Superconducting Persistent Current Qubits in Niobium

Personnel

K. Segall, D. Nakada, D. Crankshaw, B. Singh, J. Lee, K. Berggren, N. Markovic and S.Valenzuela, T. Orlando, L. Levitov, S. Lloyd and M. Tinkham

Quantum Computation is an exciting idea whose study combines the exploration of new physical principles with the development of a new technology. In these early stages of research one would like to be able to accomplish the manipulation, control and measurement of a single two-state quantum system while maintaining quantum coherence. This will require a coherent two-state system (a qubit) along with a method of control and measurement. Superconducting quantum computing has the promise of an approach that could accomplish this in a manner that can be scaled to large numbers of qubits. We are studying the properties of a two-state system made from a niobium (Nb) superconducting loop, which can be incorporated on-chip with other superconducting circuits to perform the control and measurement. The devices we study are fabricated at Lincoln Laboratory, which uses a Nb-trilayer process for the superconducting elements and photolithography to define the circuit features. Our system is thus inherently scalable but has the challenge of being able to demonstrate appreciable quantum coherence.

The particular device that we have studied so far is made from a loop of Nb interrupted by 3 Josephson junctions. The application of an external magnetic field to the loop induces a circulating current whose magnetic field either adds to (say circulating current in the clockwise direction) or opposes (counterclockwise) the applied magnetic field. When the applied field is near to one-half of a flux quantum, both the clockwise and counterclockwise current states are classically stable. The system behaves as a two-state system. The potential energy versus circulating current is a so-called double-well potential (see Figure 4), with the two minima representing the two states of equal and opposite circulating current. A SQUID magnetometer inductively coupled to the qubit can be used to measure the magnetic field caused by the circulating current and thus determine the state of the qubit. The SQUID has a switching

current which depends very sensitively on magnetic field. When the magnetic field from the qubit adds to the external field we observe a smaller switching current; when it subtracts from the external field we observe a smaller larger current. We measure the switching current by ramping up the bias current of the SQUID and recording the current at which it switches. Typically a few hundred such measurements are taken. We have performed these measurements versus magnetic field, temperature and SQUID ramping rate.

In the upper plot of Figure 3 we show the average switching current versus magnetic field for our qubit-SQUID system. The SQUID switching current depends linearly on the applied magnetic field. A step-like transition occurs when the circulating current in the qubit changes sign, hence changing whether its magnetic field adds to or subtracts from the applied field. In Fig. 1 the qubit field adds to the SQUID switching current at lower fields (< 3mG) but subtracts from it at higher fields (>3mG). Each point in the upper curve is an average of 1000 single switching current measurements. If we look at a histogram of the 1000 switching currents in the neighborhood of the transition, we discover that it represents a joint probability distribution. Two distinct switching currents representing the two states of the qubit can be clearly resolved. Changing the magnetic field alters the probability of being measured in one state or the other.

In Figure 4 we show the potential energy for the system as we sweep through the transition. (We used a different assignment for "zero" field in Figure 4 than Figure 3, which is why the step occurs at a different magnetic field value). In the first part of the transition the system has a higher probability of being measured in the left well, which corresponds to the circulating current state which adds to switching current of the SQUID. At the midpoint of the transition the system is measured in

both wells with equal probability. At higher fields the system has a larger probability of being measured in the right well. The mechanism for the system to move between the wells at these temperatures (>300 mK) is thermal activation. We have measured the system at lower temperatures, and there the mechanism is unclear. The focus of our future efforts is to determine if the mechanism changes to quantum mechanical tunneling at lower temperatures and how coherent the tunneling can be. If we are successful that will be the first indication that superconducting quantum computers in Nb are possible.
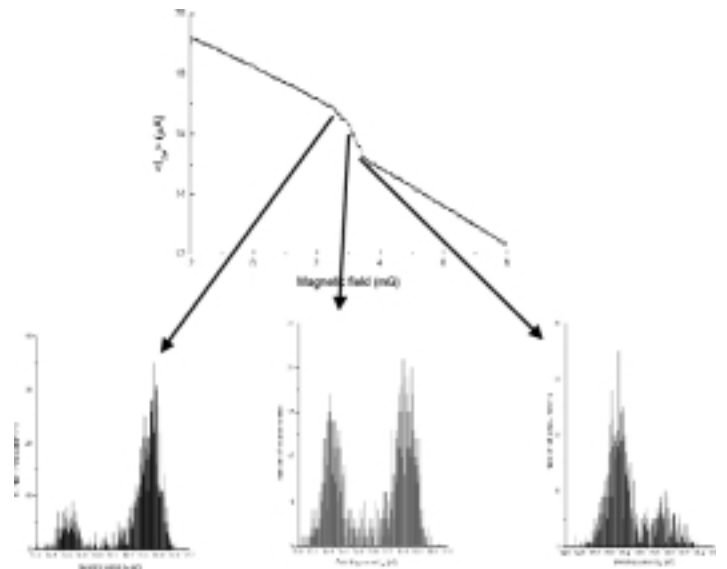

Fig. 3: Measurements of the switching current of the SQUID versus magnetic field.
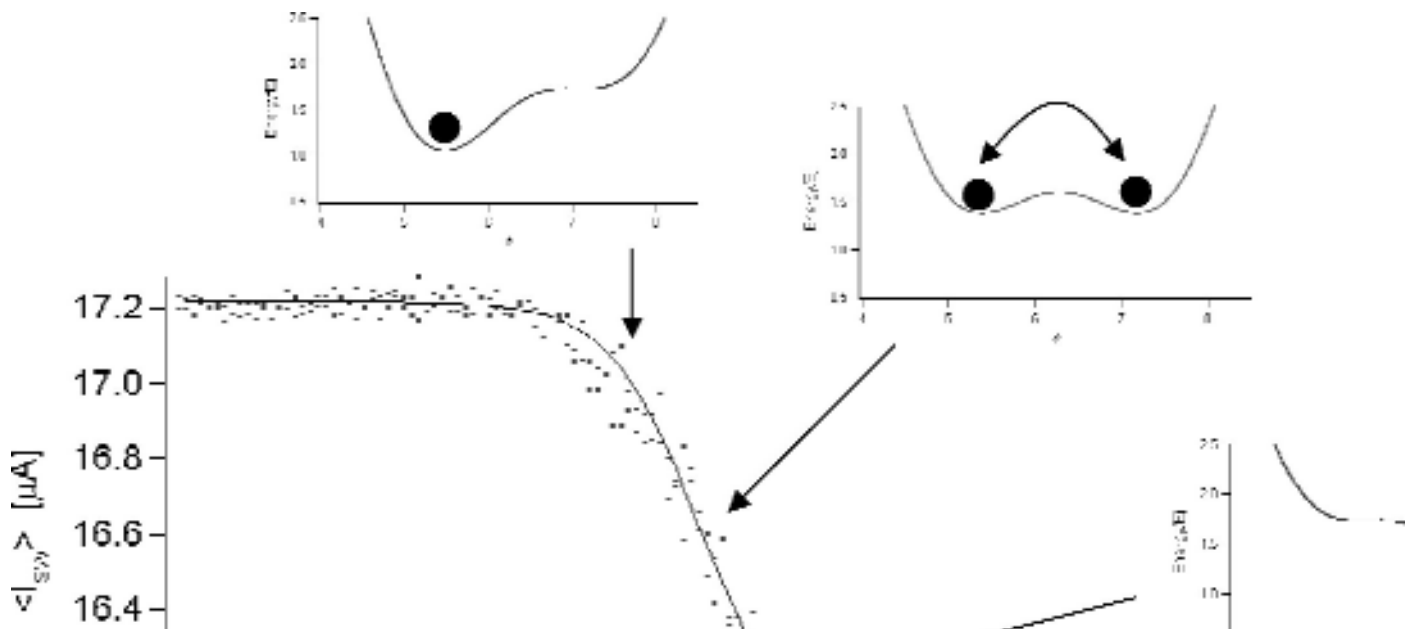

Fig. 4: Switching current versus magnetic field with the background field of the SQUID subtracted off.