Decoherence in Superconducting Qubits (DiSQ) Workshop

December 6-7, 2007

The Doubletree Hotel
Berkeley, California

Decoherence in Superconducting Qubits (DiSQ) Workshop

THURSDAY, DECEMBER 6th

7:30 – 8:45 am	Breakfast/Registration – California Break Room
9:00 – 9:30 am	Welcome/Introduction – Irfan Siddiqi, UC Berkeley (California Room)

SPEAKER SESSION I (Chair: John Martinis, UCSB) – California Room

9:30 – 10:15 am	"*Decoherence of Superconducting Qubits*" Steve Girvin, Yale University
10:15 – 11:00 am	*"Optimal Gates in Imperfect Qubits"* Frank Wilhelm, University of Waterloo
11:00 – 11:30 am	BREAK – California Break Room
11:30 – 12:15 pm	*"The Coherence Properties of Optimized Charge Qubits"* Robert Schoelkopf, Yale University
12:15 – 1:00 pm	*"Ultra-Low Noise Josephson Amplifiers for the Readout of Superconducting Qubits"* Michel Devoret, Yale University
1:00 – 2:00 pm	LUNCH – Bay Grille

SPEAKER SESSION II (Chair-Robert Schoelkopf, Yale) California Room

2:00 – 2:45 pm	*"Decoherence in flux qubit"* Yasunobu Nakamura, NEC
2:45 – 3:30 pm	*"The Phase-Slip-based flux-qubit: a low decoherence alternative?"* Kees Harmans, Delft University of Technology
3:30 – 4:00 pm	BREAK – California Break Room
4:00 – 4:45 pm	*"Suppression of the Effect of the Noise on theLarge Josephson Structures Protected by Non-Local Symmetries"* Lev Ioffe, Rutgers University
4:45 – 5:45pm	PANEL DISCUSSION I: Decoherence in Charge & Flux Qubits Moderator: John Clarke, University of California, Berkeley Panelists: Daniel Esteve (CEA, Saclay), Franco Nori (RIKEN), Will Oliver (LL/MIT), David Pappas (NIST), Dale Van Harlingen (UIUC)
6:15pm	DINNER – Bay Grille

FRIDAY, DECEMBER 7th

7:30 – 8:45 am	Breakfast – California Break Room

<u>SPEAKER SESSION III (Chair: Dale Van Harlingen, UIUC) – California Room</u>

9:00 – 9:45 am	"*Decoherence and Relaxation in Driven Circuit QED Systems"* Gerd Schön, Universität Karlsruhe
9:45 – 10:30 am	"*Model for l/f Flux Noise in Qubits and SQUIDs" -* John Clarke, University of California, Berkeley
10:30 – 11:00 am	BREAK - California Break Room
11:00 – 11:45 pm	*"Decoherence in Josephson Phase Qubits"* John Martinis, University of California, Santa Barbara
11:45 – 12:30 pm	"*Low-frequency Flux Noise in SQUIDs and Superconducting Qubits"* Robert McDermott, University of Wisconsin, Madison
12:30 – 1:30 pm	LUNCH – Bay Grille
1:30 – 2:30 pm	PANEL DISCUSSION II: Decoherence in Phase Qubits – California Room Moderator: John Clarke, University of California, Berkeley Panelists: Jim Eckstein (UIUC), Lara Faoro (Rutgers), Ray Simmonds (NIST, Boulder), Fred Wellstood (University of Maryland, College Park)
2:30 – 2:35 pm	CLOSING REMARKS
3:00 – 6:00 pm	UC Berkeley Physics Lab Tour
3:00 pm	Bus Departs Doubletree Hotel Lobby
3:30 – 5:00 pm	Guided Lab Tours
5:00 – 6:00 pm	Reception in the Berkeley Center for Theoretical Physics
6:00 pm	Bus Departs UC Berkeley for Doubletree Hotel

Decoherence of Superconducting Qubits

Steven M. Girvin
Departments of Physics and Applied Physics
Yale University

The various superconducting electrical circuit approaches to qubits and readouts offer a number of advantages in terms of relative ease of fabrication, reproducibility and potential for creating scalable architectures. Since the time of the first experiments in 1999, ensemble phase coherence times T_2^* have risen by three orders of magnitude from ~ 1 ns to ≈ 2 μs. With spin echo, T_2 can be even larger. In recent experiments the intrinsic dephasing time has been as large as T_φ ~ 6 μs so that T_2^* was primarily limited by the energy relaxation time T_1 rather than low frequency noise. This enormous progress has been the result of several generations of radically improved qubit designs, development of thorough understanding and control of the electromagnetic environment seen by these artificial atoms, and the invention quieter readout schemes. Further improvements in materials properties, qubit symmetries and microwave circuit design should allow considerable further increases in coherence times. This talk will give an introductory overview to the numerous sources of decoherence in these circuits and how they can be ameliorated.

Optimal Gates in Imperfect Qubits

Frank Wilhelm

Department of Physics and Astronomy- University of Waterloo

Realistic superconducting qubits are necessarily imperfect. In particular, they are not rigorous two-state systems, and they contain slow noise sources. In principle, weakly driven Rabi pulses at the optimum point can accommodate both imperfections to a certain extent on the expense of being slow. We are applying the openGRAPE (open systems gradient ascent pulse engineering) method to both problems, looking for optimal pulse shapes dealing with these challenges. It is shown that gates with near-unit fidelity can be achieved in a time set by the difference of the Ramsey frequencies of the working and leakage transition in a three-qubit system. This result can be understood as a composite pulse refocusing unwanted drifts in the rotating frame. In the presence of slow noise, it is shown how short modulated Rabi pulses corrected for counterrotating terms allow for the elimination of the impact of phase noise even when the coupling to one of the noise sources is strong, finding that telegraph noise can be corrected if it is faster or slower than the qubit precession.

The Coherence Properties of Optimized Charge Qubits

Rob Schoelkopf
Departments of Applied Physics and Physics
Yale University

I will describe our design for an optimized version of the Cooper-pair box, the “transmon,” which uses higher ratios of Josephson to charging energies. This produces an exponential insensitivity to charge noise and quasiparticle poisoning, while still maintaining a large matrix element for coupling to electric fields or to photons in a microwave cavity. This immunity to charge noise does not require an enhanced sensitivity to either flux or critical current noise, making these devices minimally sensitive to 1/f noise. I will present detailed spectroscopic investigations of these devices, showing excellent agreement with theory, and measurements which show that these devices can be nearly homogeneously broadened (i.e. $T_2 > T_1$), with coherence times (without echo) that are reliably more than two microseconds. These results indicate that if the qubit dissipation can be understood and reduced, further increases in coherence can be obtained even without reducing the usual levels of 1/f noise in charge, flux, or critical current.

Ultra-Low Noise Josephson Amplifiers for the Readout of Superconducting Qubits

Michel Devoret, Applied Physics
Yale University

The requirements that a superconducting qubit readout need to fulfill will be briefly reviewed, together with the concept of dispersive readout. I will then discuss the basic principles of bifurcation amplification and its current implementation in our lab using a superconducting Fabry-Perot cavity resonator in which a quantronium qubit is inserted. Last, a new strategy involving a non-degenerate parametric amplifier based on the Josephson equivalent of a ring-modulator will be presented, together with preliminary experimental results.

Decoherence in Flux Qubit

Yasunobu Nakamura

NEC, Japan

We have investigated decoherence in Josephson-junction flux qubits. Based on the measurements of decoherence at various bias conditions, we discriminate contributions of different noise sources. We present a Gaussian decay function extracted from the echo signal as evidence of dephasing due to 1/f flux noise whose spectral density is evaluated to be about $10^{-6}\ \phi_0 / \mathrm{Hz}^{1/2}$ at 1 Hz. We also demonstrate that, at an optimal bias condition where the noise sources are well decoupled, the coherence observed in the echo measurement is limited mainly by energy relaxation of the qubit. Some recent data will be also discussed.

The Phase-Slip-Based Flux-Qubit:
a Low Decoherence Alternative?

Kees J.P.M. Harmans
Kavli Institute of NanoScience
Delft University of Technology
Delft, The Netherlands

Superconducting qubits based on S-I-S Josephson junctions, employ the phase and the charge as quantum variables. To preserve coherence these variables should not be affected by uncontrolled degrees of freedom outside the qubit phase space. In flux-based qubits mostly fluctuations of the phase of the superconducting condensate lead to decoherence. These fluctuations result from strong interaction with atomic-scale local scatterers. Often these are of a two-level-fluctuator nature and reside in the Josephson junctions, mostly in the approximately monolayer-thickness insulator junction barrier. Most likely, the highly disordered nature of these insulators leads to such fluctuators.
Finding ways to realize circuits without thin insulators may lead to a reduction of decoherence. A potentially attractive approach is the use of a phase-slip wire. It is based on a narrow structure in a homogeneous high-resistivity metallic layer. In this presentation the work done in the Delft Kavli Institute will be discussed.

Suppression of the Effect of the Noise on the Large Josephson Structures Protected by Non-Local Symmetries

Lev Ioffe

Department of Physics

Rutgers University

I review theoretical and experimental attempts to realize topological protection from the effects of the noise on superconducting structures by constructing Josephson qubits containing many individual Josephson junctions. I begin with the model schemes that provide arbitrary level of protection and then discuss the minimalistic designs of Josephson arrays that provide noise suppression to the third or fourth orders in the noise. I will show the results of the Rutgers experimental group that indicate that main properties of such arrays are in a very good agreement with theoretical expectations.

Decoherence and Relaxation in Driven Circuit QED Systems

Gerd Schön [(1)], A. Shnirman [(1,2)], S. Andre [(1)], V. Brosco [(1)], A. Fedorov [(1,3)], J. Hauss [(1)],
M. Marthaler [(1)]

[(1)] University of Karlsruhe, Germany
[(2)] University of Innsbruck, Austria
[(3)] Delft University of Technology, The Netherlands

Several recent experiments on quantum state engineering with superconducting circuits realized concepts originally introduced in the field of quantum optics. Motivated by one such experiment [1] we investigate a Josephson qubit coupled to a slow LC oscillator with frequency (~MHz) much lower than the qubit's energy splitting (~GHz). The qubit is ac-driven to perform Rabi oscillations, and the Rabi frequency is tuned to resonance with the oscillator. The properties of this driven circuit QED system depend strongly on relaxation and decoherence effects in the qubit [2]. We investigate both one-photon and two-photon qubit-oscillator coupling, the latter being dominant at the symmetry point of the qubit. When the qubit driving frequency is blue detuned, we find that the system exhibits lasing behavior (single-atom laser); for red detuning the qubit cools the oscillator. Similar behavior is expected in an accessible range of parameters for a Josephson qubit coupled to a nano-mechanical oscillator.

In a different parameter regime, furthering the analogies between superconducting and quantum optical systems we investigate Sisyphus damping, which is the key element of the Sisyphus cooling protocol, as well as its exact opposite, Sisyphus amplification [3].

[1] E. Il'ichev et al., Phys. Rev. Lett. 91, 097906 (2003)

[2] Single-qubit lasing and cooling at the Rabi frequency, J. Hauss et al., cond-mat/0701041

[3] Sisyphus damping and amplification by a superconducting qubit, M. Grajcar et al., arXiv:0708.0665 [cond-mat.supr-con]

Model for l/f Flux Noise in Qubits and SQUIDs

John Clarke
Department of Physics, University of California, Berkeley
and
Materials Sciences Division, Lawrence Berkeley National Laboratory

At millikelvin temperatures, flux quantum bits (qubits) and Superconducting Quantum Interference Devices (SQUIDs) both suffer from intrinsic magnetic flux noise which has a power spectrum that scales as $1/f^b$, where f is the frequency and b is approximately unity. This noise source results in enhanced decoherence in qubits and in reduced low-frequency resolution in SQUIDs. The magnitude of the flux noise scales weakly with the area of the device, ruling out external, uniform magnetic field noise as the source. Our model assumes that the noise is generated by the magnetic moments of electrons in defect states which they occupy for a wide distribution of times before escaping. A trapped electron occupies one of the two Kramers-degenerate ground states, between which the transition rate is negligible at low temperature. As a result, the magnetic moment orientation is locked. Provided the processes are uncorrelated, the resulting random telegraph signals sum to give a 1/f power spectrum. Simulations of the 1/f noise for defects randomly distributed over the substrate with a fixed average areal density and with random orientation show that the noise scales slowly with the area of the device. Furthermore, the magnitude of the 1/f noise agrees with experimental observations for a plausible areal density of defects.

This research was performed in collaboration with David DiVincenzo and the late Roger Koch, and supported by the DOE Office of Basic Energy Sciences, Materials Sciences and Engineering Division (JC) and by the DTO through ARO).

Decoherence in Josephson Phase Qubits

John Martinis

UC Santa Barbara

All qubit implementations compromise between coherence and coupling. Superconducting qubits offer a unique experimental system in which the coupling between qubits is relatively straightforward, since quantum information can be transmitted over long distances with low loss using simple superconducting wires. Wire coupling is particularly well suited for the phase qubit, which has a low junction impedance ~10 ohms because of its large junction capacitance. However, large junction size has made this implementation particularly susceptible to decoherence effects arising from unwanted dissipation modes. I will review in my talk the progress that has been made in phase qubits, most notably the improvement in the T_1 energy decay time from about 20 ns to 500 ns due to the understanding and elimination of two-level defects in dielectrics. I will also discuss tomography experiments that carefully characterize the fidelity of qubit logic gates, including recent results that demonstrate single qubit gate fidelity of 98% and the elimination of 2-state errors to the 10^{-4} level. I will present general arguments for the need to move away from coupling schemes controlled by on/off resonant coupling, and will discuss a new design for an adjustable coupler that can be inserted between qubits in an arbitrary (non-nearest neighbor) manner.

Low-frequency Flux Noise in SQUIDs and Superconducting Qubits

Robert McDermott
Department of Physics
University of Wisconsin-Madison

Superconducting qubits are a leading candidate for scalable quantum information processing. In order to realize the full potential of these qubits, it is necessary to develop a more complete understanding of the microscopic physics that governs dissipation and dephasing of the quantum state. In the case of the Josephson phase and flux qubits, the dominant dephasing mechanism is an apparent low-frequency magnetic flux noise with a 1/f spectrum and a magnitude of several $\mu\phi_0 / Hz^{1/2}$ at 1 Hz, where $\phi_0 = h/2e$ is the magnetic flux quantum. Recent qubit results are compatible with the excess low-frequency noise measured by researchers at Berkeley more that 20 years ago in a series of experiments on SQUIDs cooled to millikelvin temperatures. The origin of this excess noise was never understood. Here we describe novel measurements that use the resonant response of a Josephson phase qubit to directly measure the spectrum of low-frequency magnetic flux noise in the circuit. In addition, we report the results of recent SQUID measurements designed to examine possible microscopic mechanisms for this noise.

DiSQ Attendees

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