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# Experimental Characterization of the Two Current States in a Nb Persistent-Current Qubit

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**Abstract**—We present experiments to characterize a Nb persistent-current qubit as a two-state system. The magnetization signal from the qubit is read-out by a DC-SQUID with near single-shot efficiency. Experiments varying SQUID ramp-rate and temperature suggest thermal activation occurs between the two circulating current states. Such data can be used to fit the parameters of the system, in order to characterize its performance as a potential quantum bit.

**Index Terms**—Niobium, persistent current qubit, quantum computing, thermal activation.

## I. INTRODUCTION

IN recent years there has been an increase in research activity on the possibility of using superconducting systems as quantum bits and eventually as quantum computers. A quantum bit can be any two-state quantum system that maintains quantum coherence for long enough to perform practical quantum operations. To make a quantum computer, these quantum bits must be controllable and measurable. In superconducting systems, Josephson junctions can be combined to design two-state systems with convenient properties. An example of such a two-state system is the persistent-current (PC) qubit [1], [2]. The PC qubit is formed by a loop of three Josephson junctions, which under certain applied magnetic fields, has two classically stable states of circulating current in opposite directions. Such a system has already been shown [3] to demonstrate superpositions of macroscopic quantum states.

Experiments thus far for the PC qubit have been performed in aluminum, made typically with electron-beam lithography and double-angle evaporation. While junctions made in Al have exhibited very good properties, circuits made with double-angle evaporation are difficult to scale to larger designs. PC qubits made from niobium can be fabricated using photolithography,

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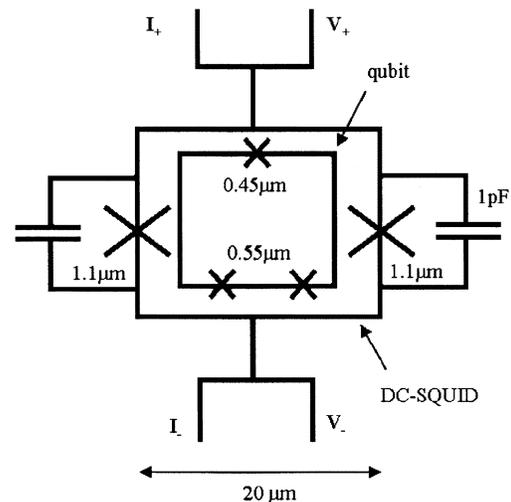


Fig. 1. Schematic of device. The PC qubit is the inner loop, with the junction sizes indicated; the DC-SQUID is the outer loop. See text for other parameters.

in addition to which they can be integrated with existing classical circuitry, also made in niobium, for qubit readout and control. In this paper we discuss the cryogenic testing of PC qubits made from niobium. We demonstrate that we can observe the two circulating current states of the system using a DC-SQUID as a readout. We show that the system is thermally activated between the two states at higher temperatures, and by modeling the experiments we can find the parameters that characterize the system.

## II. DEVICE DESCRIPTION

The devices we tested were made at MIT Lincoln Laboratory [4], with a planarized Nb trilayer process. A schematic of the device is shown in Fig. 1. The PC qubit is a loop of niobium,  $16 \mu\text{m} \times 16 \mu\text{m}$ , interrupted by three Josephson junctions. We will refer to the loop as the qubit, even though to date our experiments have not demonstrated quantum coherent properties. The junctions are Nb-AlOx-Nb, oxidized to a current density of about  $700 \text{ A/cm}^2$ . The size of the junctions are about  $0.55 \mu\text{m}$  on a side for two of the junctions, and  $0.45 \mu\text{m}$  on a side for the third junction. The Josephson energy of the larger junctions is about  $E_J = 4000 \mu\text{eV}$  (1000 GHz), giving an  $E_J/E_C$  ratio of about 600. In this regime the states of the loop are well described by states of constant flux. The critical current of the junctions is about  $1.9 \mu\text{A}$  for the two larger junctions and  $1.3 \mu\text{A}$  for the smaller junction. The ratio of the critical current of

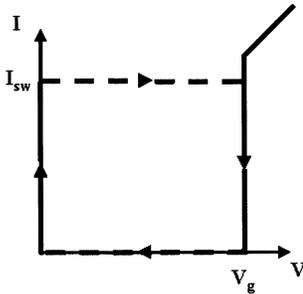


Fig. 2. Schematic drawing of an  $I$ - $V$  curve for an underdamped DC-SQUID. The switching point  $I_{sw}$  is the current where the junction switches to the gap voltage ( $V_g$ ) and is a measure of the magnetic field through the loop.

the smaller junction to larger ones ( $\alpha$ ) is about  $\alpha = 0.7$ . The self-inductance of the loop is about 40 pH.

The PC qubit is surrounded by a two-junction DC-SQUID magnetometer, which forms the readout for the state of the qubit. The SQUID loop is  $20 \mu\text{m} \times 20 \mu\text{m}$ . The junctions are  $1.1 \mu\text{m}$  on a side. The critical current of each junction is about  $11 \mu\text{A}$ , giving a value of  $E_J$  of about 16 meV. The self-inductance of the SQUID loop is about 50 pH, with a mutual inductance to the qubit loop of about 35 pH. Both junctions are shunted with 1 pF capacitors to help filter out high frequency noise.

### III. MEASUREMENTS AND RESULTS

The magnetization signal produced by the circulating current in the PC qubit is detected by the DC SQUID magnetometer. The SQUID junctions are underdamped, so we measure the switching current of the SQUID which is sensitive to the total flux in the loop. A schematic  $I$ - $V$  curve is shown in Fig. 2. The current through the SQUID is increased until it switches to the gap voltage,  $V_g$ ; this switching point,  $I_{sw}$ , is recorded. Typically several hundred such measurements are repeated, since the switching is a stochastic process.

The device was measured in a  $^3\text{He}$  refrigerator with a base temperature of 320 mK; measurements were made in the range 320 mK to 1.2 K. The current to the SQUID was provided by a triangle wave generator with a repeat frequency of 10–150 Hz. Additional circuitry was used to sample the voltage of the SQUID and hold the value of the current at the point when the switching takes place. Care was taken to properly filter the lines and reduce sources of extraneous noise. The switching measurements were taken with a digital multimeter. Software was used to extract the average value and standard deviation for each set of measurements. The standard deviation was typically in the range 0.05–0.07  $\mu\text{A}$ , while the average switching current was 7–20  $\mu\text{A}$ , depending on the applied magnetic field. At 500 mK, the standard deviation was within 20% of the theoretical value [5] in the thermally activated regime, demonstrating that sources of extraneous noise were minimal. A magnetic field was applied perpendicular to the sample to flux bias the qubit. The switching current was measured as a function of magnetic field, temperature and ramp rate of the SQUID.

The average switching current as a function of magnetic field is shown in Fig. 3. The curve shows a typical SQUID modula-

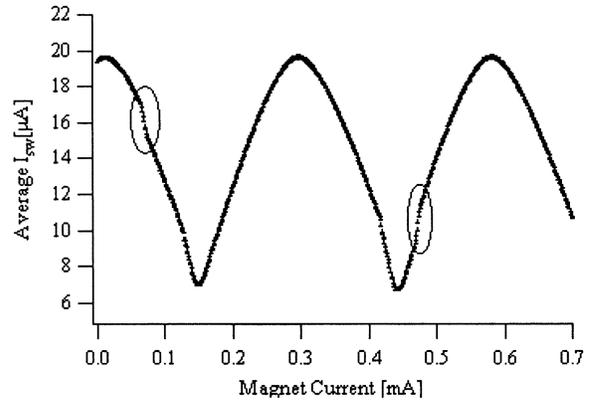


Fig. 3. Average switching current versus magnet current. The switching current is periodic in the applied flux. The transition points of the qubit are circled.

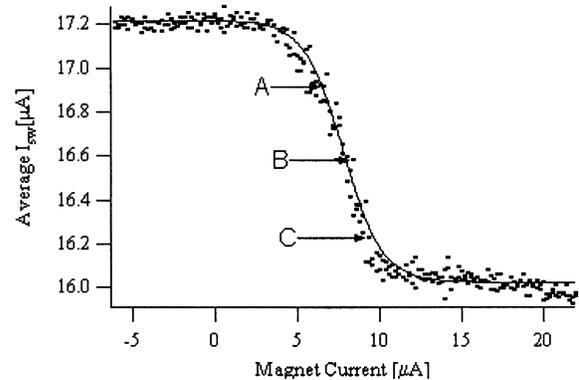


Fig. 4. Average switching current versus magnet current with the background subtracted off, showing the magnetization signal from the qubit. Points A, B, and C are indicated and their associated histograms are shown in Fig. 5.

tion curve, periodic in the applied flux with a period equal to one flux quantum. The minimum switching current measured was about 7  $\mu\text{A}$ , owing to the finite inductance of the SQUID. At various points in the SQUID modulation curve step-like features can be found. These steps correspond to the qubit changing from one flux state to the other. They are found with a periodicity in flux approximately equal to 1.5 times the periodicity of the SQUID. This is consistent with the area ratio of the two loops in Fig. 1 ( $A_{\text{SQUID}}/A_{\text{qubit}} = 1.56$ ).

In Fig. 4 we show an enlargement of one of the steps where we have subtracted off the background magnetization of the SQUID. Far to the left the qubit is in one circulating current state; far to the right it is in the other. Between these two extremes the system moves continuously from one state to another as a function of the applied flux. If we now focus in on the histogram for a point in this transition region, shown in Fig. 5, we see that the histogram is bimodal, showing both of the states. The two peaks in the histogram only slightly overlap, showing that we have nearly single-shot measurement efficiency. Any *single* measurement yields either one state or the other; the smooth transition in Fig. 4 is obtained by a continuous modulation of the probability of finding the system in one state or the other. We see this as we move from points A to B to C in Fig. 5.

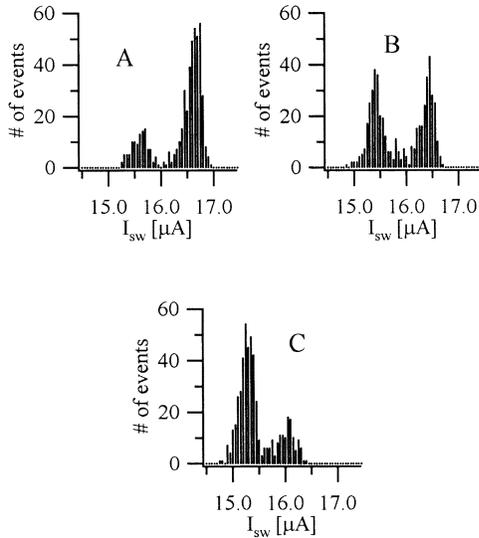


Fig. 5. Switching current histograms, showing the two states of the qubit. The probability density is modulated in moving from A to B to C.

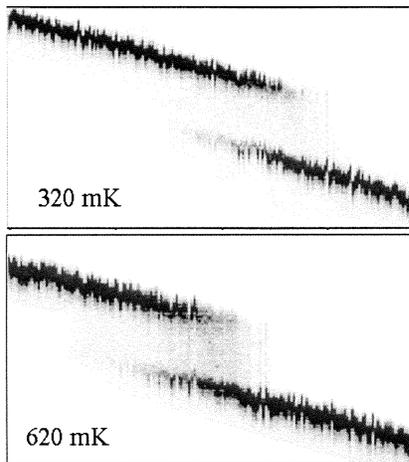


Fig. 6. Gray-scale plots of the qubit transition at 320 mK (top) and 620 mK (bottom). The horizontal axis is magnetic field, the vertical axis is switching current and the color is switching probability, with darker colors indicating higher switching probability. The two dark black lines are the two states of the qubit. The grey region in between represents thermally activated switching between the two states, with more switching evident in the 620 mK case.

These data can be viewed in a more compact fashion as shown in Fig. 6, where we view the data for two temperatures in a grey-scale scatter plot with magnetic field in the  $x$ -direction, switching current in the  $y$ -direction, and shading as the switching probability (darker shading = higher switching probability). At 320 mK we can see the two states in the transition region, with a few points in between. At 620 mK we see the same basic structure but with a denser set of points in between the two states. At these temperatures the system is being thermally activated between the two states. More thermal activation is present at higher temperatures, resulting in more smearing of the two peaks, as shown in the 620 mK data.

The center point of the transition (approximately point “B” in Fig. 4) is plotted as a function of temperature in Fig. 7. Here the units on the vertical axis are now frustration in the qubit

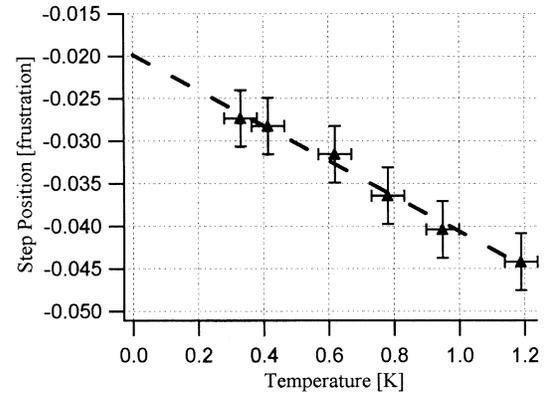


Fig. 7. Plot of the position of the step in frustration as a function of temperature. The movement indicates thermal activation during measurement.

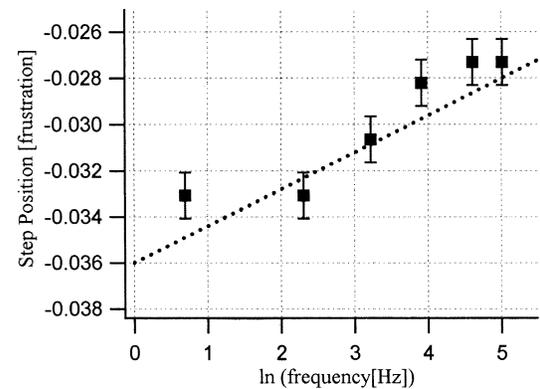


Fig. 8. Step position as a function of the log of the ramping frequency. Lower ramping rates cause the step to move in the same direction as higher temperature.

loop. We can see that as we raise the temperature the transition moves in one direction. The position movement is nearly linear in temperature from 320 mK to 1.2 K. The position also moves as a function of the SQUID ramping rate. We plot the center point of the transition as a function of the natural log of the rate in Fig. 8. The step movement is approximately logarithmic in rate. These two dependencies also support the notion that the system is being thermally activated. An explanation is that there is a timescale associated with the measurement during which the system is sensitive to thermal activation. This timescale is approximately equal to the time it takes to ramp the SQUID between the switching points associated with the two qubit states. If we increase this timescale by ramping at a lower rate (Fig. 8), we subject ourselves to more thermal activation for a given temperature. Thus lower ramping rates move in the same direction as higher temperature. A detailed theory of these dependencies will be published elsewhere [6]; this theory can be used to fit the data and can be used to extract the parameters of the device.

#### IV. SUMMARY

We have performed experiments on a Nb persistent current qubit read out by a DC-SQUID magnetometer. The measurements show clearly the two distinct magnetization states of the qubit, and can be performed with nearly single shot efficiency. Experiments versus temperature and SQUID ramping rate show

thermal activation between the two states at temperatures from 320 mK to 1.2 K.

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