Introduction to quantum computation with superconductors

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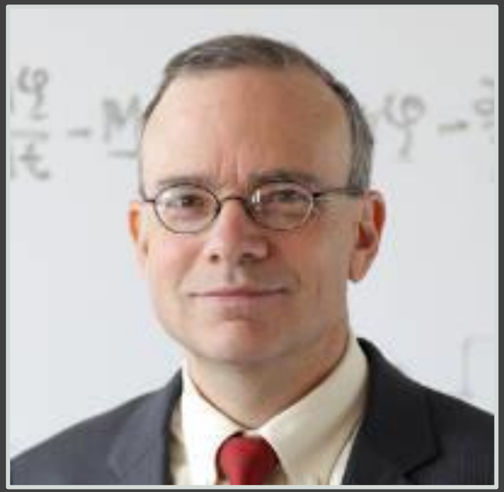
What's a Q-bit

- A Q-bit is a quanto-mechanical two level system that can be manipulated in order to store and transport information. The two levels are indicated as $|0>$ and $|1>$. The state is in general

$$|\psi>= \cos\frac{\theta}{2}|0> +e^{i\varphi}\sin\frac{\theta}{2}|0>$$

- Q-bits have been implemented with various physical systems: photon in cavity, NMR, quantum dots , etc. The most promising are trapped ions and superconducting circuits

- A useful Q-bit must respect the DiVincenzo QC criteria, concerning scalability, initialization, long coherence times, measurement, manipulation



D. DiVincenzo

What's superconductivity

- It is a phase transition characterized by a critical temperature and zero resistance
- The electrons condense in a macroscopic quantum state. The condensate can be described by a complex order parameter $\psi(\vec{r})$, similar to a wave function.

H. Kamerlingh Onnes laboratory

Refs [Gr00,Ti04,Gr03]

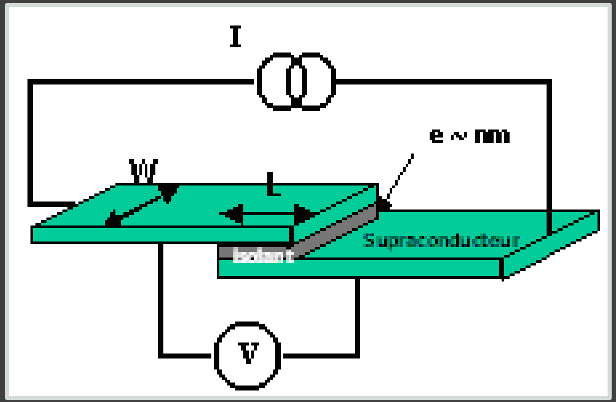
Ideal JJ

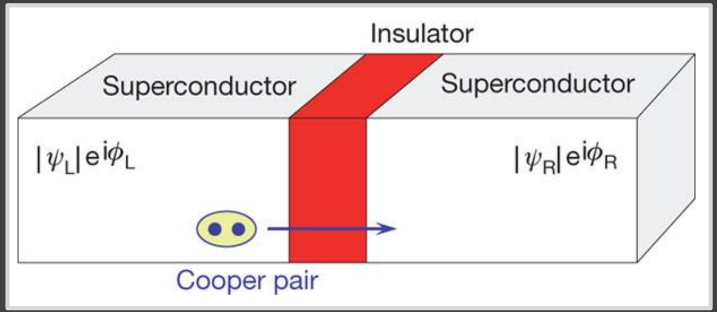
- One evidence of coherence is the *Josephson effect* in a *Josephson Junction (JJ)*.
  Josephson junctions are devices where two superconducting parts are coupled by mean of a insulator (SIS)

- The current and the voltage across a JJ is ruled by *Josephson laws*:

$$I = I_c \sin(\varphi)$$

$$V = \frac{\hbar}{2e}\frac{d\varphi}{dt}$$





Refs [Gr00,Ti04,Gr03]

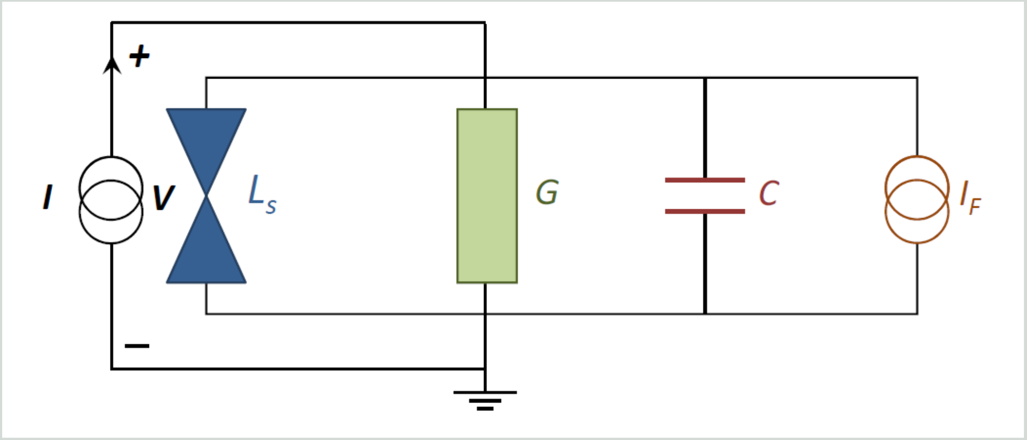
CSJ model

➢The behavior of a JJ can be modeled better within the *RCSJ model* (Resistance-Capacitance Shunted Junction). We focus on zero noise and zero dissipation CSJ model.

$$H(N,\varphi) = \underbrace{E_C N^2}_{\text{Kinetic term}} - \underbrace{E_J \left(\cos(\varphi) + \frac{I}{I_C}\varphi \right)}_{\text{Tilted washboard potential}}$$

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

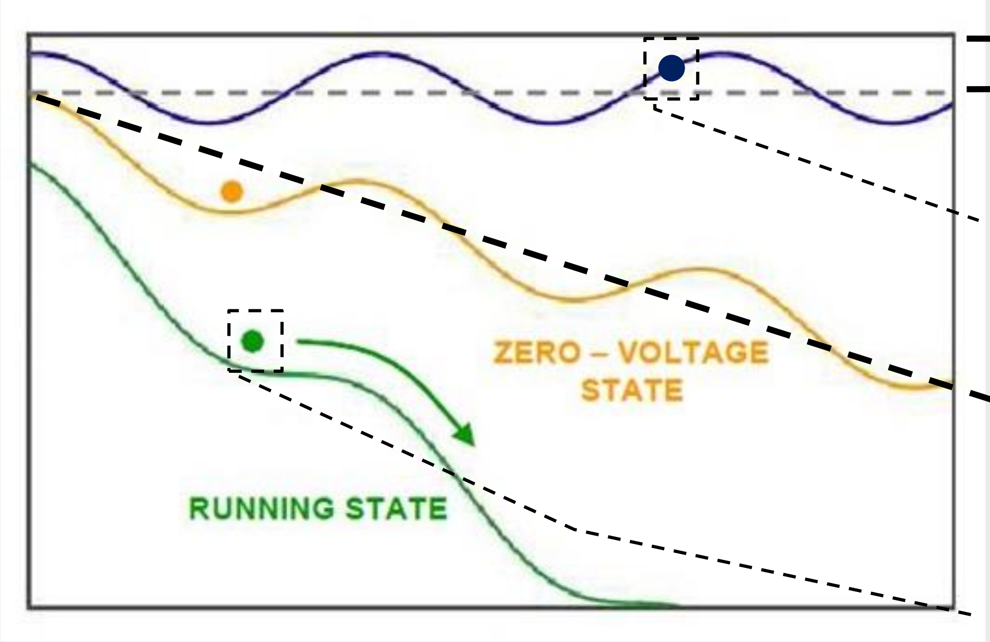
$$E_J = I_c \frac{\hbar}{2e}$$



Tilted washboard potential

$$H(N,\varphi) = E_C N^2 - E_J\left(\cos(\varphi) + \frac{I}{I_C}\varphi\right)$$

$U(\varphi)$



φ

E_J

Mass: $1/C$

Tilting:

$$U = -E_J\frac{I\varphi}{I_C}$$

Speed: $\frac{d\varphi}{dt} \propto V$

Secondary macroscopic quantum effect

- In quantum mechanics, phase and number of particle are conjugate variables. It holds

$$[\hat{\varphi}, \hat{N}] = i$$

$$\Delta\varphi \Delta N \geq 1$$

- The Hamiltonian can be quantized:

$$H(N, \varphi) = E_C \hat{N}^2 - E_J \left(\cos(\hat{\varphi}) + \frac{I}{I_C} \hat{\varphi} \right)$$

Refs [Ti04,Gr03]

Superconducting Q-bits

There are three types of superconducting Q-bits based on insulator JJ.
In order of realization, with respective citation:

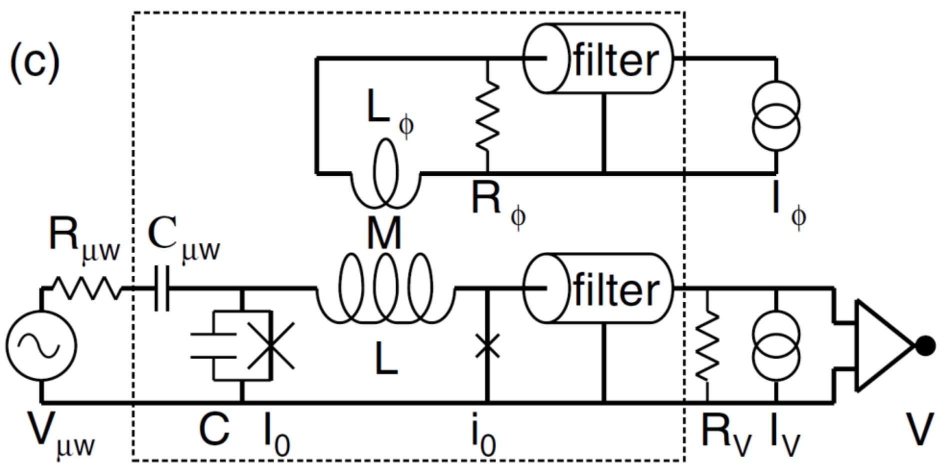
- Charge Q-bit — P. Lafarge et al., Nat. **365**, 422 (1993)
  Y. Nakamura et al. Nat. **398**, 786 (1999))
- Flux Q-bit — W. H. Caspar et al., Science 290, **773** (2000)
  J. R. Friedman et al., Nat. **406**, 43 (2000)
- Phase Q-bit — J. M. Martinis et al., PRL **89**, 117901 (2002)

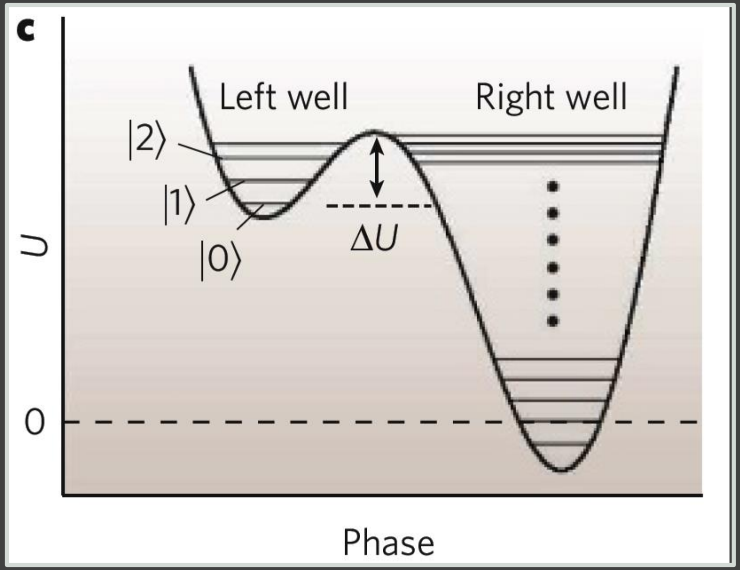
FOR SIMPLICITY, IN THE FOLLOWING SLIDES WE'RE GOING TO DEAL WITH PRIMITIVE PROOF-OF-PRINCIPLE ARCHITECTURES.
Many issues (e.g. coherence, noise, readout, coupling) have brought to more complex architectures

Refs [La93, Na99, Ca00, Fr00, Ma02]

Phase Q-bit

- The phase Q-bit is a single JJ driven by an external current. The junction state is brought near the voltage state, with $I \approx I_C$. The potential is then approximatively cubic with bound states
- Inizialization is accomplished by thermalization and adiabatic bias
- Manipulation of the state can be done by mean of the bias current.
- Read out is given by $|1> \rightarrow |2>$

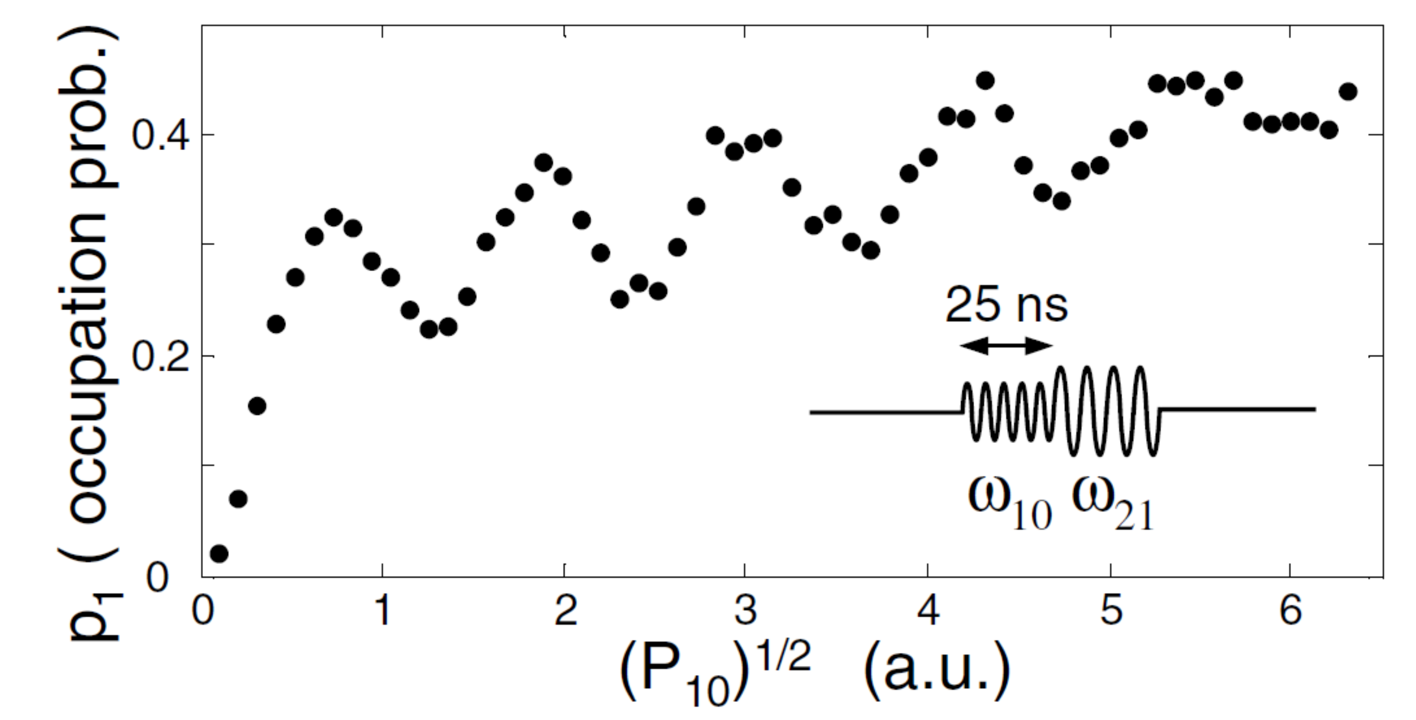




Refs [Ma02]

Phase Q-bit: experimental facts

- Evidence of Rabi Oscillations depending on excitation pulse amplitude



Refs [Ma02]

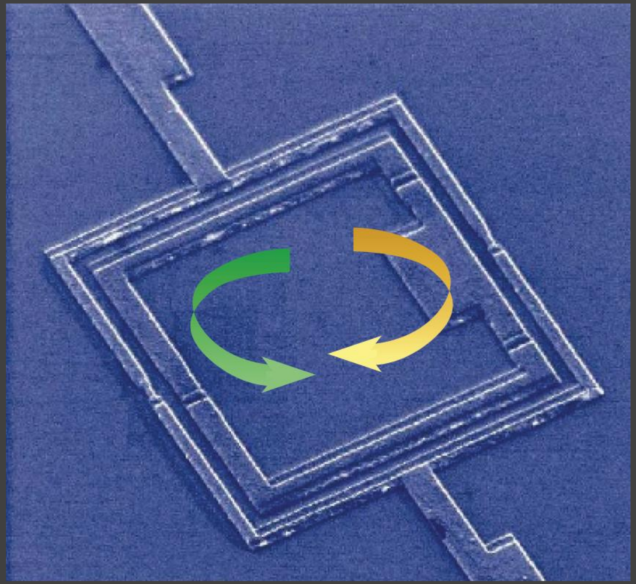
Flux Q-bit

- The flux Q-bit is constituted by an insulated superconducting ring interrupted by JJ (simplest config).
- Working principle: flux quantization

$$\Phi_0 = \frac{h}{2e}$$

- Let us consider for simplicity a single junction loop (alias RF-SQUID).. The Hamiltonian of the system is

$$H(N, \tilde{\Phi}|\Phi_e) = E_C N^2 + \frac{\tilde{\Phi}^2}{2L} - E_J \cos\left(\frac{2e}{\hbar}(\tilde{\Phi} - \Phi_e)\right)$$



Refs [Wa00, Fr00]

Flux Q-bit

- The potential is a corrugated parabola. If the external flux is set to

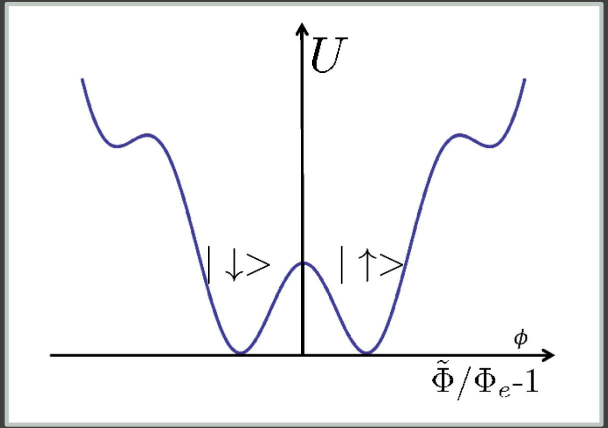
$$\Phi_e = \frac{1}{2}\Phi_0 \qquad \Phi_0 = \frac{h}{2e}$$

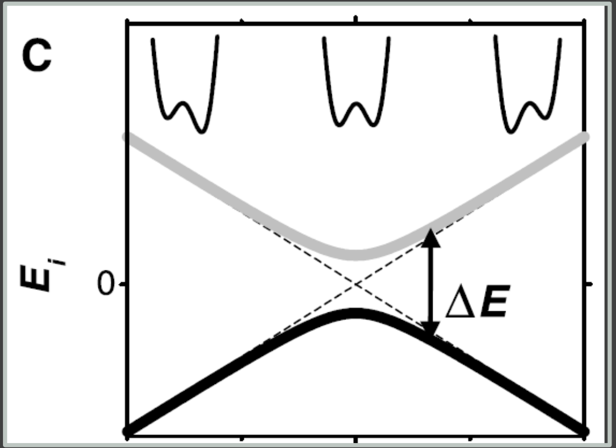
the potential takes a quartic form (mexican hat).

- Classically, the two fundamentals state correspond to current circulating clockwise or counterclockwise with degenerate energy.

- The quantum tunneling removes degeneracy, so that the two lowest states are superpositions of $|\uparrow>$ and $|\downarrow>$.

- As function of the external parameter, the excitation energy shows a typical anticrossing behavior.

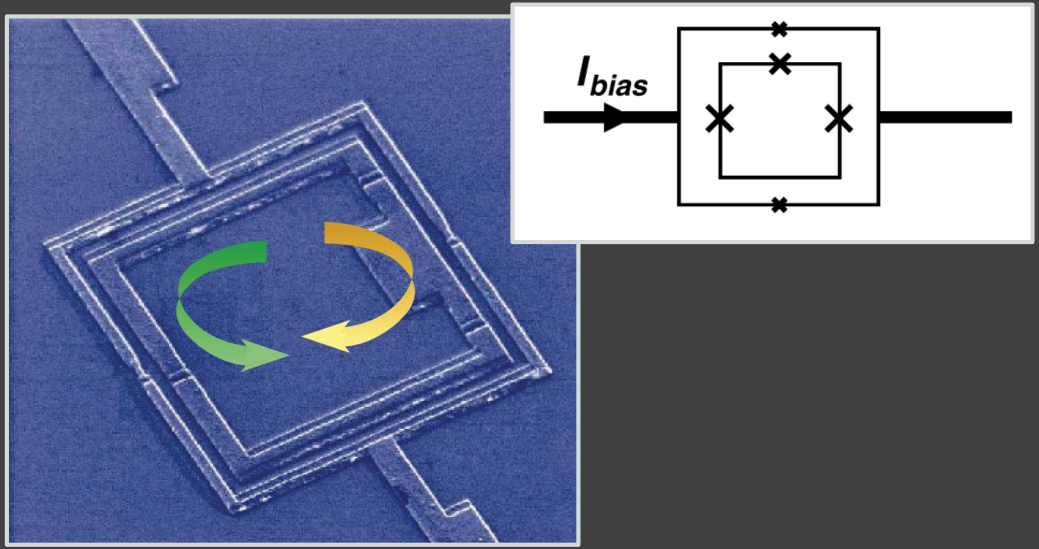


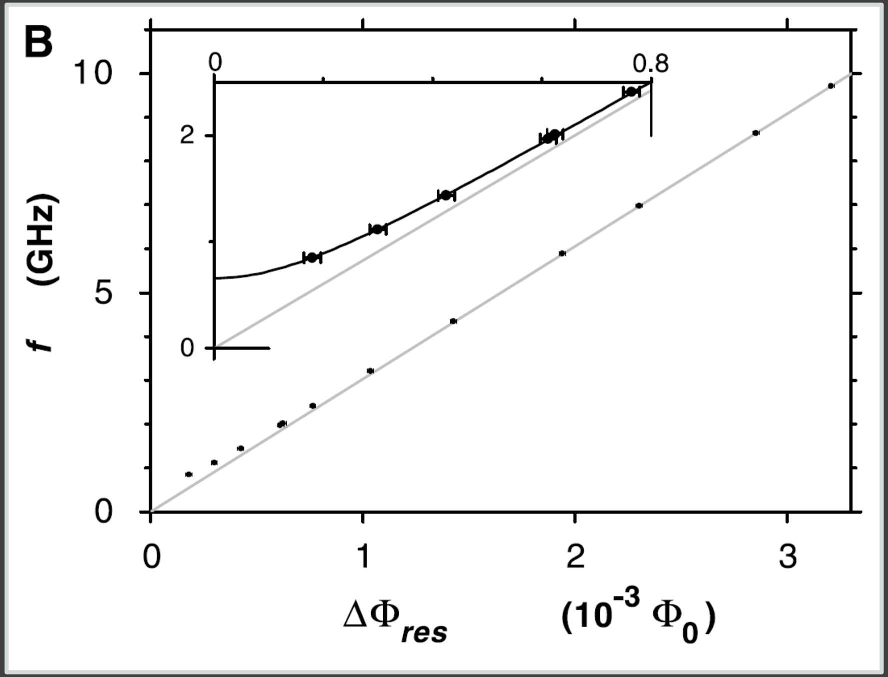


Refs [De04, We08]

Flux Q-bit

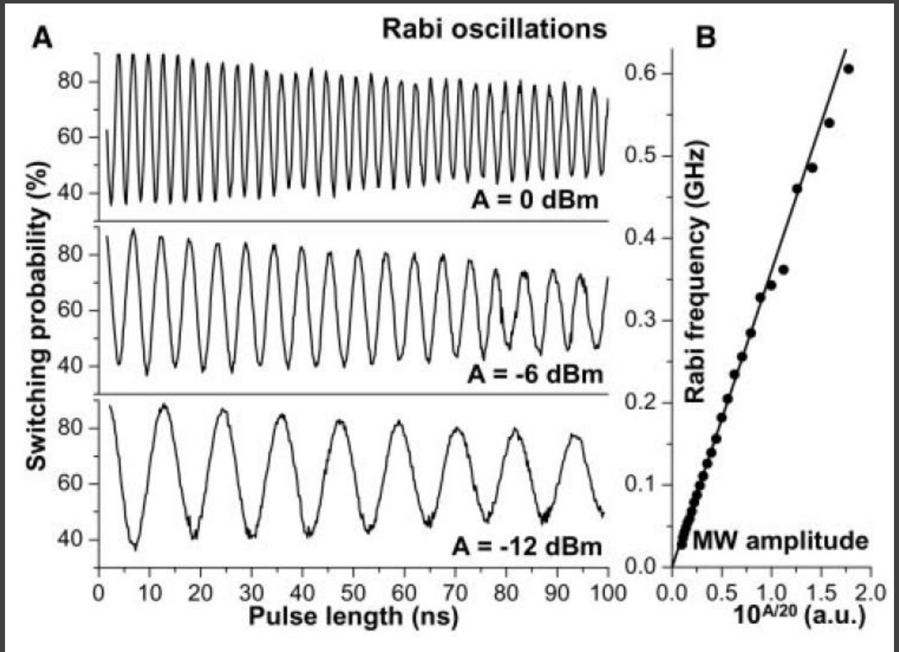
- Read out is made by a DC-SQUID that measures the threading flux if counterclockwise of clockwise
- Measurement of current switching under fixed tuned frequency returns a anti-crossing figure

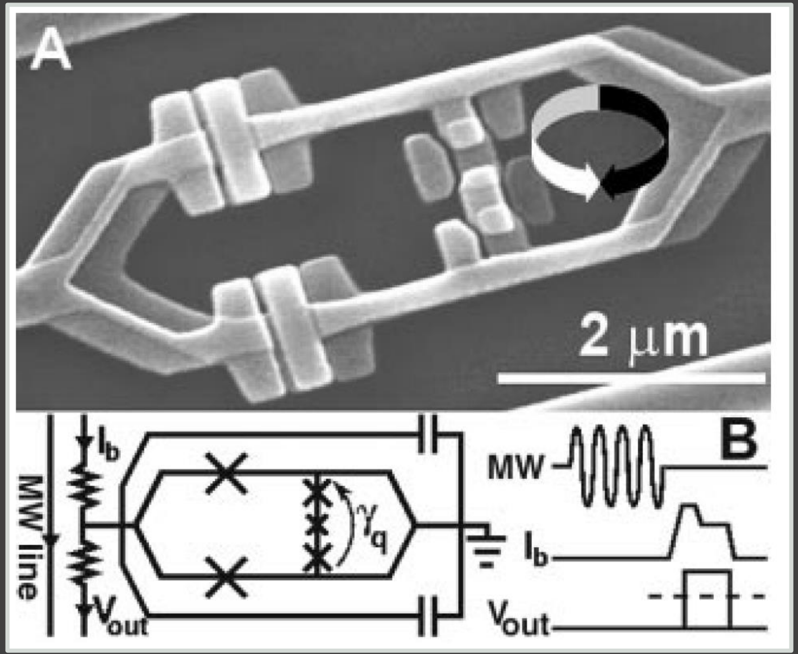




Flux Q-bit

- Manipulation occurs by a coupled microwave line, that produces GHz oscillating magnetic field in the loop.
- Also in this case, Rabi oscillation were detected



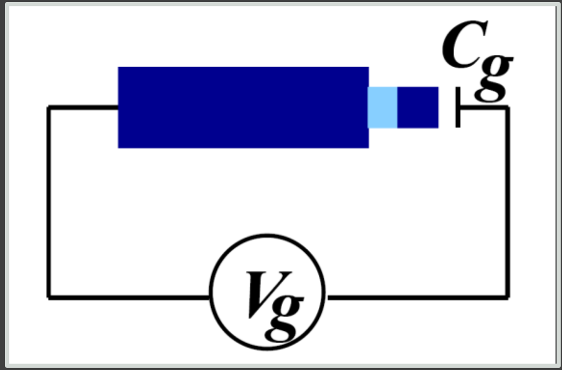


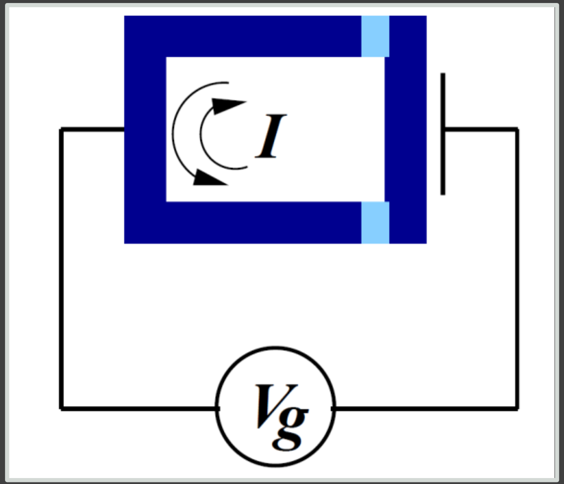
Charge Q-bit

- In the charge Q-bit, the observable exploited for QC is the number of Cooper pairs in a superconducting small volume, called Cooper pair box (SCB)

- The Hamiltonian of a SCB under gating is

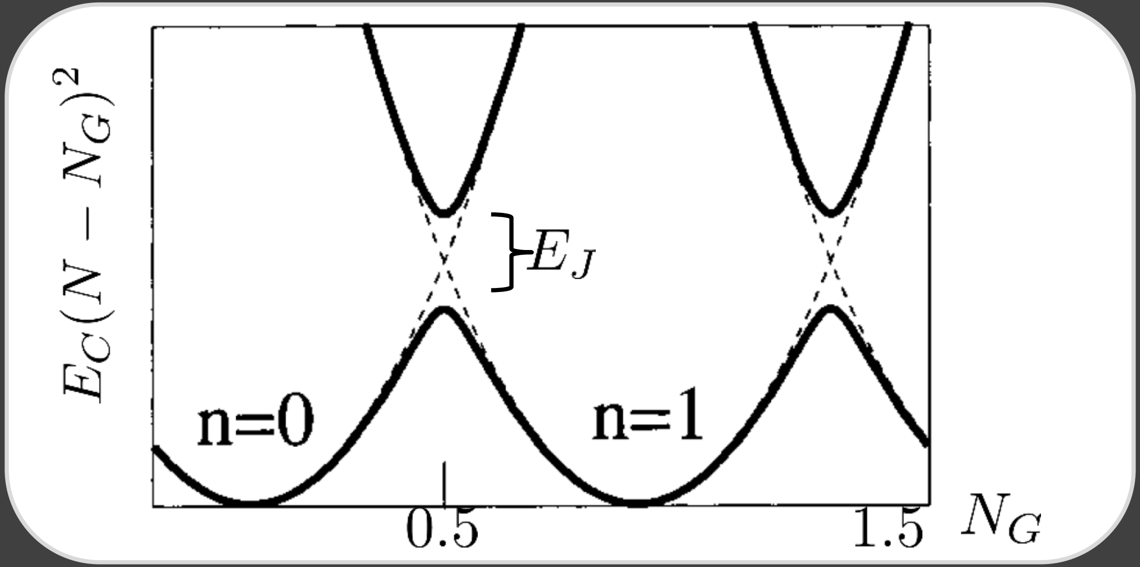
$$H(Q,\varphi) = E_C(N - N_G)^2 - E_J\cos(\varphi)$$

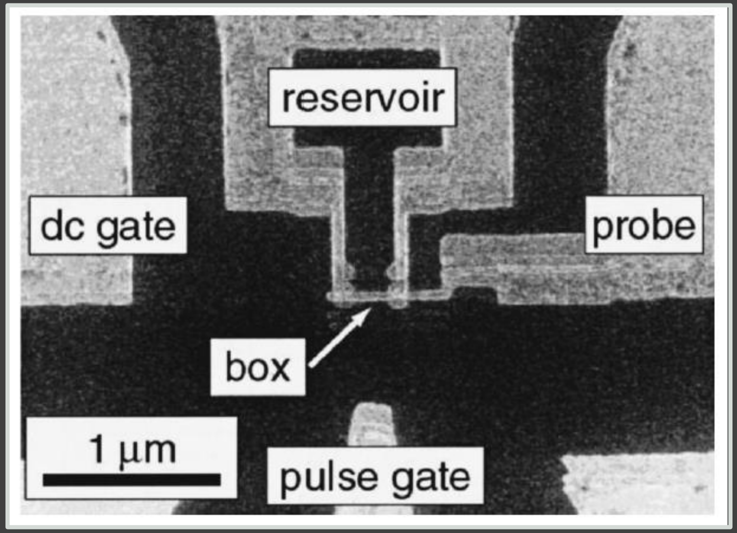




Charge Q-bit

- The classical parabola branches are splitted by Josephson potential. In this region, QC can be realized
- One read readout scheme consists in coupling a normal probe to the SCB with a high resistance tunnel junction. Then a –excedent- Cooper pair can decay in two quasiparticles and generate a detectable current in the probe

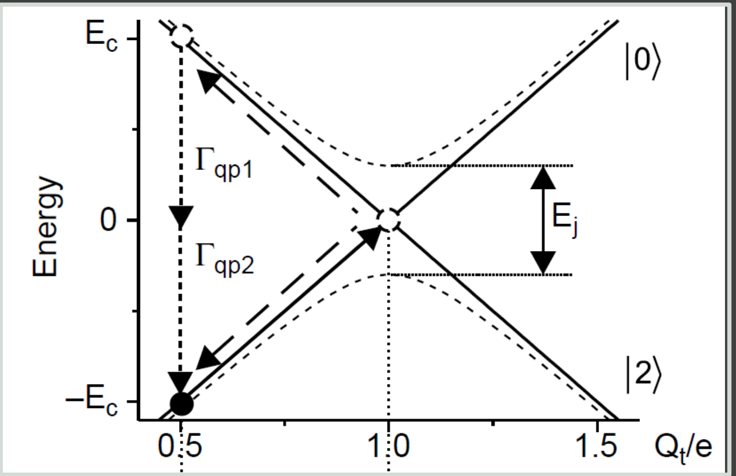


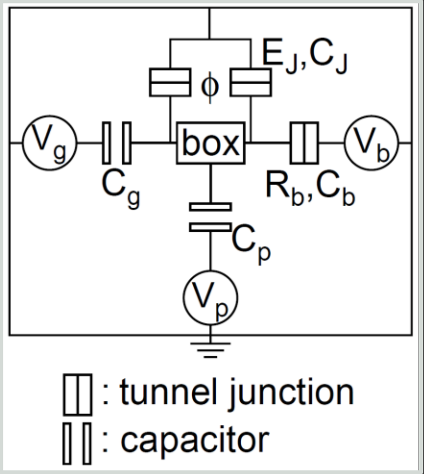


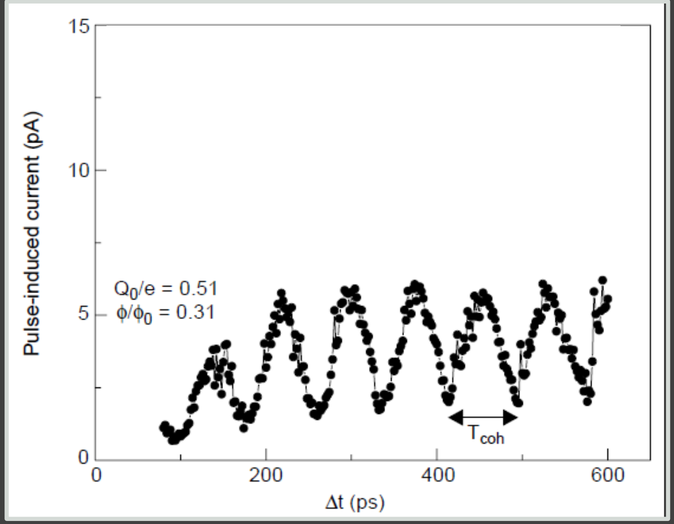
Refs [Na99, We08]

Charge Q-bit

➢With this readout scheme, coherent oscillations were observed with this measuring scheme [Na99]:
1. Polarize with a DC gate the SCB a little away from the anticrossing point
2. Give a sharp pulse in a pulse gate to make a non adiabatical transition
3. Keep the pulse voltage on for a desired time interval (so, let the system evolve)
4. Turn off the pulse. Now the system is in the desired superposition. Excited state will decay in two quasiparticles





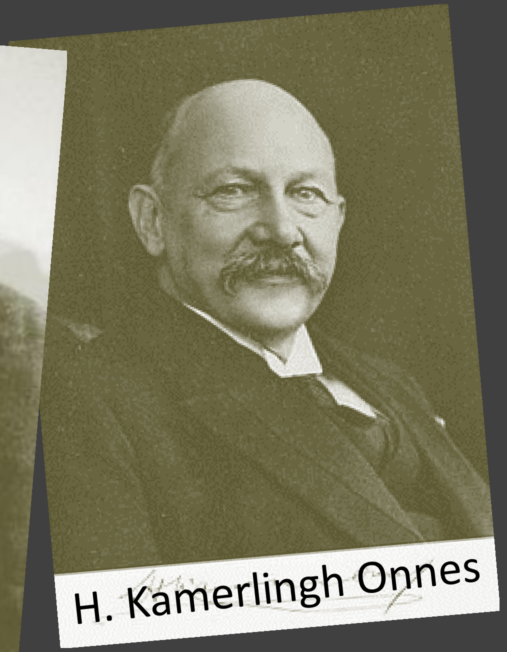


Refs [Na99]

Summary

- Superconductor devices are one way to implement QC, and the most promising after trapped ions
- The fundamental component is the JJ
- There are three types of Q-bits exploiting different form of hamiltonian (table)

Q-bit type	Potential polynomial approx	External param.	Parameter static component
Charge	Parabolic	Gate voltage	$V_G \approx \frac{E_C}{e}$
Flux	Quartic power (mexican hat)	Magnetic Flux	$\Phi \approx \frac{\Phi_0}{2}$
Phase	Third power	Current	$I \to I_C$



Thank you for the attention!

ANY QUESTION?

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