Mr.SQUID® electronic box (Figure 9)[15]. Once the suggested adjustments are made, the horizontal part of the curve can be read along Channel 1, till before the knee from the origin (either right or left). This represents the $2I_C$, as the SQUID has two parallel junctions and I_C is across a single junction, in a certain direction. As a result, the calculated I_C is 30 μA.

The SQUID becomes resisitive as soon as the current is raised above I_C. This normal state resistance is calculated by determining the slope joining the maximum points on either side

[3] The level of liquid nitrogen in the dewar must be enough that the probe is completely covered. This makes sure that the temperature of the SQUID remains constant and it remains in the superconducting phase.

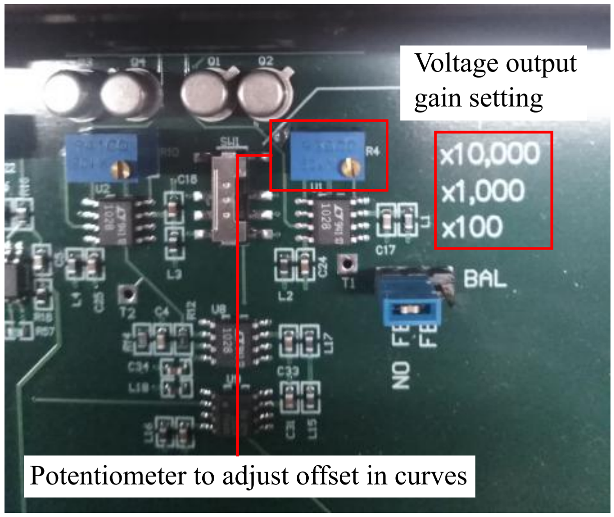


Figure 9: Offset adjustment can be made by changing the resistance of the potentiometer pointed in the figure. The gain factors in the box in the top right corner are the amplification factors for the voltage output (also see Figure 3).

of the curve as shown in Figure 8b. This is the resistance of one junction of the `SQUID`, and since the two junctions are parallel to one another, the resultant value for resistance will be twice the calculated slope. Taking in account the parameters, the calculated normal state resistance of the `SQUID` becomes $R_N \approx 1.44\ \Omega$, with voltage gain factor of 100.

Thus, it can be concluded, that the current which flows through the `SQUID` below the critical temperature can remain without a potential difference till a certain current value (i.e. I_C), above which resistance and voltage appear. This is responsible for the characteristic shape of V–I curve.

3.3 Observing the AC Josephson Effect

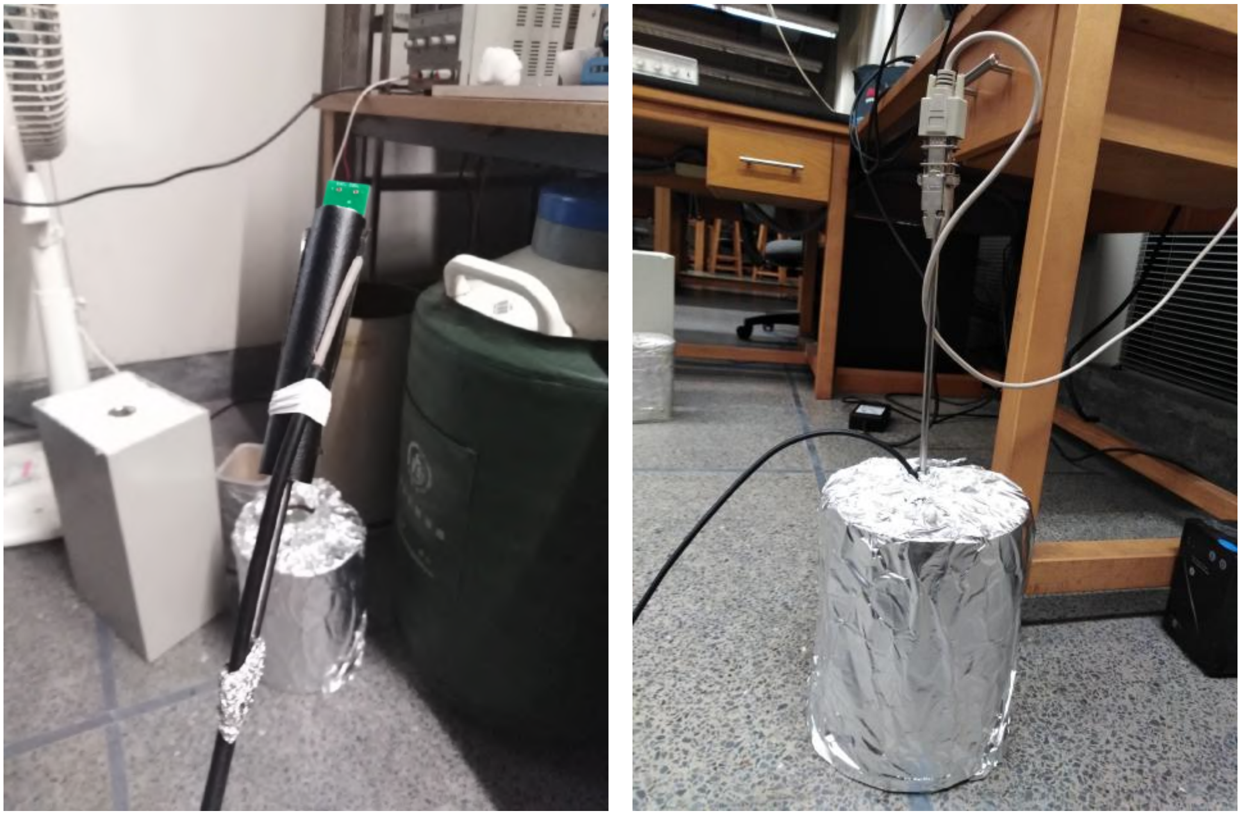
In experiment 3.2, we had observed the DC Josephson effect, in which the direct current crossed the insulating barrier, in the absence of magnetic flux and voltage. Here, we observe the effect of an applied AC voltage across the `SQUID` junctions, and the response of superconducting current to the constant voltage. A microwave source is used to cause the production of oscillating voltage.

The principle behind the AC Josephson effect was explained in section 1.1.3, where we saw that the current through `SQUID` oscillates according to the equation,

$$f = \frac{2eV}{h}.$$

This means that for applied voltage of 1 μV, the current oscillates at 4.84×10^8 Hz.

To observe this phenomenon, we first set a frequency generator of range 2-4 GHz, with reference frequency of 12.8 MHz, which could be analyzed on a spectrum analyzer. The decibel to power ratio is set to 10 dBm which makes the DC voltage as approximately 2 V. The microwave generator is turned off and an N–BNC female cable with wires open at one end is used as a wave transmitter. The central wire of the open end is used as an antenna by exposing 2-3 cm of its length, out of the coaxial cable.



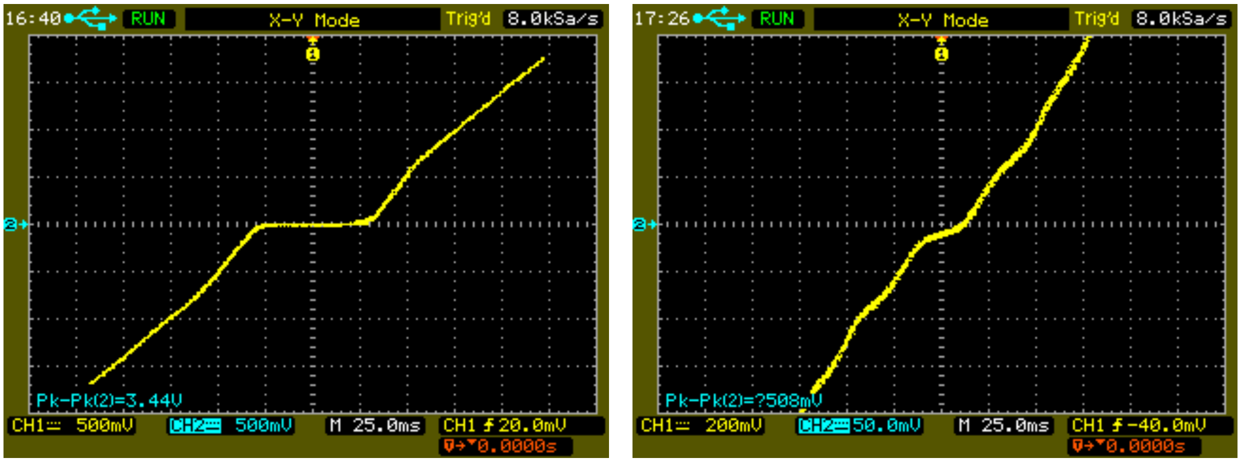
(a) (b)

Figure 10: (a)Probe and the antenna from the microwave generator tied together to apply DC voltage when in superconducting state. (b) A non–metallic dewar covered in aluminum foil is used for this experiment, to prevent the internal reflections of the high frequency waves inside its walls.

The `SQUID` is then cooled to superconducting state to get a V–I curve (Figure 11a). Then, a signal of the lowest frequency is sent through the antenna to the probe inside the dewar. The amplitude is gradually increased from the oscillator control box. Increasing the amplitude of the signal slowly decreases the critical current in the junction. This results in the ultimate diminishing of the the I_C, until a slope appears. Once this happens, the amplitude of the voltage source is decreased back, until $1/2$ to $1/3$ of the original I_C is returned. At this set amplitude, the frequency of the wave signal is increased by 100 MHz at each step, until curves or steps on the V–I curve start appearing. Figure 11 demonstrates the effect described.

The steps formed are known as the microwave induced Shapiro steps[4]. At each step the voltage remains constant but the current oscillates between two fixed values .

[4]Using a higher band voltage source can result in clearer and wider Shapiro steps.



(a) (b)

Figure 11: (a) V–I Curve with critical current region covering two big divisions. (b) Curve with Shapiro steps and suppressed critical current.

3.4 Observing the Voltage response across the SQUID in applied Magnetic Field

In this observation, we observe the periodic variation of voltage when the SQUID loop is biased with a fixed current ($I_B > I_C$) and flux is generated by the internal modulation coil. In this analysis, the V–ϕ mode is used(refer to table in Figure 7).

Firstly, the V–I graph is adjusted using the flux offset to get the critical current at its maximum, by tweaking the flux offset knob. This minuscule change in flux, generates screening currents in the SQUID loop, which add to the total current in the loop. Then, the position of the knee on the curve is noted and the sweep output knob is turned completely anticlockwise until a point appears on the origin of the scope's axes. Using the bias offset knob, the current through the SQUID is biased at a value slightly greater than the critical current (at the knee of the curve), setting a constant DC supply through the SQUID.

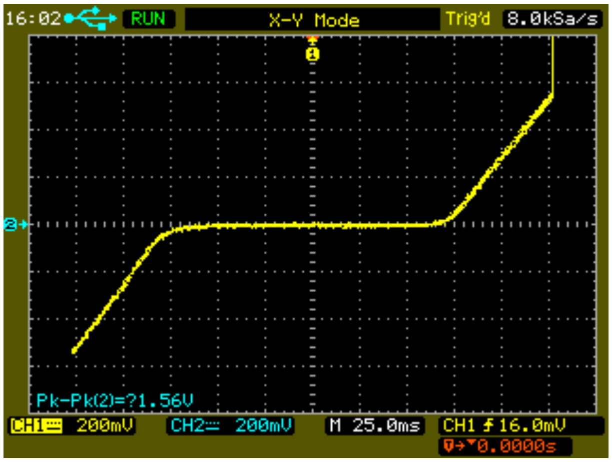
The flux offset is turned periodically clockwise and anti–clockwise. This knob passes current through the internal modulation coil which applies flux on the SQUID loop. Voltage is then induced in the loop which makes the point on the scope oscillate up and down. This oscillation traces out the periodic rise and fall of the voltage in the chip as the quantum system generates screening currents in reaction.

The manually modified flux in the latter step, can be observed by switching to the V–ϕ mode. In this mode, the horizontal axis represents the current linearly related to flux (ϕ_o), while the vertical axis yields the voltage. Channel 2 on the oscilloscope is AC coupled to observe the changing voltage levels[5]. Turning the sweep output clockwise, traces out a sinusoidal curve, due to the magnetic field applied through the internal modulation coil. This was also shown in Figure 4b.

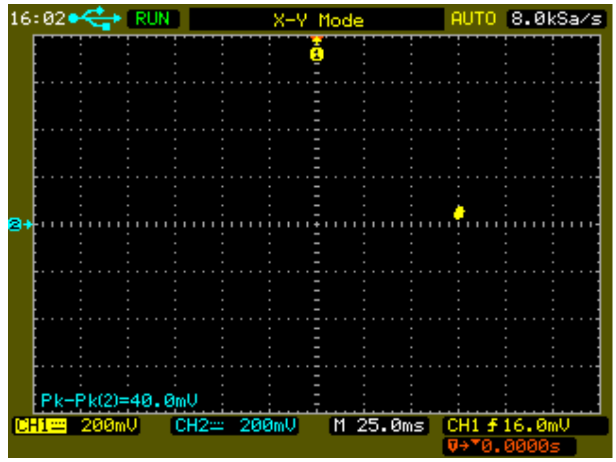
From our curve, we can now calculate the modulation depth, ΔV, which is the peak–peak

[5] Channel 1 must remain in DC coupling mode.

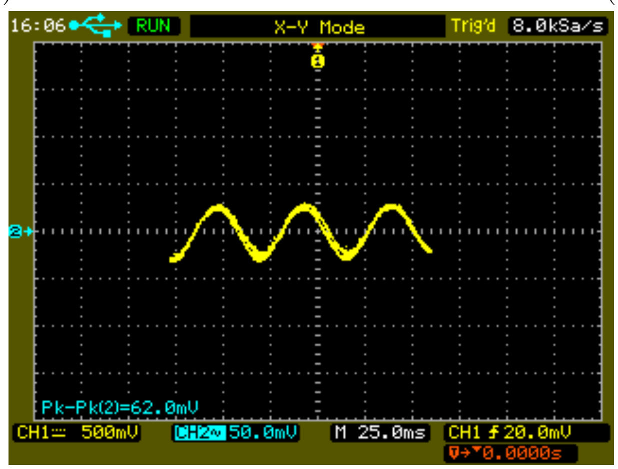
voltage of the graph, or twice the amplitude of the curve[6]. The ΔV for our graph is 6.2 μV, with voltage gain setting at $10,000$ (Figure 12c).



(a)



(b)



(c)

Figure 12: Steps followed to produce a V–ϕ curve. (a) Critical current adjusted to maximum with the flux offset knob. The sensitivity of the horizontal axis was increased improve the visibility. (b) Shows current biased slightly above the critical current, on the knee of the V–I curve, (c) V–ϕ curve with modulation depth of 6.2 μV.

3.5 Additional Parameters of the `SQUID` coils

We already calculated the values of I_C, R_N and ΔV of the `SQUID`. Now, we can use this data to calculate other meaningful parameters for our `SQUID`.

[6]In order to produce a clear V–ϕ curve, Channel 2's digital filter can be turned on (digital oscilloscope), or averaging could be done. See Figure 28b in section 4.

3.5.1 Modulation Depth

Modulation depth is the characteristic voltage of the `SQUID`. This voltage defines the maximum voltage which can be achieved by the `SQUID` when one quantum of magnetic flux is applied on it. It is calculated as following:

$$\begin{aligned} V &= I_C R_N \\ &= (30\ \mu A)(1.12\ \Omega) \\ &= 33.6\ \mu V \end{aligned}$$

3.5.2 McCumber Parameter

"McCumber" or modulation parameter (β_L, where L denotes the total inductance of `SQUID`) is the factor that determines the extent to which magnetic fields can be shielded by the currents in the `SQUID`. It also defines the flux to voltage transfer ratio of the `SQUID`. There are two ways of calculating the β_L:

$$\beta_L = \frac{4 I_C R_N}{\pi \Delta V} - 1 \tag{5}$$

$$= \frac{2 I_C L}{\phi_o} \tag{6}$$

Using equation 5, the calculated value obtained is $\beta_L \approx 4.35$, while the equation 6 gives the result of $\beta_L \approx 2.12$ ($\beta_L \approx 1$ being the desirable value). This stark difference is the consequence of the thermal effects which no longer keep the thermal energies minuscule enough to make them comparable with the energy of a fluxon (ϕ_o/L). In addition, these thermal interruptions occur due to the relatively high critical temperature of of the `SQUID` used ($T_C \approx -183.15$ °C).

3.5.3 Mutual Inductance

The mutual inductance (M) of the `SQUID`, is the value that describes the current to flux relation. Inductance is the induction of voltage in a current carrying material, due to the development of magnetic flux with the changing current. Thus, it is a requisite to have this factor calculated. The `SQUID` loop's inductance is 100 pH, and the internal modulation coil has 35 pH. With our taken measurements in experiments 3.4 and 3.2, the mutual inductance of the external modulation coil can be calculated. M_{int} can be expressed as:

$$M = \frac{\phi_o}{\Delta I}$$

Thus, the our mutual inductance attained becomes 37.6 pH.

3.6 Relation between Temperature and Resistance of the SQUID

We had seen in experiment 3.2 that the resistance of the SQUID falls with decreasing temperature drastically. In this experiment, we study the rate with which the resistance of the SQUID drops with decreasing temperature. To execute the goal of this experiment, 1N4001–MIC Germanium diode is used as a temperature sensor. For this, it is necessary to find the relation between the voltage of the diode and the temperature. We did not use the thermocouple directly to measure the variance of resistance of the SQUID , as the thermocouple's range and reaction to the temperatures we are concerned with, are unsuitable. Thus, voltage calibration with temperature is done.

To begin with, the diode is connected with a resistor in series using the copper wires. This circuit is completed using BNC–Crocodile cable to connect the current source to the diode's wires. A thermocouple's connections are made with a separate multi–meter, and the temperature measurement mode is switched to °C. The thermocouple is bound with the diode using Teflon tape. This close positioning makes sure that the thermocouple and the diode are at the same temperature. The reading of diode's voltage at room temperature (20 °C) is then taken [7].

A heat gun is used to raise the temperature of the diode to take the corresponding voltage values for the potential difference across the diode. The temperature is raised till approximately 200 °C. This heat and trial method is done in order to test the proper voltage response of the diode to changing temperature[8].

The diode attached with the thermocouple, is held above the opening of the dewar containing liquid nitrogen, and is very slowly lowered to take values for the voltage with decreasing temperature, until it is completely immersed in liquid nitrogen. The collected data is then used to plot a relation between the temperature and voltage of the diode (see appendix 4).

The diode is brought back to room temperature and fastened with Teflon tape behind the SQUID probe as shown in Figure 33 in appendix 4. Care must be taken that the tape is not made to cover the chip directly to prevent hindrance with its temperature response. The probe is covered with its mu–metal shield again and placed at the mouth of the opening of the dewar to lower it very slowly inside to make its temperature drop gradually; while taking the measurements of the resistances of the SQUID from the oscilloscope with changing temperature.

The voltages noted earlier for corresponding values of resistances of the SQUID, are used to find the equivalent temperatures from the graph shown in Figure 34. Consequently, the temperature values for the resistances can be acquired to study the variation (see graph 13).

[7]The temperature reading is confirmed using both the thermocouple and the temperature sensor of the lab.

[8]The readings are taken once both the temperature and the voltage values on the multi–meters become stable to decrease the extent of inaccuracy in the final results.

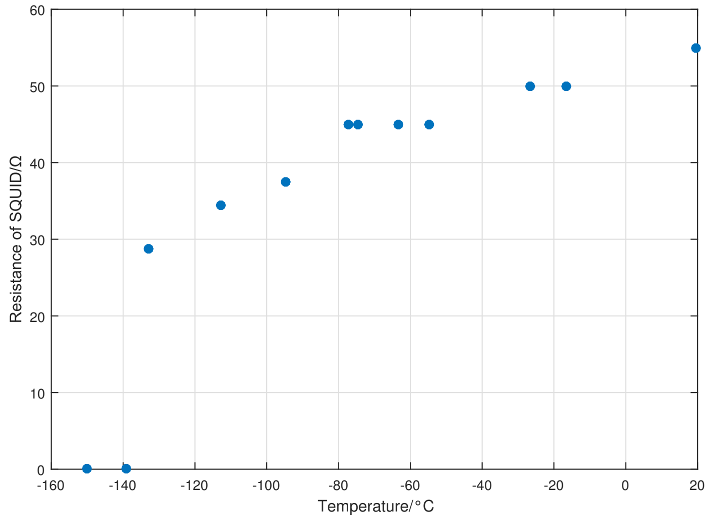


Figure 13: The graph shows that the resistance of the `SQUID` decreases at a slower rate initially until it reaches the T_C, at which it suddenly drops to zero (transition to superconducting state). The critical temperature is shown as -139 °C. This is due to the limit of the type of thermocouple used which did not register temperature below -139°C, its saturation point, during the calibration of the diode. The temperature inside the dewar's environment drops at such a rate that the diode is unable to respond to the swift shift.

3.7 Analog Flux Locked Loop Circuit as a Flux Detector

In experiment 3.4, we applied magnetic flux using the internal modulation coil and studied the voltage response of `SQUID` loop. Now, we will see how the net magnetic field can be controlled with the feedback external coil. An analog flux locked loop circuit is used to lock magnetic flux in the `SQUID` loop by canceling out the effect of any magnetic flux applied to the `SQUID` coil by the internal modulation coil. It operates by taking input from the voltage output of the Mr.SQUID® electronic box. This voltage is the result of applied magnetic flux on the `SQUID`. The circuit amplifies and inverts this voltage, and the corresponding output current is led to the external coil, which generates feedback flux to cancel the applied flux.

The `FLL` circuit being used amplifies the input voltage by a factor of -10 [9]. This means that the output of the Flux Locked Loop circuit would be ten times amplified but in opposite direction of the input signal. Figure 16a shows the `FLL` circuit's amplitude gain test in which a function generator is used to give input to the circuit, which is to be amplified and inverted. The peak–peak voltage of the input signal is seen as 1 V, whereas the amplified signal is 10 V.

To cater the amplification, the `FLL` circuit is given voltage by two 9 V transistor batteries. Test point one (TP1) on the circuit is the point at which the original voltage output from the electronic box can be observed on the oscilloscope. Whereas, test point two (TP2) displays the output of the `FLL` circuit. The amplifiers shown in Figure 14 carry out the process of amplifying the voltage to the desired value.

[9] Any other amplification factor could also be used depending on need.

This output voltage from the FLL is then fed into the external modulation coil. The corresponding current that passes produces magnetic flux which cancels the flux of internal modulation coil. Any further increase in applied flux is countered by the FLL to hold the SQUID in a flux "locked" condition.

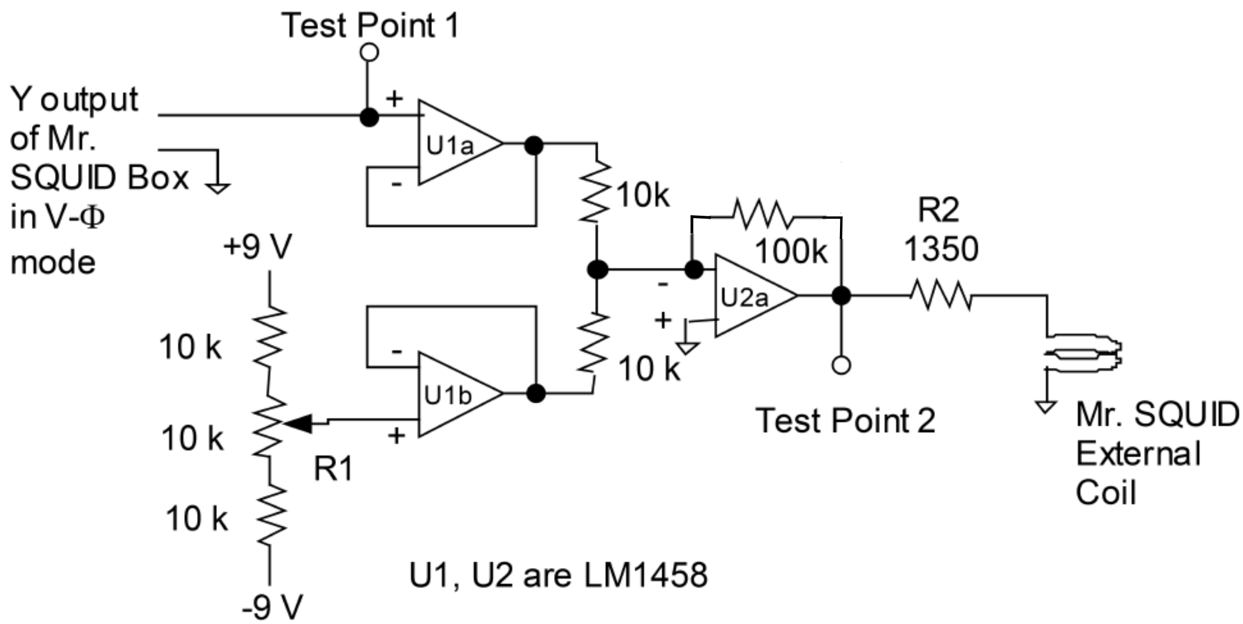


Figure 14: Circuit diagram for analog FLL showing a buffer amplifier, U1a, which isolates the input voltage from the electronic box. U1b isolates the +9 V and −9 V voltage supply. U2a is the gain amplifier which amplifies the voltage output of U1 by a factor of −10. R1 is a potentiometer and R2 a resistor of 1350 Ω resistance. Test points 1 and 2 can be tested to show input and output voltages of the circuit respectively.[13]

To begin with the experiment, the (FLL) circuit, is prepared on a soldered breadboard, whose schematic diagram is shown in Figure 14. Two copper wires are connected to the external coil's terminals on the probe, to take the coil's resistance in liquid nitrogen once the experiment has begun (Figure 15a). The measured value is 48.4 Ω.

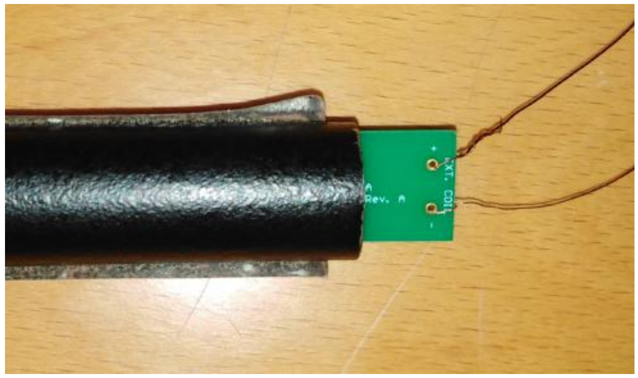
The SQUID probe is cooled after connecting it to the DB-9 connection at the back of the electronic box, with flux offset and bias offset knobs in the 12' o clock positions, while the sweep output completely counter clockwise. Nearby electronic devices are turned off to prevent RF interference. It is preferable to conduct this experiment in an isolated area where electromagnetic waves do not interfere with the signals detected by the SQUID[10].

Since external coil is being used, a switch inside the Mr.SQUID® electronic box in "BUF" (buffered) position is turned to "DIR" (direct) position, to allow the direct connection between the external coil and a 100 mA fuse at position "F1". This is necessary as the current flowing to the external coil is directly controlled by the user, and can reach critical values which may cause the coil to melt (see Figure 15b).

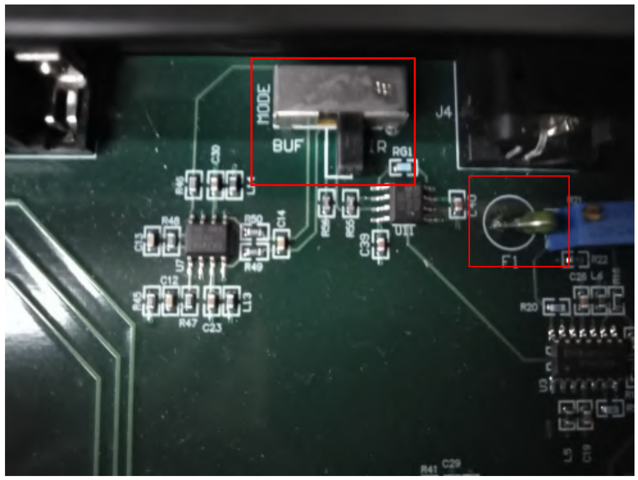
A V–ϕ curve is obtained as described in Section 3.4[11]. The current is biased at $I_B = 32\ \mu$A,

[10]Refer to section 4 for details about receiving clean and clear signals.

[11]Gain factor of voltage output of Mr.SQUID® should be set at the default of ×10,000 to produce clear



(a)



(b)

Figure 15: Prerequisites for the analog flux locked loop experiment. (a)Copper wires connected to terminals of the external coil, to take its resistance at 77 K. (b) Switch inside the electronic box switched to DIR position which creates a direct connection to the external coil through a 10 mA fuse. The BUF position creates a connection through a buffer amplifier with output ratio of 100 μA/V.

when the $I_C = 25\ \mu$A. The flux threading the loop by this current in the loop will be:

$$\begin{aligned} \phi_{SQ} &= M_{SQ} \times I_B, \\ &= 73\ pH \times 32\ \mu A, \\ &\approx 2.34 \times 10^{-15}\ Wb. \end{aligned}$$

The graph is adjusted by centering the curve symmetrically about the origin, in a single waveform, using the flux offset knob (setting the DC level of the flux) and the sweep output knob (setting the oscillating level of the flux) (16b). The horizontal axis in Figure 16b is used to calculate the current flowing through the internal modulation coil as $I_{int} = 45\ \mu$A. Since the curve represents only one sine wave (one fluxon Φ_0), the cancellation needs 45 μA/Φ_0. With the mutual inductance of the internal modulation coil of 37.6 pH as calculated in 3.5,

V–ϕ curves.

the magnetic flux applied by the internal coil is[12]:

$$\begin{aligned}\phi_{int} &= M_{int} \times I_{int}, \\ &= 37.6\ pH \times 45\ \mu A, \\ &\approx 1.69 \times 10^{-15}\ Wb.\end{aligned}$$

The voltage output of the electronic box is connected to the input of the `FLL` circuit. Testing probe is then used to observe the voltage changes on the oscilloscope, from test points 1 and 2. Since the output on TP1 is simply the `SQUID` voltage output, it remains same as before. TP2 signal is received as shown in Figure 16c. This amplified curve may also have a DC offset (can be observed by switching the Channel 2 to DC mode), which can be removed by adjusting the resistance of the potentiometer in the `FLL` circuit (see Figure 14). Once the offset is removed, the amplitude of the curve on either side of the vertical axis becomes equal.

So far, the external coil has remained disconnected from the `FLL` circuit. The voltage supply to the `FLL` is disconnected and the external coil's connection is made with the output of the `FLL` circuit using BNC–Crocodile cables. Test Point 1 at this point gives the regular V–ϕ curve as observed earlier (Figure 16b). This assures that the `SQUID` is still in a superconducting state with no flux trapping upon connection with the external coil.

In order to cancel the applied flux, the voltage source is reconnected to send current to the external coil. Consequently, the output from Test Point 1 (showing voltage output of the `SQUID`) would ideally show a horizontal straight line, as the voltage drop in the `SQUID` falls to zero (refer to Figure 16d). This line may however, not exactly be horizontal, owing to the incomplete cancellation of flux. When a fraction of the applied flux is left uncancelled, some voltage is still induced across the `SQUID` junctions due to the remnant flux. This would appear as a straight line with little slope (showing the rise in the vertical axis–voltage). TP2 signal shows the voltage given to the external coil (Figure 16e).

The current going to the external coil at the output of the `FLL` circuit is measured as $I_{ext} = 104\ \mu$A, which along with the coil's mutual inductance of 35 pH, gives the feedback flux as,

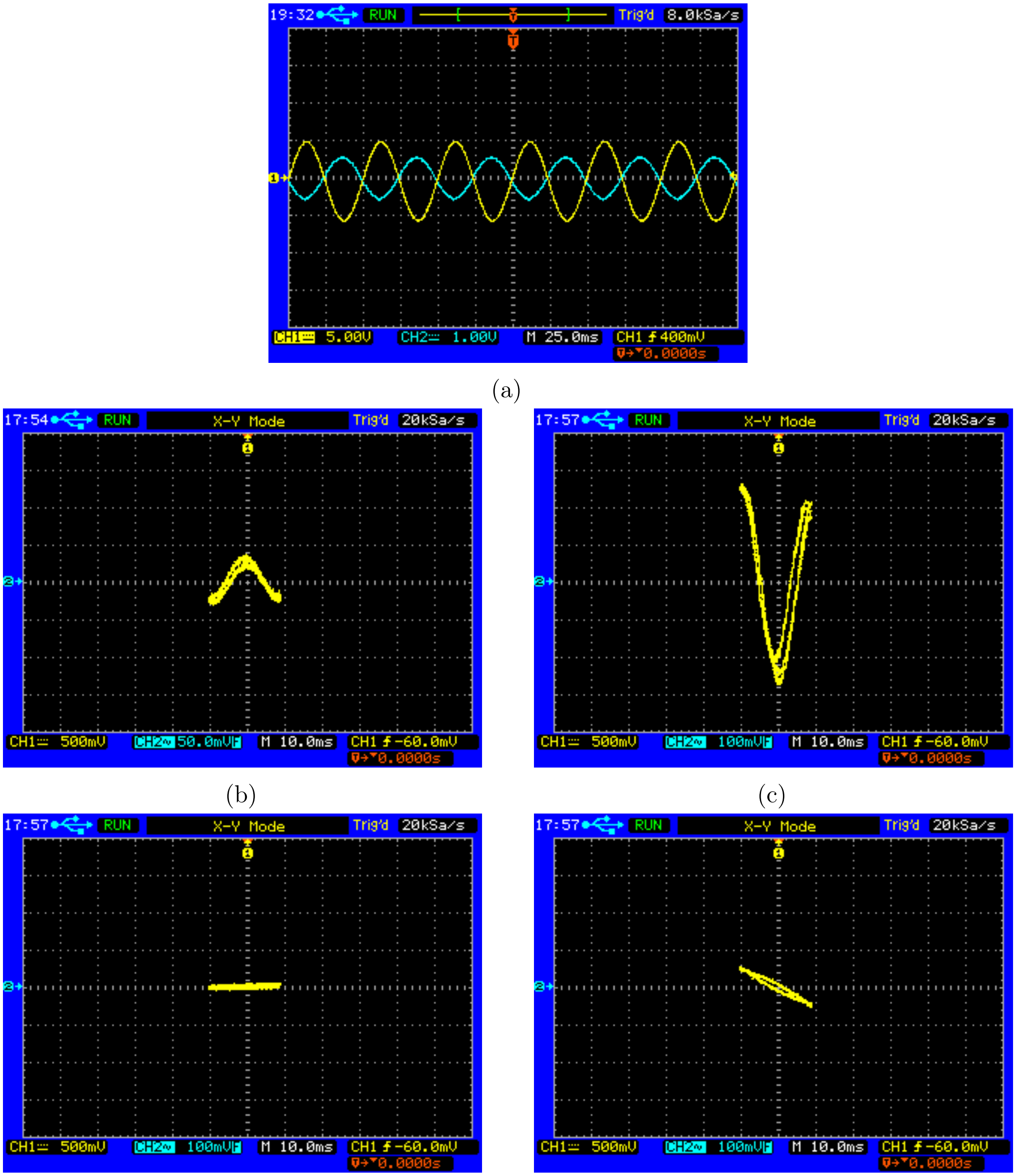
$$\begin{aligned}\phi_{ext} &= M_{ext} \times I_{ext}, \\ &= 35\ pH \times 104\ \mu A, \\ &\approx 3.64 \times 10^{-15}\ Wb.\end{aligned}$$

The net flux held constant in the `SQUID` is,

$$\begin{aligned}\phi_{net} &= \phi_{SQ} + \phi_{int} - \phi_{ext}, \\ &= \phi_{total} - \phi_{ext}, \\ &= 2.336 \times 10^{-15}\ Wb + 1.692 \times 10^{-15}\ Wb - 3.64 \times 10^{-15}\ Wb, \\ &= 4.028 \times 10^{-15}\ Wb - 3.64 \times 10^{-15}\ Wb, \\ &\approx 0.38 \times 10^{-15}\ Wb.\end{aligned}$$

[12]The applied flux is not exactly equal to the value of a fluxon, as not all of the flux remains within the loop and may be lost to the surrounding region.

By studying the graphs in Figure 16, it can be concluded that the application of the feedback flux results in the linearization of the relation of voltage and magnetic flux. Increasing the applied flux any more would result in the increase in the potential difference across the SQUID loop.



(a)

(b)

(c)

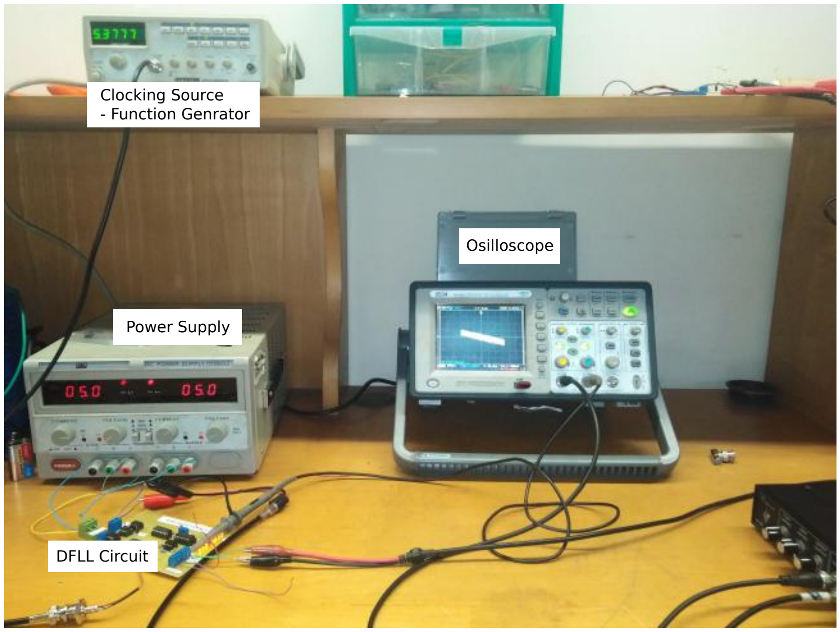
(d)

(e)

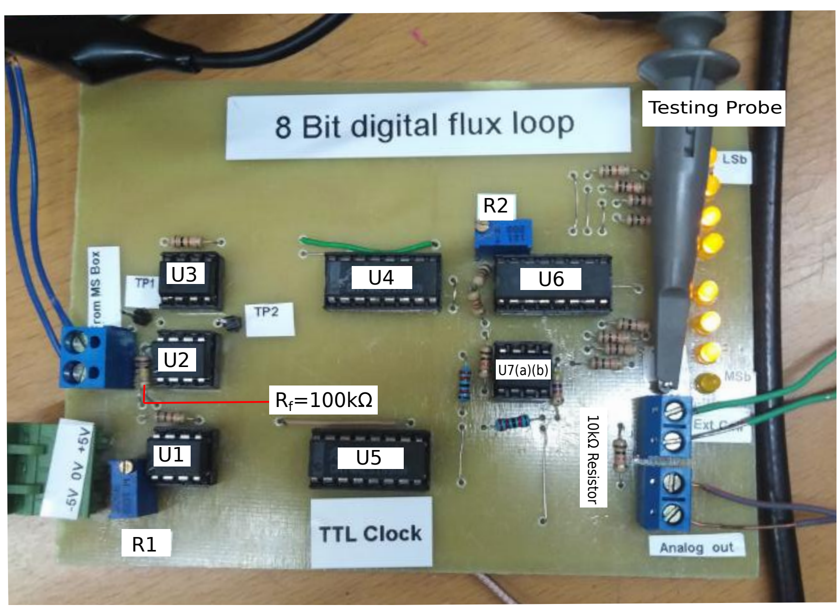
Figure 16: (a) Amplitude test with input signal from SQUID (blue–channel 2) and function generator's signal (yellow–channel 1). The peak to peak voltage of the input signal is seen as 1 V, whereas the amplified signal is 10 V.

3.8 Digital Flux Locked Loop

In this experiment we will perform the same task of flux cancellation using a FLL, as done in Section 3.7, but by using digital signals. This time, we will cancel the internal coil's flux by feeding the external coil with current through a circuit operated by binary operators using counters, amplifiers and comparators.



(a)



(b)

Figure 17: Digital Flux Locked Loop Experiment:(a) Experimental Setup(b) Circuit for 8–bit DFLL Circuit

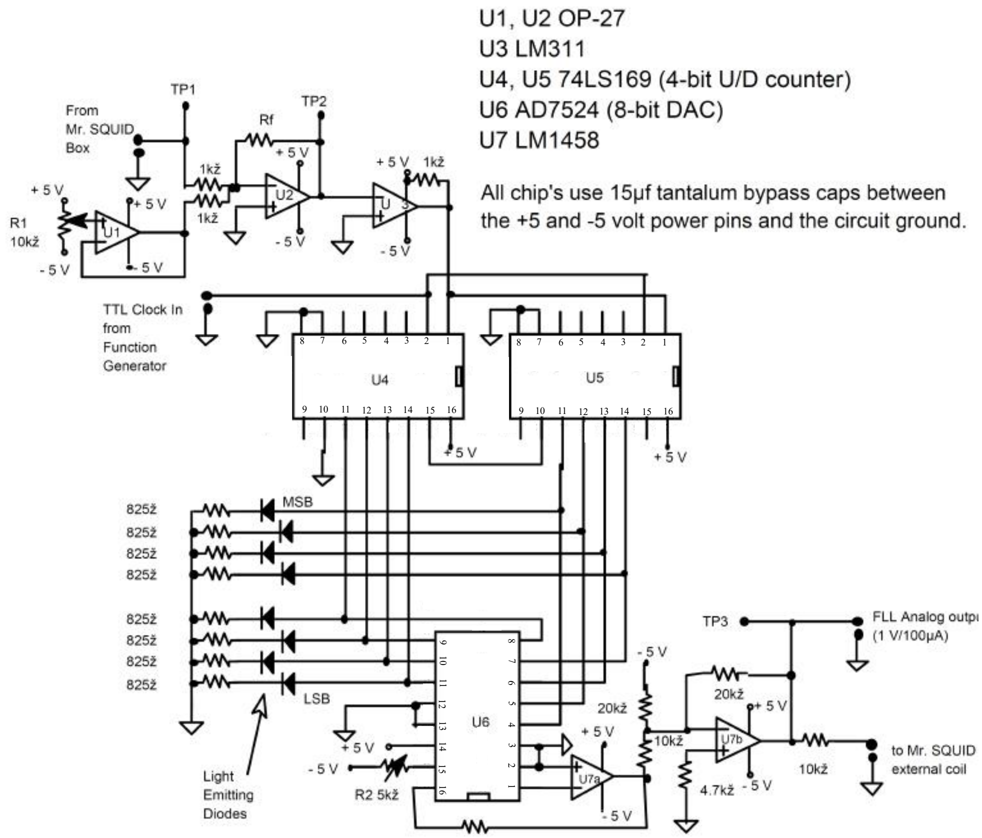


Figure 18: Circuit Diagram for 8–bit `DFLL` circuit. The circuit is equipped with operational amplifiers (op–amps), 4–bit up and down synchronous counters, and a digital to analog converter (DAC).

Theory of Operation:

Digital Flux Locked Loop (`DFLL`) works by taking input from the output voltage of the electronic box. This voltage is amplified and inverted by an op–amp (OP–27), U2, shown in Figure 18), by a factor of -100. The gain factor can be changed by changing the resistance of feedback resistor R_f which is connected to pins 2 and 6 of amplifier U24. The gain also depends on the resistor connected to pin 2 (negative input) of U2, (i.e. OP–27),

$$\begin{aligned} Gain &= \frac{R_f}{R_{-in}} \\ &= \frac{100\ k\Omega}{1\ k\Omega} \\ &= 100 \end{aligned}$$

The amplification is aided by a voltage supply of +5 V and −5 V potential, with a common ground, which is buffered through another op–amp, U1 (OP–27). U1 isolates the output of the 10 kΩ potentiometer which is supplied by voltage. Its output is independent of the rest of the circuit's operation.

U3 (LM311) is a comparator, which compares the output voltage of the amplifier U2, with ground, and is capable of passing only two discrete signals, 0 Vand 5 V, to the counters U4

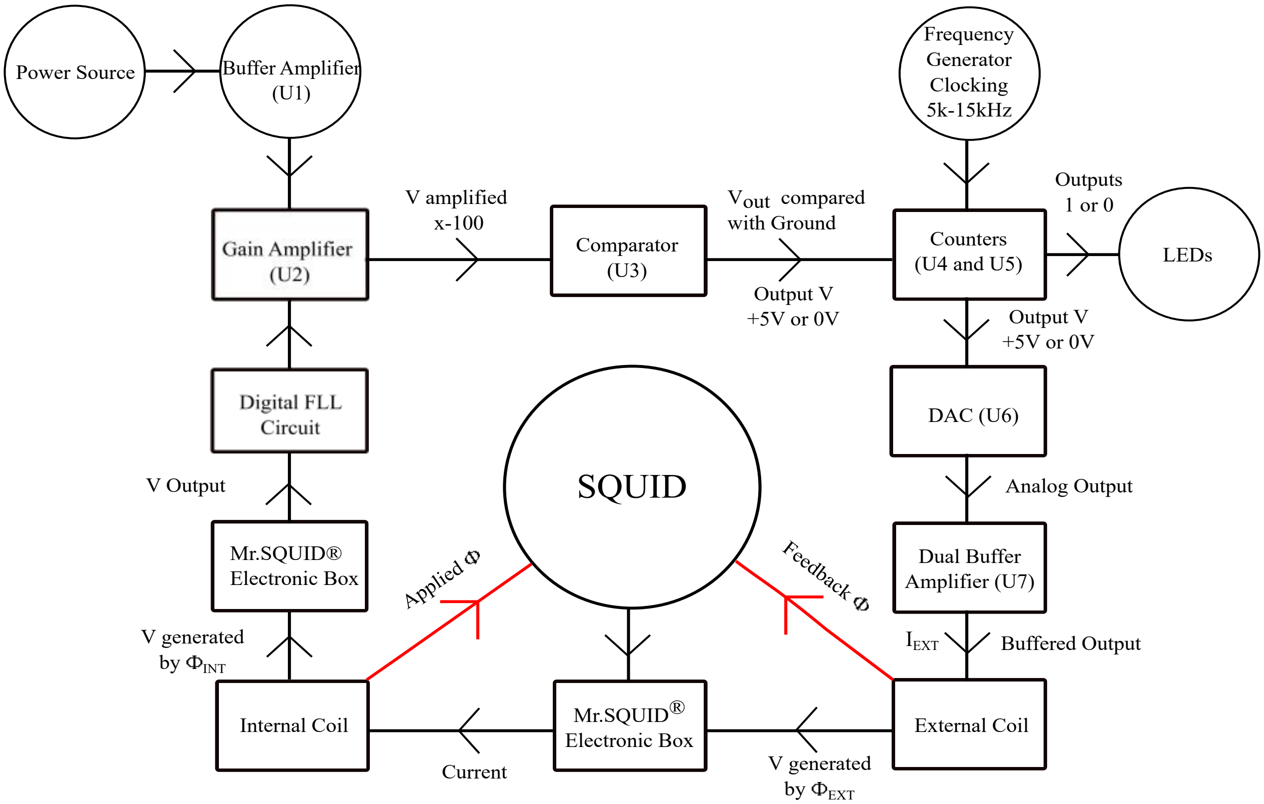


Figure 19: Schematic Representation of Digital Flux Locked Loop Experiment

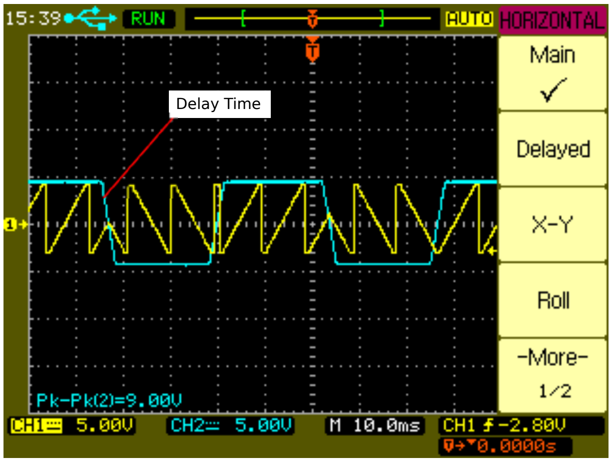
and U5 ($74LS169$, 4–bit U/D counters)[4]. U3 passes 5 V, if its output is greater than 0 V, and passes 0 V otherwise. This is received by the counters as logical data.
The counters together work using Boolean Logic as 8–bit counters, and are continuously clocked by a function generator at a certain frequency. At each clock, they count the output of U3 as either 1 (for 5 V) or 0 (for 0 V). This is directly displayed on the 8 light emitting diodes (`LED`'s) connected to the output pins $11 - 14$ of either counter[13].

U4 then begins its count from 0 Least Significant Bit (0000) till 15 (1111), and repeats the increment from 0 to 15. U5 begins its count from 16 (binary 0001 1111) (continuation of the preceding 4–bit count by U4) till the Most Significant Bit, 128[11]. The cycle then repeats. The clock pattern is visible through the turning on (logical 1), and off (logical 0) of the `LED`'s.

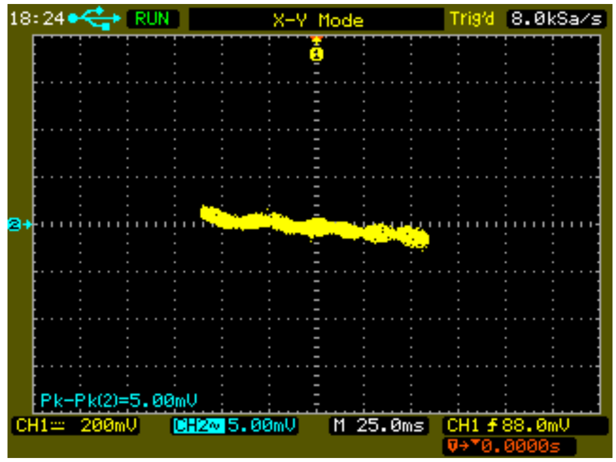
Next in the cycle is a DAC (U6, AD7524; 8–bit DAC)[5], which uses these logical outputs to display as analog signals. These appear as small steps on the analog output signal. The higher the clocking frequency, the smaller the appearance of step [14]. Ultimately, a dual operational amplifier, U7 (LM1458)), buffers (or isolates) the analog output of U6, to send current to the external coil.

To conduct this loop, the circuit is connected to the power supply, with separate negative and positive potentials of 5 V, and a common ground between them. Before beginning the experiment, it is necessary to make sure that the output voltage of the circuit is 0 V, when

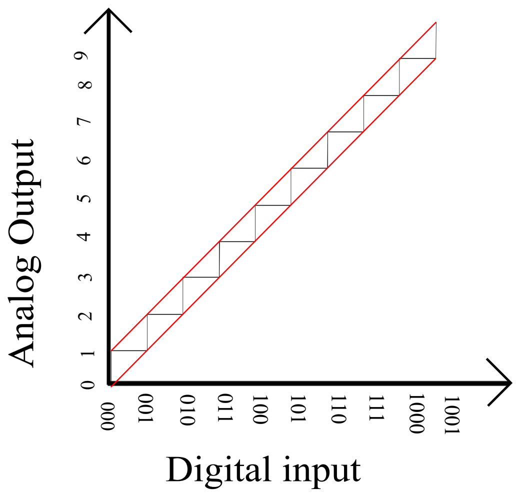
[13] See Figure 18 for pin configuration. Check the data sheet for the pin functions of LS169 4–bit counter cited under reference [4].
[14] A test circuit to test the working of the digital to analog converter can also be set (refer to Section 4).



(a)



(b)



(c)

Figure 20: (a) Output signal of counters in terms of 1's and 0's shown in main mode in blue. The slight slope of the wave indicates the delay time of the integrated circuits used. (b) Steps seen as slight curves due to increase sensitivity of the horizontal and vertical scales. (c) Digital signals to analog output

no input is given. Any offset has to be removed. The counters U4 and U5 are removed (to disconnect their output from the DAC input), and the DAC's (U6) pins 5 to 11 are connected to the circuit ground. These pins are the inputs of the converter[5]. Pin 4 of the converter is connected to the 5 V terminal, and voltage at TP3 (output) is measured using a voltmeter. In our case, it is a non–zero voltage, and was set to 0.000 V by adjusting the resistance of R2 resistor (Figure 18). The `SQUID` probe is cooled and the V–ϕ curve is obtained. The output voltage is connected to the input of the `DFLL` circuit and tested at Test Point 1 (Figure 22a). The current through the internal coil from the curve is calculated as 1.65×10^{-4} A, using the horizontal axis. This translates to 82.5 μA/Φ_0, since two sines are displayed. The applied

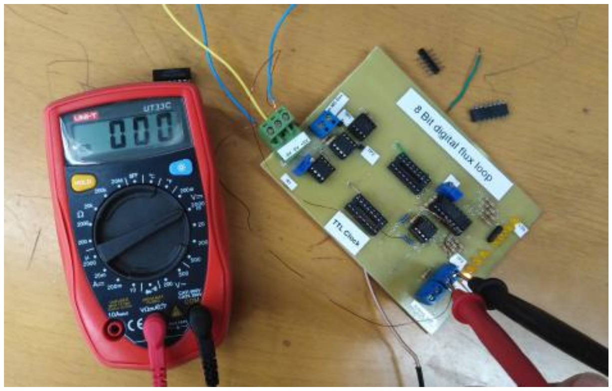


Figure 21: Output Voltage bias removed

flux from external coil was,

$$\begin{aligned}&= M_{int} \times I_{int},\\&= 37.6\ pH \times 165\ \mu A,\\&\approx 6.20 \times 10^{-15}\ Wb.\end{aligned}$$

This with the flux generated by the `SQUID` loop of $2.19 \times 10^{-15} Wb$, with $I_B \approx 30\ \mu$A becomes 8.394×10^{-15} Wb.

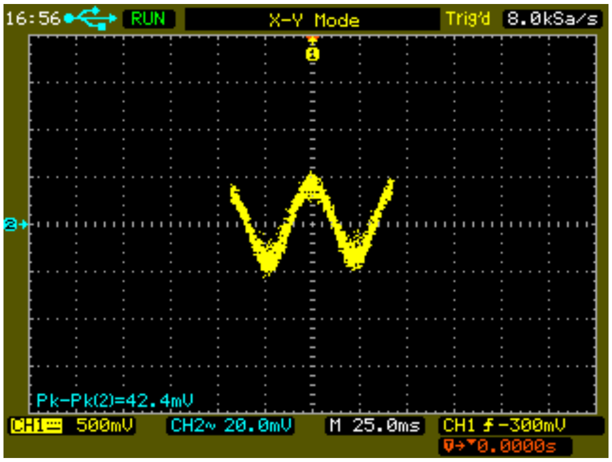
The voltage supply is connected to the respective terminals to give the net voltage as 0 at the common terminal. The curve is then observed by testing on TP2 (amplified and inverted). This curve is adjusted by coupling the Channel 2 to DC mode, and adjusting the potentiometer (R1), to set equal amplitude on either side of the vertical axis (see Figure 22b).

The amplification factor calculated from the peak–peak voltages of curves 22a and (bottom left, written in blue) is calculated as approximately −107.5. The power is disconnected, and the external coil connected to circuit output. A frequency generator with range of at least 5 kHz-15 kHz signal is used to connect its TTL (transistor–transistor logic) clock output to the counters' input using a BNC–BNC connection. The frequency is set to 5 kHz. The wave type was set to square wave. The power is reconnected and signal at TP2 resulted as a horizontal linear line indicating the cancellation of flux (Figure 22c). Signal at TP3 shows the output voltage given to the external coil to keep the flux constant inside the `SQUID`. The voltage across the external coil is $-5.2\ m$V , which makes $I_{ext} \approx 107.4\ \mu$A. The calculated flux is,

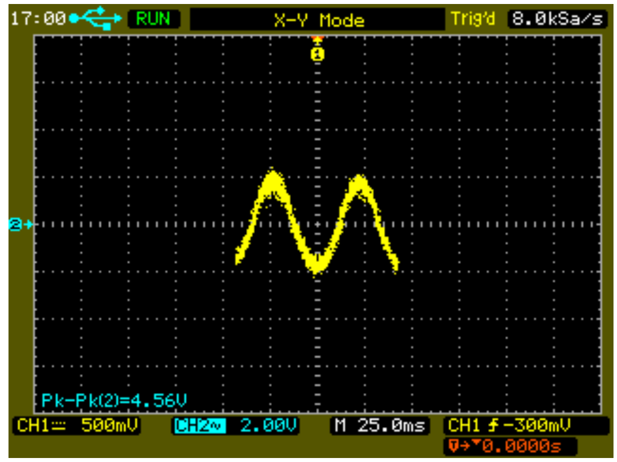
$$\begin{aligned}\phi_{ext} &= M_{ext} \times I_{ext},\\&= 35pH \times 107.4\ \mu A,\\&= 3.76 \times 10^{-15}\ Wb.\end{aligned}$$

The net flux is,

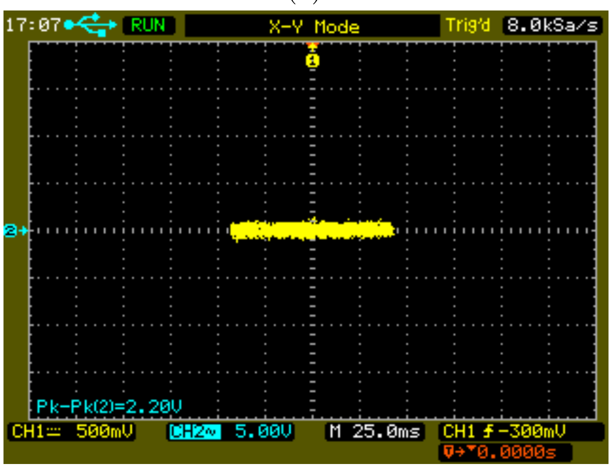
$$\begin{aligned}\phi_{net} &= \phi_{SQ} + \phi_{int} - \phi_{ext},\\&= \phi_{total} - \phi_{ext},\\&= 8.39 \times 10^{-15} Wb - 3.75 \times 10^{-15} Wb,\\&\approx 4.64 \times 10^{-15} Wb.\end{aligned}$$



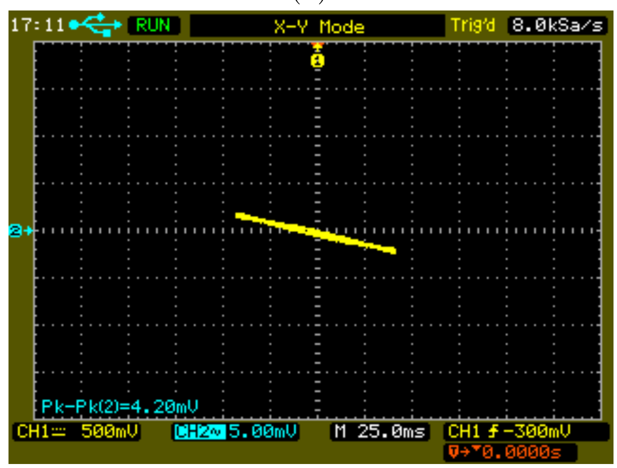
(a)



(b)



(c)



(d)

Figure 22: (a) TP1 showing FLL's input signal, (b) TP2 showing the inverted and amplified signal (factor −100). (c) TP2 shows the cancelled flux when digital counting begins (external coil connected) (d) TP3 showing the analog output being fed into the external coil.

This flux did not remain constant due to varying voltage output of the DFLL circuit, changing the current in the external coil. Analog voltage is calculated by taking the binary output on the LED's as inputs for the DAC and using the algorithm followed by the DAC,

$$V_{analog} = \frac{D}{2^n} V_{reference},$$

where $V_{reference}$ is the voltage at pin 15 of the DAC, and D is the input binary number [14],

$$\begin{aligned} V_{analog} &= \frac{1101\ \ 1111}{2^8}(-3.52), \\ &= \frac{255}{256}(-3.52), \\ &\approx -3.51V. \end{aligned}$$

The analog output measured is −1.53 V, which continues to fluctuate one or two volts about this value. This means that our digital and analog results vary due to the uncertainties created from the fluctuating counting cycles.

Acknowledgments

We acknowledge the Physlab team for insightful discussions and help, including Muhammad Shafique for his contribution in the making of circuits for this experiment. Special thanks to Khadim Mehmood, Hafiz Muhammad Rizwan, and Muhammad Ayyaz Mehmood for the making of shielded dewar. We also pay gratitude to Ali Hassan for his assistance in lab resources. Emaan Sohail would like to acknowledge Dr. Athar Osama and Pakistan Innovation Foundation for facilitating this programme.

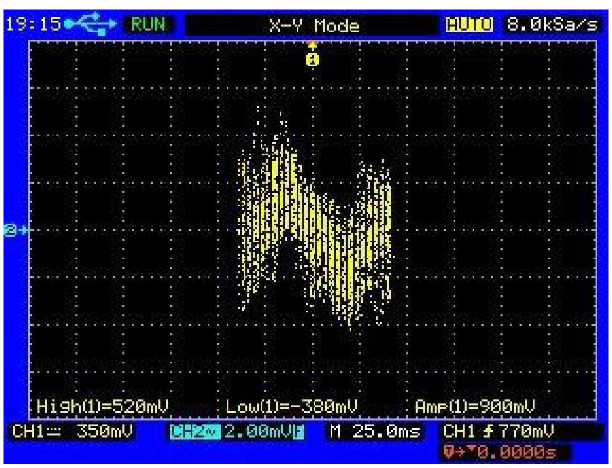
4 Appendices

Troubleshooting the Problems faced in the Project

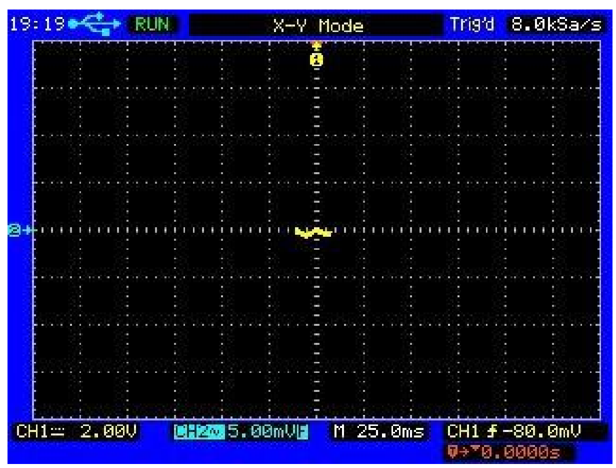
This section describes the obstacles faced in the performance of the experiments, and the corrective actions taken to solve them.

Radio Frequency Interference and Noise

Given its high sensitivity, the `SQUID` is able to detect unwanted signals from the environment, which may dominate over the signals we want to observe; and put disruptive effects on our outputs. For this reason, it is suggested to turn off all the nearby electronic devices, especially the wireless technology. The effects may include noisy signals like the ones received by us in Figure 23a , or suppressed amplitude of the V–ϕ curve (Figure 23b). This may result in the flattening of the curve as a result of quantization error. Quantization error occurs when the noise of the electronics with the radio frequency interference from environment is greater than the wanted output signal. Increase in noise may be the result of low quality BNC–BNC cable usage or the usage of testing probes with high resistances. Checking the terminal to terminal resistances of the cables should be done before experiment.



(a)



(b)

Figure 23: Possible Effects of External Environment on the V–I Graphs. (a) RF interference (b) V–I Curve with decreased amplitude

To carry out a smooth experiment, we looked for isolated places to conduct the experiment to obtain desirable V–ϕ curves. This quest for interference free environment led to the conclusive action of making a Faraday shield for our `SQUID` probe. However, before making one, it is reasonable to explore suitable areas for experimentation to identify the sources of disruption in the results.

- *FLL Experiment in the Basement of SSE building, LUMS*
  Basements are rather dormant in terms of cellular and wireless network usage, along

with working machinery. Thus, they can serve as ideal locations to qualitatively test curves. As predicted, the results were relatively better (see Figure 26a). The apparatus was set up as shown:

Figure 24: Apparatus Set up in Basement: The distance between the apparatus and the `SQUID` had been kept at its maximum.

- *Cold Room*
  A cold room enclosed within metal walls and doors, with the temperature of 9°C temperature was thought of a good location to suppress the incoming interference. However, the room did not shield the signals; in fact the interference came with time intervals in the form of pulses, indicating oscillating interference signals (see Figure 26b).

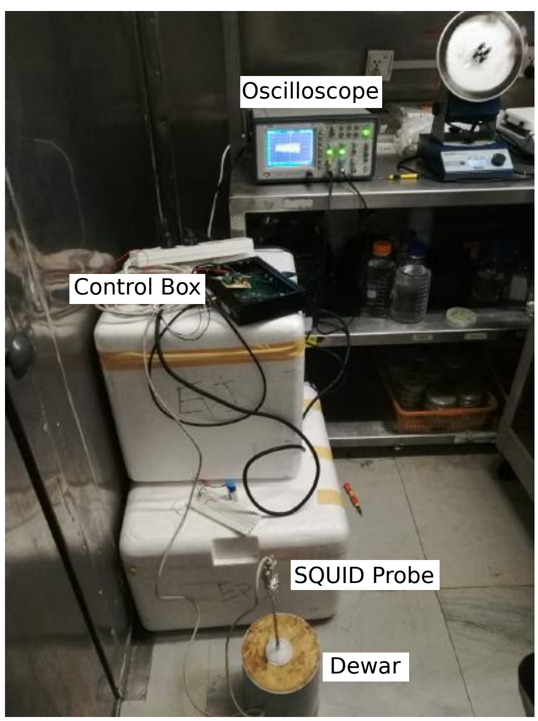
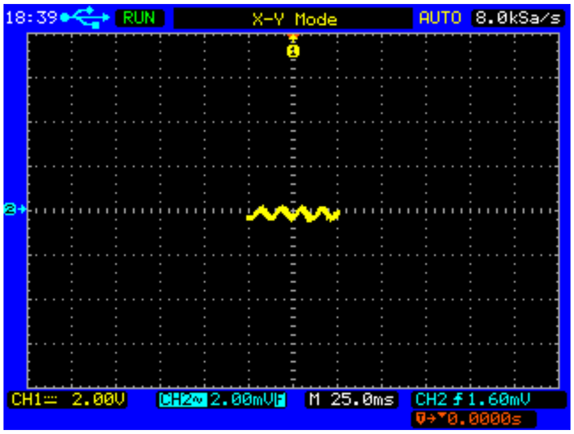
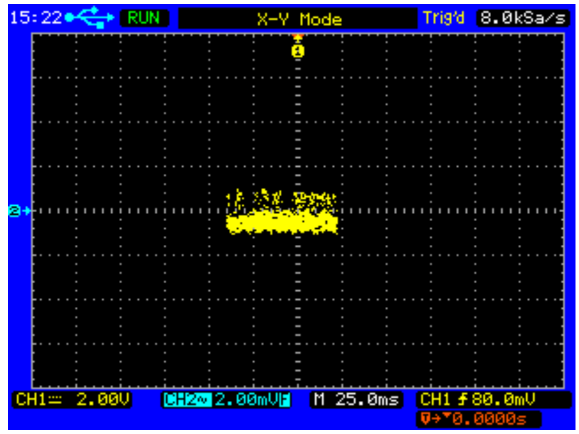


Figure 25: Experimental set up in the cold room. The metallic walls can be seen.

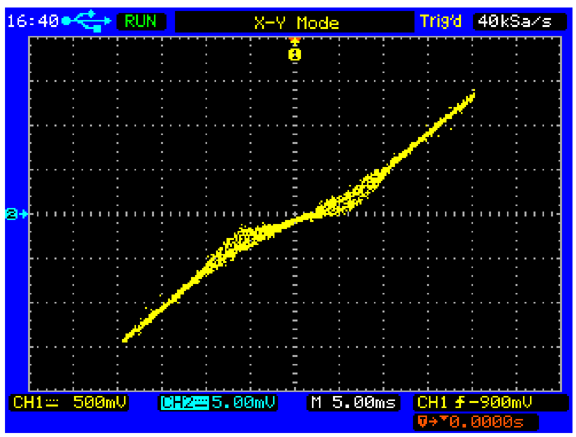
- *Annex*
  This place is a detached part of the main building bordered by a metal cage. It could shield from waves with larger wavelengths. However, from the results, we conclude that outdoor locations are not an ideal location. The V–I curve traced can be seen in Figure 26c.



(a)



(b)



(c)

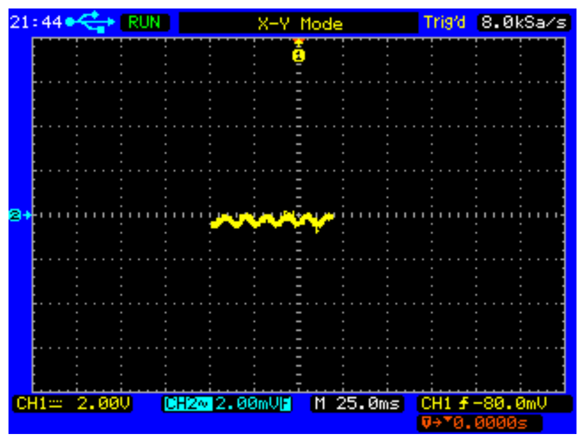
Figure 26: Results obtained at different locations to check for RF interference. (a) Relatively clear V–ϕ curve produced in basement. (b) Increased RF interference in a refrigerated cold room(-9 °C). (c) V–I curve unstable in annex.

- *Degaussing*
  Another cause for suppressed V–ϕ curves could be flux trapping inside the `SQUID` probe, which is a frequent circumstance. A flux may remain trapped within the `SQUID` if its shield is magnetized. In such situations, it may get challenging to identify the cause for flat V–ϕ curves. This can be dealt by demagnetizing the magnetic shield of the probe (See appendix 4).

- *Faraday Shield*
  A Faraday shield or cage is a metallic covering which blocks the interference by electromagnetic waves. The waves' wavelengths are larger than the penetration gaps in the metal of the shield or cage which does not let them pass through. The waves

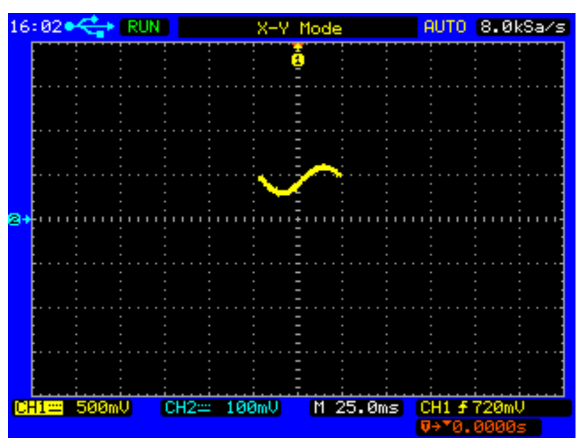
surrounding the shield, cause the electrons in the metal to be repelled by their own oscillating electrons. This keeps the waves outside the inner regime metal container [6]. This cancels the effect of the radiations striking the shield. Non-magnetic conductors provide better shielding. The skin depth of the conductor (distance covered by the EM wave before it is attenuated by metal surface) must also be smaller than the metal layer's thickness[16]. This prohibits its penetration. Since wireless network frequencies range from 2.4 GHz to 300 GHz, and the fact that skin depth decreases with increasing frequencies, a metal layer of few millimeters could easily be used as an effective shield. Within the range of frequencies mentioned, the wavelengths of the radiation range from 10 cm to 1 mm (1mm being at highest frequency). This concludes that the holes of any effective Faraday cage must not be wider than 1 cm. Yet, A non–metallic dewar can be wrapped with aluminum foil to suppress interference (see Figure 10b), or a shield could be made. Several prototypes were made keeping in consideration the requirements of a Faraday shield. It concluded in the assembly of a dewar made of metal.

(a)

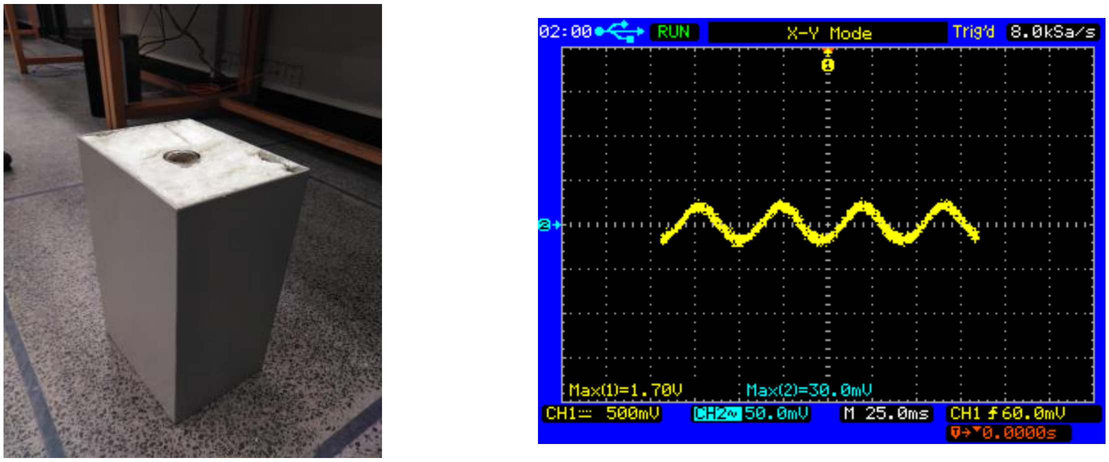


(b)

(c)



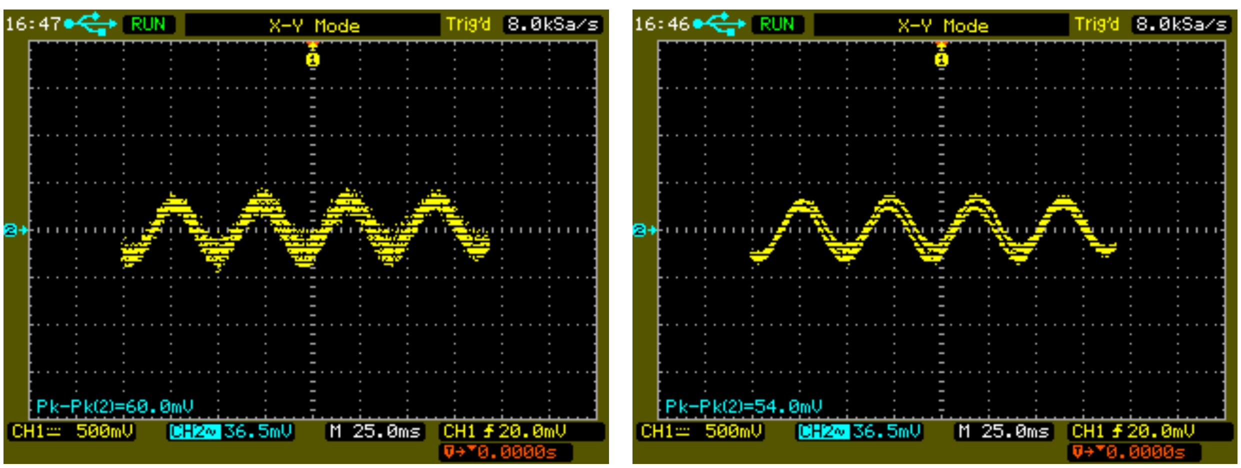
(d)



(e) (f)

Figure 27: First Prototype: (a) Dewar made of thick metallic sheet. (b) Relative increase in amplitude of the V–ϕ. Second Prototype: (c) The dewar from (a) placed in a metallic box, with insulation. (d) Increased amplitude. Third Prototype: (g) Effective insulation to increase durability of liquid nitrogen. (h) The amplitude of curve suppressed with removal of a layer of metal sheet from dewar.

- *Use of Digital Filter*
  The output on oscilloscope can be made clear from noise, by turning on the digital filter, which takes average signals within certain random signals, which get cancelled.



(a) (b)

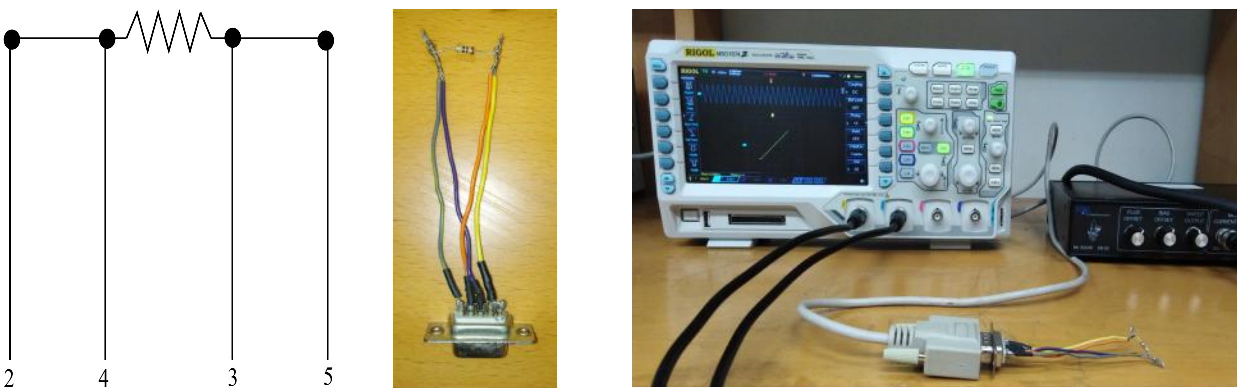
Figure 28: (a) V–ϕ curve `without` channel 2 digital filter. (b) V–ϕ curve `with` channel 2 digital filter.

Testing the working of the IC, DAC (AD7524), of digital flux locked loop circuit

For experiments like `DFLL`) in section 3.8, the IC's being used may show symptoms of being faulty by getting overheated, or not performing their function. This can be countered by the use of temporary circuits made on breadboards to independently test the working. To deal with the situation, the circuit was set up using the schematic diagram in Figure 18, by giving the DAC inputs (originally received from counters) through pins $5 - 11$[15], as either +5 V (representing logical 1) or −5 V (representing logical 0). The inputs on these pins were varied, and there corresponding outputs on pins 14and15 were read for correct changes.

Testing the SQUID electronic box

In order to test the Mr.SQUID® electronic box, 10 Ω (×1) and 20 Ω (×1) resistors can be used to calculate resistances. The confirmation of known data through the calculations would ensure that the electronic box carries out its function correctly. The oscilloscope and Mr.SQUID® electronic box are connected to the power supply, and V–I mode is turned on the electronic box, while X–Y mode on the scope. The 10 Ω resistor is connected to a spare DB–9 male connector as shown in Figure 29b, which is then plugged into the DB–9 female connection[16] on the back of the electronic box.



(a) (b) (c)

Figure 29: (a), (b) Resistor connected to DB–9 male connector. Pins 2 and 4 are connected to one terminal of the resistor, and pins 3 and 5 are connected to the other terminal of the connector.

Both Channel 1 (horizontal axis connected to the current output on electronic box) and Channel 2 (vertical axis connected to voltage output) on the scope are DC coupled to generate a voltage–current graph.

The plots shown in Figure 30a, are used to calculate the gradient of the graph, which gives the value of resistance connected. The coordinates of the plots can be read using the scaling options shown in Figure 30a, where the Channel 1 and 2 indicate 1 V/division and 100 mV/division respectively[17]. The gain for voltage output is ×100 [18] .

[15]Check data sheet for AD7524 under the reference [7]

[16]Check pin configuration for DB–9 male connector under reference [8].

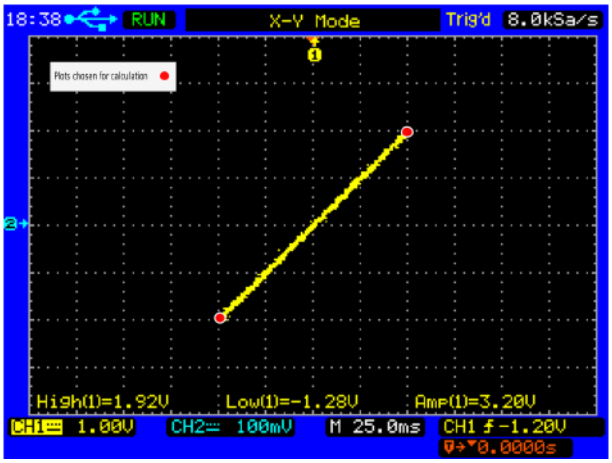
[17]In order to directly calculate the change in voltage and current, "cursor" or "measure" options on a digital scope can be used, which directly gave the shifts in axes (see Figures 31).

[18]The voltages received from the `SQUID` are too small, and need to be amplified for the ease of display and calculation. Therefore, a default amplification factor of ×10,000 is set for the voltage output of Mr.SQUID® electronic box. This factor may however be switched to ×100 or × 1000 from the circuit board shown in

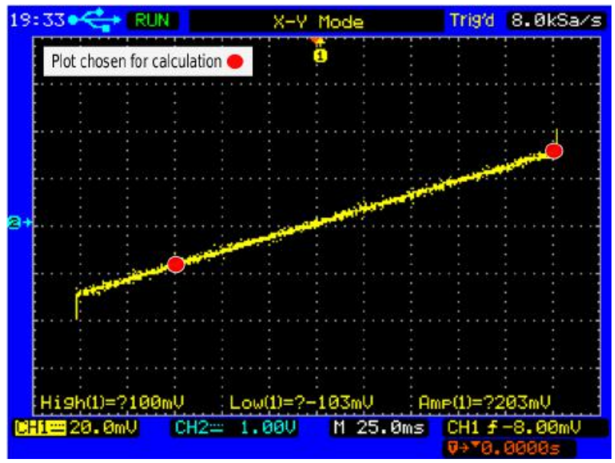
The following value accurately gives the answer of 10 Ω:

$$
\begin{aligned}
\text{Resistance} &= \frac{Voltage}{Current} \\
&= \frac{\text{Voltage from Channel 2 Gain}_V}{\text{Voltage from Channel 1/10,000}\Omega} \\
&= \frac{2\ V - (-2\ V)/100}{200\ mV - (-200\ mV)/10,000\ \Omega} \\
&= 10\ \Omega
\end{aligned}
$$

This is repeated for a parallel combination for 10 Ω and 20 Ω resistors(Figure 30b). The ohmmeter is used to confirm the resistances calculated.

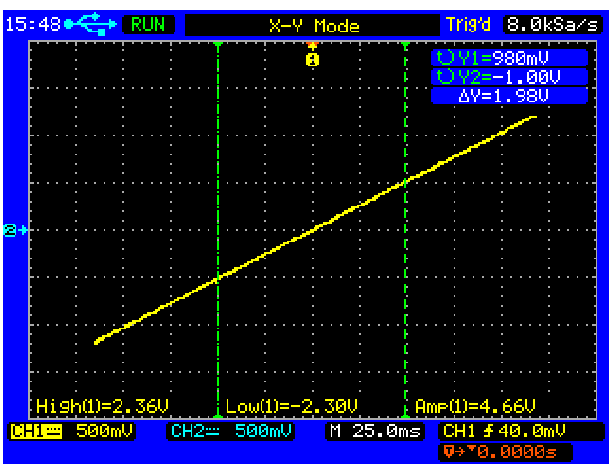


(a)

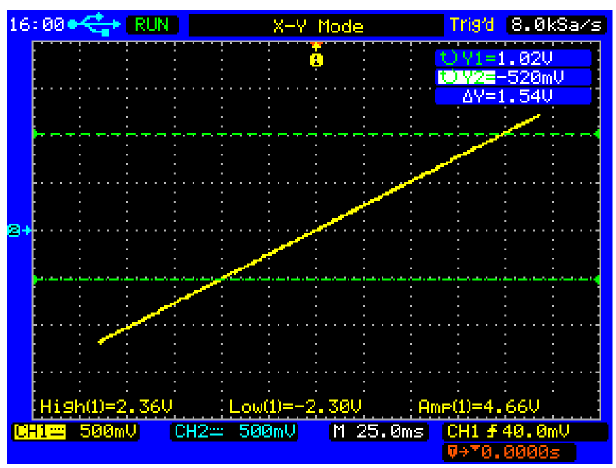


(b)

Figure 30: (a)V–I graph for a 10 Ω resistor. (b) 20 Ω and 10 Ω in parallel



(a) Measuring horizontal shift



(b)

Figure 31: Using cursor to take measurements. (a) Measuring horizontal shift (b) Measuring vertical shift.

Figure 9 as per user's choice. The current output from the electronic box, is a conversion to voltage across a $10,000\Omega$ resistor and needs to be reconverted to current by dividing it with $10,000\Omega$. The scaling factor can further be adjusted using the "Probe" factor in the oscilloscope's channel settings.

Demagnetization of the `SQUID` 's magnetic shield

The magnetic shield of the `SQUID` can also become magnetised when frequently exposed to magnetic fields. Thus, in order to assure safe experimentation to detect sensitive signals, the shield was degaussed. This was done by placing the shield in a solenoid and passing alternating current through it which generates constantly changing magnetic field. This changes the ordered alignment of the magnetic domains inside the shield. The AC voltage is first increased to a certain value in the solenoid, and is then slowly decreased until it is zero.

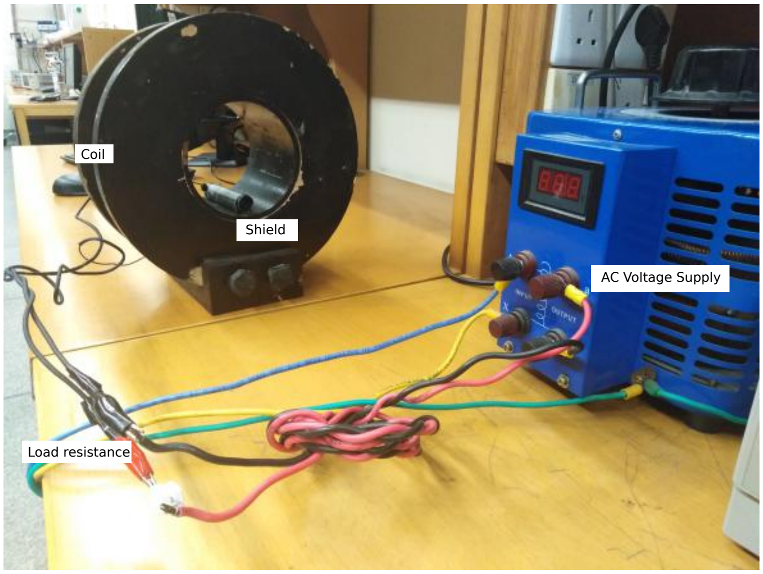
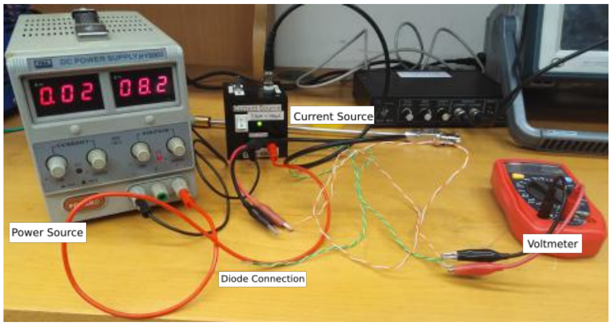


Figure 32: Demagnetising Shield

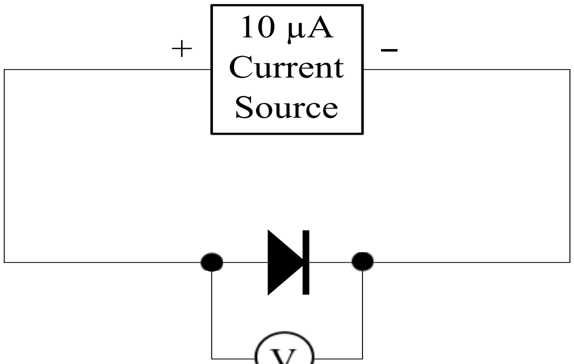
Figures and Diagrams

Refer to the respective experiments to view complete procedures for the following figures.

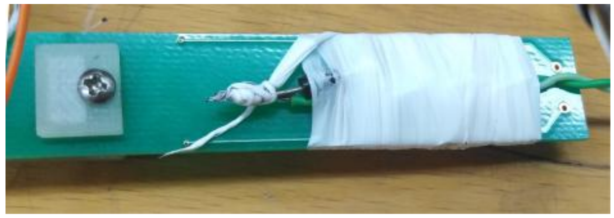
Temperature–Voltage Relation of Diode



(a)



(b)



(c)

Figure 33: (a) Diode connected with a 10 μA current source. (b) Circuit diagram for taking potential drop across the diode. (c) Diode fastened with the `SQUID` probe.

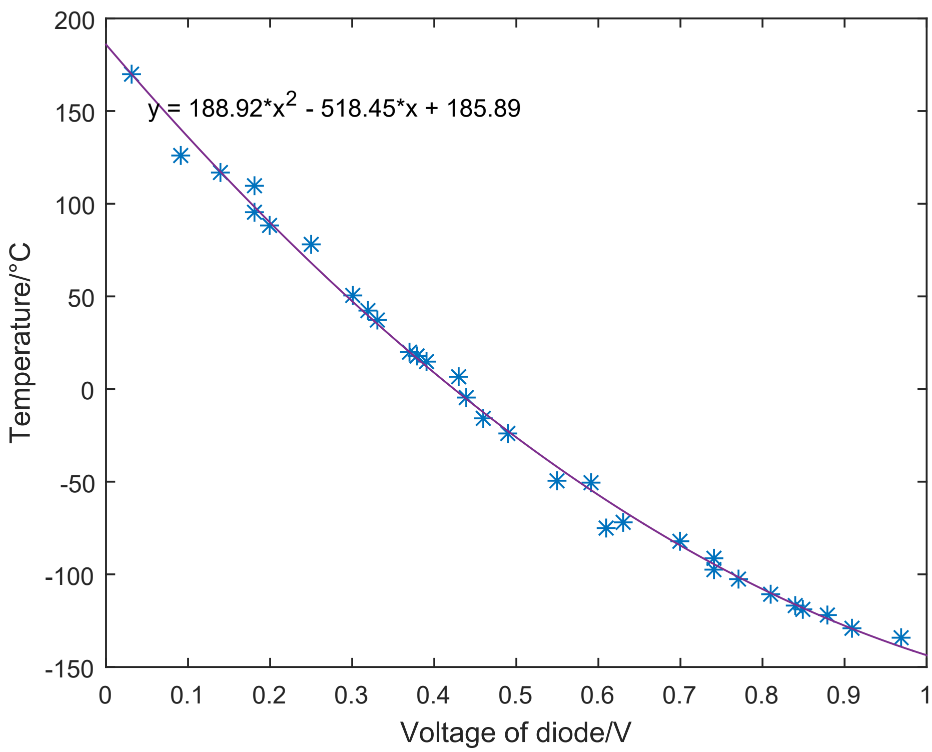


Figure 34: Plot for the voltage across 1N4001–MIC Germanium diode with changing Temperature

The voltage across 1N4001–MIC Germanium diode is taken as it is increased to 200 °C, brought back to room temperature, until it is cooled to −196 °C. This data is then plotted. A quadratic equation is obtained to define the relation by the curve fitting of the plot:

$$y = 188.92x^2 - 518.45x + 185.89. \tag{7}$$

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