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June 1997

TEMPERATURE-DEPENDENT RESPONSE OF A **DC SQUID**

Harold S. Wilson

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Approved by: R.E. Erickson
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Abstract

This report describes an experimental investigation of the temperature dependences of the output of a DC SQUID (SQUID = Superconducting Quantum Interference Device) and the mutual inductance between the SQUID and external electronics. The method of measuring tiny changes in the mutual inductance M is described in detail. It is concluded that the temperature dependence of M is

$$\frac{1}{M}\frac{dM}{dT} = +3.1 \times 10^{-3} \, / \, \mathrm{K}$$

which is large and of the opposite sign to the expected result. The method used also revealed small nonlinearities in the SQUID feedback electronics. The SQUID was cooled in the Earth's magnetic field and the temperature and pressure dependence of the SQUID output signal was large.

Résumé

Dans ce rapport nous décrivons une recherche expérimentale des variabilités avec la température du rendement de sortie d'un DC SQUID (SQUID = Superconducting Quantum Interference Device c.-à-d. un dispositif supraconducteur d'interférence quantique) et l'induction réciproque entre le SQUID et les électroniques externes. Nous décrivons en détail la méthode pour mesurer des changements minuscules de l'induction réciproque M. Nous concluons que la variabilité avec la température de M est

$$\frac{1}{M}\frac{dM}{dT} = +3.1 \times 10^{-3} \, / \, \mathrm{K}$$

ce qui est grande et du signe opposé au résultat anticipé. La méthod utilisé a aussi révélé de petites non-linéarités dans les électroniques de rétroaction du SQUID. Le SQUID s'est refroidi dans le champ magnétique de la Terre et la variabilité avec la température el la pression du signal de rendement de sortie du SQUID était grande.

Executive Summary

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Title : Temperature-Dependent Response of a DC SQUID
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Background

The Surveillance and Ship Silencing Group at Esquimalt Defence Research Detachment (EDRD) of Defence Research Establishment Atlantic is investigating the feasibility of using SQUID magnetic gradiometers (SQUID=Superconducting Quantum Interference Device) to detect and localize targets in airborne antisubmarine warfare. A major part of this program has been investigations of noise in moving gradiometers. One of the sources of noise is believed to be SQUID signals that originate in changes in the superconductors when small temperature fluctuations occur. Temperature fluctuations are caused by motion of stratified liquid helium in the sensor and by small pressure changes. The temperature changes in turn result in a small change in the magnetic behaviour of the superconductors.

This report describes an experimental investigation of temperature-dependent changes in the coupling between a Nb thin-film DC SQUID and external electronics. This is equivalent to a gain change in the SQUID. The method used also allowed an investigation of weak nonlinearities in the SQUID electronics. Also presented are measurements of the temperature dependence of the output signal for a shielded SQUID.

Principal Result

The effective mutual inductance that couples the SQUID to the electronics is temperature dependent, and the change with temperature variations is opposite to that expected. The SQUID electronics exhibit a weak nonlinearity.

Significance of Results and Future Research

If the temperature in a moving SQUID gradiometer fluctuates, the altered SQUID-electronics coupling will introduce noise in addition to the previously-known temperature dependence of the SQUID output signal. It may also introduce a nonlinearity into the SQUID system. This may be important in understanding noise in the superconducting gradiometer being built for EDRD by CTF Systems, Inc., of Port Coquitlam, B.C. which uses thin-film DC SQUIDs to sense the magnetic field.

Table of Contents

List of Tables

List of Figures

1. Introduction

The Surveillance and Ship Silencing Group at Esquimalt Defence Research Detachment (EDRD) of Defence Research Establishment Atlantic (previously the Magnetic Anomaly Detection Group of Defence Research Establishment Pacific) are investigating the application of SQUID magnetic gradiometers in airborne antisubmarine warfare (SQUID= Superconducting Quantum Interference Device). A test of a gradiometer in 1983 showed that SQUID sensors could be made to operate reliably in field trials, but that the gradiometer showed greatly enhanced noise when moving. Since then, a major part of EDRD's program has been an investigation of sources of noise in moving SQUID sensors.

EDRD's SQUIDs are mounted in vertical dewars and are cooled by direct immersion in liquid helium which maintains the sensor temperature at the helium boiling point (4.22 K at normal atmospheric pressure). However, liquid helium tends to stratify, so motion can make the SQUID temperature fluctuate resulting in elevated sensor noise if the SQUID output is temperature dependent. Further, it is possible that pressure fluctuations could compress or deform components of the sensor, resulting in elevated noise. Thus it is important to study the effects of pressure and temperature fluctuations in mobile SQUID systems.

Refs.[1-3] presented DREP's previous studies of temperature-dependent signals in shielded RF SQUIDs. This report describes a set of measurements performed on a single shielded Nb thin-film DC SQUID using the digital SQUID electronics described in Ref.[4]. The combination of the DC SQUID's low noise and resetting SQUID electronics means that, for the first time, we have been able to measure the temperature dependence of the SQUID gain as well as the SQUID output. ('SQUID gain' is defined in Section 2(i) below.) The surprising result of this study is that the SQUID gain is much more temperature dependent than expected.

A brief analysis of a SQUID sensor is provided in Section 2, which shows the relation between the output of the electronics and the magnetic fluxes in the SQUID. Section 2 also shows how resetting systems, such as EDRD's electronics, can measure extremely small changes in the gain of the SQUID sensor.

Section 3 discusses the simple experimental procedures used here and Section 4 gives the results. The results derived from measurements of the system gain are displayed in Figures 6 and 7.

Section 5 provides a brief discussion and speculates on the physical origin of the temperature dependence of the SQUID gain.

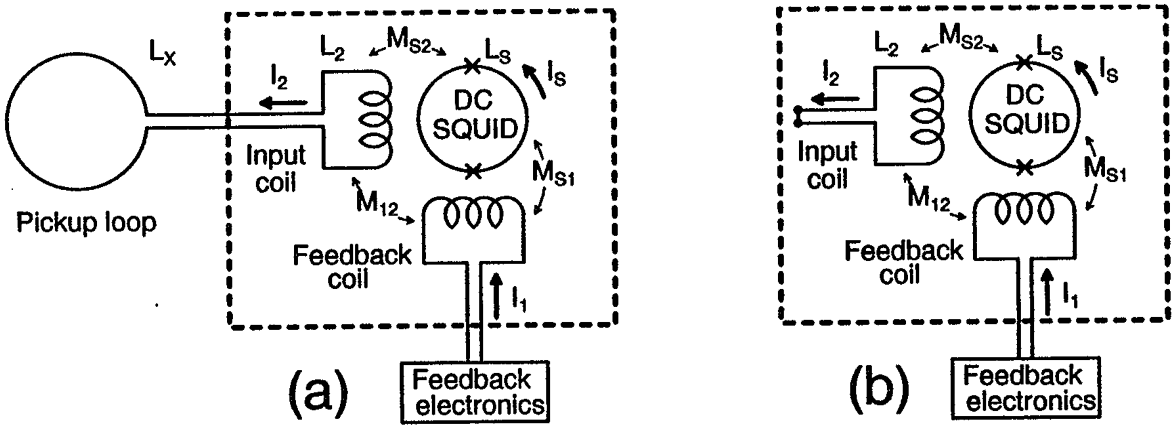


Figure 1. Schematic drawing of a DC SQUID showing coupling coils and mutual inductances. I_1 is the feedback current required to keep the SQUID flux constant. (a) A SQUID coupled to a pickup coil for sensing external magnetic fields. (b) A shielded SQUID. The heavy dashed lines indicate the superconducting magnetic shield that surrounds the SQUID. The connection of the SQUID output to the electronics is not shown.

2. System Analysis

2(i) Magnetic coupling in the SQUID

The system analysis presented here is basically the same as the analysis of SQUIDs presented in Section 5(b) of Ref.[5]. Figure 1 shows a DC SQUID and the coils that couple it to the magnetic field and the feedback electronics. The bias current and the IF amplifier have been omitted for simplicity : see Ref.[4] for a more detailed discussion of DC-SQUID electronics. The magnetic fluxes Φ_S and Φ_2 linking the SQUID and the input loop (pickup loop and input coil) are

$$\Phi_S = \Phi_{SX} + I_1 M_{S1} + I_2 M_{S2} + I_S L_S \quad , \tag{1}$$

$$\Phi_2 = \Phi_{2X} + I_1 M_{12} + I_2 \left(L_2 + L_X \right) + I_S M_{S2} \quad . \tag{2}$$

The feedback electronics adjust I_1 to maintain $\Phi_S = n\phi_0$ and $I_S = 0$ (n is an integer and $\phi_0 = 2.1 \times 10^{-15}$ Wb is the flux quantum). (Ref.[4], Section II.2 discusses a deviation from $\Phi_S = n\phi_0$, but the difference is a constant and it makes no difference to the discussion.) Φ_2 is the magnetic flux linking a loop of superconductor so it is constant in time. Φ_{SX} and Φ_{2X} are the total fluxes applied to the SQUID and input coil by external magnetic fields and by fields 'frozen' in superconductors when they were initially cooled below their transition temperature. From (1) and (2), I_1 is :

$$I_1 = \frac{M_{S2}}{M\left(L_2 + L_X \right)} \Phi_{2X} + \frac{n\phi_0}{M} - \frac{\Phi_0}{M} \quad , \tag{3}$$

where

$$M = M_{S1} - \frac{M_{12}M_{S2}}{L_2 + L_X} \qquad \text{and} \qquad \Phi_0 = \Phi_{SX} + \Phi_2 \frac{M_{S2}}{L_2 + L_X} \quad .$$

M is the effective mutual inductance between the feedback coil and the SQUID and it acts like a gain parameter for the SQUID sensor.

In a shielded-SQUID (Figure 1(b)), the external pickup loop is disconnected (L_X=0) and Φ_{2X} becomes constant and so (3) may be written more simply by redefining Φ_0 :

$$I_1 = \frac{n\phi_0}{M} - \frac{\Phi_0}{M} \quad , \tag{3a}$$

where the new definition of Φ_0 is

$$\Phi_0 = \Phi_{SX} + \Phi_2 \frac{M_{S2}}{L_2} - \Phi_{2X} \frac{M_{S2}}{L_2} \quad .$$

In ideal operation of a shielded SQUID, everything on the right side of (3a) is constant in time, except, in resetting electronic systems, n. This note reports a temperature dependence in the effective mutual inductance M (the SQUID 'gain'). Because M is a function of several inductances, it is not possible from this measurement alone to isolate the particular aspect of the SQUID that is temperature dependent.

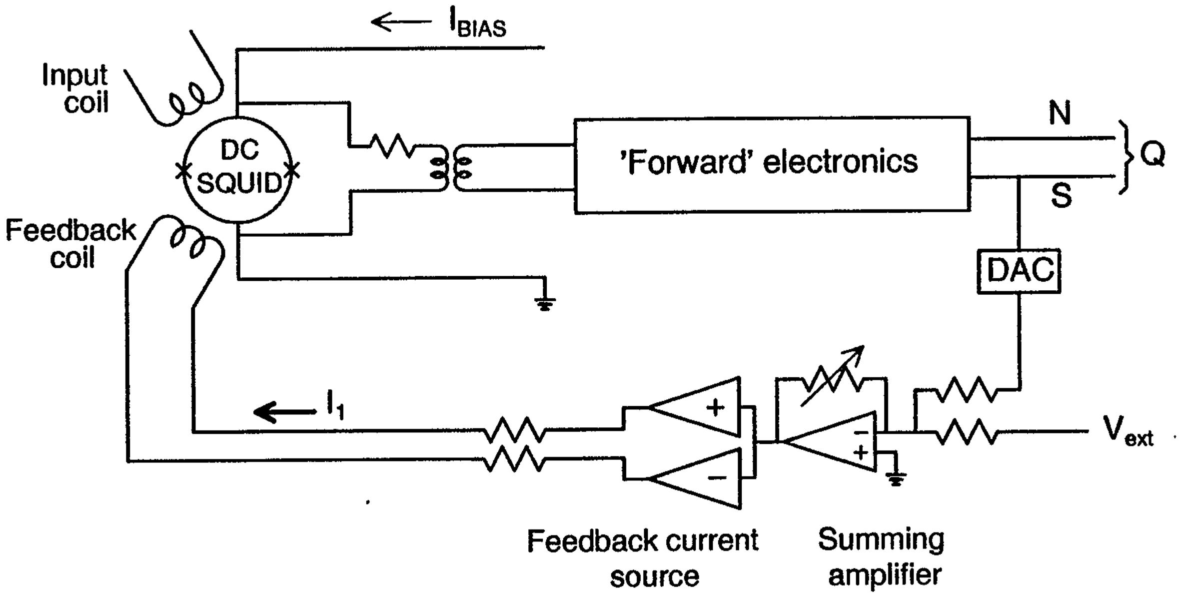
2(ii) SQUID electronics and reverse gain

In order to obtain a SQUID system with unlimited dynamic range, EDRD and CTF Systems have produced electronics that reset the feedback current I_1 so it never applies more than $\pm 1\phi_0$ to the SQUID (i.e. $|I_1 M| \leq \phi_0$). The operation of the SQUID electronics and the output noise contributed by the resets has been described in detail previously (see Ref.[4], Sections II.3.i, III.4 and III.6.iv, and Ref.[5],Section 10(b)), but the discussion is repeated here because it is central to the method of measuring small changes in parameter M.

Resetting SQUID electronics exploit the fact that the response of a SQUID to an applied magnetic flux is periodic with period ϕ_0, where ϕ_0 is the flux quantum. The electronic output is the sum of a integer counter N and a fractional part S :

$$Q = N + S$$

where S is restricted to the range $-1<S<1$. When the inputs change enough that S exceeds +1, the system increments N by +1, S is reduced by ~1, n is reduced by 1 (see (3) and (3a)), and the feedback loop starts operation with the SQUID flux reduced by exactly ϕ_0. Since the SQUID response is supposed to be perfectly periodic with period ϕ_0, the sensor operation should be unchanged.



<u>Figure 2</u> The SQUID feedback electronics showing the summing amplifier and feedback current source that control the reverse gain.

Figure 2 is a block diagram of EDRD's digital SQUID electronics showing the coupling to the SQUID, the feedback current source and the external input which is included for test purposes. The current in the feedback loop is related to the electronics output S and the external input V_{ext} by

$$I_1 = -\alpha S - \beta V_{ext} \quad , \tag{4}$$

where α and β are gain parameters determined by the transfer functions of the DAC (Digital to Analog Converter), resistor ratios in the summing amplifier, and the total resistance of the feedback line. α and β are independent of the inductances and mutual inductances of the SQUID components and the capacitance and inductance of the feedback line at the low frequencies at which SQUID electronics operate (<100 kHz). (4) assumes that the feedback current is a linear function of the electronics output S and V_{ext}. In fact, DACs have unequal steps and the summing amplifier and feedback-current source have nonlinearities.

The dimensionless reverse gain g of the feedback electronics is given by

$$g = \alpha M/\phi_0$$

and the flux applied to the SQUID by the feedback electronics is just $-gS$. Substituting for I_1 in (3a) gives the relation among S, V_{ext} and n for a shielded SQUID :

$$S = \frac{1}{g}\left(\Phi_0/\phi_0 - n\right) - \frac{\beta}{\alpha} V_{ext} \quad . \tag{5}$$

The feedback flux applied to the SQUID and the electronic outputs N, S, and Q, just before and just after a ΔN=+1 reset, are listed below.

	Before	After
$\Phi = MI_1$	$-g\phi_0$	$(1-g)\phi_0$
N	$N_1 - 1$	N_1
S	1	$1 - 1/g$
$Q = N + S$	N_1	$N_1 + 1 - 1/g$

Note that a step of height $1-1/g$ appears in the output Q each time the loop is reset upwards (and a step $-1+1/g$ for ΔN=-1). At the optimum setting, g=1 giving zero step height ; the difference e=g-1 is called the reverse-gain error. (For $|e|<<1$ (i.e. the usual case), the step height is very nearly equal to e.) The jump is independent of the source of signal variation (i.e. it could be due to magnetic-field changes in an unshielded SQUID, or due to the external input in a shielded SQUID).

The changes in M reported here were observed by measuring changes in the reset-step height at different SQUID temperatures and pressures.

2(iii) Measuring the reverse-gain

The method of measuring the reset-step height and the reverse gain is straightforward. EDRD's digital SQUID electronics run at a loop sample rate of 100 kHz. Every 10th sample is transmitted via optical fibre to a data-acquisition computer which low-pass filters the signal and then stores it on a disk, usually at a subsample rate of 312.5/s (=10 kHz/32). Following a loop reset, the electronics transmits a flag to the data-acquisition computer, which stores the flag information in the output file including which point in the 10-kHz data stream had the flag. Thus the time of the loop reset is fixed to a 100-μs interval. Ref.[4] has a complete discussion of the digital feedback loop.

To determine reset-step heights, the 312.5/s data are scanned for flagged points, and if possible the basic SQUID signal is subtracted. (For example, if the signal is due to a sinusoidal V_{ext}, a sinusoid would be subtracted from the SQUID output.) Segments of data containing flags are shifted so that the flagged points are aligned and then an average of all the data is calculated. Knowing the exact flag-point positions (i.e. to within 1/32 point for 312.5/s data) and the low-pass filter allows a precise determination of the shape that the step-edge should have. Finally, the aligned and averaged data are fit to a smooth background plus the computed step-edge shape.

With EDRD's shielded DC SQUID and a stack of 350-400 steps, this procedure gave step-height measurements with statistical errors of $\sim 5\times10^{-6}$.

3. **Experimental details**

This section describes the method for raising and measuring the SQUID temperature and discusses the details of the experimental methods and the equipment used.

3(i) SQUID

The measurements were made on a DC SQUID manufactured by CTF Systems. It is an integrated device using a Nb-Al-Al_2O_3-Nb Josephson Junctions with a square SQUID washer, and Nb coupling coils (T_C~9.2 K). The details of the SQUID are not important for this discussion except to note that the Nb film thickness is ~0.3 μm, the strip width for the coupling coils is ~10 μm, and the central hole is ≥150 μm on a side. Superconducting films are separated by ~0.8 μm of insulator.

3(ii) The trapped magnetic field

The SQUID was mounted on a stainless-steel probe which was inserted into a 100-l liquid-helium storage dewar. There was no attempt to reduce the magnetic field during the cooldown, so it is expected that the superconducting components trapped the applied field which was ~20 μT horizontal and 50 μT vertical. (Since the thin-film SQUID is mounted vertically, it is expected that only the horizontal field will apply flux to the SQUID and be trapped in the thin-film components.) Expulsion of the magnetic field by the Meissner effect will not reduce the trapped field for superconductors as far from spherical as thin films and cylindrical SQUID shields.

The critical magnetic field of bulk Nb is 40 mT, although it may be as low as 2.5 mT in stressed thin films (Ref [6]). In any case, it is ≤2% of the critical field, so we expect that the trapped field should have almost no measurable effect on the inductances in the SQUID which control the SQUID gain parameter M. Previous experience (Refs.[1-3] suggest that cooling the SQUIDs in the Earth's magnetic field increases the temperature-sensitivity of the SQUID output.

3(iii) Changing the SQUID temperature

The temperature of the SQUID was raised by increasing the helium-gas pressure in the storage dewar and then maintaining the higher pressure until heat entering the dewar raised the liquid-helium temperature to its new boiling point. This was a very slow process because storage dewars are designed to admit very little heat and they have a large heat capacity. Therefore the measurements reported here required 60 hours for the temperature to rise and reach equilibrium 0.25 K and 200 torr above the starting temperature and pressure. To ensure that equilibrium had been reached, the system was left at the elevated pressure for a further 24 hours. The temperatures were reduced by decreasing the pressure so that, at each pressure, the liquid was its boiling temperature.

The major problem here is helium stratification in the storage dewar. With very little heat entering through the dewar wall, there is not enough convection to keep the liquid helium mixed, and the helium spontaneously stratifies : the helium at the surface will become warmer than the helium near the bottom. This makes it difficult to be sure that the SQUID temperature really is the boiling temperature of liquid helium.

3(iv) Measuring the SQUID temperature

There was no easy way to attach a temperature-sensor to the probe carrying the shielded DC SQUID, so a different approach was needed. Since the Josephson-Junction critical currents in the DC SQUID drop quickly as the temperature rises, it was determined that the SQUID itself could be used as a thermometer.

Figure 3 is a schematic outline of the IV curves for a DC SQUID at 4.2 K and at slightly-higher temperature (4.5 K in the figure). If the bias current (see Figure 2) is set at I_{TEST} as shown in Figure 3(a), so the SQUID has a very small response at 4.2 K, then the SQUID's response will be strongly dependent on the critical currents and, thus, on the temperature. Figure 3(b) sketches the voltage that appears across the SQUID as the flux applied by the feedback coil is swept through several ϕ_0's. The height of the voltage pattern is a measure of the SQUID temperature.

During the experiment, each temperature measurement was made by reducing the bias current to I_{TEST} and then opening the feedback line between the DAC and the summing amplifier (Figure 2). An external signal was applied so the SQUID flux was a ±2 ϕ_0, 5.5-kHz triangle wave, giving a slew rate of 44000 ϕ_0/s. This slew rate was chosen because 44 kHz lies near the peak of the

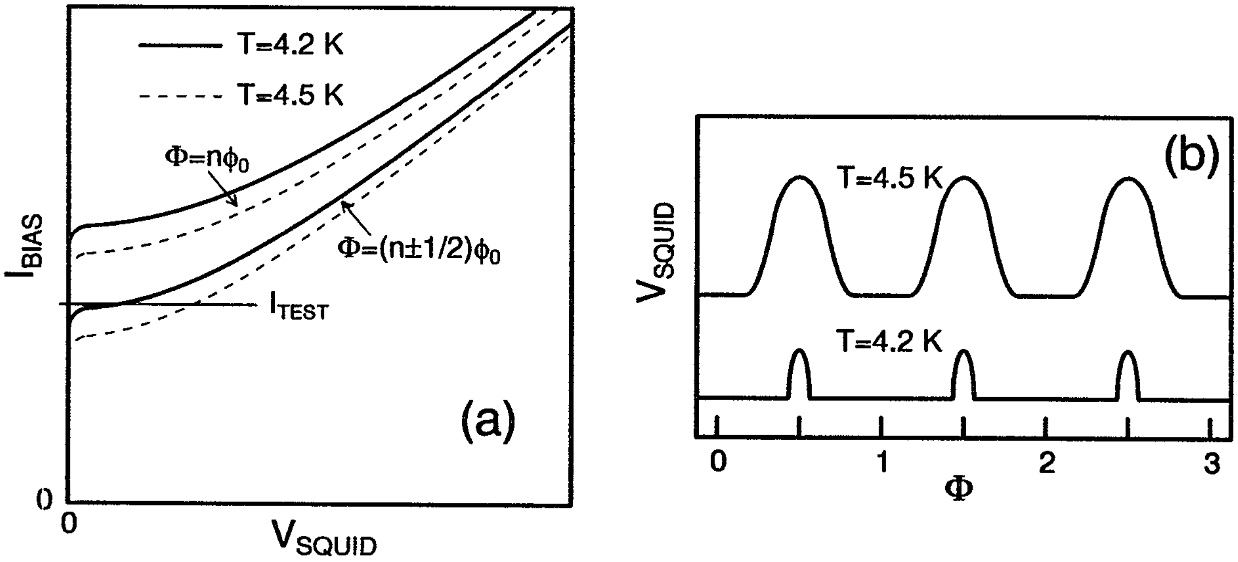


Figure 3 (a) A sketch of the I-V curves for a DC SQUID. I_{TEST} is the SQUID bias current for temperature measurements. (b) The voltage patterns observed at the amplifier output at different SQUID temperatures.

SQUID amplifier gain (see Figure 6 of Ref.[4]). The peak-to-trough amplitude of the amplifier output was measured with an oscilloscope.

This method must be calibrated each time the SQUID is cooled through its superconducting transition temperature because the critical currents of the Josephson Junctions vary from one cooldown to the next if the Earth's magnetic field is trapped in the SQUID. To calibrate the thermometer, the SQUID voltage pattern is measured when the liquid helium is 'known' to be at its boiling point. Thus the voltage pattern is measured before the dewar pressure is raised, after equilibrium is reached at high pressure, and at one or two points while the pressure is being reduced.

In this experiment, temperatures were measured at two different values of I_{TEST}. Comparison of the two sets of temperatures shows that this method was able to measure the temperature with a random error of 7 mK (RMS). This combines the errors in setting I_{TEST} to the same levels each time the temperature is measured and in estimating the height of the SQUID voltage patterns on the oscilloscope. This is probably about the same as the systematic error due to liquid-helium stratification which resulted in the SQUID temperature lying below the boiling temperature.

This method of thermometry is far from ideal. It is time consuming to reset the SQUID electronics for each temperature measurement, and it is impossible to measure the temperature while recording SQUID data. However, for this experiment it was adequate.

3(v) Collecting reset-step data

In a shielded SQUID, the only source of signal variation is the external input V_{ext}. In these experiments, a 0.406-Hz sinusoidal signal was applied to the external input so the SQUID output ranged from -2.11 to +1.97 ϕ_0. Thus, on each cycle, as shown in Figure 4, the electronics were reset up 3 times up and down 3 times, with a minimum separation of 0.19 s between resets, and the SQUID operated with 4 different values of flux Φ (equivalently, 4 different feedback currents I_1). This slow rate of data collection was chosen so the resets would be well separated in time.

In preliminary experiments, it was found that the quality of the external signal made a significant difference to the analysis. The 'best' sine wave sources use an output derived from a digital signal generator and a DAC, and consequently contain small steps where the DAC output changes. This is not usually a problem, but a DC SQUID is an extraordinarily low-noise device, and the DAC edges in V_{ext} appeared clearly in the SQUID output after the step edges were aligned and averaged. To eliminate this problem, the 0.406-Hz sinewave was smoothed with a 0.3-Hz second-order low-pass filter. This added some 2nd and 3rd-harmonic distortion to the signal, but removed the source-DAC edges. Thus any edges that appeared in the output were due only to the SQUID and its electronics, particularly the DAC in the feedback line.

3(vi) Reverse-gain adjustment

Figure 2 shows a variable resistor that is included in the electronics so the reverse gain can be adjusted, but this presents a problem maintaining a constant g since variable resistors are strongly

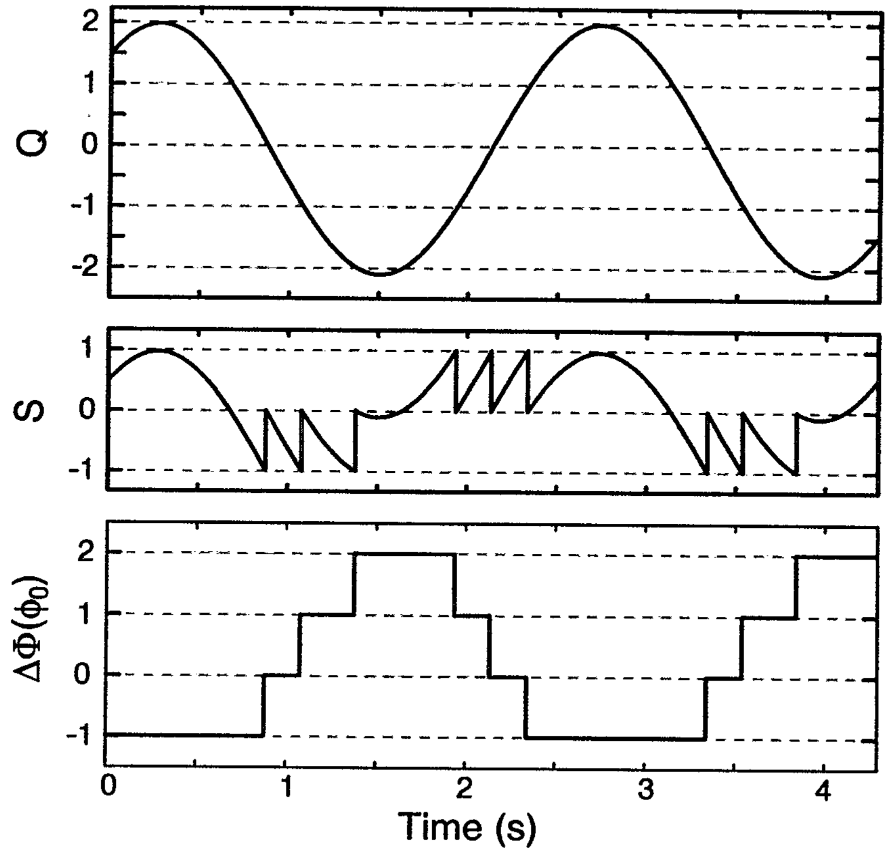


Figure 4 *Response to a sinusoidal V_{ext}. Q and S are the total and fractional outputs of the electronics. $\Delta\Phi$ ($=I_l/M$) is the difference between the SQUID flux and the response to $V_{ext}=0$.*

temperature dependent, and it is easy to change their resistance by touching them. Therefore, for these measurements, the reverse-gain was adjusted and then the variable resistor was removed from the circuit and replaced with a fixed, high-quality metal-film resistor of the same value. This ensured that the reverse gain was determined only by the ratios of fixed resistors and the gain of the DAC. During the experiment, the room temperature did not vary outside the range 21-26°C.

4. Results

The experiment was performed over a period of 8 days because of the long equilibration times required. At the start of the experiment, the shielded SQUID in the liquid helium was raised so it was 5 cm below the level where the temperature started to rise. This meant that the SQUID was well immersed in liquid, but also that it was below the surface stratified layer. This probably contributed to the long time to reach equilibrium and some temperature drifts that appeared during the pressure reduction phase of the experiment.

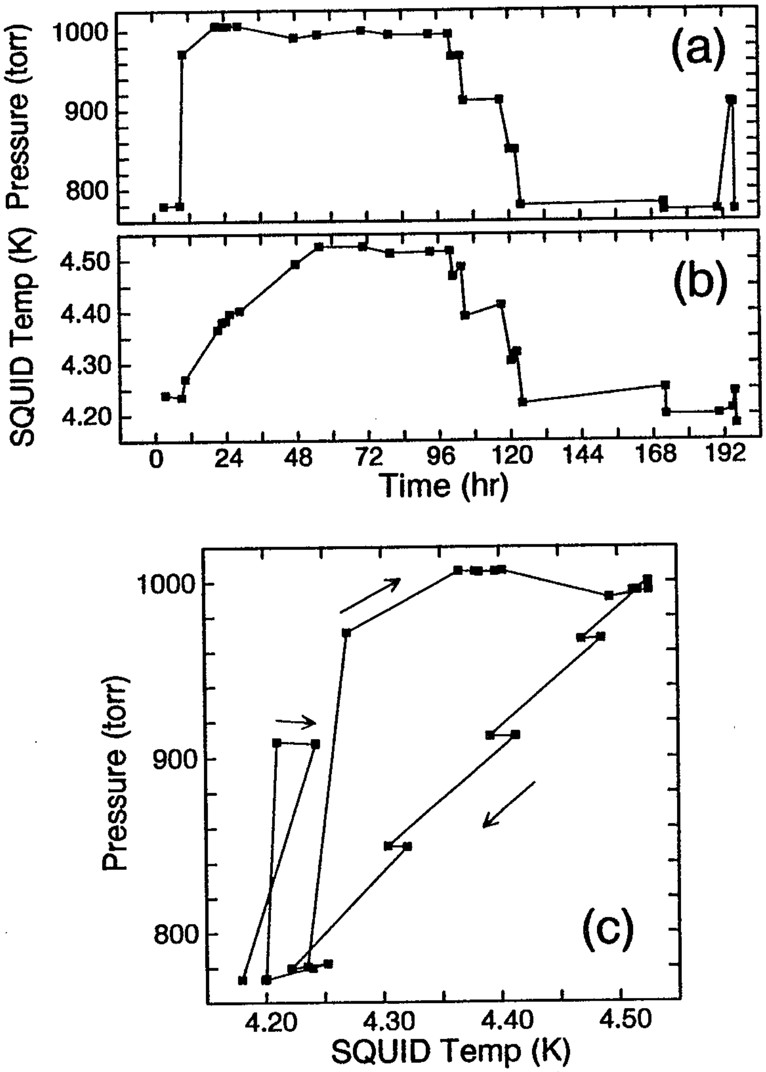


Figure 5 *(a) The pressure and (b) the temperature during the experiment.*
(c) A plot of pressure against temperature.

Figure 5 shows the pressure and temperature during the experiment. The first part of the experiment consisted of a long run in which the He pressure was raised from 780 to 1000 torr, held near 1000 torr for 88 hours, and then reduced to 770 torr in 4 stages over a period of 24 hours. This was followed by a second run where the pressure was raised from 770 to 910 torr and then returned to 770 torr after 1.5 hours. Figure 4(c) plots P *vs.* T and shows that enough of the (P,T) plane was covered to make it possible to separate pressure and temperature-dependent variations in the SQUID signals.

4(i) Reverse-gain temperature dependence

24 measurements of the step heights were made during the experiment (essentially, a run was done at each point in Figure 5 following the procedures described above in Section 3(v)). The step edges were separated into six categories according to the sign of the reset (up or down) and SQUID flux (see Figure 4), and then separate averages and statistical uncertainties were calculated for the positive and negative resets. The reset step heights were fit to a linear model of pressure and temperature dependence :

$$step = G_0 + \sigma_P(P - 760 \text{ torr}) + \sigma_T(T - 4.215 \text{ K}) \quad , \tag{6}$$

and the fit chi-square was estimated from the step-height uncertainty. For both signs of resets, the fit had $\chi^2 \sim 90$ for 21 degrees of freedom, so error estimates in the fit results were multiplied by a factor $\sqrt{90/20} = 2.1$ to account for the poor fit. The large value of χ^2 probably reflects uncertainties in the temperature estimates. Table I lists the values of G_0, σ_P, and σ_S.

The pressure dependence is essentially zero. This is not surprising since a pressure change of 200 torr should result in a negligible compression of the SQUID and SQUID shield, so it is expected that the inductances that define parameter *M* will be independent of pressure. We conclude that there is no significant pressure effect on the reverse-gain of the SQUID, and further analysis assumes only a temperature dependence. (A pressure dependence did appear in the experiment, and it is described in section 4(iii)).

In addition, the temperature dependence is nearly the same for the positive and negative resets. This makes sense : if the temperature dependence is due to the superconducting components of the SQUID, then the same variation in *M* occurs for both signs of resets.

Finally, there is a constant difference between the positive and the negative steps. Analysis of the difference shows that $G_0(+\text{ve})-G_0(-\text{ve})=(1.17\pm0.02)\times10^{-4}$ for all of the data, independent of pressure or SQUID temperature (the error is the standard deviation of the mean of 24 estimates). This difference is attributed to electronic nonlinearities in the DAC and the summing amplifier that drives the feedback current. On a positive reset, the DAC output switches from +1 to 0, while on a

Table I. The fit parameters for reset-step heights when pressure dependence is included in the fit (see (6)). The error estimates have been increased to account for the large χ^2 values of the fits.

	G_0	σ_P (torr^{-1})	σ_T (K^{-1})
positive resets	$(8.008 \pm 0.020)\times10^{-3}$	$(-1.2 \pm 2.4)\times10^{-7}$	$(3.20 \pm 0.18)\times10^{-3}$
negative resets	$(7.899 \pm 0.020)\times10^{-3}$	$(-1.7 \pm 2.4)\times10^{-7}$	$(3.19 \pm 0.18)\times10^{-3}$

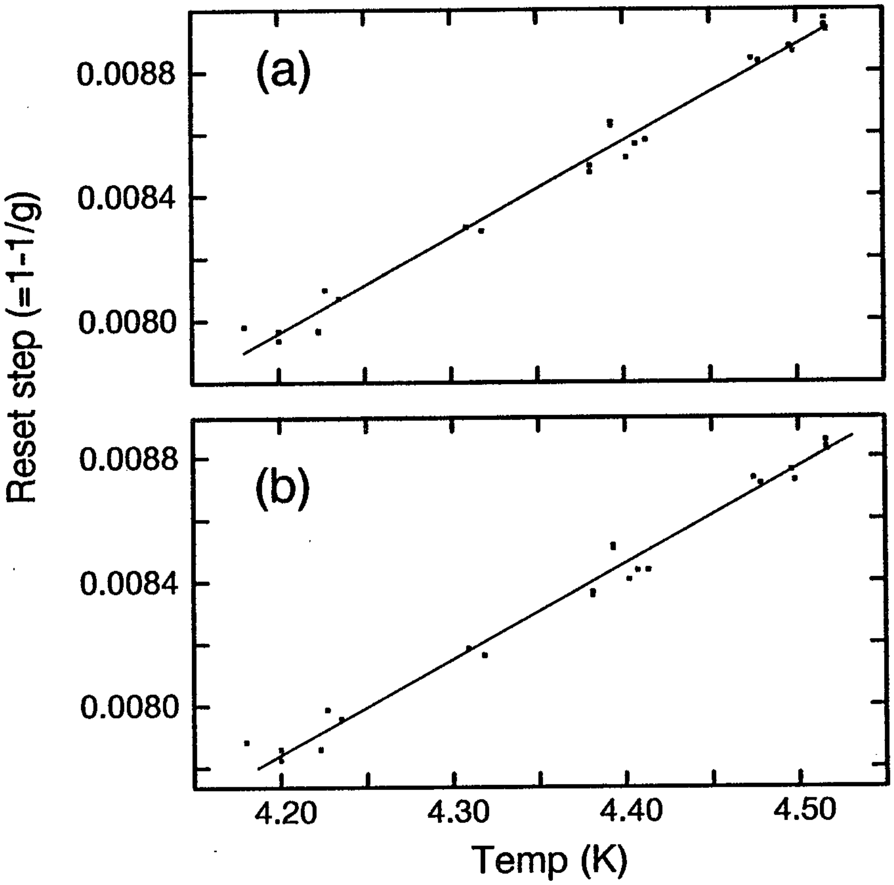


Figure 6 *The temperature dependence of the average reset-step height for (a) positive resets and (b) negative resets. The lines show the best fit to the temperature dependence (slope=3.09×10^{-3}/K). The difference between positive and negative resets is attributed to electronic nonlinearities.*

negative reset, it switches from -1 to 0. If the DAC gain is slightly different for negative and positive inputs, then the reverse gains really will be different (in other words, (4) should be modified to include a small non-linear dependence on S). This sort of nonlinearity is well within the specifications for the 12-bit DAC used in EDRD's electronics.

There is a further level dependence in the step heights which we attribute to a small nonlinearity in the summing amplifier. This is discussed in section 4(ii) below.

Ignoring pressure effects, the step heights measured in the 24 runs are displayed in Figure 6. The straight line has slope σ_T=3.09×10^{-3} /K for both reset signs (this is the best fit value when pressure is not included, and the negative and positive resets are constrained to have the same σ_T).

4(ii) Reverse gain dependence on signal level

Sections 2(i) and 2(ii) emphasized that the magnetic flux linking the SQUID changes by ϕ_0 each time the feedback electronics are reset. The basic assumption is that the SQUID response is a periodic function of flux, with period ϕ_0, at least over the dynamic range of the input signals. Measurement of the reverse gain as a function of signal levels gives a direct way to detect nonlinearities in the transfer function between the loop output S and the flux applied to the SQUID (in other words to examine whether the simple linear model of (4) is adequate).

Figure 4 shows that there were six different electronic resets in this measurement (two reset signs and three different SQUID-flux levels). The reset step heights for the six transition types were calculated separately for each of the 24 step-height measurements, and then the differences among them were calculated. Figure 7 summarizes the step-height differences (i.e. the difference between the step heights for each of the six transitions and the average over all transitions). The error bars show the RMS deviation in the 24 measurements (i.e. the error bars are $\sqrt{24}\times$(standard deviation of the mean)).

Section 4(i) discussed the difference between the positive and negative resets and attributed it to DAC nonlinearity, although it did not rule out a nonlinearity in the summing amplifier. The difference among transitions of the same sign, but different SQUID fluxes, can be due only to (1) the

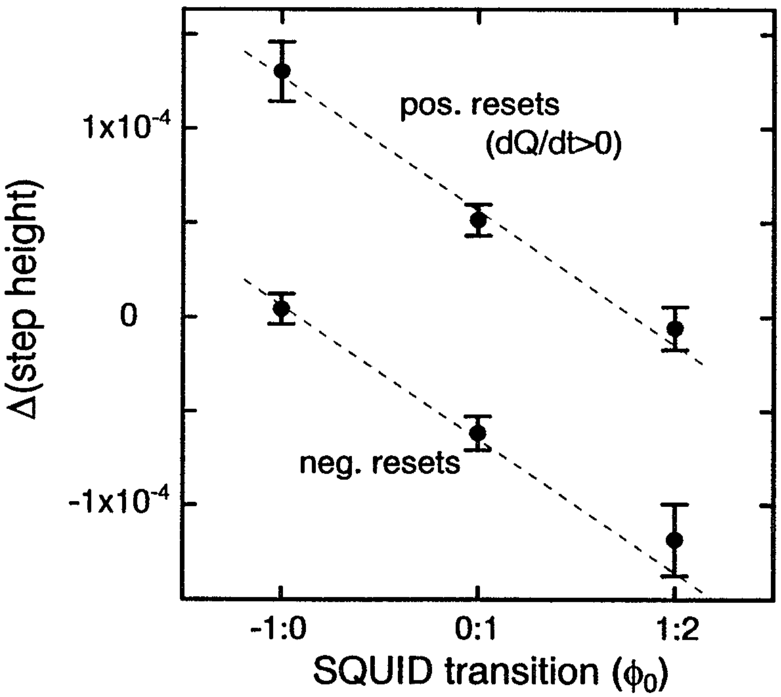


Figure 7 *The reset-step height as a function of SQUID flux (equivalently, as a function of feedback current I_1). The variation is attributed to nonlinearity in the summing amplifier/feedback current source.*

amplifier which sums the DAC output and the external input V_{ext}, and drives the feedback current, or (2) the SQUID.

The linearity of the summing amplifier/current source was tested by isolating it from the SQUID and the rest of the electronics and measuring its transfer function directly with digital voltmeters. In addition, harmonic-mixing measurements were made in which sinewaves of different frequencies were applied in place of the DAC output and V_{ext}, and a signal analyzer was used to search for the sum frequency in the output. Both measurements indicated quadratic nonlinearities within a factor of 2 of the nonlinearity required to explain the level dependence in Figure 6.

The summing amplifier and feedback current source used three operational amplifiers on a single Texas Instruments TLE2074C chip. This is a high-quality device, but it displays weak nonlinearities. In most applications such small deviations from linearity in the output would be inconsequential, but it in SQUIDs with a high linearity requirement, it can become the limiting feature in the system. It is interesting to note that the same nonlinearity (within ~10%) was observed when the TLE2074C was replaced with another chip with a different batch number, so the nonlinearity must be intrinsic to the design. Further, the amplifier was operating with supply voltages of ±13 V, while the outputs never exceeded ±6 V, so the problem is not that the output was being forced too close to the supply voltage

In operation with a magnetometer, there is no external input so the output of the summing amplifier varies over a smaller range (i.e. at most $\pm\phi_0$), and the data in Figure 6 show that the amplifier nonlinearity will contribute a gain error of only 5×10^{-5}.

4(iii) Temperature and pressure sensitivity of SQUID signal

The SQUID signal was recorded while the dewar pressure was changing. Analysis of the changes in output during these runs gave the following sensitivities to temperature and pressure :

$$\frac{\partial\Phi}{\partial T} = -0.23 \pm 0.04\phi_0 / K \quad ; \quad \frac{\partial\Phi}{\partial P} = (-7.0 \pm 0.6)\times10^{-5}\phi_0 / \text{torr} \quad .$$

The uncertainty reflects the fact that the data were not fit well by the simple model

$$\Delta\Phi = \frac{\partial\Phi}{\partial T}\Delta T + \frac{\partial\Phi}{\partial P}\Delta P \quad .$$

The reason for the poor fit is not known.

These results are comparable to the sensitivities of point-contact and thin-film RF SQUID reported previously in Refs.[1-3]. It is not known whether the T and P sensitivities are the the result of magnetic fields trapped in the SQUID when it was cooled in the Earth's field, or whether they are the consequence of not demagnetizing some small magnetic components used to couple the SQUID to the 'forward' electronics (see Figure 2). The lack of pressure dependence in the reverse-gain (i.e. in M) indicates that the pressure is not affecting the superconductors directly.

By comparison, CTF Systems Ref.[7] has demagnetized similar SQUIDs and then cooled them in ≤2% of the Earth's field and they report temperature and pressure sensitivities in the range

$$\left|\frac{\partial\Phi}{\partial T}\right| = (0.002-0.03)\,\phi_0\,/\,K \quad ; \quad \left|\frac{\partial\Phi}{\partial P}\right| = (0.2-2)\times10^{-5}\phi_0\,/\,\text{torr} \quad .$$

5. Conclusions

The principal result of the experiment described in this report is the significant temperature sensitivity in the effective mutual inductance M between the feedback coil and the SQUID. Without a detailed calculation of the magnetic field and current distribution in coupled thin-film superconductors, it is difficult to say anything definite about which parts of the SQUID are giving the high temperature sensitivity.

The London penetration depth in Nb is λ_L=39 nm. Assuming that $\lambda_L(T)$ varies like $\left[1-(T/T_C)^4\right]^{-1/2}$, the temperature derivative at T=4.2K is

$$\frac{d\lambda_L}{dT} = -0.86\ \text{nm}/\text{K} \quad .$$

The effect of increasing penetration depth should be to increase the effective separation of the super-conductors and, consequently, to reduce their mutual inductance. Thus it is to be expected that M will decrease when the temperature rises. Figure 6 shows the opposite : $dM/dT>0$. However (3) shows that M is a function of several inductances, so it is possible that the observed temperature dependence is due to a decrease in one of the mutual inductances that appears with a minus sign.

It is interesting to note that the temperature dependence of λ_L divided by the separation of the thin films is in the same order of magnitude, but significantly smaller and of opposite sign to the observed temperature derivative of M:

$$\frac{d\lambda_L}{\text{film separation}} \sim \frac{-0.86\ \text{nm}/\text{K}}{800\ \text{nm}} = -1\times10^{-3}\,/\,\text{K}$$

compared to

$$\frac{1}{M}\frac{dM}{dT} = 3.1\times10^{-3}\,/\,\text{K}$$

but it is not clear that there is any physical significance to this comparison.

It will be necessary to do a complete calculation of the magnetic coupling of thin-film superconductors to understand the temperature variation in M, possibly even taking explicit account of magnetic penetration using the methods described in Ref.[8].

It is not possible to predict the effect of the gain variation on the motion noise of a mobile SQUID gradiometer. If the effect is due only to the coupling between the feedback coil and the SQUID, then it can be removed completely by monitoring changes in the reverse gain and correcting the recorded data. If, on the other hand, the sensitivity of the pickup loop is changing because of fluctuations in the input-coil inductance at the same time as parameter M is changing, it will not be possible to correct the temperature effect. This effect will appear as enhanced noise and also as a nonlinearity in the response, so common-mode balancing is likely to be affected.

On a optimistic note, it must be emphasized that the new gradiometer that is presently being built for EDRD by CTF Systems, Inc., is designed to minimize SQUID-temperature fluctuations by reducing the liquid-helium temperature stratification. Consequently, the temperature dependence in M may not contribute significant noise at all.

The temperature and variation of the SQUID output signal presented in Section 4(iii) shows that the temperature dependence has the same magnitude as measured previously with point-contact and thin-film RF SQUIDs. Since these temperatures refer to a high-magnetic-field cooldown, they may not be directly applicable to the situation in a moving SQUID gradiometer which should be cooled carefully in as small a field as possible. Note that the temperature and pressure-dependent effects can be reduced by demagnetizing the SQUIDs and cooling in a low magnetic field.

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The problem of a temperature-dependence in the SQUID mutual inductances was brought to the attention of EDRD by Mr. Ulrich Fath and Dr. W. Eschner of Dornier GmbH in Friedrichshaven, Germany. Dr. P. Kubik of CTF Systems corrected errors in the first draft of this report.

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This report describes an experimental investigation of the temperature dependences of the output of a DC SQUID (SQUID=Superconducting Quantum Interference Device) and the mutual inductance *M* between the SQUID and external electronics. The method of measuring tiny changes in the mutual inductance *M* is described in detail. It is concluded that the temperature dependence of *M* is

$$\frac{1}{M}\frac{dM}{dT} = +3.1 \times 10^{-3}\,/\,\mathrm{K}$$

which is large and of the opposite sign to the expected result. The method used also revealed small nonlinearities in the SQUID feedback electronics. The SQUID was cooled in the Earth's magnetic field and the temperature and pressure dependence of the SQUID output signal was large.

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SQUID temperature-dependence
SQUID magnetic coupling

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