

3 GETTING STARTED WITH MR. SQUID[®] (NEW USERS)

The directions that follow assume that you have some familiarity with the basics of superconductivity including zero resistance, flux quantization, and the Josephson effect. If not, you may wish to read some of Section 5, An Introduction to Superconductivity and SQUIDS, before going any further.

The Mr. SQUID[®] chip contains a dc SQUID made with thin film YBCO superconductor. The dc SQUID is a simple circuit that can be schematically represented like this:

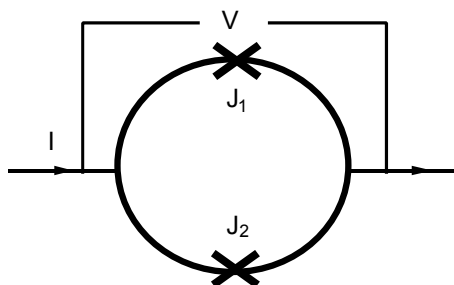


Figure 3-1 Schematic representation of a dc SQUID.

The dc SQUID is simply a ring of superconductor containing two Josephson junctions, which are marked by the X's labeled J₁ and J₂ in the circuit diagram above. The Josephson junctions can be thought of as weakened areas of the superconductor, which nevertheless still allow a certain amount of resistanceless current to flow. The simplest experiment to perform with this circuit is to pass current "I" from left to right across the ring and to measure the voltage "V" that appears across the ring. If the two junctions in the SQUID are identical, in the absence of any magnetic field, the current will divide evenly and half of it will pass through each junction before recombining at the right side.

The Mr. SQUID[®] control box allows you to perform this experiment quite easily. If you have set up the system according to the instructions in the previous section, you are ready to try this voltage-current experiment.

3.1 Setting Up the Output Device

Once again, we assume that you are familiar with the operation of your oscilloscope or x-y recorder. For initial settings, try an x sensitivity of 0.2 volts per division (or whatever value is closest to this on your instrument) and a y sensitivity of around 50 millivolts per division. You may want to adjust these values as needed later. Now refer to the diagram of the Mr. SQUID[®] control box (Figure 3-2) below.

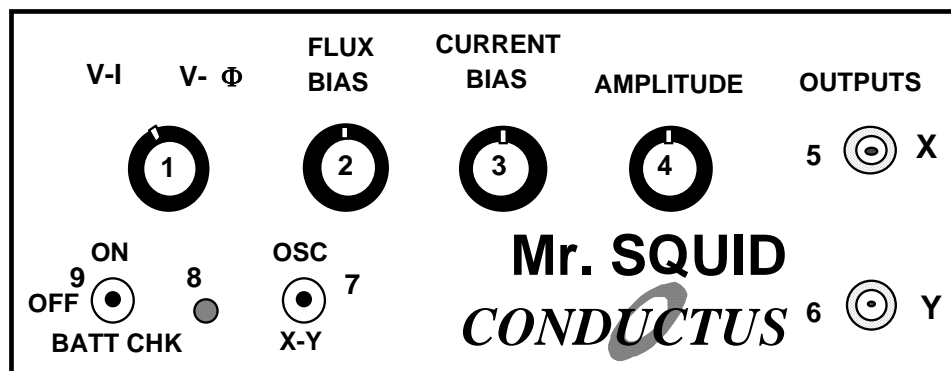


Figure 3-2 Front panel of the Mr. SQUID® electronics box.

STEP 1:

If you are using an oscilloscope, set the oscillator frequency toggle switch (7) to the OSC (high-speed) position. If you are using an x-y recorder, use the X-Y (low-speed) position.

STEP 2:

Before turning on the power, make sure the amplitude control (4) is at its minimum (fully counter-clockwise) position and set the flux bias control (2) and the current bias control (3) to their 12-o'clock (straight up) positions.

STEP 3:

Make sure the function switch (1) is in the V-I position. In this position, the BNC cable connected from the X output on the front panel (5) reads the current being fed through the SQUID. The cable connected to the Y output (6) reads the voltage across the SQUID. Set the power switch (9) to the ON position. On an oscilloscope, there should be a small bright spot on the center of the screen. On an x-y recorder, the pen should be stationary in the middle of the page. You may have to adjust the offset controls on your display device to achieve this in either case.

3.2 Varying the Current Bias

The current bias control (3) varies the current being sent through the SQUID. Slowly turn this knob in either direction. The spot on the oscilloscope screen or the plotter pen will move in response to the changing current. As you turn the knob back and forth, you will trace out a curve representing the relationship between the current fed through the SQUID and the voltage across the SQUID. This curve is called the *V-I* curve for the SQUID.

3.3 Varying the Amplitude of the Current Sweep

Return the current bias control to the 12 o'clock position and now slowly turn the amplitude control (4) in the clockwise direction. This function sweeps the current through the SQUID back and forth between preset values, thus automating the procedure you performed by hand using the current bias control. A solid curve should now appear on the oscilloscope screen; alternatively, the pen on your plotter will repeatedly trace out the curve on the page.

If you now turn the current bias control, the center point of the curve being traced on the screen or page will move. The current bias control sets a single value of current being passed through the SQUID and the amplitude control sweeps the current back and forth about that set value.

3.4 Calculating the Current

Your output device acts like a voltmeter. The sensitivity settings on it determine how much voltage corresponds to a division on the screen or on the page of graph paper. The current output on the Mr. SQUID[®] box (5) actually represents the voltage across a 10,000 Ω resistor in the electronics box. According to Ohm's Law ($I = V/R$), the current flowing through the resistor is therefore equal to the voltage across it divided by 10,000 Ω .

The typical voltage levels from the SQUID are small enough that we have provided amplification in the Mr. SQUID[®] control box. Thus, to calculate the actual voltages across the SQUID, the measured value on the oscilloscope or x-y plotter should also be divided by 10,000.

3.5 The V-I Curve

If the settings on the Mr. SQUID[®] box and your output device are correct, and if the SQUID is behaving properly, you will see a curve that looks more-or-less like this on the screen or page:



Figure 3-3 Typical Mr. SQUID[®] V-I characteristic.

It is important that there is a flat region in the center of the curve as shown above, although its width may vary from device to device. If what you see looks like a straight line, as in Figure 3-4 below, then either you don't have enough liquid nitrogen in the dewar, you have not let the probe get cold, or there may be trapped magnetic flux in the SQUID. The latter is a very common occurrence because the SQUID is very sensitive to external magnetic fields. Refer to the discussion on trapped flux in Section 6.3, Magnetic Flux Trapping in SQUIDs, if this appears to be the problem. Assuming you see the proper curve, how can we understand its shape?

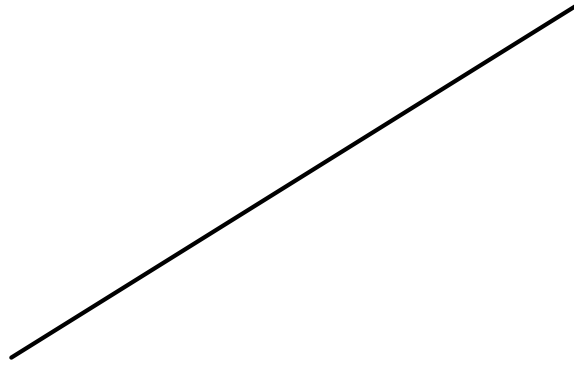


Figure 3-4 A linear $V-I$ characteristic.

What you are looking at is the $V-I$ characteristic of two Josephson junctions connected in parallel with one another. Assuming they are identical junctions (in practice, they are at least very similar), the $V-I$ characteristic you see is the same as for a single junction. The most important feature of the curve is the flat spot in the middle, called the critical current. In this region, there is current flowing with no voltage – it is a supercurrent. This is the dc Josephson effect: a resistanceless current that flows through a superconductor Josephson junction.

A Josephson junction consists of two regions of superconductor that are weakly coupled together. The meaning of this statement is that the junction behaves like a superconductor but can only carry a small amount of resistanceless current before it becomes resistive. Any superconductor has the same property: it ceases to be resistanceless as soon as the current it is carrying exceeds a maximum value called the critical current. A Josephson junction is a weak link between two regions of superconductor, and this weak link carries far less resistanceless current than the superconductor on either side. The maximum supercurrent that can flow through a Josephson junction is called the critical current of the junction.

At this point, you might want to adjust the flux bias control (2) on the control box. This control feeds current into a coil that produces a magnetic field that couples to the loop the SQUID. As explained in Section 5, a changing magnetic flux through the SQUID loop will modulate the critical current in the SQUID in a very specific manner. By turning the flux bias control knob, the critical current in the junction will change visibly on the oscilloscope screen or on your plotter page. At this point, try to adjust the flux bias current such that the flat region of the $V-I$ curve is widest. The response to these changes may be quite sensitive; it may take some practice to tune the critical current to its maximum value. This procedure may be especially useful if some small amount of magnetic field was already present in the SQUID loop. A zero applied field will yield the largest critical current through the junction.

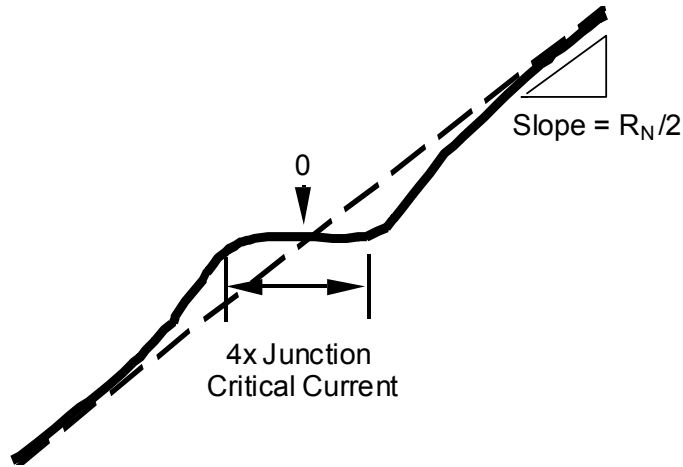


Figure 3-5 Determining the junction parameters from the V - I characteristic.

You can determine the critical current of the junctions in Mr. SQUID[®] by measuring the width (in volts) of the flat part of the V - I curve and dividing that number by 10,000 Ω to convert your answer into amperes of current. If the flat region is 1 volt wide, for example, then the corresponding current is 100 microamps. However, you are looking at the current through both of the junctions in the SQUID, not just one. Therefore, assuming the junctions are identical, the current through one junction is half the value you are measuring (in our example, 50 microamps). Is this the critical current of the junction? Not quite. The curve you are looking at drives the current symmetrically about zero (marked in the drawing). The current you have measured is actually composed of a contribution in the positive direction and a contribution in the negative direction. If the curve is symmetric, they are equal. As a result, the real critical current of the junction is half the value you infer from the measurement. Thus, in our example, the critical current is 25 microamps, 1/4 of the original measurement. The flat region on the curve corresponds to 4 times the junction critical current.

Apart from the critical current of the junction (usually written as I_c), there is also a parameter of the junction known as the normal-state resistance or R_N . You can determine it by measuring the slope of the V - I curve out at the ends where it is essentially a straight line. To obtain a resistance, you must convert the x-axis value into amperes from volts and take into account the amplification of the y-axis signal. This is all very simple since the conversion factor for each axis is the same value of 10,000. Remember that the dc SQUID contains two junctions in parallel, so that the measured resistance corresponds to half the resistance of a single junction (assuming they are identical.) Thus, simply taking the slope numbers in volts off your oscilloscope or x-y recorder will give you one-half the normal-state resistance in ohms. The product of the critical current and the normal state resistance ($I_c R_N$) is a voltage that is an important parameter for the operation of a SQUID. Make a note of it now for use later. Note that $I_c R_N$ for one of the junctions has the same value for the SQUID, which has two junctions in parallel. For the junctions in Mr. SQUID[®] operating in liquid nitrogen, you will probably obtain a value between 10 and 100 microvolts. This value sets the maximum voltage change in the SQUID by an individual magnetic flux quantum, and is discussed later in this section.

As you observe the properties of the Josephson junctions in Mr. SQUID[®], realize that such an experiment just a few years ago required the use of liquid helium and several pieces of sophisticated electronic instrumentation. In this era of high-temperature superconductivity, Josephson electronics is becoming a far more accessible technology.

3.6 Observing $V-\Phi$ Characteristics using Mr. SQUID[®]

Up to this point, we have been looking at the properties of Josephson junctions. Now we will turn our attention to the properties of the dc SQUID itself. The dc SQUID has the remarkable property that there is a periodic relationship between the output voltage of the SQUID and applied magnetic flux. This relationship comes from the flux quantization property of superconducting rings that is discussed in detail in Section 5. The Mr. SQUID[®] control box will allow you to observe this periodic relationship in the form of $V-\Phi$ characteristics on your oscilloscope screen or x-y plotter page.

You have already observed the effects of a magnetic field on the $V-I$ characteristics of the SQUID by adjusting the flux bias control current. The $V-\Phi$ characteristics are basically an automatically plotted version of this behavior. The physics underlying the $V-\Phi$ curve is discussed in Section 5.

3.7 Modulating the Critical Current of the SQUID

As we saw before, in the $V-I$ operating mode one can apply a magnetic field to the SQUID using the flux bias control. This dial controls a current that is applied to the “internal” modulation coil (coil 2 in Figure 3-6) that produces a magnetic field that couples to the SQUID; a second coil (coil 1 in Figure 3-6) is the “external” modulation coil that allows you to couple a magnetic field to the SQUID produced by an external source of current. The labels “internal” and “external” refer to the accessibility of the coils to the Mr. SQUID[®] user. Electrical connections to the “external” coil are made through the BNC connector on the back of your Mr. SQUID[®] electronics box. The “internal” coil is used by the Mr. SQUID[®] electronics to apply flux to the SQUID, and is not directly accessible to the user.

If you slowly turn the flux bias control knob, you will see the change in the critical current and the changing $V-I$ curve that occurs as the magnetic flux threading the loop of the SQUID is varied. Another way to see the sensitivity of the SQUID to external fields is to rotate a small horseshoe magnet slowly in the vicinity of the dewar. If you experiment carefully with the flux bias control, you will see that the critical current of the SQUID oscillates between a maximum value (the flat region of the $V-I$ curve is at its widest) and a minimum value at which point the $V-I$ curve may be more-or-less linear.

The Mr. SQUID[®] control box allows you to view the periodic behavior of the SQUID in a convenient, automated way. To obtain the $V-\Phi$ plot, the bias current is set so that the SQUID voltage is most sensitive to changes in applied magnetic field. This occurs at the “knee” of the $V-I$ curve, the area highlighted in Figure 3-7 below.

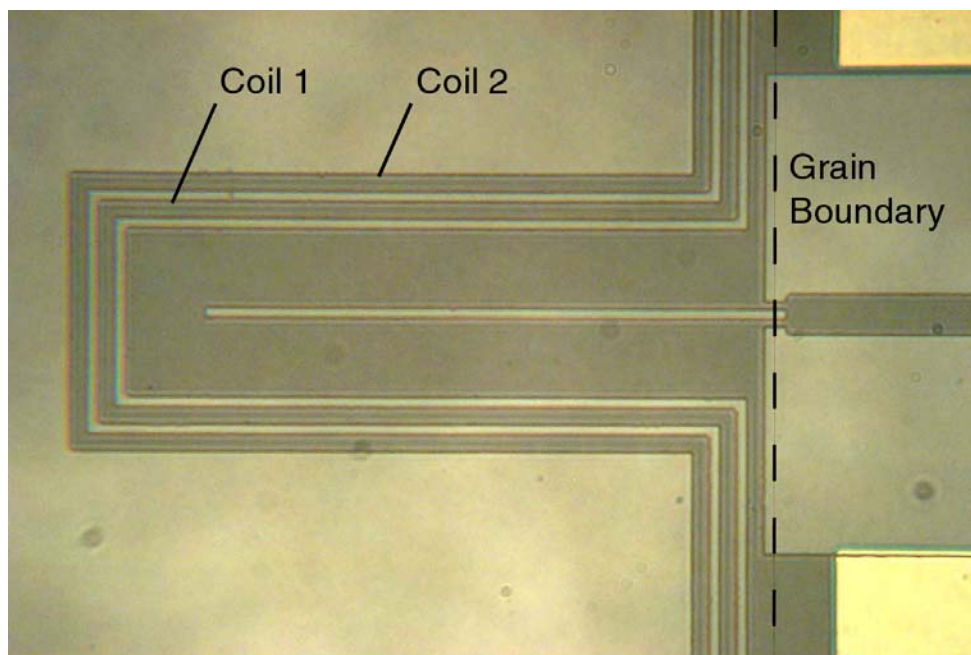


Figure 3-6 Photograph of the Mr. SQUID[®] chip showing the two modulation coils. Coil 1 is the “external” coil, coil 2 is the “internal” coil. See Sec. 9.2 for Mr. SQUID[®] specifications.

To find this point, first adjust the flux bias control (2) (for numbering, see page 14) so that the critical current is at its largest value. Then, turn down the amplitude control (4) all the way so that only a point is visible on the oscilloscope screen or so that the pen is stationary on the plotter page. In this mode, you can then sweep the point up and down the V - I curve by adjusting the current bias control (3), as you did initially. Set the current bias level so that the point rests at either knee in the V - I curve. Now turn the flux bias control (2), which controls the amount of magnetic flux through the hole in the SQUID loop. You should see the point move back and forth vertically on the screen or page. This periodic motion arises because the screening currents in the SQUID body depend on the applied magnetic flux in a periodic manner. The period is determined by the magnetic flux quantum (Φ_0). This phenomenon is a manifestation of the macroscopic quantum nature of superconductivity.

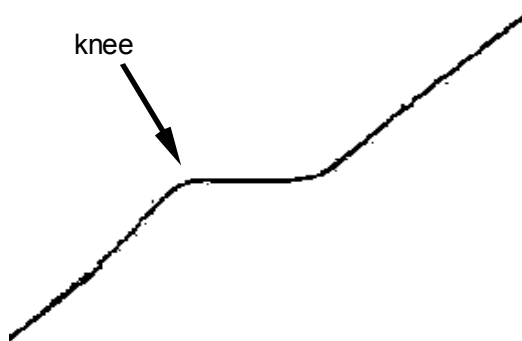


Figure 3-7 The “knee” in the V - I characteristic.

To automate this procedure, switch the function switch (1) from $V-I$ to $V-\Phi$. In this new mode, all of the controls on the Mr. SQUID[®] control box work the same way as before, except for the amplitude control (4). Instead of controlling the sweep of the drive current through the SQUID, it now controls the amplitude of the current through the modulation coil, which is linearly related to the magnetic field applied to the SQUID. To view as many $V-\Phi$ periods as possible, turn the amplitude control (4) in the clockwise direction. Depending on the particular SQUID and coil in your probe, you should be able to see at least four or five periods of oscillation, as shown in Figure 3-8.

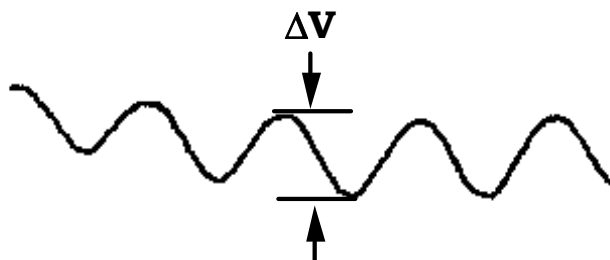


Figure 3-8 A typical Mr. SQUID[®] $V-\Phi$ characteristic. The maximum ΔV may range from 10 to 30 μV or higher.

The voltage change that occurs due to the influence of the magnetic field appears now on the vertical axis of your display device. The voltage amplification provided by the Mr. SQUID[®] box is unchanged from before. To determine the actual voltage across the SQUID, you must divide by 10,000. However, since the SQUID modulation signals are smaller than the junction voltages you examined earlier, you will need to increase the sensitivity of the vertical scale on your display device. The maximum peak-to-peak voltage swing of the SQUID modulation in Mr. SQUID[®] (ΔV) typically is between 10 and 30 μV (or 100 to 300 mV output from the front panel of the Mr. SQUID[®] control box). Depending on the setting of the amplitude control, you may wish to change the x sensitivity to more conveniently view the oscillations of the SQUID.

In addition, it may be necessary to use the position knob on your output device to center the curve. If your oscilloscope can be operated in an AC-coupled mode on the vertical channel, you can use this mode for more convenient viewing of the $V-\Phi$ curve (never use the AC mode to look at the $V-I$ curve, or it will be completely distorted on the oscilloscope screen.) You should see a curve that resembles the one shown in Figure 3-8. Depending on the particular device and on the settings on the control box, you may see many more periods than shown here. At this point, you can try to maximize the signal by fine-tuning the current bias control (3) to the most sensitive part of the $V-I$ curve (just keep your eye on the $V-\Phi$ curve as you "tweak" the current bias control until you get the maximum modulation). There will be some setting of the current bias control that gives the largest modulation amplitude.

Notice the effect that the flux bias control (2) has on the $V-\Phi$ curve. It allows you to set the central value of applied flux about which the amplitude control sweep varies. In other words, this control allows you to apply a static magnetic field to the SQUID on top of the oscillating field applied with the amplitude control. Turning the flux bias control will therefore allow you to move left and right along the $V-\Phi$ curve and thereby explore more of it than the amplitude sweep permits. You can accomplish the same thing in a less controlled manner by waving a small permanent magnet near the probe. Another way to see the effect of an additional applied field is to rotate the entire dewar. This rotates the SQUID with respect to the earth's magnetic field and causes a shift. Actually, the magnetic shield on the probe screens out most of the earth's field, but the amount of field that gets by the shield is quite enough to move the $V-\Phi$ pattern noticeably on the screen.

Later on, you may want to warm up the probe to room temperature to remove the magnetic shield from the bottom of the probe. This may be done by loosening the small setscrew that supports the shield. Set both the shield and the screw aside in a safe place so that they can be reinstalled later. If you now cool down the probe and set up the $V-\Phi$ measurement, you will find that the SQUID is tremendously more sensitive to its environment. In fact, you may have a great deal of difficulty in getting a good $V-I$ curve without flux trapping (see the discussion in Section 6). Assuming you succeed in observing the $V-\Phi$ curve without the magnetic shield (which may be impossible in many environments), you will find that almost any magnetic disturbance anywhere near the dewar will be visible on an oscilloscope screen. Try swiveling a metal chair, for example!

The most sensitive mode of operating a SQUID is to "flux-locked" the SQUID using closed loop feedback electronics. In the flux-locked loop (FLL) mode, a feedback current is used to counteract any change in external magnetic field. By measuring the amount of feedback current, it is possible to detect magnetic fields corresponding to a tiny fraction of the characteristic field required to produce a quantum of flux on the SQUID. This experiment is detailed in Section 7, Advanced Experiments.

3.8 Additional SQUID Measurements

Now that you can measure a variety of properties of the SQUID in the Mr. SQUID[®] probe, you can determine a key parameter of the device, namely the β_L parameter. This is defined by

Eqn. 3-1
$$\beta_L = \frac{2I_c L}{\Phi_0}$$

where L is the inductance of the SQUID loop.

Earlier we mentioned that the maximum modulation voltage depth ΔV as measured from the $V-\Phi$ curve is related to the $I_c R_N$ product that can be determined from the $V-I$ curve. As we will discuss in Section 5, this relationship can be expressed simply in terms of the β_L parameter.

Eqn. 3-2
$$\beta_L = \frac{4I_c R_N}{\pi \Delta V} - 1$$

The above expression provides an approximate way to determine the β_L parameter empirically (*i.e.*, without knowing the inductance L of the SQUID). This expression is strictly correct only if

the critical currents of the two junctions are equal and only if thermal noise effects are negligible. Both of these are approximations for the junctions in your Mr. SQUID[®].

The inductance of the Mr. SQUID[®] chip (see Figure 3-6) may be written as the sum of three terms,

Eqn. 3-3
$$L = L_{sl} + L_k + L_j,$$

where L_{sl} is the inductance of the long slit in the SQUID body, L_k is the small kinetic inductance of the SQUID body (arising from the “inertia” of the electrons¹), and L_j is the inductance of the Josephson junction bridges, which also includes a small kinetic inductance contribution. The slit inductance per unit length is about 0.46 pH/μm, and the slit length (excluding the length of the junction bridges) is 125 μm. Then, $L_{sl} = 58$ pH. The kinetic inductance of the SQUID body is more difficult to determine precisely but is estimated to be about 7 pH. The inductance of the Josephson junction bridges is estimated to be about 8 pH, which includes the kinetic inductance contribution (the inductance per unit length of the bridges is much higher than 0.46 pH/μm because of the narrow width of the bridges). Thus, the total inductance is approximately $L = 73$ pH.

The horizontal axis of the $V-\Phi$ curve measures the current through the modulation coil, and this is linearly related to the magnetic flux in the SQUID. The current gain in the Mr. SQUID[®] control box is 10,000 V/A (*i.e.*, 1 Volt = 10^{-4} Amperes). The period of the modulation of the magnetic flux in the Mr. SQUID[®] loop is the flux quantum, Φ_0 (2.07×10^{-15} Wb in MKS units.) By measuring the amount of current (ΔI) in the coil that is required to produce a change of one fluxon through the hole of the SQUID, you can determine the mutual inductance (M) of the internal modulation coil with respect to the SQUID, using the following formula:

Eqn. 3-4
$$M = \frac{\Phi_0}{\Delta I}$$

You can find the value of β_L for the SQUID in your Mr. SQUID[®] probe using Eqn. 3-1, your measurement of I_c , and $L \approx 73$ pH. From the measured values of I_c and ΔV , you can calculate β_L using Eqn. 3-2. Compare these two values. Do they agree?

The fact that the values calculated using Eqn. 3-1 and Eqn. 3-2 do not agree was a mystery for a number of years after the 1986 discovery of high- T_c materials, as these equations worked quite well for SQUIDS made using traditional low- T_c materials. This lack of agreement was resolved in 1993 with the recognition that thermal effects were playing a large role in the behavior of high- T_c SQUIDS.² The lack of agreement between Eqn. 3-1 and Eqn. 3-2 is in large part due to the fact that the Mr. SQUID[®] is at a relatively high temperature where thermal energies ($k_B T$) are no longer small compared to the energy of a flux quantum (Φ_0^2/L). The relationship between the observed voltage modulation and β_L at a nonzero temperature T changes Eqn. 3-2 to:²

¹ *Principles of Superconductive Devices and Circuits*, T. Van Duzer and C.W. Turner (Elsevier, New York, 1981) pp 114-116.

² K. Enpuku, Y. Shimomura, and T. Kisu, “Effect of thermal noise on the characteristics of a high T_c superconducting quantum interference device”, *J. Appl. Phys.* **73**, 7929 (1993)

$$\text{Eqn. 3-5} \quad \beta_L = \frac{4I_c R_N}{\pi \Delta V} \left(1 - 3.57 \frac{\sqrt{k_B T L}}{\Phi_0} \right) - 1$$

Figure 3-9 illustrates the differences between the β_L values calculated using Eqn. 3-1, Eqn. 3-2, and Eqn. 3-5.

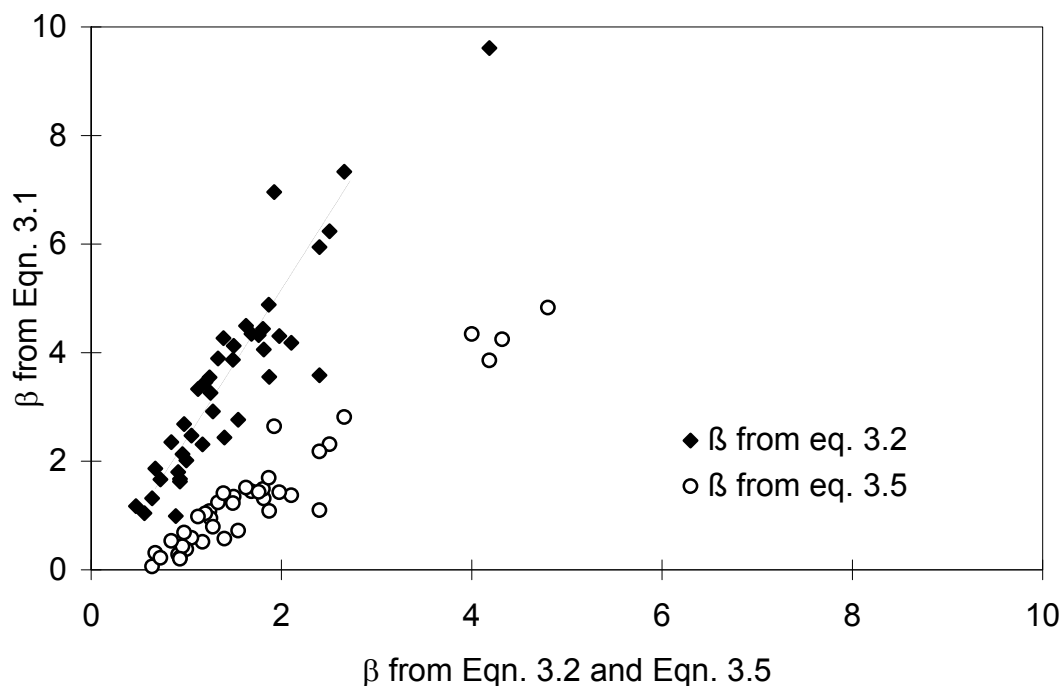


Figure 3-9 Values of $\beta = 2I_c L / \Phi_0$ versus measurements of β based upon $I_c R_N / \Delta V$ for 44 Mr. SQUID[®] probes.

As one can see from Figure 3-9, the method of calculating β_L that takes thermal effects into account agrees quite well with the inductive β_L measurements.

On the following page, we include a data sheet for your SQUID. You may wish to use it (or better still, a photocopy) to enter your measurements on Mr. SQUID[®]. An interesting and important issue for SQUID applications is how the SQUID sensor varies with age. You can track this with Mr. SQUID[®] by filling out a copy of the data sheet each time you use the system.

3.9 Summary of Basic Experiments

By going through the previous set of experiments, you should have been able to observe the fundamental properties of Josephson junctions and SQUIDs and calculate the values of these key parameters:

- Critical current of the SQUID, $2I_c$,
- Normal-state resistance of the SQUID, $R_N/2$,
- Characteristic voltage of the SQUID, $I_c R_N$,

- Maximum voltage modulation depth, ΔV ,
- Inductance of the SQUID, L , and
- Modulation parameter β_L determined using two methods.

More advanced experiments with SQUIDs, including those that use the external modulation coil, can be found in Section 7, Advanced Experiments.

Mr. SQUID[®] Data Sheet

SQUID Serial Number:		
Date:		
Parameter	Units	Measured Value
SQUID Critical Current, $2I_c$	μA	
SQUID Normal Resistance, $R_N/2$	Ω	
Characteristic Voltage, $I_c R_N$	μV	
Modulation Depth, ΔV	μV	
SQUID Inductance, L	pH	

β_L from Modulation Depth:	
β_L from Inductance:	