Relaxation and dephasing in a flux qubit

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We report detailed measurements of the relaxation and dephasing times in a flux-qubit measured by a switching DC SQUID. We studied their dependence on the two important circuit bias parameters: the externally applied magnetic flux and the bias current through the SQUID in two samples. We demonstrate two complementary strategies to protect the qubit from these decoherence sources. One consists in biasing the qubit so that its resonance frequency is stationary with respect to the control parameters (optimal point); the second consists in decoupling the qubit from current noise by choosing a proper bias current through the SQUID. At the decoupled optimal point, we measured long spin-echo decay times of up to 4μs.

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A long-standing problem for the use of superconducting circuits as quantum bits (qubits) in a quantum computer is their relatively short dephasing time compared to the requirements of many-qubit quantum computation. Dephasing is due to the coupling of the qubit’s degrees of freedom with the many fluctuating uncontrollable ones commonly denoted as the environment. From the perspective of quantum information, it is crucial to quantitatively identify the various dephasing sources and to find strategies to overcome these, either by reducing the amount of fluctuations or by protecting the qubit against it. An important step in this direction has been accomplished in [6]. The authors showed that dephasing can be significantly reduced by biasing the qubit at an optimal point where its resonance frequency is stationary with respect to its control parameters - in that case, gate voltage and magnetic flux.

In this letter we report detailed measurements of the relaxation and dephasing times in a flux-qubit as a function of its bias parameters for two different samples. Our measurements allow us to identify certain dephasing mechanisms and quantify their effect on the qubit. We find that energy relaxation is dominated by spontaneous emission towards the measuring circuit impedance. Dephasing is mainly caused by noise in the external magnetic flux biasing the qubit, thermal fluctuations of our measuring circuit, and low-frequency noise originating from microscopic degrees of freedom, probably causing critical current noise in the qubit junctions. We moreover demonstrate strategies to efficiently fight each of these noise sources.

Our flux-qubit consists of a micron-size superconducting loop intersected with three Josephson junctions. When the total phase across the three junctions \( \gamma_Q \) is close to \( \pi \), the loop has two low-energy eigenstates (ground state \( |0\rangle \) and excited state \( |1\rangle \)) well separated from the higher-energy ones, which can thus be used as a qubit. The flux-qubit is characterized by two parameters: the minimum energy separation \( \Delta \) between \( |0\rangle \) and \( |1\rangle \), and the persistent current \( I_p \). Around \( \gamma_Q = \pi \), the energy separation between these two levels depends on \( \gamma_Q \) and can be written as \( E_1 - E_0 = h f_Q = h/\Delta^2 + c^2 \), where \( c \equiv (I_p/e)(\gamma_Q - \pi)/(2\pi) \). The qubit is inductively coupled to a SQUID detector (with a coupling constant \( M \)), which is biased at a current \( I_b \). The phase drop \( \gamma_Q \) has two origins: the magnetic flux threading the qubit loop \( \Phi_x \), and the currents in the SQUID loop which depend on \( I_b \). Thus, we can write \( \epsilon = \eta(\Phi_x) + \lambda(I_b) \).

The coupling of \( \epsilon \) to fluctuating sources leads to decoherence. Noise in the magnetic flux \( \Phi_x \) or in the bias current \( I_b \) induces fluctuations of the qubit frequency \( f_Q \) and thus dephasing. A first strategy to protect the qubit from decoherence consists in biasing it at \( \epsilon = 0 \) so that \( df_Q/d\epsilon = 0 \). This is the optimal point strategy, which was first invented and demonstrated in [6]. An additional possibility is to decouple the external noise from the variable \( \epsilon \), by canceling the sensitivity coefficients \( d\eta/d\Phi_x \) and \( d\lambda/dI_b \). The flux noise can not be decoupled since \( d\eta/d\Phi_x = 2I_p/h \) is constant. As we will show below, the bias current noise can be decoupled by biasing the SQUID at a current \( I_p^{\ast} \) such that \( d\lambda/dI_b(I_p^{\ast}) = 0 \), which is the decoupling condition. At the decoupled optimal point, \( (\epsilon = 0 \text{ and } I_b = I_b^{\ast}) \) we expect that the qubit quantum coherence is best preserved, since the qubit is sensitive to flux noise to second order, and to bias current noise to fourth order. We also note that a strong dependence of the dephasing time on the bias current would be clear experimental evidence that current noise, and not flux noise, is the factor limiting the quantum coherence.

In the two samples, shown in figures [8] and [14], the qubit loop is merged with its measuring SQUID. The dependence of \( \epsilon \) on the bias current \( I_b \) arises from the way this bias current redistributes in the SQUID and eventually generates a phase shift across the qubit junctions via the superconducting line shared by the qubit and the SQUID. The detailed configuration of the shared line is related to the specific fabrication process. We use 2-angle shadow evaporation so that the lines consist effectively of 2 layers. This induces a large asymmetry in the coupling if the qubit loop contains an odd number of junc-
In this article, we compare the results obtained for a three- (sample A) and a four- (sample B) junction qubit (see figure 1a and b), and demonstrate that such asymmetry can be removed by using an even number of junctions in the qubit loop. A model for the qubit electromagnetic environment in both samples is shown in figure 1c. The SQUID is modeled by its Josephson inductance $L_J$ shunted by a capacitor $C_{sh}$ via superconducting lines of inductance $L$. It is connected to the output voltage of our waveform generator $E$ via an impedance $Z_{in}$, and to the input of a room-temperature preamplifier through an impedance $Z_{out}$. $Z_{in}$ and $Z_{out}$ include on-chip gold resistors.

We measured our sample parameters and $\lambda(I_b)$ by studying the dependence of the qubit Larmor frequency on both the external flux $\Phi_x$ and the bias current $I_b$. We performed spectroscopy by applying a 500ns microwave pulse of variable frequency, and measuring the SQUID switching probability with a short subsequent DC current pulse for different values of $\Phi_x$. We added a 1µs plateau at the value $I_{bpl}$ in order to adjust the bias current through the SQUID during the application of the microwave pulse. The complete pulse sequence is depicted in figure 2a. In figure 2b, the measured qubit resonance frequency for sample A is shown as a function of the external flux $\Phi_x$ for three different values of $I_{bpl}$. We observe that for each value of the bias current, a specific value of external flux $\Phi_x(I_{bpl})$ realizes the optimal point condition.

We fitted all the curves with the formula $f_Q = \frac{\Delta^2 + [\lambda(I_b) + 2I_p(\Phi_x - \Phi_0/2)/h]^2}{4I_b^2 \omega_p^2 C_{sh} R_e(Z_{in})^2}$ for different values of $I_b$. The obtained curves $\lambda(I_b)$ are shown in figure 2c and 2d for both samples. The decoupling occurs at $I_b^* = 2.9 \pm 0.1 \mu A$ for sample A and at $I_b^* = 180 \pm 20 \mu A$ for sample B. Note that although the SQUID critical current is similar in both samples, the decoupling current is much closer to 0 in sample B due to the presence of the fourth junction which restores the symmetry of the coupling. We biased our qubit at the decoupled optimal point by setting $I_b = I_b^*$ and $\Phi_x = \Phi_x^*(I_b^*)$. The qubit line shape under these conditions is shown in figure 2e for sample A and 2f for sample B. For sample A, we could fit it with a Lorentzian of width $\Delta = 3.1 \pm 0.5 MHz$ (FWHM). This width yields a dephasing time $T_2 = 1/\pi \Delta$ $\approx$ 100ns consistent with the Ramsey fringe measurements as discussed below. For sample B, the line was split, due to the action of a strongly coupled two-level fluctuator. We fitted it by the sum of two Lorentzians of widths 7 and 6MHz. We note that in addition to the fluctuator responsible for the splitting of the line, the value of the qubit frequency at the optimal point $\Delta$ exhibited occasional jumps of around 100MHz. Also the width of the line changed significantly in time. This indicates that dephasing was probably dominated by some low-frequency noise due to one or more strongly coupled microscopic fluctuators, likely generating critical current noise.
stress that we had no evidence for such instabilities with sample A.

We first studied the dependence of the dephasing time as a function of $\epsilon$ while keeping $I_b = I_b^*$. For sample A, we measured Ramsey fringes by applying a sequence of microwave pulses as schematized in figure 3a, for each value of $\Phi_x$. The Ramsey fringes measured at the decoupled optimal point are shown. They decay exponentially with a time constant $T_2$. Figure 3b (bottom) shows the dependence of $T_2$ with $\Phi_x$. The dephasing time exhibits a sharp maximum $T_2 = 120 \text{ ns}$ at the optimal point $\epsilon = 0$ for which $d\Phi_x/d\epsilon = 0$ as expected.

To account for the rapid degradation of the dephasing time when $\epsilon \neq 0$, we first evaluated the effect of thermal fluctuations in the plasma mode. Instead, we numerically integrated the master equation for the joint density matrix of the “qubit-plasma mode” system. The results represent a significant improvement over previously reported coherence times in superconducting qubits. We finally studied the bias current $I_b$ dependence of $T_2$ and $T_{\text{echo}}$ together with the energy relaxation time $T_1$ at $\epsilon = 0$. The results are shown in figure 3c and d for samples A and B respectively. All these curves exhibit a clear maximum at $I_b = I_b^*$. This indicates that at $I_b \neq I_b^*$ both relaxation and dephasing are limited by coupling to the measuring circuit. In particular, the fact that in sample B $T_1$ is strongly reduced away from $I_b^*$ is a clear indication that energy fluctuations in the plasma mode account qualitatively for the rapid degradation of the dephasing time when $\epsilon \neq 0$. Assuming that the flux-noise power spectrum has a frequency dependence given by $S_{\phi} = A/f$ which is consistent with noise measurements found in the literature, we can use the data from figure 3a to evaluate $A$. With calculations similar to those for sample B, we find that $A = 3 \pm 1.5 \times 10^{-12} \text{Hz}$ gives a good agreement (dotted line in figure 3b). Such a level of noise is comparable to the lowest values reported in SQUID measurements.

As could be expected from the lineshape shown in figure 2, the Ramsey fringe signal measured with sample B had a non-exponential damping so that it was impossible to measure $T_2$. To circumvent the low-frequency noise mentioned above, we used a spin-echo type sequence of microwave pulses shown in figure 3b (top), as demonstrated in the case of low-frequency charge noise. The results are shown in figure 3a at the decoupled optimal point, by a set of curves corresponding to different delays between the two $\pi/2$ pulses. We fitted each curve by a gaussian multiplied by a sine curve. Then we fitted the decay of the echo amplitude as a function of the delay between the two $\pi/2$ pulses with an exponential of time constant $T_{\text{echo}}$. At the decoupled optimal point, we measured $T_{\text{echo}} = 3.9 \pm 0.1 \mu s$. We stress that these results represent a significant improvement over previously reported coherence times in superconducting qubits. We studied the dependence of $T_{\text{echo}}$ as a function of $\epsilon$ (figure 3c, bottom, full squares) for $I_b = I_b^*$. Again we found a sharp maximum at $\epsilon = 0$. For sample B, thermal fluctuations in the plasma mode account qualitatively for the experimental data (dashed curve in figure 3c, bottom).
FIG. 4: (a) Relaxation ($T_1$, black squares) and dephasing ($T_2$, empty circles) times at the optimal point ($\phi = 0$) as a function of the bias current $I_b$ for sample A. (b) Pure dephasing time $T_\phi$ (full squares) as a function of $I_b$. The dashed line is the result of a simulation taking into account the thermal fluctuations of the plasma mode. (c) Relaxation ($T_1$, black squares) and echo ($T_2$, empty circles) times at the optimal point ($\phi = 0$) as a function of the bias current $I_b$ for sample B. (d) Pure dephasing component of the echo time $T_\phi^{\text{echo}}$ (full squares) and calculated effect of the thermal fluctuations in the plasma mode (dashed line).

Relaxation occurs by spontaneous emission towards the circuit impedance seen by the qubit. A weaker dependence is observed for sample A, which could indicate that additional environmental modes at the qubit frequency are involved. The dephasing time $T_2$ measured in sample A is strongly dependent on $I_b$. This indicates that dephasing at the optimal point is limited by noise in the bias current. For both samples, the dephasing time measured at the optimal decoupled point is similar to or larger (sample A) than the relaxation time, so that dephasing was partly limited by relaxation. To quantify the pure dephasing contribution, we calculated $T_\phi$, defined as $T_\phi = (T_2)^{-1} - (2T_1)^{-1}$ for sample A (full square curve in figure 4b) and calculated similarly $T_\phi^{\text{echo}}$ for sample B (full square curve in figure 4b). Our calculations taking into account the thermal fluctuations in the plasma mode are shown as the dashed curve in figures 4b and d. They are in qualitative agreement with the data, although systematically overestimating the dephasing time by a factor typically 5 compared to the measurements.

In conclusion, we presented detailed measurements of the relaxation and dephasing times as a function of bias parameters for two flux-qubit samples. We showed that the optimal point concept already demonstrated for the quantum circuit is also valid for the flux-qubit design. Making use of the SQUID geometry of our detector, we could moreover decouple the qubit from current fluctuations by biasing the SQUID at a specific current $I_b^*$. We showed that adding a fourth junction to the qubit loop enhances the symmetry of the coupling, thus lowering the value of $I_b^*$. We showed that low-frequency noise limits the dephasing time, but that spin-echo techniques provide a powerful tool to fight it. We observed remarkably long decay times of the echo signal of 4\mu s, limited by relaxation. We provided quantitative evidence that at the optimal point dephasing is induced by the thermal fluctuations of the photon number in the plasma mode of our SQUID detector. These results indicate that long coherence times can be achieved with flux qubits.

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