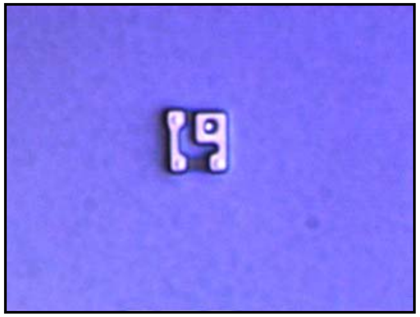
Lecture 1: General Introduction to Quantum Computing and Superconducting Devices

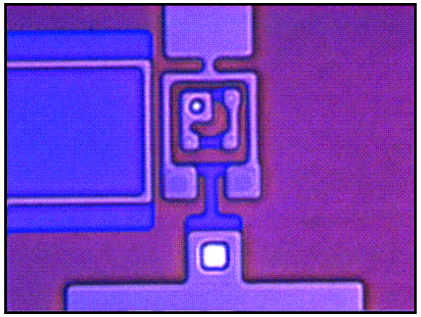
Terry P. Orlando

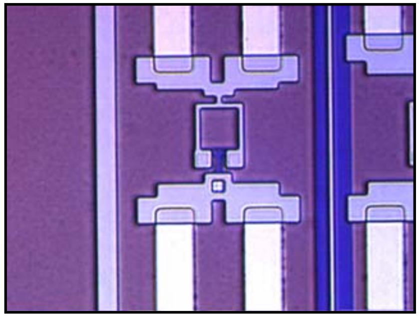
6.975 EECS MIT

February 4, 2003

Orlando Group Website: http://rleweb.mit.edu/superconductivity







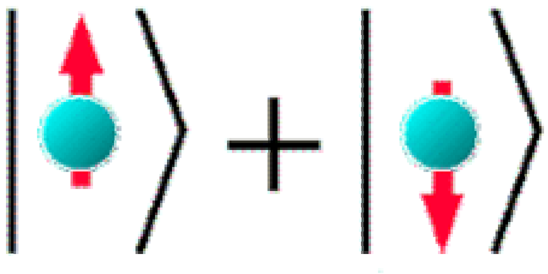
Some viewgraphs from Janice Lee, Ken Segall, Donald Crankshaw, Daniel Nakada, and Yang Yu.

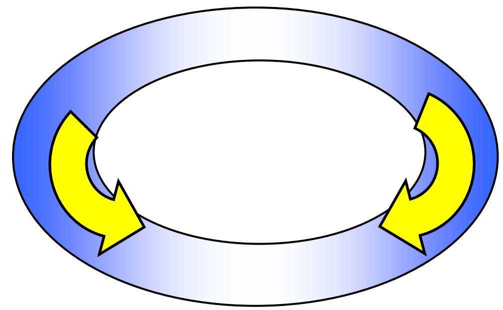
Outline

1. **Introduction to Quantum Computation**
   a. The Unparalleled Power of a Quantum Computer
   b. Two State Systems: Qubits
   c. Types of Qubits
2. **Background on Superconductors**
   a. What is a Superconductor
   b. Uses for Superconductors
3. **Quantum Circuits**
4. **Building a Quantum Computer with Superconductors**
   a. Types of Superconducting Qubits
   b. Experiments on Superconducting Qubits
      1. Charge qubits
      2. Phase/Flux qubits
      3. Hybrid qubits
   c. Advantages of superconductors as qubits
5. **Outline of Class**

The "Magic" of Quantum Mechanics

States 0 and 1 are stored and processed AT THE SAME TIME





→ Parallel Computation → Exponential Speedup to get Answers

Qubits: Quantum Bits

- Qubits are two level systems
  - a) Spin states can be true two level systems, or
  - b) Any two quantum energy levels can also be used

- We will call the lower energy state $|0\rangle$ and the higher energy state $|1\rangle$

- In general, the wave function can be in a superposition of these two states

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Computing with Quantum States

- Consider two qubits, each in superposition states

$$|\psi\rangle_a = |0\rangle_a + |1\rangle_a \qquad\qquad |\psi\rangle_b = |0\rangle_b + |1\rangle_b$$

- We can rewrite these states as a single sate of the 2 spin system

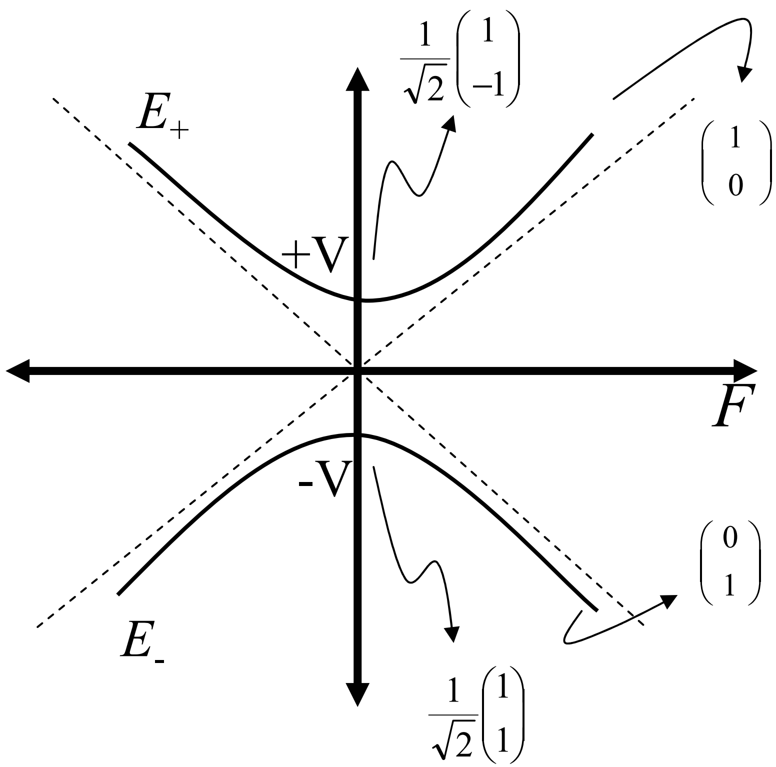
$$\begin{aligned}|\psi\rangle &= |\psi\rangle_a \otimes |\psi\rangle_b = (|0\rangle_a + |1\rangle_a) \otimes (|0\rangle_b + |1\rangle_b) \\ &= |0\rangle_a|0\rangle_b + |0\rangle_a|1\rangle_b + |1\rangle_a|0\rangle_b + |1\rangle_a|1\rangle_b \\ &= |00\rangle + |01\rangle + |10\rangle + |11\rangle\end{aligned}$$

- All four “numbers” (0, 1, 2, & 3 in binary notation) exist simultaneously

- Algorithm designed so that states interfere to give one “number” with high probability

Two Level Systems

$$H = \begin{pmatrix} -F & -V \\ -V^* & F \end{pmatrix} \quad , \quad |\psi\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$



Eigenenergies $E = \sqrt{F^2 + V^2}$

At F=0, let $|\psi(t=0)\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$

$$|\psi(t)\rangle = \frac{1}{2}\begin{pmatrix} 1 \\ 1 \end{pmatrix} e^{i\frac{V}{\hbar}t} + \frac{1}{2}\begin{pmatrix} 1 \\ -1 \end{pmatrix} e^{-i\frac{V}{\hbar}t}$$

$$= \begin{pmatrix} 1 \\ 0 \end{pmatrix} \cos\frac{V}{\hbar}t + i\begin{pmatrix} 0 \\ 1 \end{pmatrix} \sin\frac{V}{\hbar}t$$

System oscillates between $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$ with period $T = \frac{h}{2V}$

Rabi Oscillations

Drive the system with $V(t)=V_0\, e^{i\omega t}$ at the resonant frequency $\omega = E_+ - E_-$

If $\left|\psi(t=0)\right\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$, then $\left|\psi(t)\right\rangle = \cos\frac{V_0 t}{\hbar}\begin{pmatrix} 1 \\ 0 \end{pmatrix} + i\sin\frac{V_o t}{\hbar} e^{i\omega t}\begin{pmatrix} 0 \\ 1 \end{pmatrix}$

Oscillations between states can be controlled by V_0 and the time of AC drive, with period

$$T = \frac{h}{2V_0}$$

The Promise of a Quantum Computer

A Quantum Computer …

- Offers exponential improvement in ***speed*** and ***memory*** over existing computers

- Capable of ***reversible computation***

- e.g. Can factorize a 250-digit number in seconds while an ordinary computer will take 800 000 years!

Evolution of Computing Technology

Vacuum Tubes

- Slow
- Power consuming
- Huge in size

Transistors

- Improved size and efficiency
- Heat dissipation

Integrated Circuits

- Fitting everything on a chip

VLSI, ULSI

- Yet smaller sizes

Quantum Computer

1940s-50s — 50s-60s — 60s-70s — 70s - ?

1. Quantum Computing Roadmap Overview
2. Nuclear Magnetic Resonance Approaches
3. Ion Trap Approaches
4. Neutral Atom Approaches
5. Optical Approaches
6. Solid State Approaches
7. Superconducting Approaches
8. "Unique" Qubit Approaches
9. The Theory Component of the Quantum Information Processing and Quantum Computing Roadmap

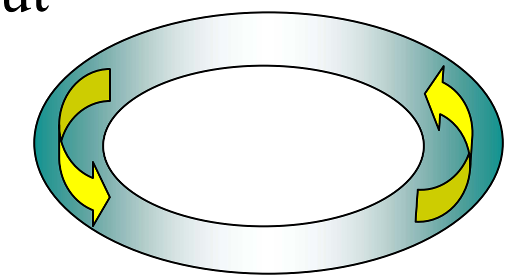
http://qist.lanl.gov

Outline

1. **Introduction to Quantum Computation**
    a. The Unparalleled Power of a Quantum Computer
    b. Two State Systems: Qubits
    c. Types of Qubits
2. **Background on Superconductors**
    a. What is a Superconductor
    b. Uses for Superconductors
3. **Quantum Circuits**
4. **Building a Quantum Computer with Superconductors**
    a. Types of Superconducting Qubits
    b. Experiments on Superconducting Qubits
        1. Charge qubits
        2. Phase/Flux qubits
        3. Hybrid qubits
    c. Advantages of superconductors as qubits
5. **Outline of Class**

What is a Superconductor?

"A ***Superconductor*** has *ZERO* electrical resistance *BELOW* a certain critical temperature. Once set in motion, a persistent electric current will flow in the superconducting loop *FOREVER* without any power loss."



<u>Magnetic Levitation</u>

A ***Superconductor*** *EXCLUDES* any magnetic fields that come near it.

How “Cool” are Superconductors?

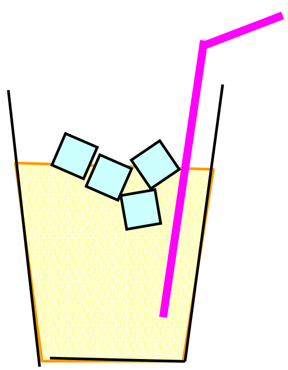
Below **77 Kelvin** (-200 ºC):

• Some Copper Oxide Ceramics superconduct

Below **4 Kelvin** (-270 ºC):

• Some Pure Metals e.g. Lead, Mercury, Niobium superconduct

<u>Keeping at 0 ºC</u>

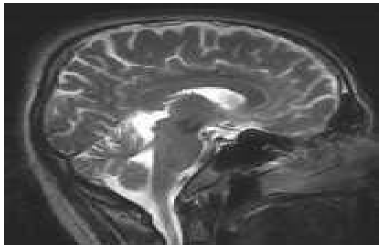


<u>Keeping at 77 K</u>

<u>Keeping at 4K</u>

Uses for Superconductors

- Magnetic Levitation allows trains to "float" on strong superconducting magnets (MAGLEV in Japan, 1997)



- To generate Huge Magnetic field e.g. for Magnetic Resonance Imaging (MRI)
- A SQUID (Superconducting Quantum Interference Device) is the most sensitive magnetometer. (sensitive to 100 billion times weaker than the Earth's magnetic field)
- Quantum Computing

Picture source: http://www.superconductors.org

Outline

1. **Introduction to Quantum Computation**
    a. The Unparalleled Power of a Quantum Computer
    b. Two State Systems: Qubits
    c. Types of Qubits
2. **Background on Superconductors**
    a. What is a Superconductor
    b. Uses for Superconductors
3. **Quantum Circuits**
4. **Building a Quantum Computer with Superconductors**
    a. Types of Superconducting Qubits
    b. Experiments on Superconducting Qubits
        1. Charge qubits
        2. Phase/Flux qubits
        3. Hybrid qubits
    c. Types of Superconducting Qubits
5. **Outline of Class**

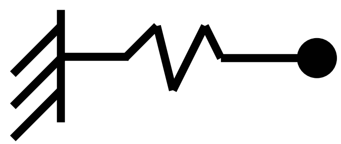
Circuits for Qubits

- Need to find dissipationless circuits which have two “good” energy levels
- Need to be able to “manipulate” qubits and couple them together

Quantization of Circuits

- Find the energy of the circuit
- Change the energy into the Hamiltonian of the circuit by identifying the canonical variables
- Quantize the Hamiltonian
- Usually we can make it look like a familiar quantum system

Harmonic Oscillator



$$H = \frac{1}{2} m v^2 + \frac{1}{2} m \omega^2 x^2$$

$$v = \frac{dx}{dt}$$

$$H = \frac{1}{2} m \left(\frac{dx}{dt} \right)^2 + \frac{1}{2} m \omega^2 x^2$$

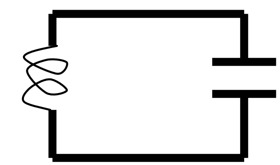
$$p = m \frac{dx}{dt}$$

Quantum Mechanically

$$\Delta x \Delta p \geq \hbar / 2$$

$$E = \hbar \omega (n + \frac{1}{2})$$

LC Circuit



$$H = \frac{1}{2} C V^2 + \frac{1}{2} L I^2$$

$$v = \frac{d\Phi}{dt} \quad and \quad I = \frac{\Phi}{L}$$

$$H = \frac{1}{2} \underbrace{C}_{M} \left(\frac{d\Phi}{dt} \right)^2 + \frac{1}{2} \underbrace{C}_{M} \underbrace{\frac{1}{LC}}_{\omega^2} \Phi^2$$

$$p = C \frac{d\Phi}{dt} = C V$$

Quantum Mechanically

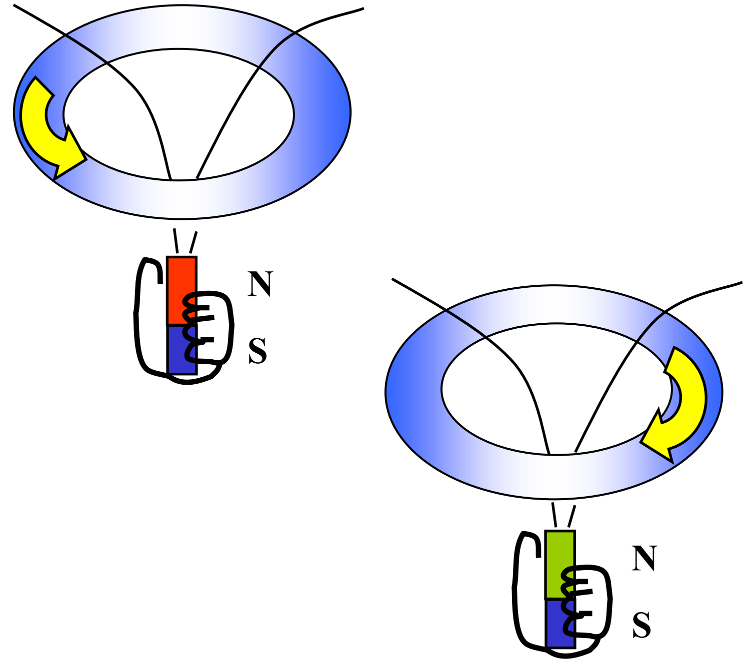
$$L C \Delta I \Delta V \geq \hbar / 2$$

$$E = \hbar \omega (n + \frac{1}{2})$$

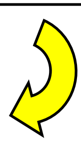
Outline

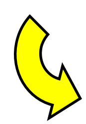
1. **Introduction to Quantum Computation**
    a. The Unparalleled Power of a Quantum Computer
    b. Two State Systems: Qubits
    c. Types of Qubits
2. **Background on Superconductors**
    a. What is a Superconductor
    b. Uses for Superconductors
3. **Quantum Circuits**
4. **Building a Quantum Computer with Superconductors**
    a. Types of Superconducting Qubits
    b. Experiments on Superconducting Qubits
        1. Charge qubits
        2. Phase/Flux qubits
        3. Hybrid qubits
    c. Advantages of superconductors as qubits
5. **Outline of Class**

The Superconducting "Quantum Bit"

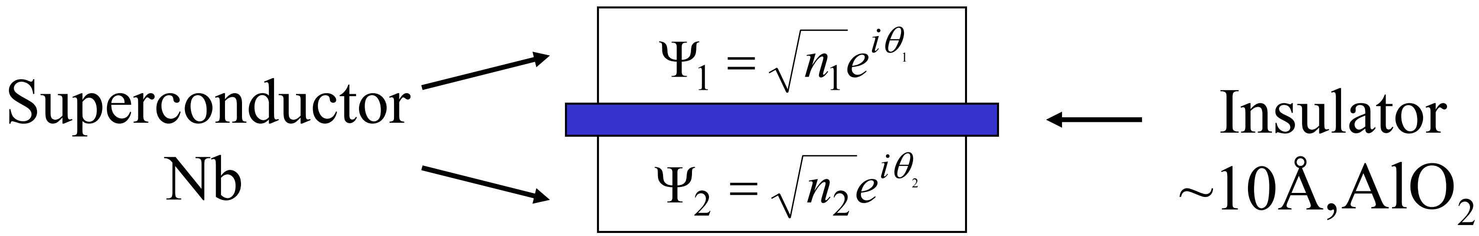


- An External Magnet can induce a current in a superconducting loop
- The induced current can be in the opposite direction if we carefully choose a *different* magnetic field this time
- To store and process information as a computer bit, we assign:

 as state $|\,0\,\rangle$

 as state $|\,1\,\rangle$

Josephson Junction



- Josephson relations:

$$I = I_c \sin\varphi$$

$$V = \frac{\Phi_0}{2\pi}\frac{d\varphi}{dt}$$

$$\varphi = \theta_2 - \theta_1 - \frac{2\pi}{\Phi_0}\int_2^1 \vec{A}(r,t)\cdot d\vec{l}$$

- Behaves as a nonlinear inductor:

$$V = L_J \frac{dI}{dt},$$

where $L_J = \dfrac{\Phi_0}{2\pi\, I_c \cos\varphi}$

Φ_0 = flux quantum

483.6 GHz / mV

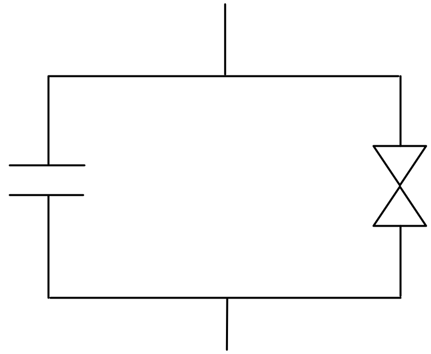
Quantization of a Josephson Junction

Charging Energy

$$U_C = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}CV^2$$

$$= \frac{1}{2}\left(\frac{\Phi_0}{2\pi}\right)^2 C\left(\frac{\partial\varphi}{\partial t}\right)^2$$

$$E_C = \frac{e^2}{2C}$$



Josephson Energy

$$U_J = \frac{\Phi_0 I_c}{2\pi}(1-\cos\varphi)$$

$$E_J = \frac{\Phi_0 I_c}{2\pi}$$

Hamiltonian: $$H = \frac{1}{2}\left(\frac{\Phi_0}{2\pi}\right)^2 C\left(\frac{\partial\varphi}{\partial t}\right)^2 + \frac{\Phi_0 I_c}{2\pi}(1-\cos\varphi)$$

Circuit behaves just like a physical pendulum.

For Al-Al_2O_3-Al junction with an area of 100x100 nm^2
C = 1fF and I_c=300 nA, which gives E_C=10μeV and E_J=600μeV

To see quantization, Temperature < 300 mK

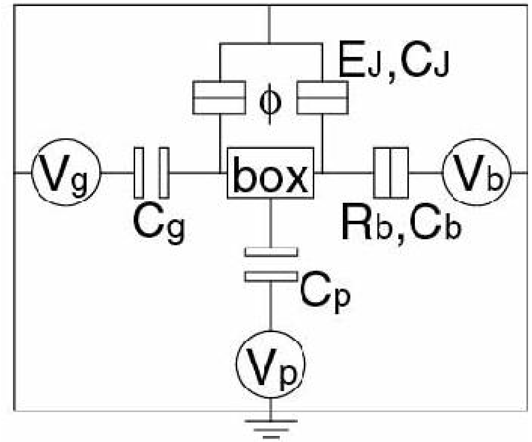
Types of Superconducting Qubits

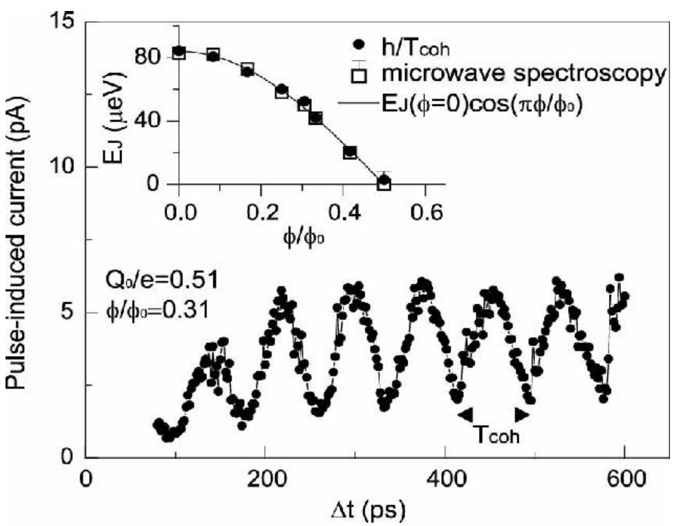
- Charge-state Qubits (voltage-controlled)
  - Cooper pair boxes

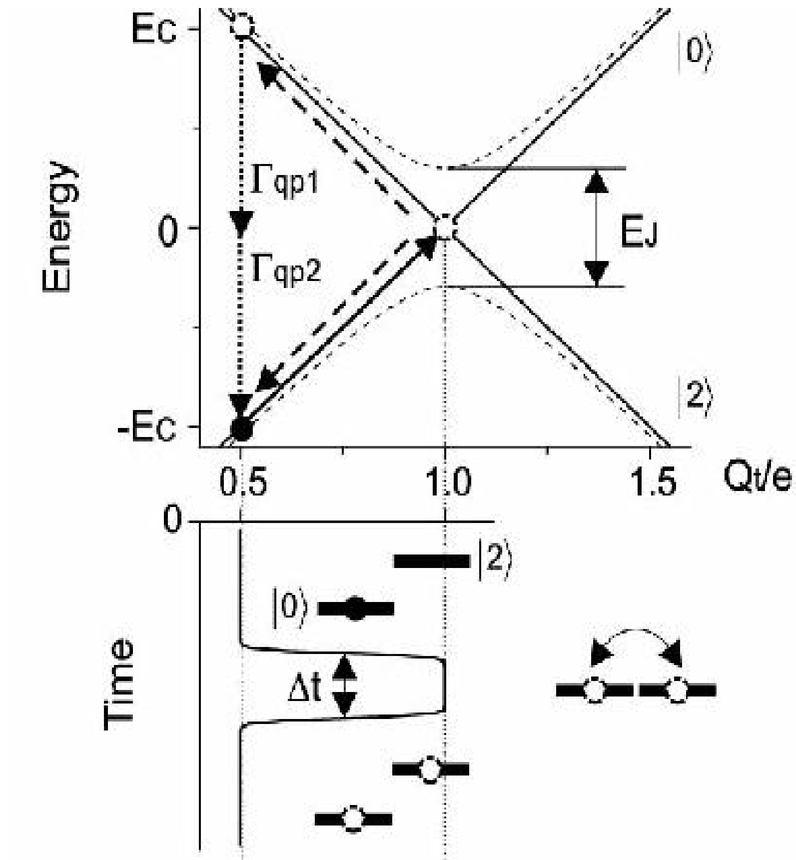
- Flux/Phase-state qubits (flux-current control)
  - Persistent Current Qubits
  - RF SQUID Qubits
  - Phase Qubits (single junction)

- Hybrid Charge-Phase Qubits

Charge-State Superconducting Qubit







TOP: "Electrical schematic"

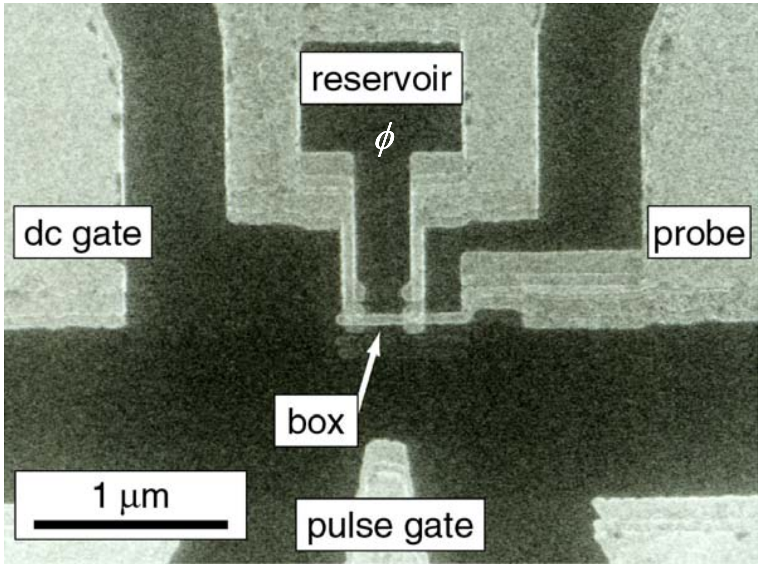
BOTTOM: "Evidence of Rabi Oscillations"

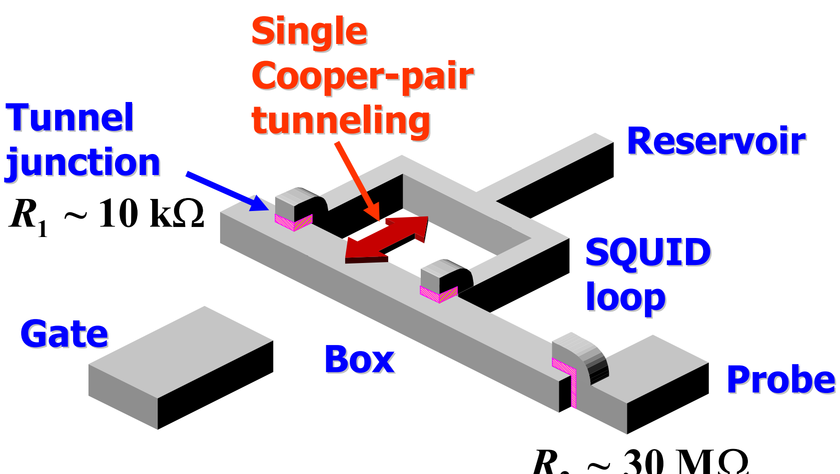
Y. Nakamura, Yu A. Pashkin, and J.S. Tsai, *Nature* **398**, 786 (1999).

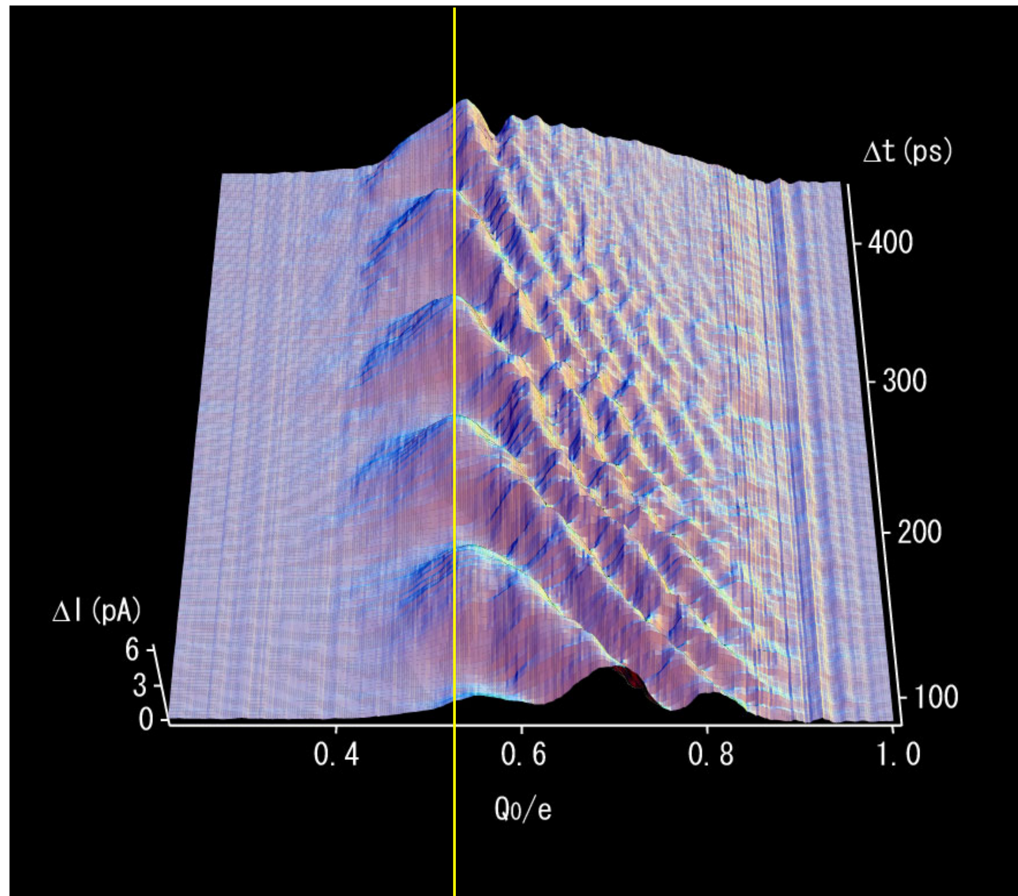
Charge qubit

a Cooper-pair box $E_J / E_C \sim 0.3$

Coherence up to ~ 5 ns, presently limited by background charge noise (dephasing) and by readout process (relaxation)



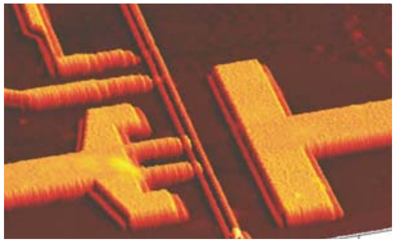




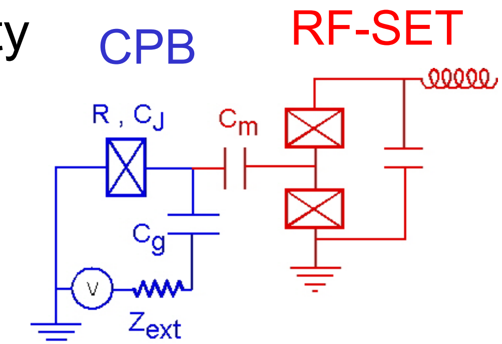
Y.Nakamura *et al.*, Nature **398**, 786 (1999).

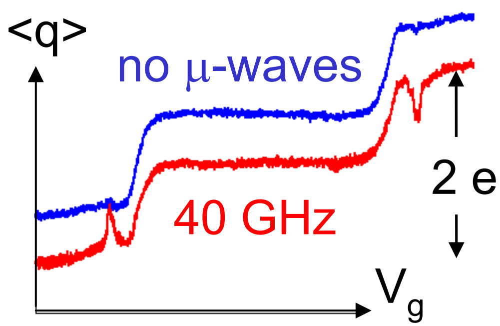
Quantum Coherence in the Cooper-Pair Box Measured with an RF-SET

Schoelkopf Group, Yale University



- Superconducting charge qubit: the Cooper-pair box (CPB)
- Fast, single-charge readout: the RF single-electron transistor





- **Quantum coherence of Cooper-pair box qubit observed by CW microwave spectroscopy**

- Transition frequency ~ 40 GHz: $\mathbf{Q_\phi = \omega_{10} T_\phi \sim 250}$ **&** $\mathbf{Q_1 = \omega_{10} T_1 > 10^5}$
- Ensemble decoherence time from linewidth: T_ϕ = 1 ns
- Lifetime from time-resolved decay of photon peaks: T_1 = 1.6 μs

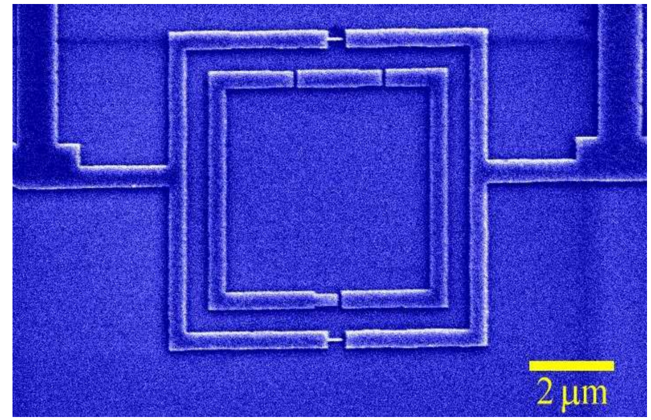
<u>Next steps:</u>

- Operate @ charge-noise insensitive point to reduce decoherence
- Perform time-gated, single-shot measurements

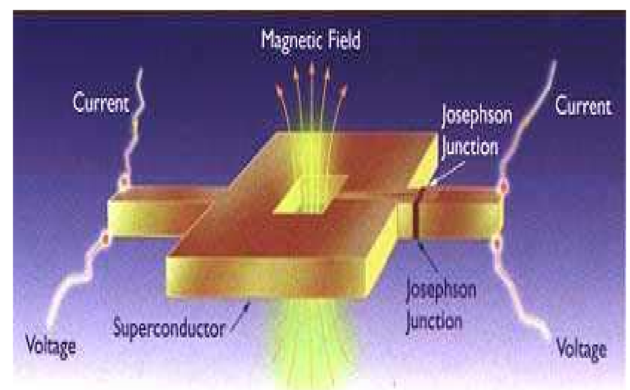
Funding: ARO/ARDA/NSA

Our Persistent Current Qubit

- Depending on the direction of the current, state $|0\rangle$ and state $|1\rangle$ will *add* a different magnetic field to the external magnet

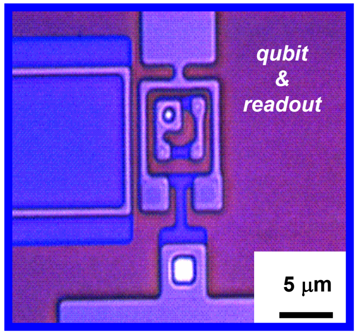


- This difference is very small but can be distinguished by the extremely sensitive SQUID sensor

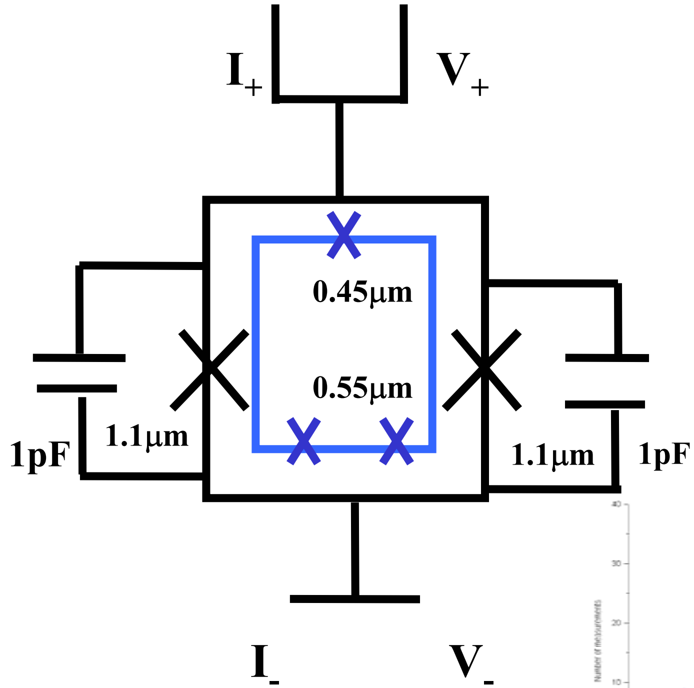


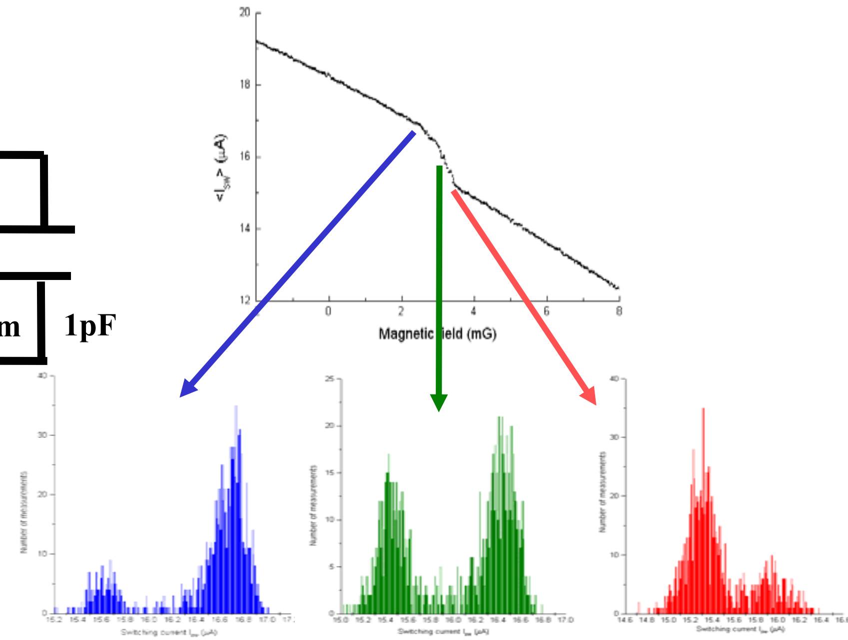
Quantum Computation with Superconducting Quantum Devices

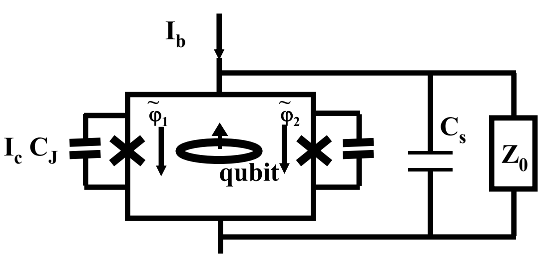
T.P. Orlando, S. Lloyd, L. Levitov, J.E. Mooij - MIT
M. Tinkham – Harvard; M. Bocko, M. Feldman – U. of Rochester
in collaboration with K. Berggren, MIT Lincoln Laboratory



Fabrication modeling, and measurements



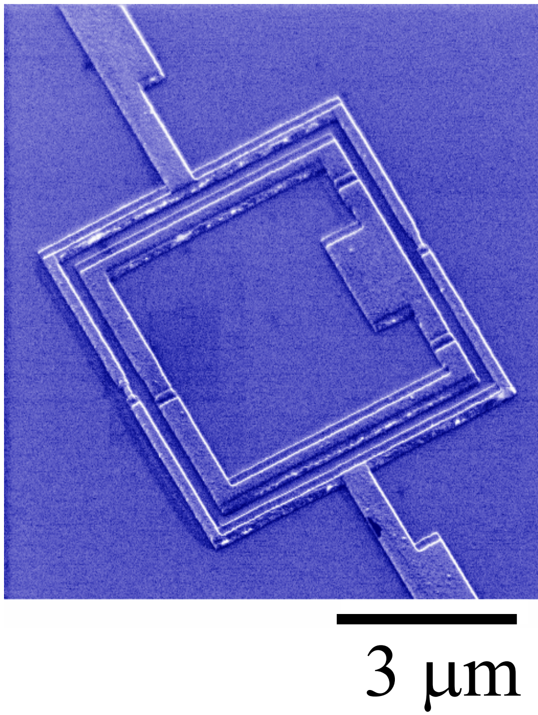


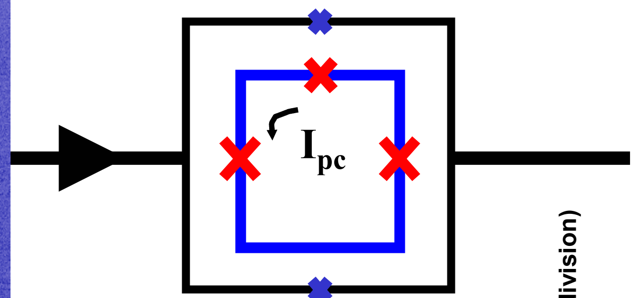


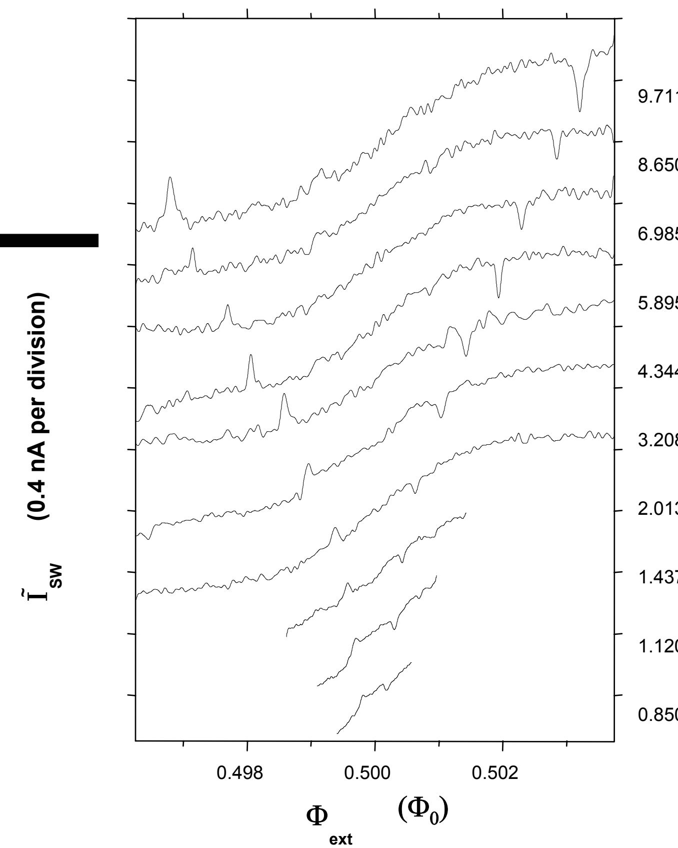
- Persistent current qubit fabricated in Nb with submicron junctions
- Two states seen in measurement (thermal activations and energy levels)

Macroscopic quantum superposition in a Josephson junction loop

Delft University of Technology & DIMES The Netherlands *MIT Cambridge*
Caspar van der Wal, A. Ter Haar, Kees Harmans, Hans Mooij T. Orlando, L. Levitov, S. Lloyd







- ***Superposition of states observed***
- ***Relaxation time 5 µsec,***
- ***Dephasing time 0.1 µsec***

TU Delft Technische Universiteit Delft
DIMES Delft Institute of Microelectronics and Submicron Technology
FOM
MIT

Observation of Coherent Superposition of Macroscopic States

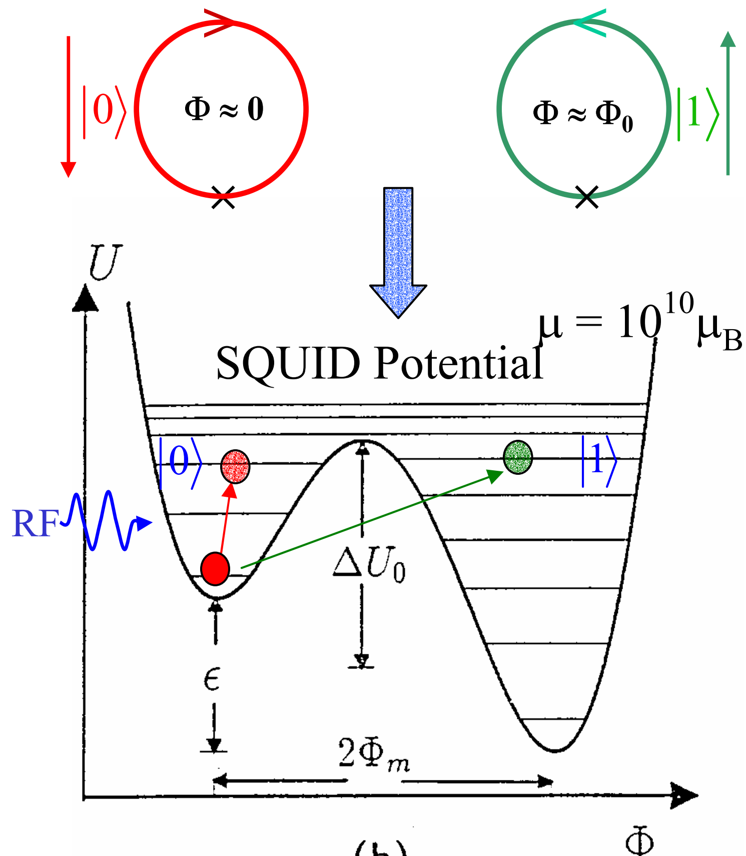
Jonathan Friedman, Vijay Patel, Wei Chen, Sergey Tolpygo and James Lukens

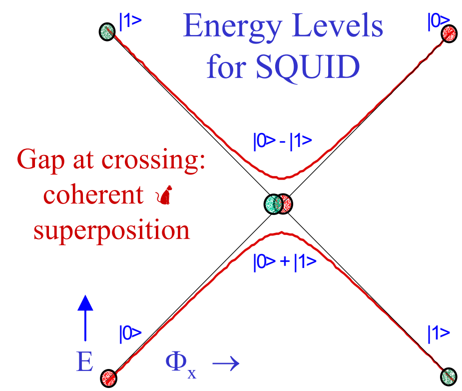
The SQUID

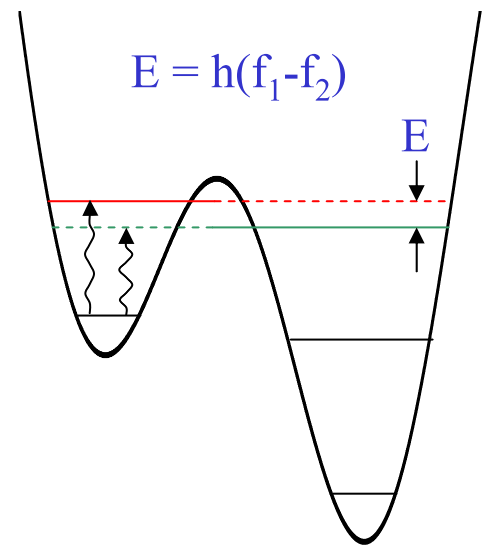
(Superconducting QUantum Interference Device)

- SQUIDs like integer flux quanta, Φ_0

$\Phi_x \approx ½ \, \Phi_0$







J. Friedman, *et al.*, Nature, **406**, 43 (July, 2000).

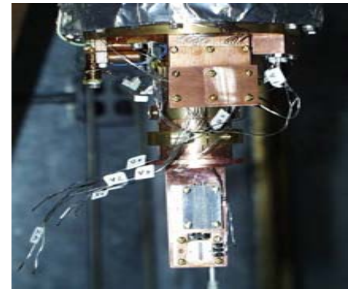
C. Van der Wal, *et al.*, Science, 290, 773 (Oct. 2000)

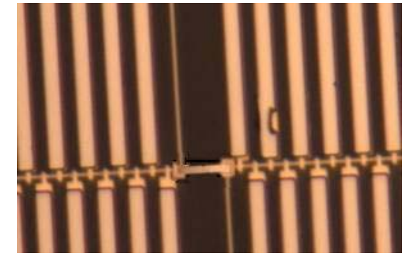
Quantum Computing with Superconducting Devices

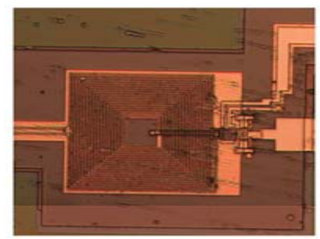
F.C. Wellstood, C.J. Lobb, J.R. Anderson, and A.J. Dragt, Univ. of Md.
lobb@squid.umd.edu / http://www.physics.umd.edu/sqc/

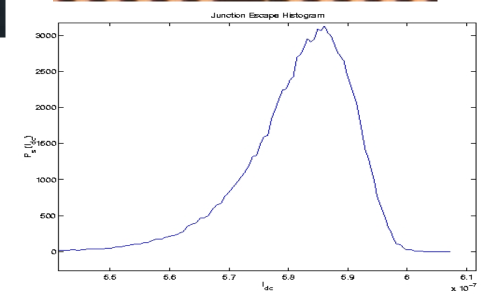
Objective

- Measure energy levels and decoherence rates in single Josephson junctions and SQUIDs
- Manipulate states of the systems
- Perform 1-qubit operations
- Design and test 2-qubit systems of junctions and SQUIDs









Objective Approach

- Build Josephson junctions that are well isolated from measurement leads to achieve low dissipation and long coherence times at milliKelvin temperatures.
- Measure macroscopic quantum tunneling, energy levels and decoherence rate.
- Use microwaves to pump from |0> to |1>
- Model SQUID qubits to guide experimental program.

Status

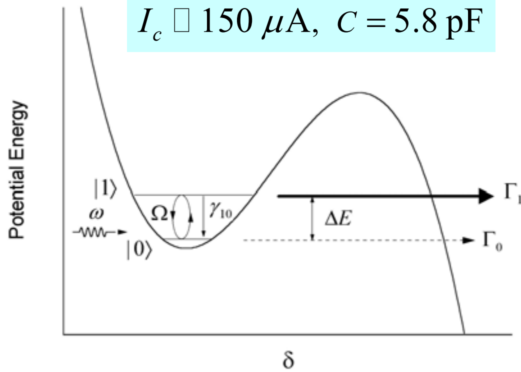
- Built resistively isolated Al/AlOx/Al junctions and measured switching distributions with and without microwave excitation
- Assembled SQUID detection scheme for measuring junctions and rf SQUIDs
- Measured switching distributions for SQUID at mK temperatures, $\Delta\Phi = 10^{-3}\Phi_o$

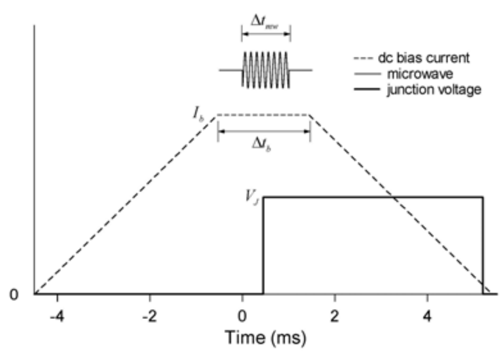
Recent Results from DURINT Quantum Computing Project

Siyuan Han, Yang Yu et al., University of Kansas

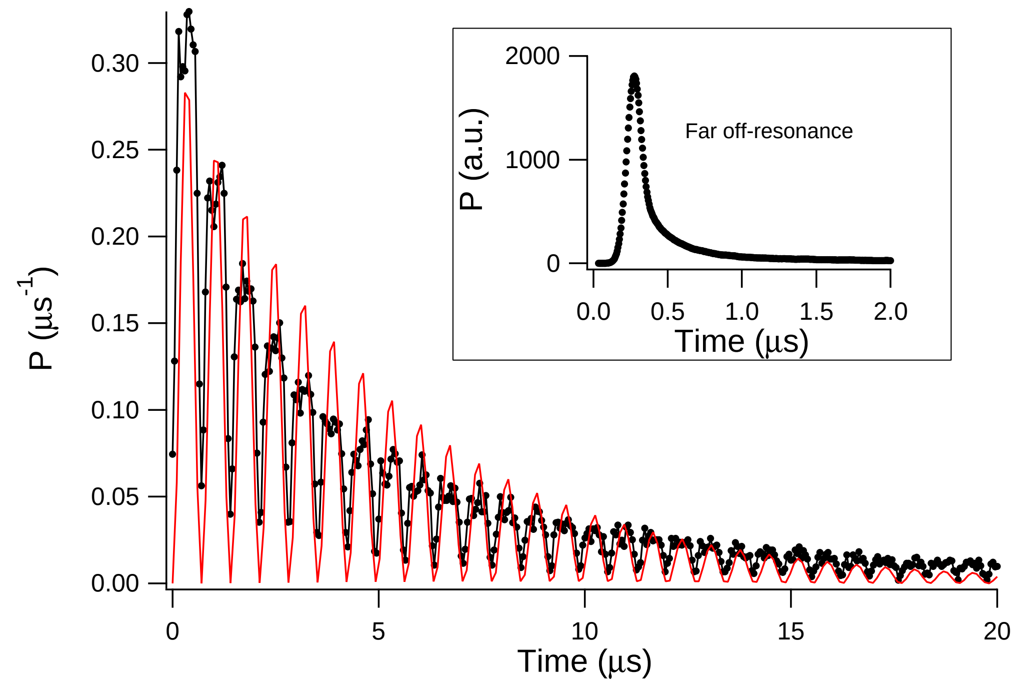
Observation of Rabi oscillations in a Josephson Tunnel Junction

$I_c \approx 150\ \mu\text{A},\ C = 5.8\ \text{pF}$





Generation and detection of RO in JJ



$$\Gamma = \frac{1}{2}(\Gamma_0 + \Gamma_1 + \gamma_{10}) + \gamma_\varphi$$

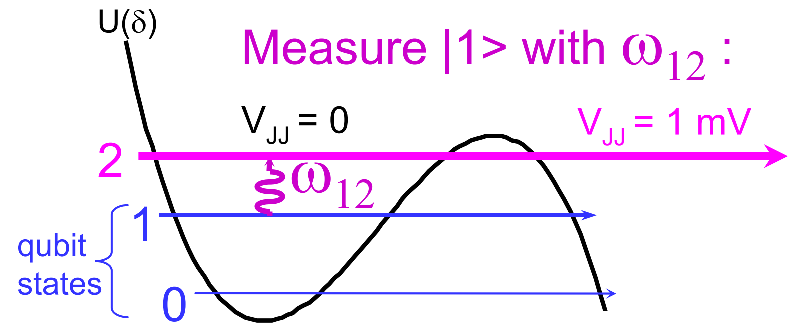
$\mathit{decoherence\ time} > 4.9\ \mu s$

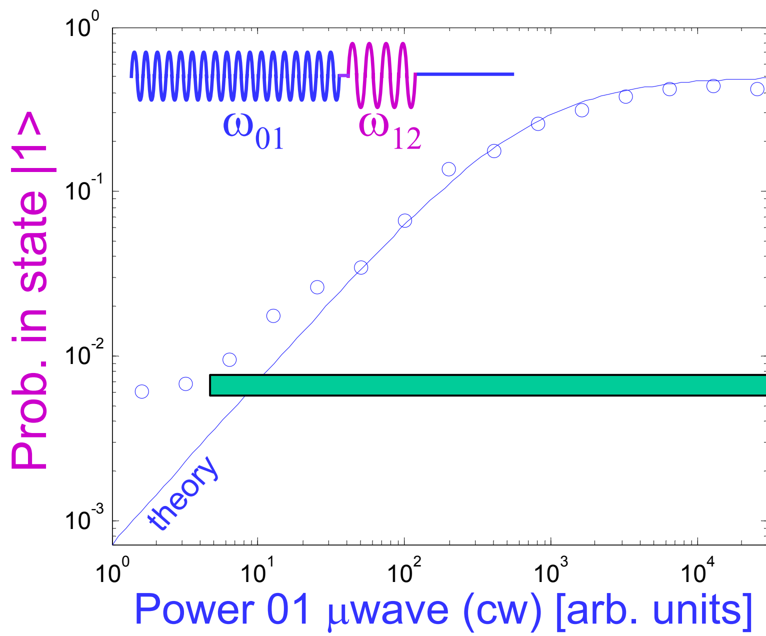
Quantum Computing with Current-Biased Josephson Junctions

John Martinis, S.W. Nam, J. Aumentado, C. Urbina; NIST Boulder

Key Advantages:

- Large area junctions - reliably fabricated using optical lithography
- Large capacitance allows coupling to many other qubits





|1> state meas : >80%

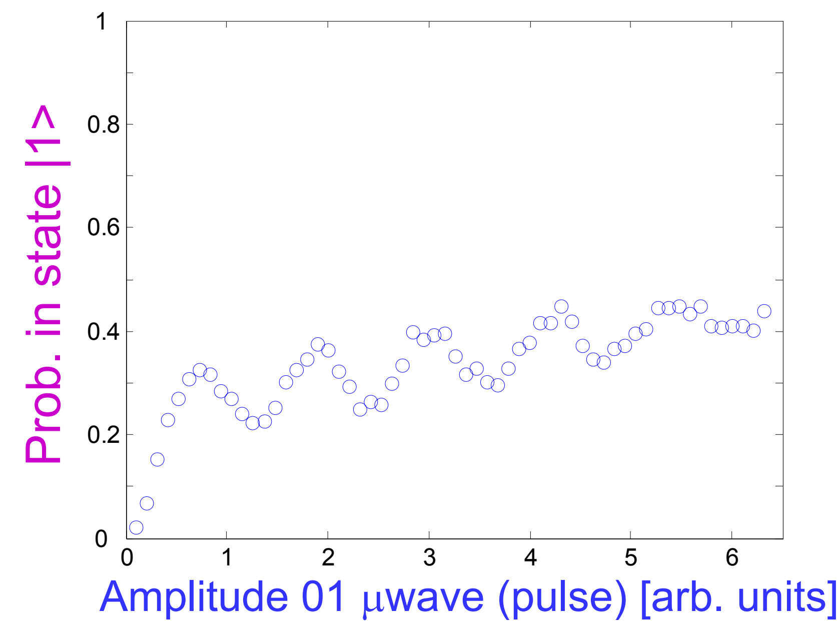
High Fidelity
state preparation
& measurement

|0> state prep : >99%

|0> state meas : >99%

Quantum Computing with Current-Biased Josephson Junctions

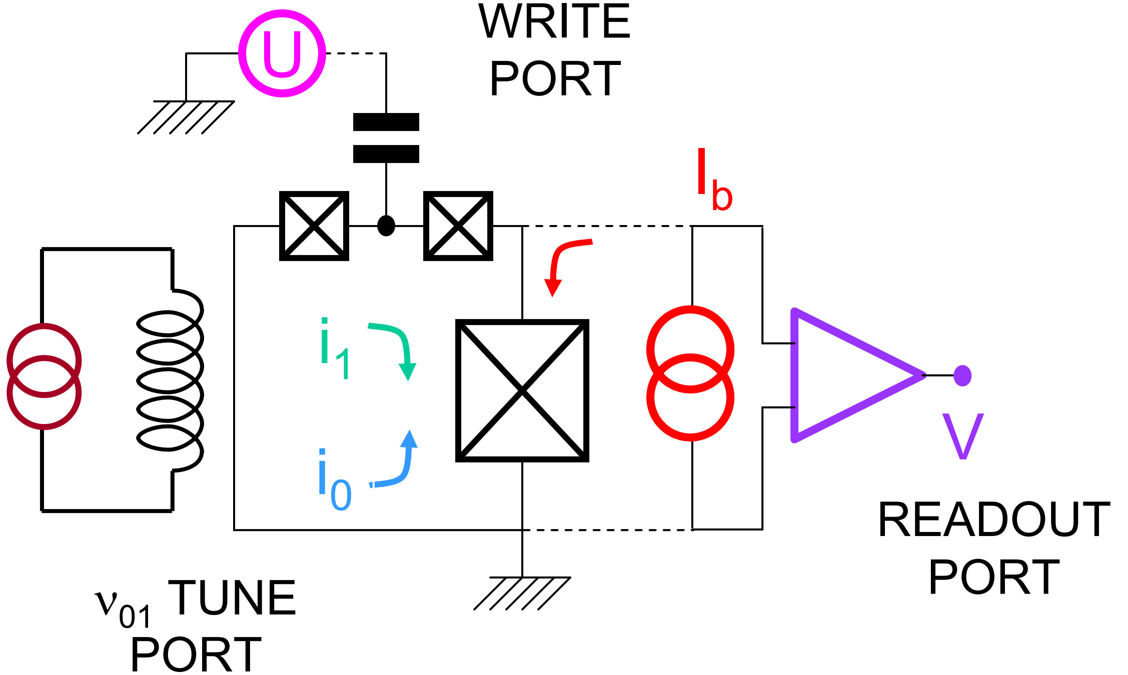
John Martinis, S.W. Nam, J. Aumentado, C. Urbina; NIST Boulder



Rabi Oscillations

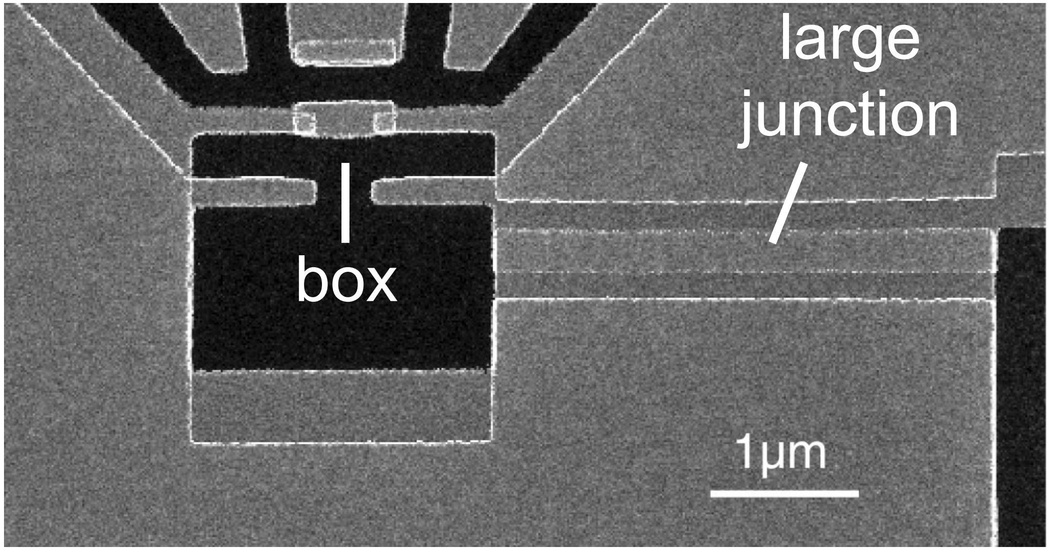
$\tau_{coh} \sim 40$ ns

CHARGE-FLUX QUBIT



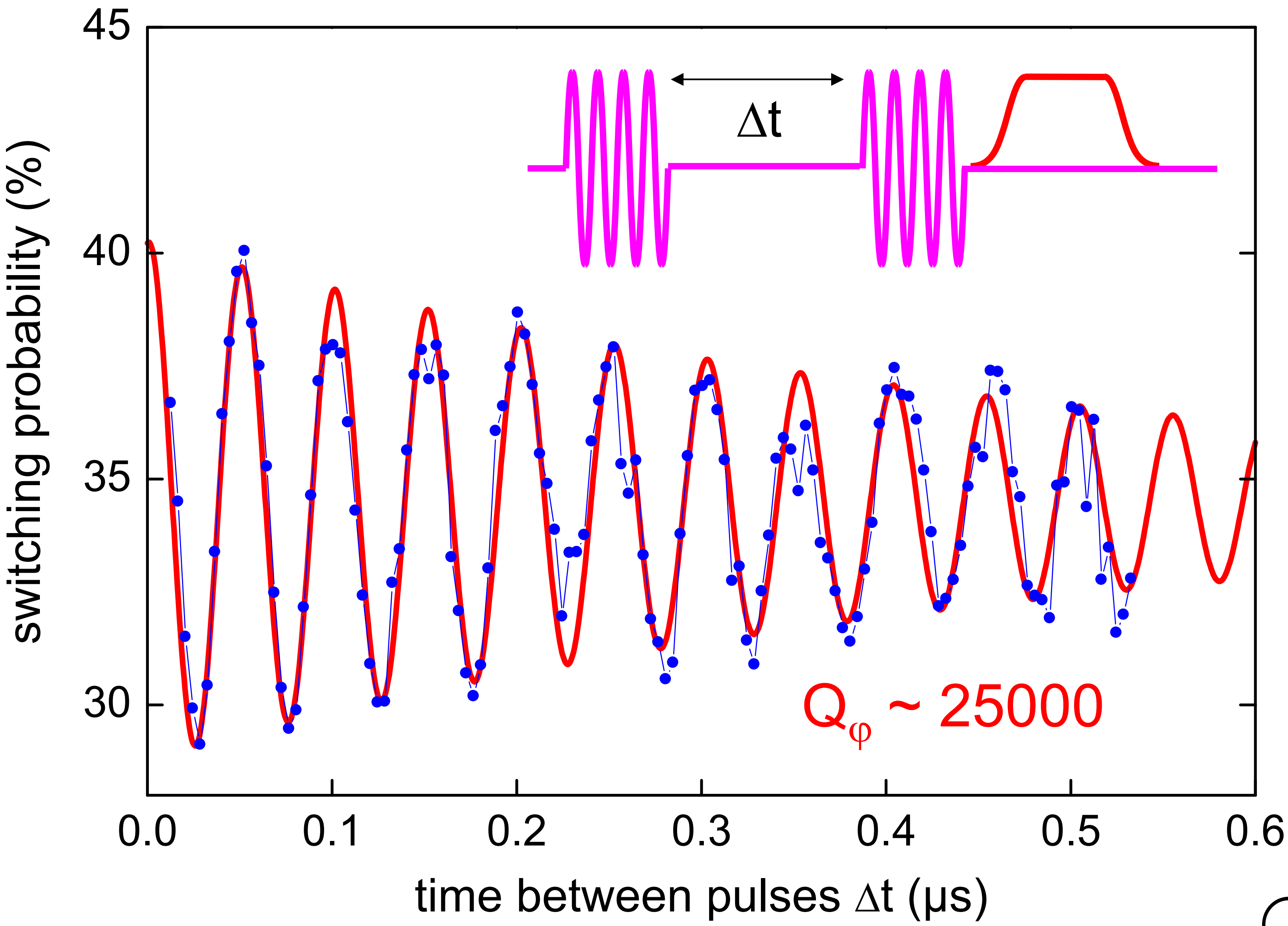
Quantronics Group
CEA-Saclay
France

M. Devoret (now at Yale)
D. Esteve, C. Urbina
D. Vion, H. Pothier
P. Joyez, A. Cottet



Coherence time measured by Ramsey fringes : 500ns
Qubit transition frequency: 16.5 GHz; coherence quality factor: 25 000

RAMSEY FRINGES



Outline

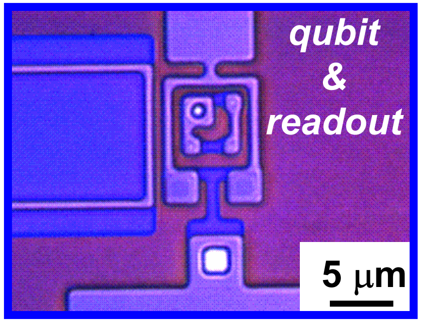
1. **Introduction to Quantum Computation**
    a. The Unparalleled Power of a Quantum Computer
    b. Two State Systems: Qubits
    c. Types of Qubits
2. **Background on Superconductors**
    a. What is a Superconductor
    b. Uses for Superconductors
3. **Quantum Circuits**
4. **Building a Quantum Computer with Superconductors**
    a. Types of Superconducting Qubits
    b. Experiments on Superconducting Qubits
        1. Charge qubits
        2. Phase/Flux qubits
        3. Hybrid qubits
    c. Advantages of superconductors as qubits
5. **Outline of Class**

Advantages of Superconductors for Quantum Computing

- Employs lithographic technology
- Scalable to large circuits
- Combined with on-chip, ultra-fast control electronics
  - Microwave Oscillators
  - Single Flux Quantum classical electronics

Circuits Fabricated at Lincoln Laboratory

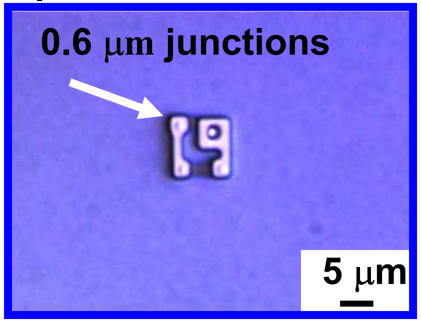
- **Persistent-current qubit**



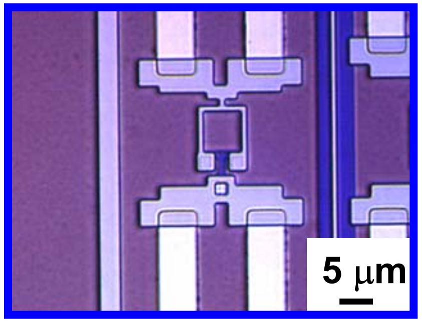
monolithic

flip-chip

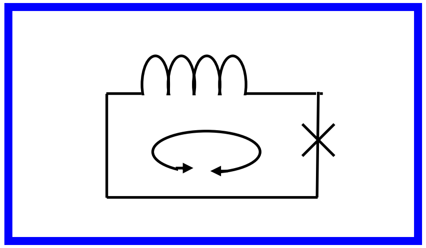
qubit



readout

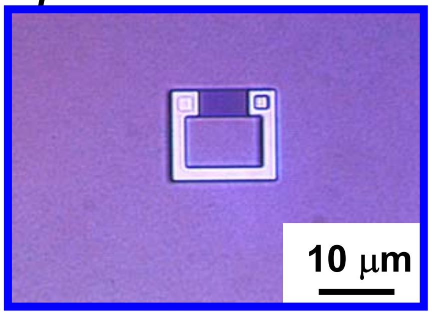


- **RF SQUID qubit**

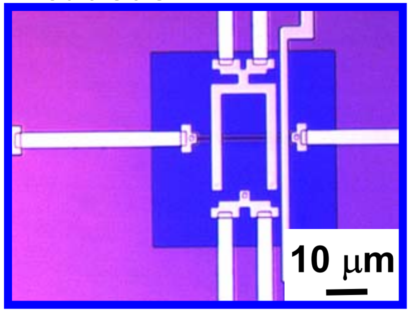


Friedman et al.

qubit



readout

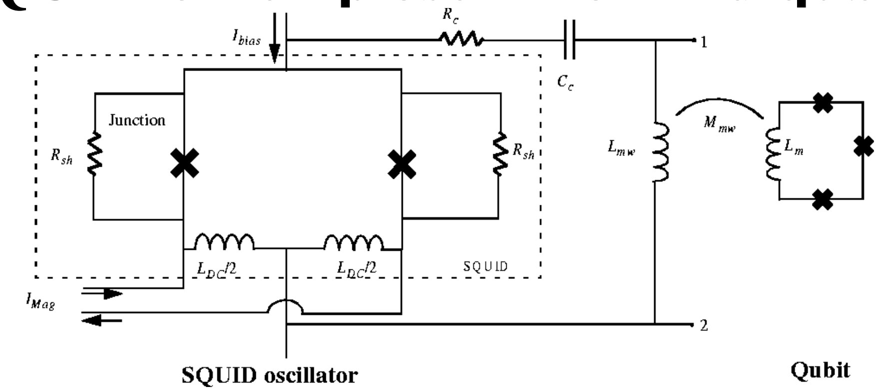


Flip chip process has no hard-wire connections, magnetic field is the only coupling between circuits

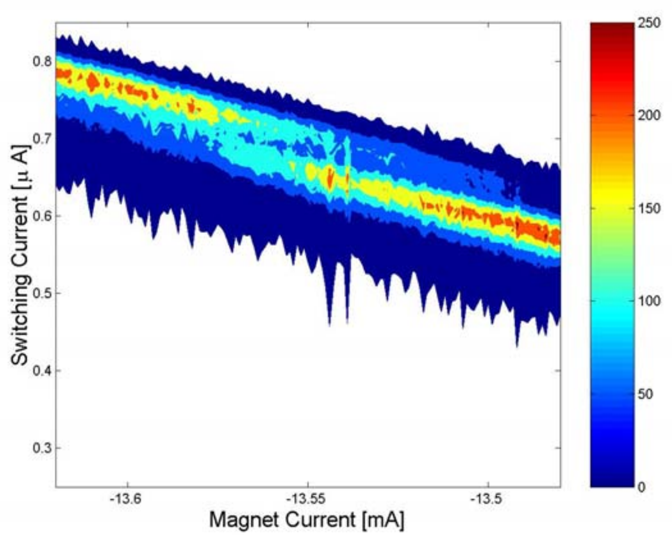
T.P. Orlando, Ken Segall, D. Crankshaw, D.Nakada, S. Lloyd, L. Levitov,- MIT
M. Tinkham , Nina Markovic, Segio Vanenzula– Harvard;
K. Berggren, Lincoln Laboratory

ARDA

SQUID on-chip oscillator and qubit

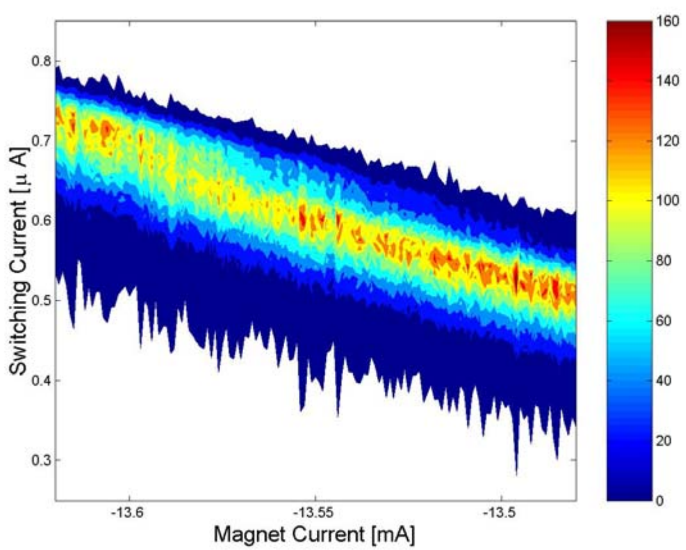


Without oscillator on



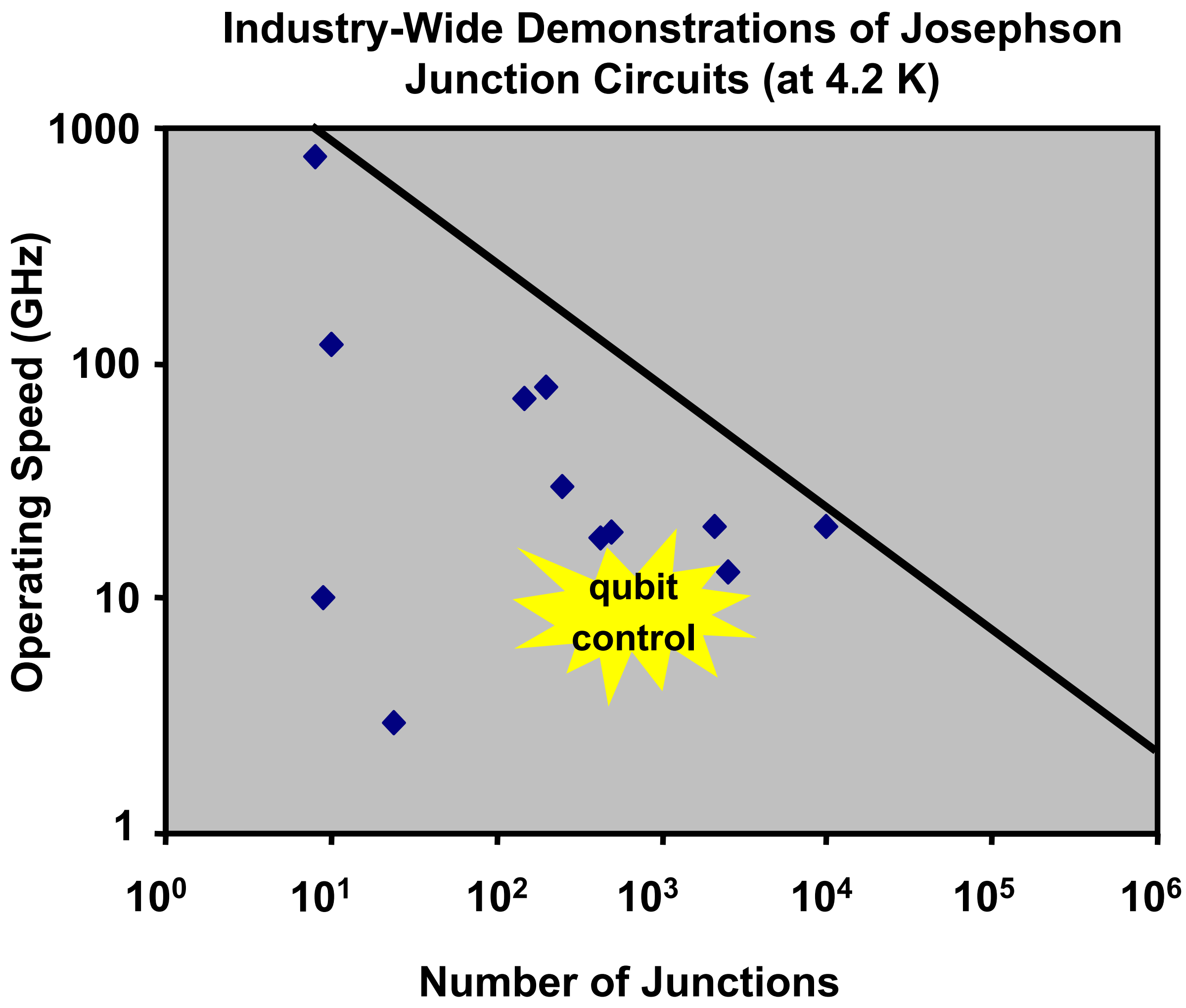
300mK

With oscillator on



On-chip oscillator couples to qubit: No spectroscopy yet due to high temperature

Feasibility of Superconductive Control Electronics Fabrication



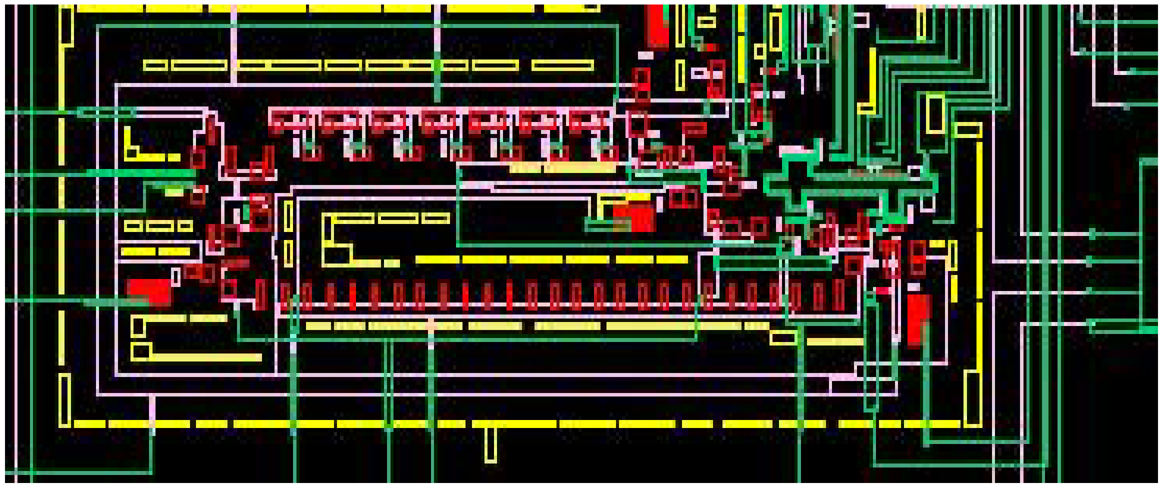
SOURCES
Berkeley
Hitachi
Hypres
Lincoln Laboratory
NEC
Northrop-Grumman
Phys.-Tech.-Bundesanstalt
State University of Moscow
U. of Stonybrook
TRW
others

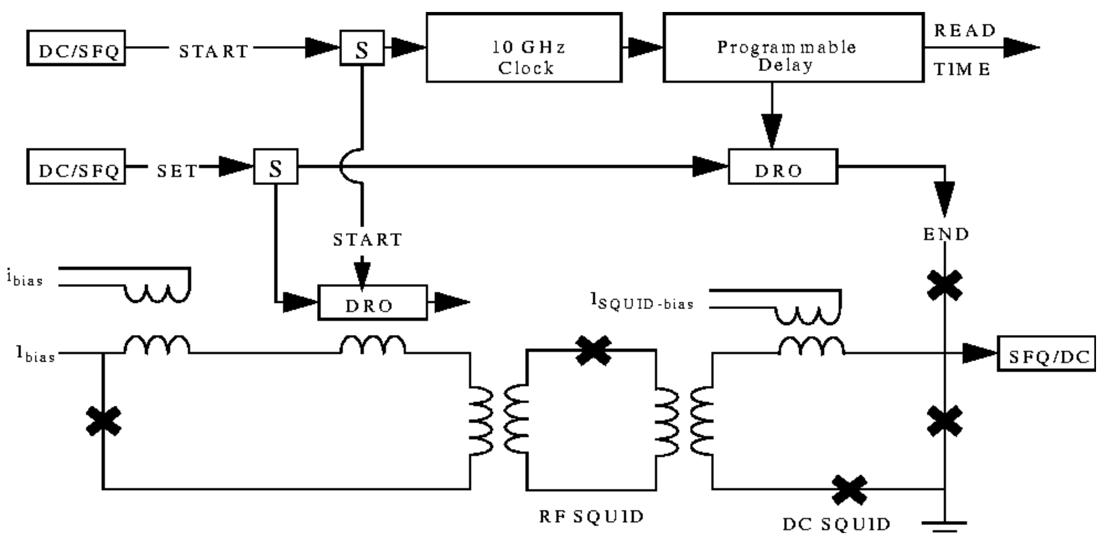
Compiled by K. Berggren

On-chip Control for an RF-SQUID

M.J. Feldman, M.F. Bocko, Univ. of Rochester

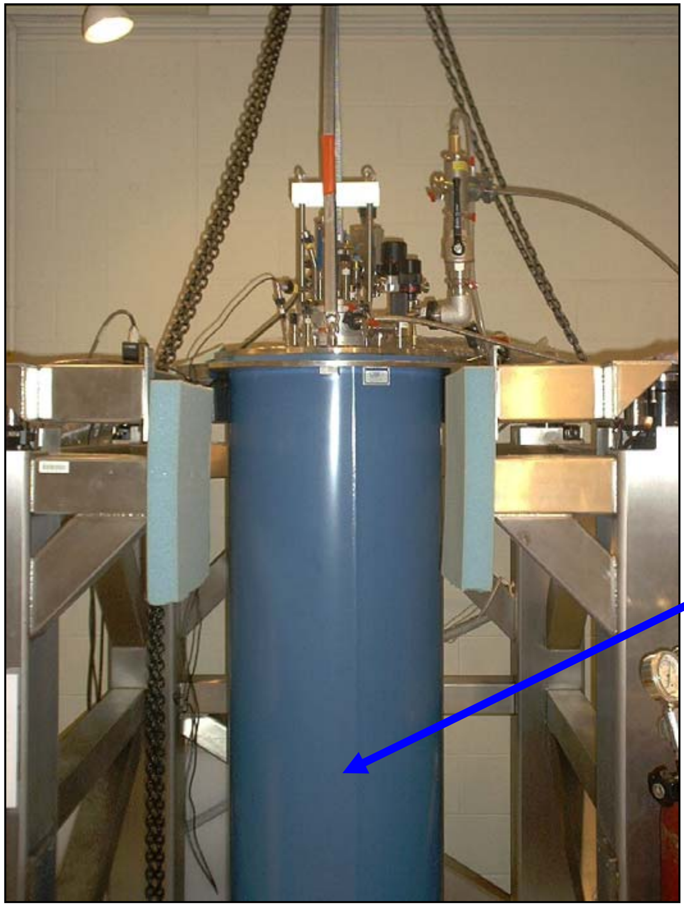
feldman@ece.rochester.edu   www.ece.rochester.edu/~sde/



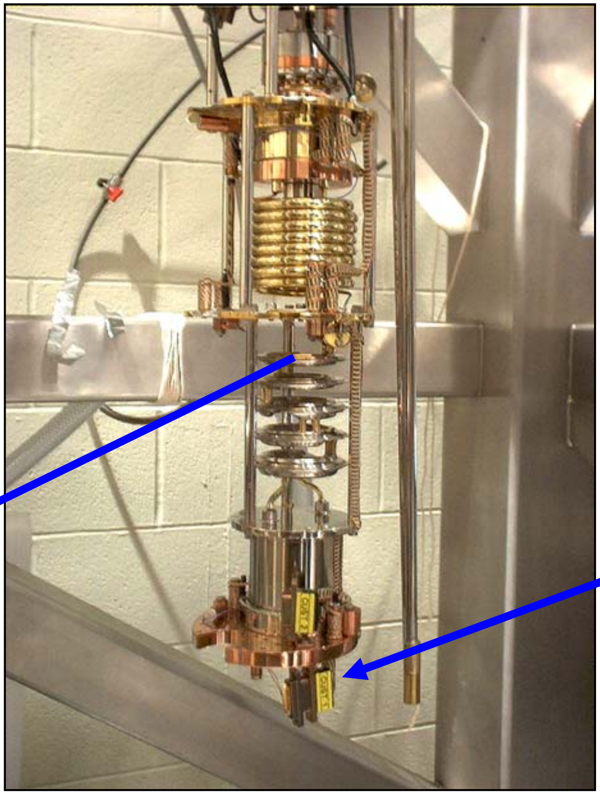


T.P. Orlando, Yang Yu, D.Nakada, B. Singh, J. Lee, D. Berns,
Ken Segall, D. Crankshaw, B Cord- MIT
ARDA

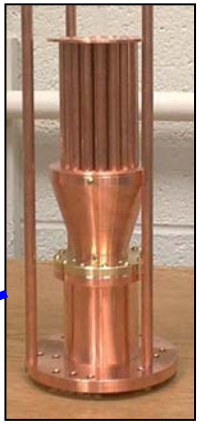
Dilution Refrigerator



Insert



Sample Holder



Installed and to begin dc data taking in February and ac data taking in April

Outline

1. **Introduction to Quantum Computation**
    a. The Unparalleled Power of a Quantum Computer
    b. Two State Systems: Qubits
    c. Types of Qubits
2. **Background on Superconductors**
    a. What is a Superconductor
    b. Uses for Superconductors
3. **Quantum Circuits**
4. **Building a Quantum Computer with Superconductors**
    a. Types of Superconducting Qubits
    b. Experiments on Superconducting Qubits
        1. Charge qubits
        2. Phase/Flux qubits
        3. Hybrid qubits
    c. Advantages of superconductors as qubits
5. **Outline of Class**

Outline of Class 6.975

1. **General Introduction and Overview of Quantized Circuits and Quantum Computing**
2. **Simple Quantized Circuits**
   a. Resistanceless circuits
   b. Superconducting Josephson circuit elements
   c. Energy storage in resistanceless circuits
   d. Quantization of LC Oscillator Circuit
   e. Quantization of Josephson junctions
3. **Superconducting Quantum Circuits and Qubits**
   a. Charge and phase descriptions
   b. Solutions to Schrödinger's Equation for circuits
   c. Single Josephson junction
   d. Cooper pair box
   e. Quantum RF SQUID
   f. Persistent Current Qubits
   g. Hybrid circuits

Outline of Class 6.975

4. Quantum Computing

- a. Two state system model
- b. Qubits and coupled qubits
- c. Manipulations of qubits
- d. Fast control circuitry: SFQ electronics

5. Dissipation in Quantum Circuits

- a. How to model a resistor
- b. Decoherence: relaxation and dephasing
- c. Spin-Boson model

Outline of Class 6.975

6. **Quantization of General Circuits**
   a. General network theory for classical circuits
      i. Branch, nodal, and mesh formulations
      ii. Inclusion of sources
      iii. Lagrangian and Hamiltonian formulations
   b. Network theory for quantum circuits
      i. General canonical variables: charge, phase, and mesh currents
      ii. Quantization without sources
      iii. Transformations among canonical variables
   c. Quantization with voltage and current sources
7. **Assessment and Future Research in Quantum Circuits**