Flux Qubits at IBM

David DiVincenzo, IBM

Princeton Center for Theoretical Physics, 9/2007

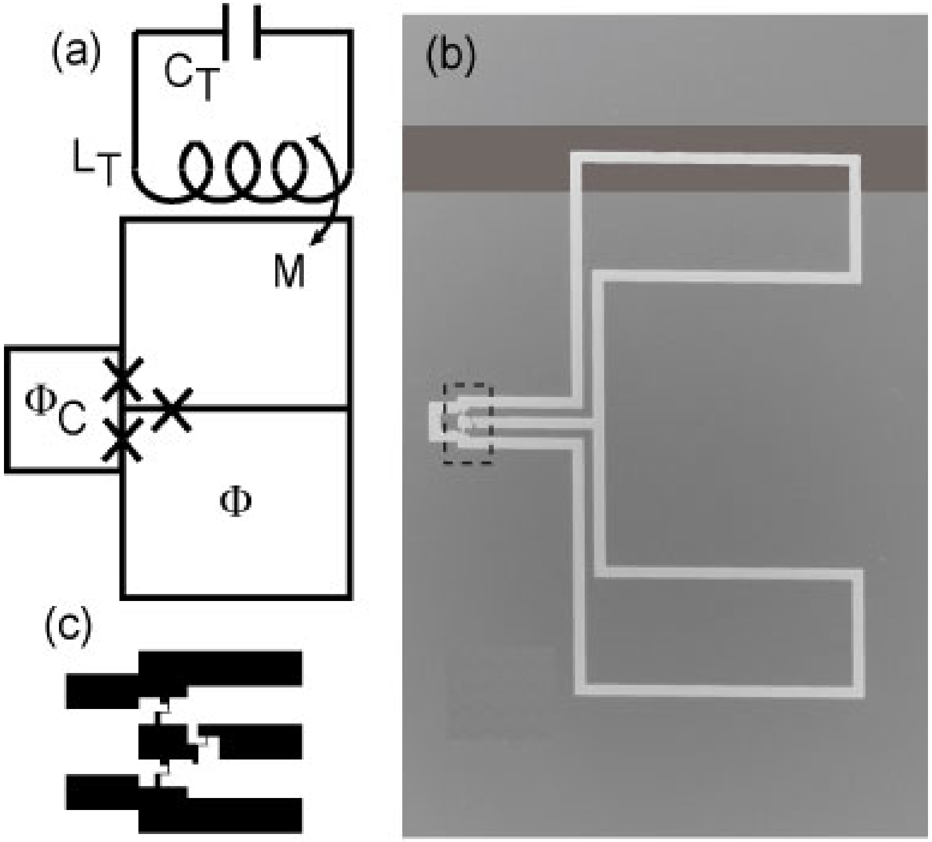
Flux qubits at IBM

- R. Koch 1950-2007
- The IBM design, and a theorists view of flux qubits
  - The inductive energy of a flux qubit, and linear response theory
- Potential landscapes
- Energy bands and principles of operation
- Oscillator stabilization, more energy bands, experimental results
- Dreaming of large systems
- What has become of the five criteria?

(with Roger Koch, Matthias Steffen, Fred Brito, Guido Burkard)


R. Koch
1950-2007

IBM Josephson junction qubit

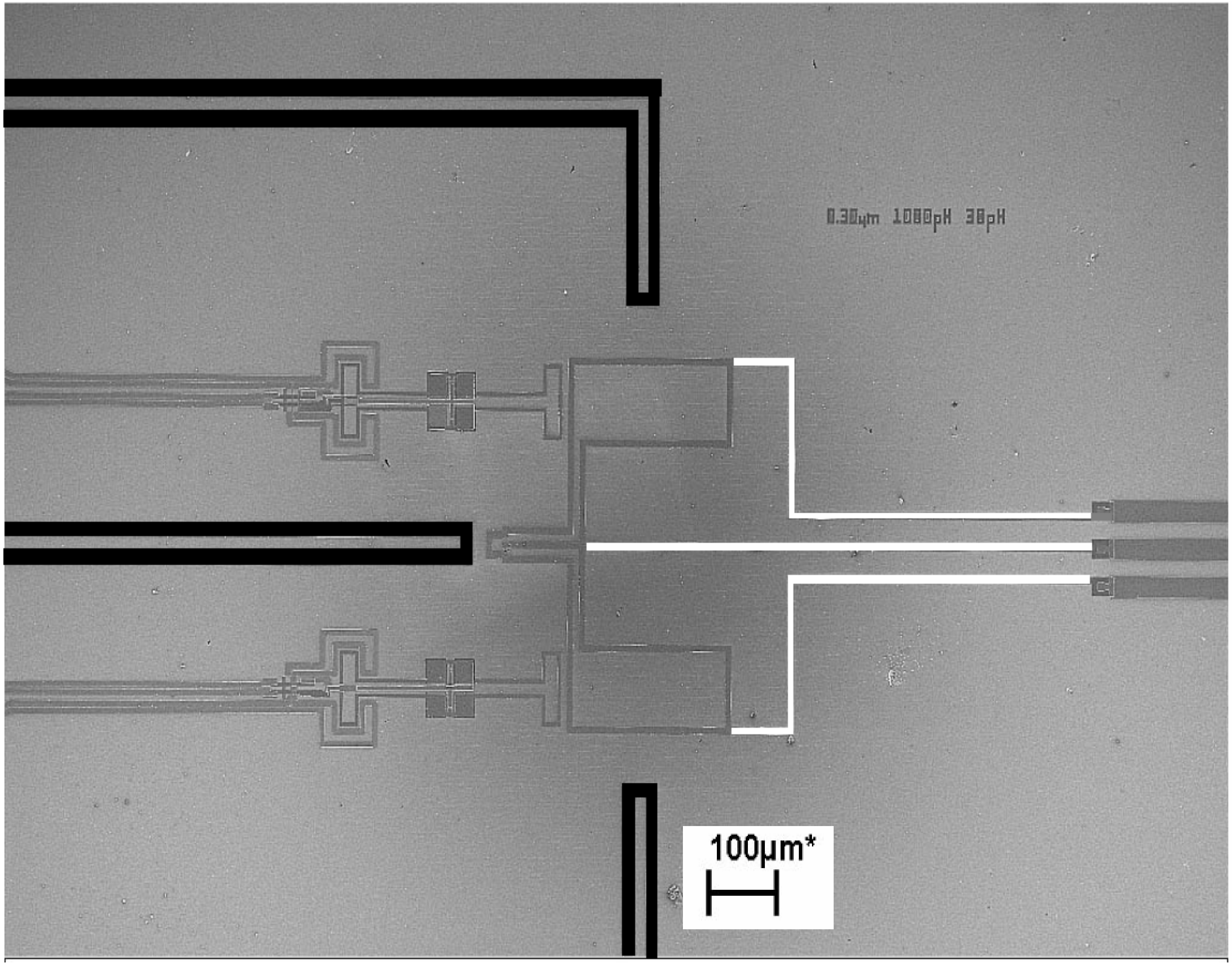


“qubit” =
of electric current
in one direction or
another (????)

Low-bandwidth control scheme for an oscillator stabilized Josephson qubit

R. H. Koch, J. R. Rozen, G. A. Keefe, F. M. Milliken, C. C. Tsuei, J. R. Kirtley, and D. P. DiVincenzo
IBM Watson Research Ctr., Yorktown Heights, NY 10598 USA
(Dated: November 16, 2004)

IBM qubit with associated



I_c=1.3 µA

L_1=32pH

L_3=680pH

M_{1cf}=0.8pH

M_{3flux}=0.5pH

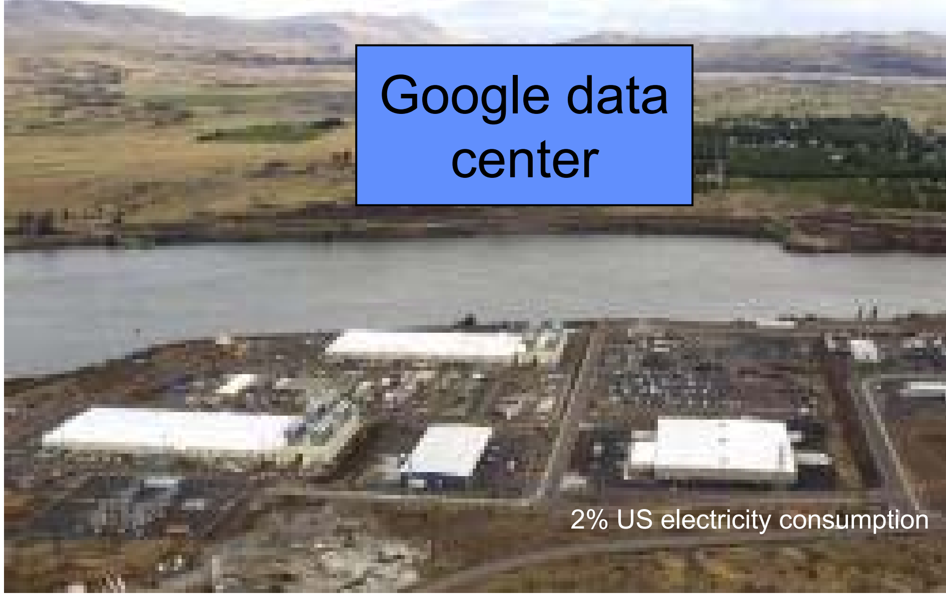
ω_T=2π 3.1 GHz

Z_0= 110 Ω

L_T=5.6 nH

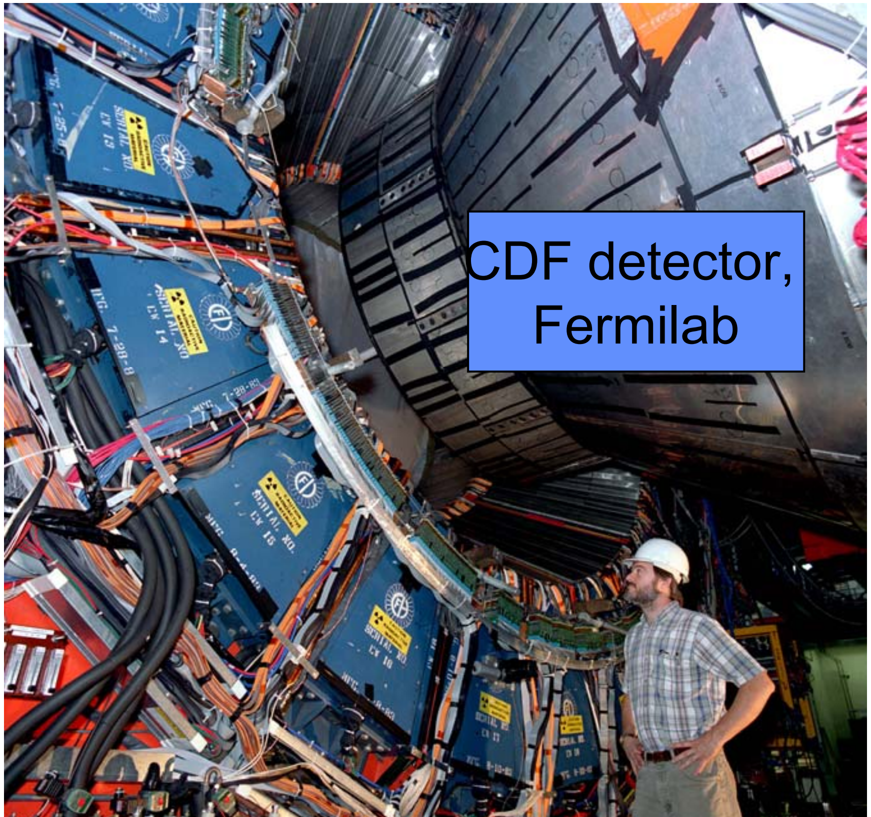
M_{qT}=200 pH

“No power is required to perform computation.”
CH Bennett



“Quantum computers can operate autonomously.”
N Margolus

(inventor of “computronium”)



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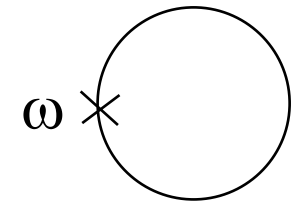
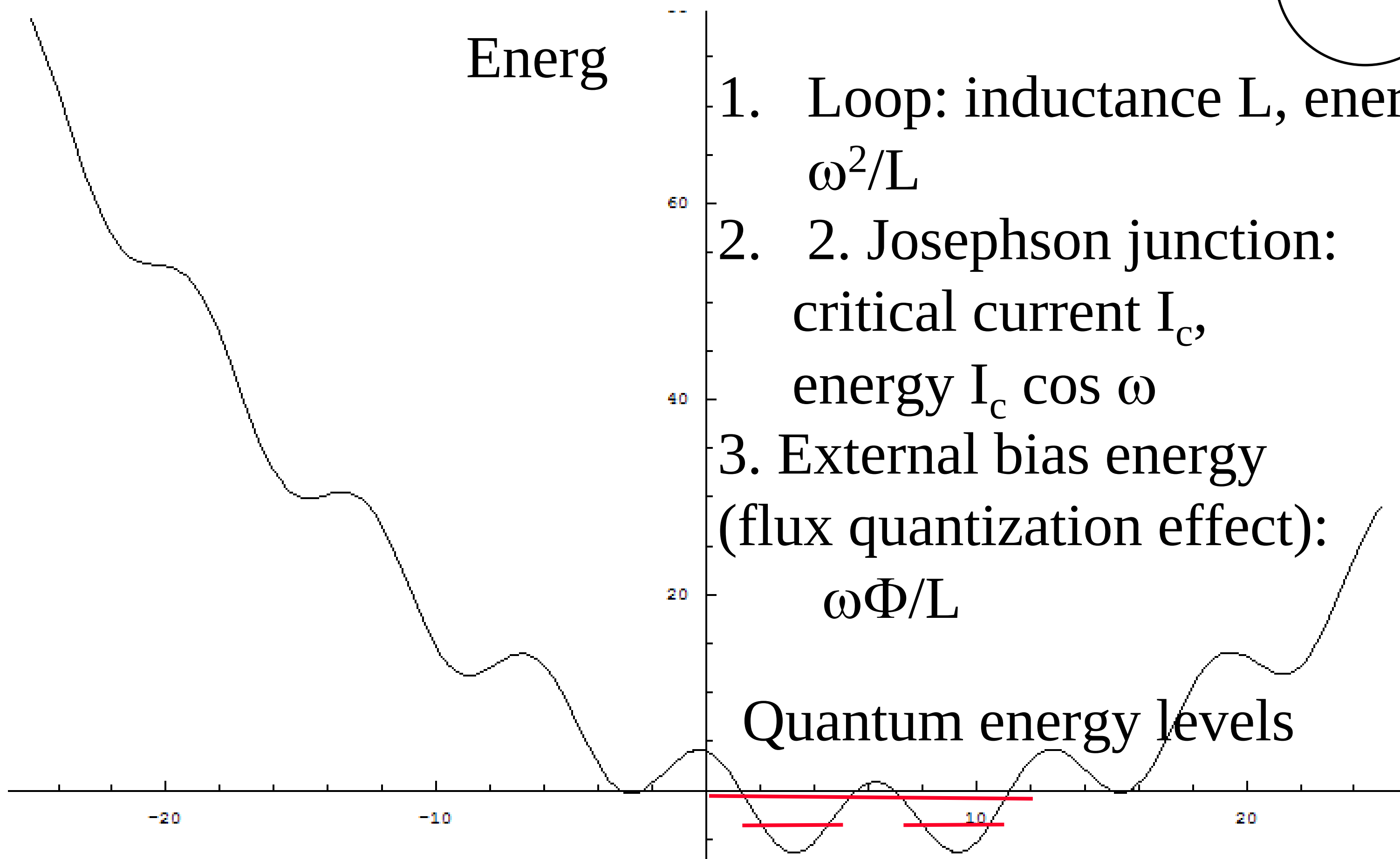
Quantum SQUID characteristic: the "washboard"





1. Loop: inductance L, energy ω^2/L
2. 2. Josephson junction: critical current I_c, energy $I_c \cos \omega$

3. External bias energy (flux quantization effect): $\omega\Phi/L$

Junction capacitance C, plays role of particle mass

Equation of motion of a complex circuit:

$$\mathbf{C}\ddot{\varphi} = -\mathbf{L}_J^{-1}\mathbf{sin}\varphi - \mathbf{R}^{-1}\dot{\varphi} - \mathbf{M}_0\varphi - \mathbf{M}_d * \varphi - \frac{2\pi}{\Phi_0}\mathbf{N}\mathbf{\Phi}_x - \frac{2\pi}{\Phi_0}\mathbf{S}\mathbf{I}_B$$

small

The lossless parts of this equation arise from a simple Hamiltonian:

H; U=exp(iHt)

$$\frac{1}{2}\mathbf{Q}_C^T\mathbf{C}^{-1}\mathbf{Q}_C + U(\varphi)$$

$$U(\varphi) = -\sum_i L_{J;i}^{-1}\cos\varphi_i + \frac{1}{2}\varphi^T\mathbf{M}_0\varphi + \frac{2\pi}{\Phi_0}\varphi^T\left(\mathbf{N}\mathbf{\Phi}_x + \mathbf{S}\mathbf{I}_B\right)$$

Burkard, Koch, DiVincenzo, PRB (2004).

the equation of motion (continued):

$$\mathbf{C}\ddot{\varphi} = -\mathbf{L}_J^{-1}\mathbf{sin}\varphi - \mathbf{R}^{-1}\dot{\varphi} - \mathbf{M}_0\varphi - \mathbf{M}_d * \varphi - \frac{2\pi}{\Phi_0}\mathbf{N}\mathbf{\Phi}_x - \frac{2\pi}{\Phi_0}\mathbf{S}\mathbf{I}_B$$

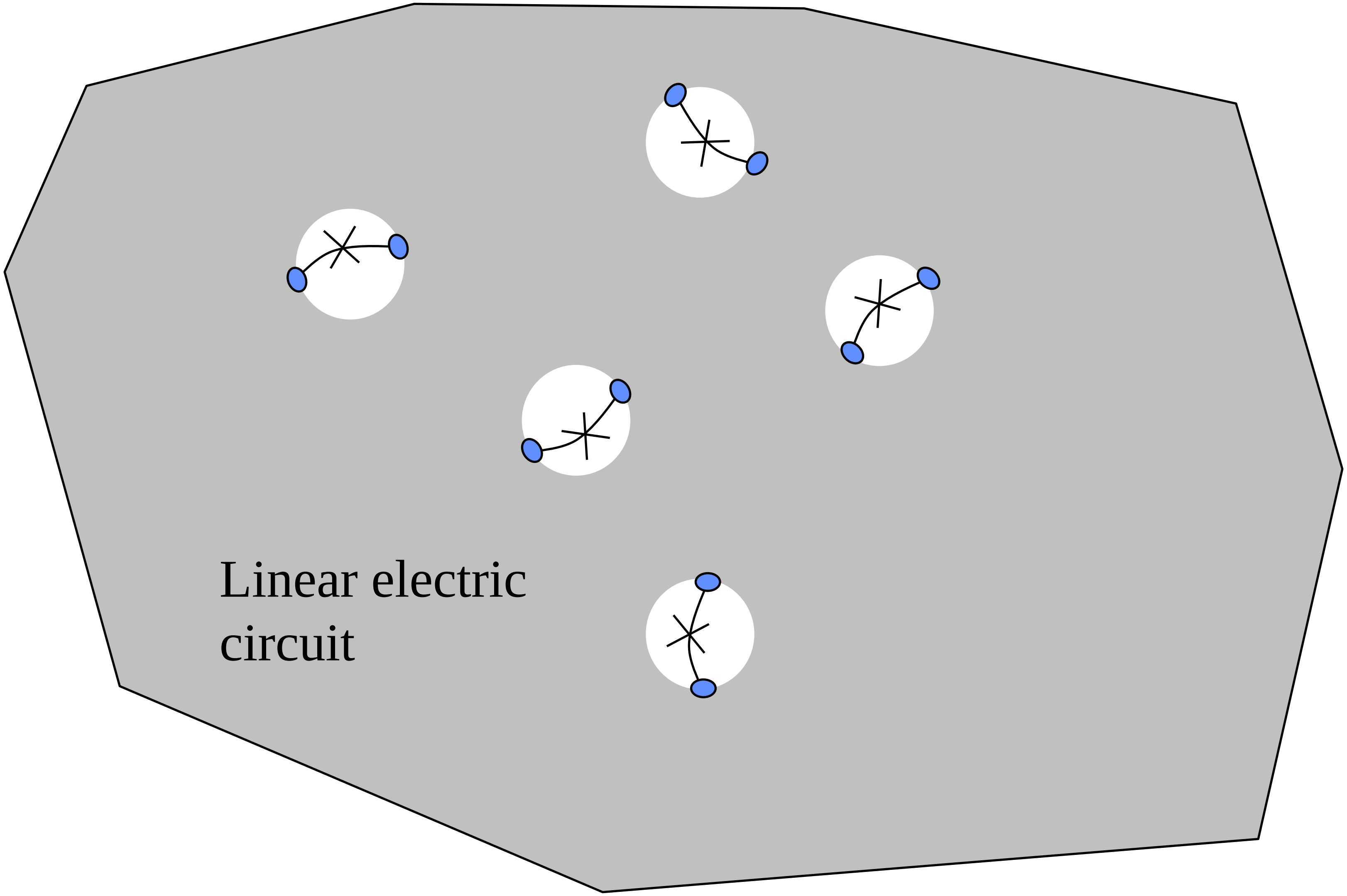
small

$$\begin{aligned} \mathbf{M}_0 &= \mathbf{F}_{CL}\tilde{\mathbf{L}}_L^{-1}\bar{\mathbf{L}}\mathbf{L}_{LL}^{-1}\mathbf{F}_{CL}^T, \\ \mathbf{N} &= \mathbf{F}_{CL}\tilde{\mathbf{L}}_L^{-1}\bar{\mathbf{L}}\mathbf{L}_{LL}^{-1}, \ \dots \end{aligned}$$

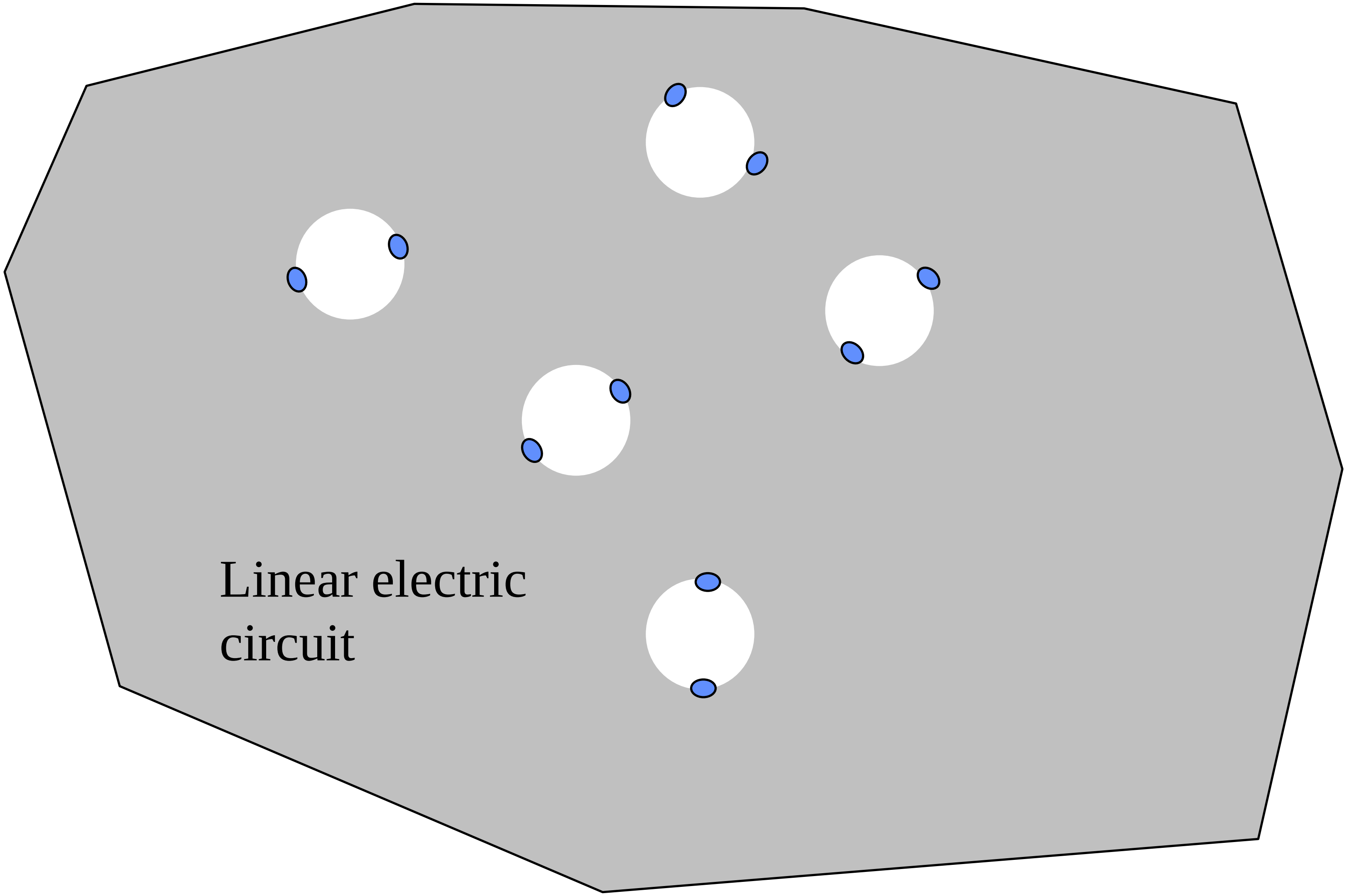
$$\begin{aligned} \bar{\mathrm{N}}(\omega=0) = \mathrm{F}_{\mathrm{CL}} & \Big[1_{\mathrm{L}} + \mathrm{L}^{-1}\mathrm{L}_{\mathrm{LK}}\left(\mathrm{L}_{\mathrm{K}} - \mathrm{L}_{\mathrm{LK}}^T\mathrm{L}^{-1}\mathrm{L}_{\mathrm{LK}}\right)^{-1} \\ & \left(1_{\mathrm{K}} - \mathrm{L}_{\mathrm{K}}\left(\mathrm{F}_{\mathrm{KL}} - \mathrm{L}_{\mathrm{K}}^{-1}\mathrm{L}_{\mathrm{LK}}^T\right)\mathrm{L}^{-1}\mathrm{L}_{\mathrm{LK}}\left(\mathrm{L}_{\mathrm{K}} - \mathrm{L}_{\mathrm{LK}}^T\mathrm{L}^{-1}\mathrm{L}_{\mathrm{LK}}\right)^{-1}\right)^{-1}\mathrm{L}_{\mathrm{K}}\left(\mathrm{F}_{\mathrm{KL}} - \mathrm{L}_{\mathrm{K}}^{-1}\mathrm{L}_{\mathrm{LK}}^T\right)\Big] \quad (89) \\ & \Big[\mathrm{L} - \mathrm{L}_{\mathrm{LK}}\mathrm{L}_{\mathrm{K}}^{-1}\mathrm{L}_{\mathrm{LK}}^T + \mathrm{F}_{\mathrm{KL}}^T\left(1_{\mathrm{K}} - \mathrm{L}_{\mathrm{K}}\left(\mathrm{F}_{\mathrm{KL}} - \mathrm{L}_{\mathrm{K}}^{-1}\mathrm{L}_{\mathrm{LK}}^T\right)\mathrm{L}^{-1}\mathrm{L}_{\mathrm{LK}}\left(\mathrm{L}_{\mathrm{K}} - \mathrm{L}_{\mathrm{LK}}^T\mathrm{L}^{-1}\mathrm{L}_{\mathrm{LK}}\right)^{-1}\right)^{-1}\mathrm{L}_{\mathrm{K}}\left(\mathrm{F}_{\mathrm{KL}} - \mathrm{L}_{\mathrm{K}}^{-1}\mathrm{L}_{\mathrm{LK}}^T\right)\Big]^{-1}. \end{aligned}$$

Straightforward (but complicated!) functions of
the topology (F matrices) and the inductance matrix

The physics of the coupling matrices

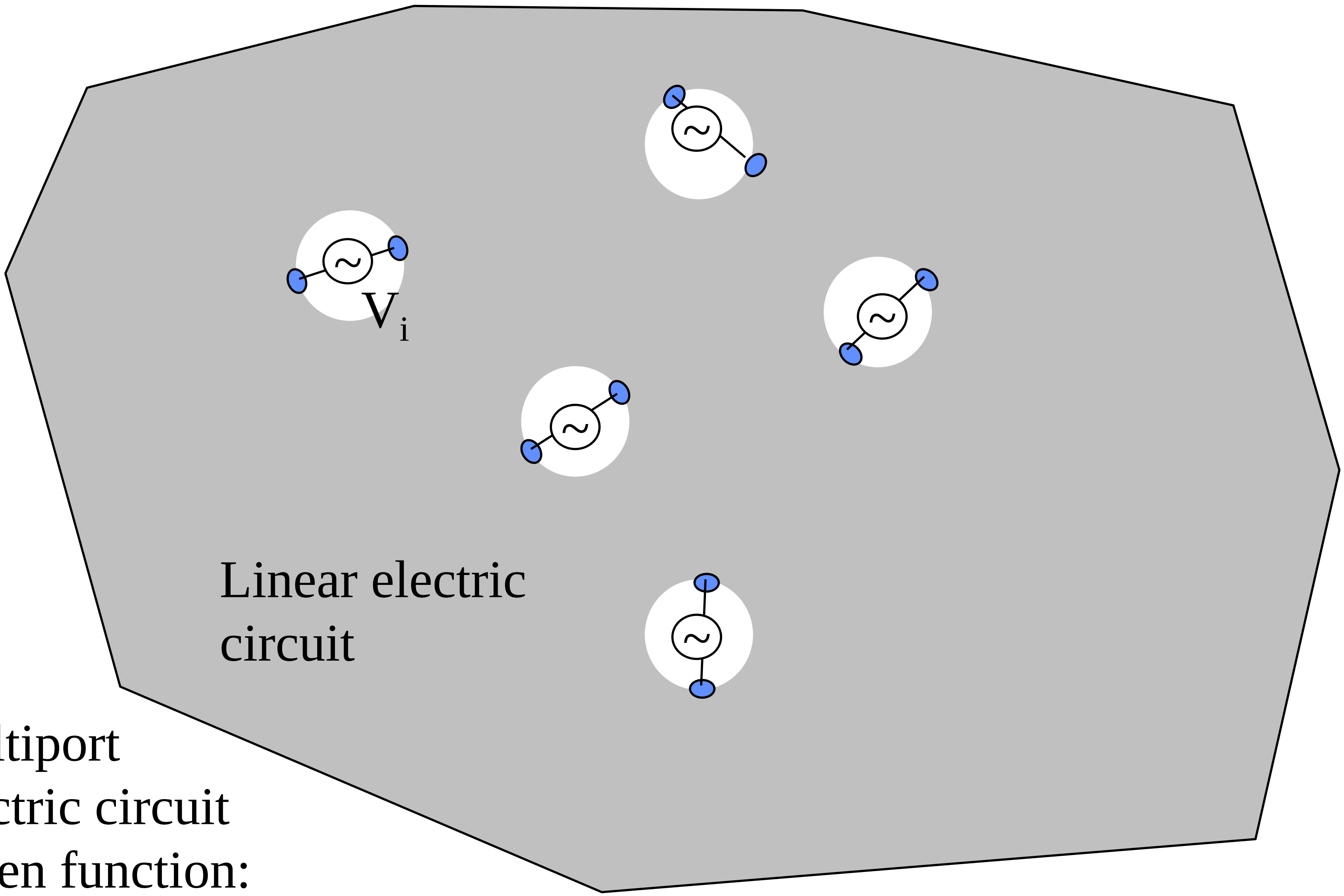


The physics of the coupling matrices



Cut out the Josephson junctions…

The physics of the coupling matrices



Multiport
Electric circuit
Green function:

$$I_j(\omega)=Y_{ij}(\omega)V_i(\omega), \quad Y_{ij}(\omega)=\frac{1}{i\omega}\left(L^{-1}\right)_{ij}+\mathrm{K} \; =\frac{\breve{M}_0}{i\omega}+\mathrm{K}$$

DiVincenzo, Brito, and Koch, Phys. Rev. B (2006).

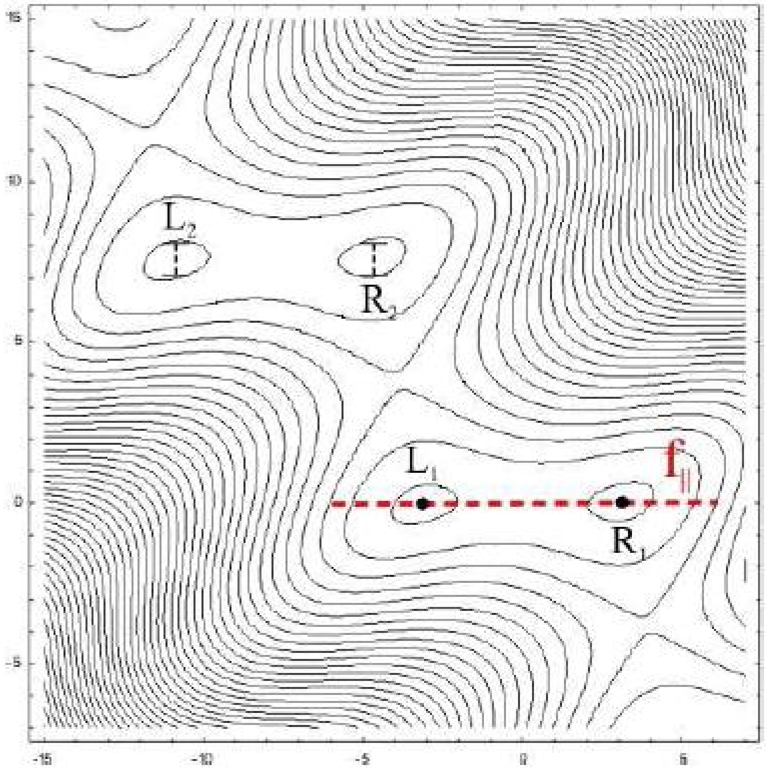


FIG. 2: Contour plot of the potential $U'(\mathbf{f})$ on the S line for the external fluxes $\Phi_c = 0.36\Phi_0$ and $\Phi = \Phi_0$. The red dashed line indicates the "slow" direction $f_\parallel$. Along this direction the potential is a symmetric double well, with the two relevant minima of the potential indicated by dots. The bars show the spatial extension of the wave function, in the vicinity of the minima, in the "fast" direction $f_\perp$ with the smallest curvature of the potential.

small-loop noise: gradiometrically protected

Large-loop noise: bad, but heavily filtered

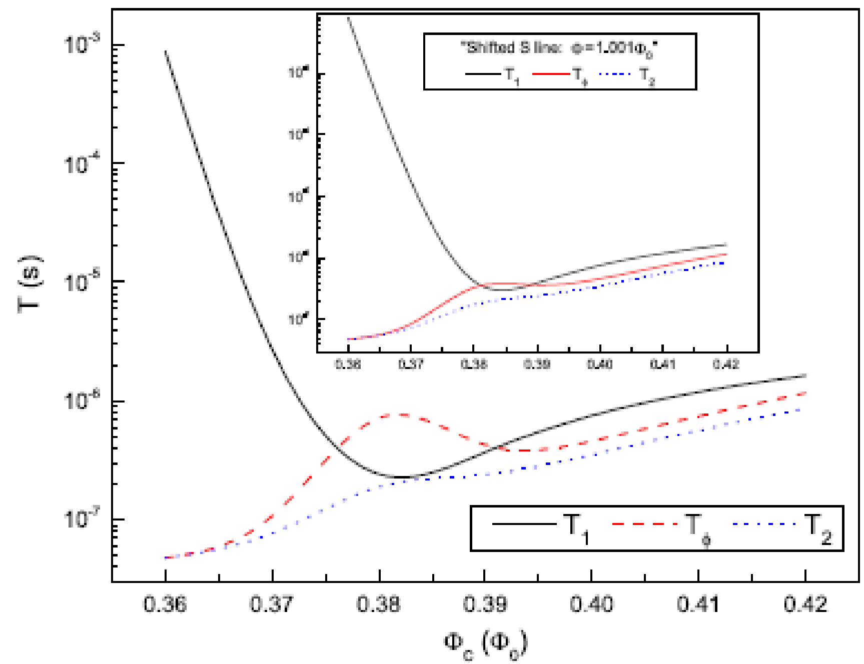


FIG. 20: The total relaxation, dephasing and decoherence times (T_1, T_ϕ and T_2, respectively) along the S line. We can see that T_ϕ (T_1) strongly increases (decreases) as a function of Φ_c. These facts cause there to be a window of desirable operating parameters for the qubit.

IBM Josephson junction qubit: scheme of operation:

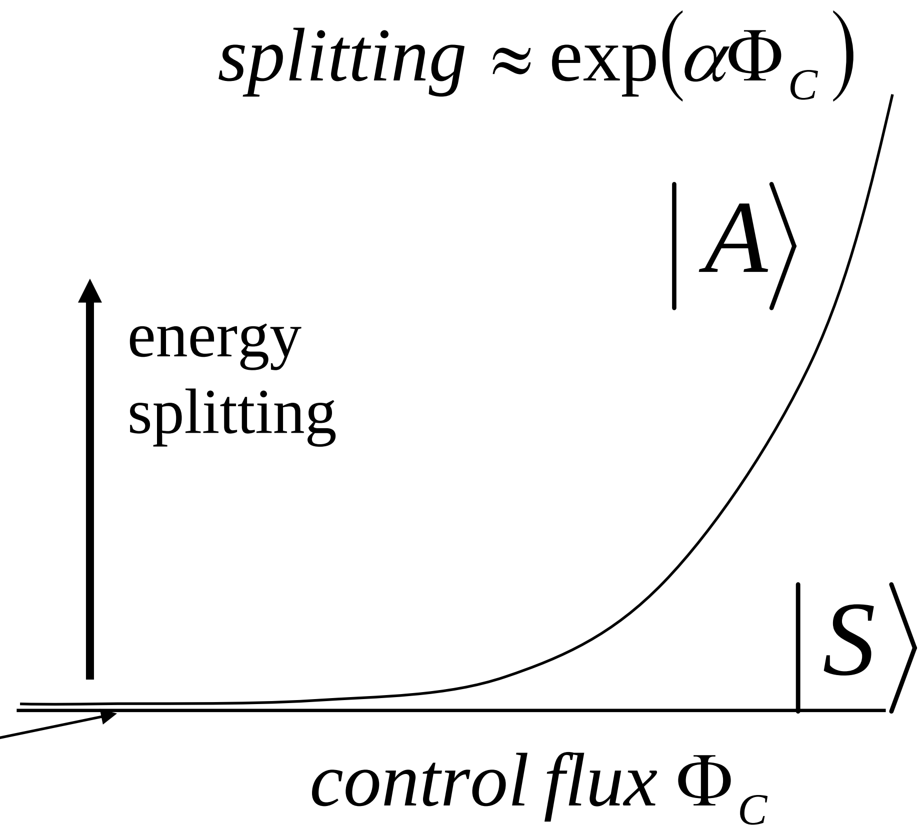
--fix ε to be small

--initialize qubit in state

$$|L\rangle = \frac{1}{\sqrt{2}}\left(|S\rangle + |A\rangle\right)$$

--pulse small loop flux, reducing barrier height *h*

ε = asymmetry of double well



N.B. –
eigenstates are $|L\rangle$ and $|R\rangle$

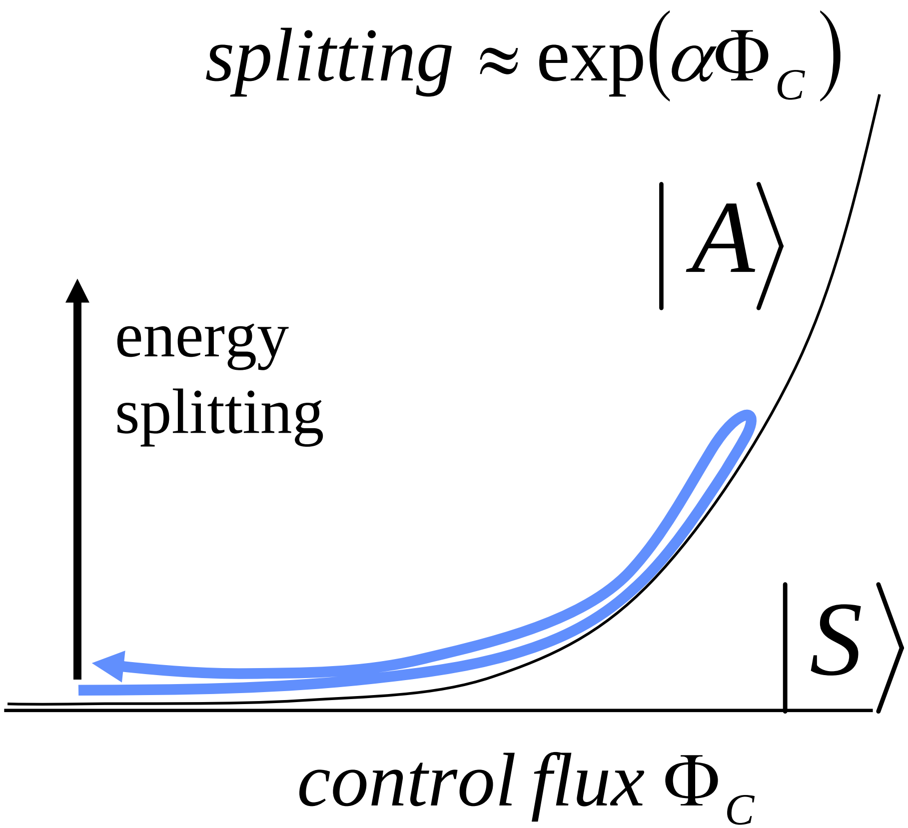
IBM Josephson junction qubit: scheme of operation:

--fix ε to be small

--initialize qubit in state

$$|L\rangle = \frac{1}{\sqrt{2}}\left(|S\rangle + |A\rangle\right)$$

--pulse small loop flux, reducing barrier height *h*



IBM Josephson junction qubit: scheme of operation:

--fix ε to be small
--initialize qubit in state

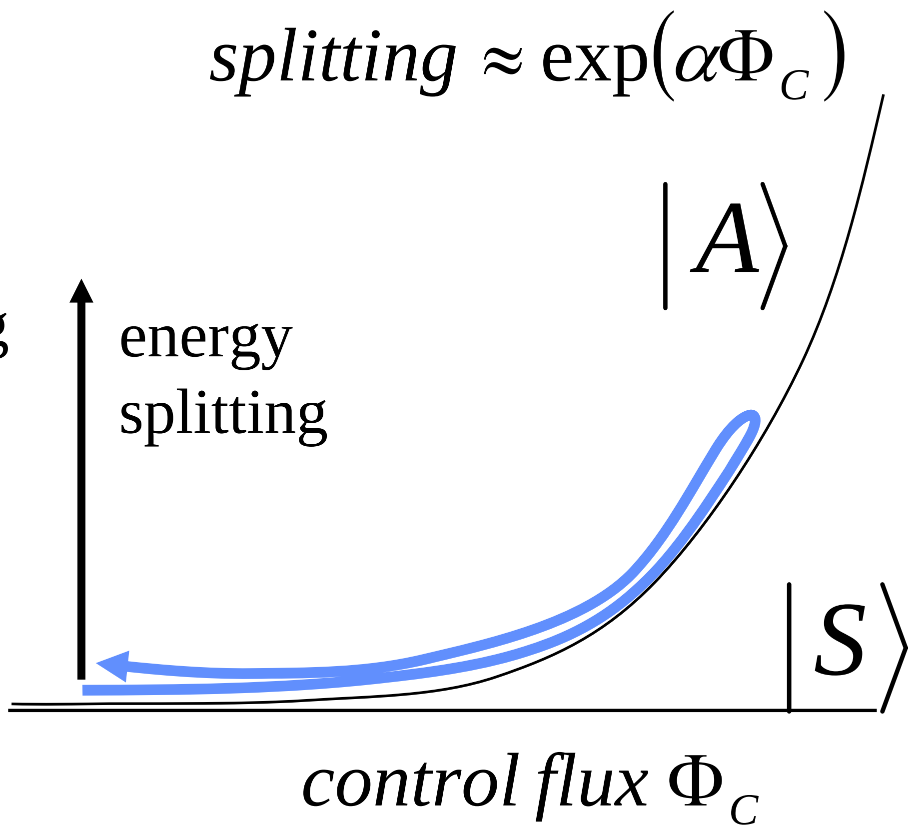
$$|L\rangle = \frac{1}{\sqrt{2}}\left(|S\rangle + |A\rangle\right)$$

--pulse small loop flux, reducing barrier height *h*
--state acquires phase shift

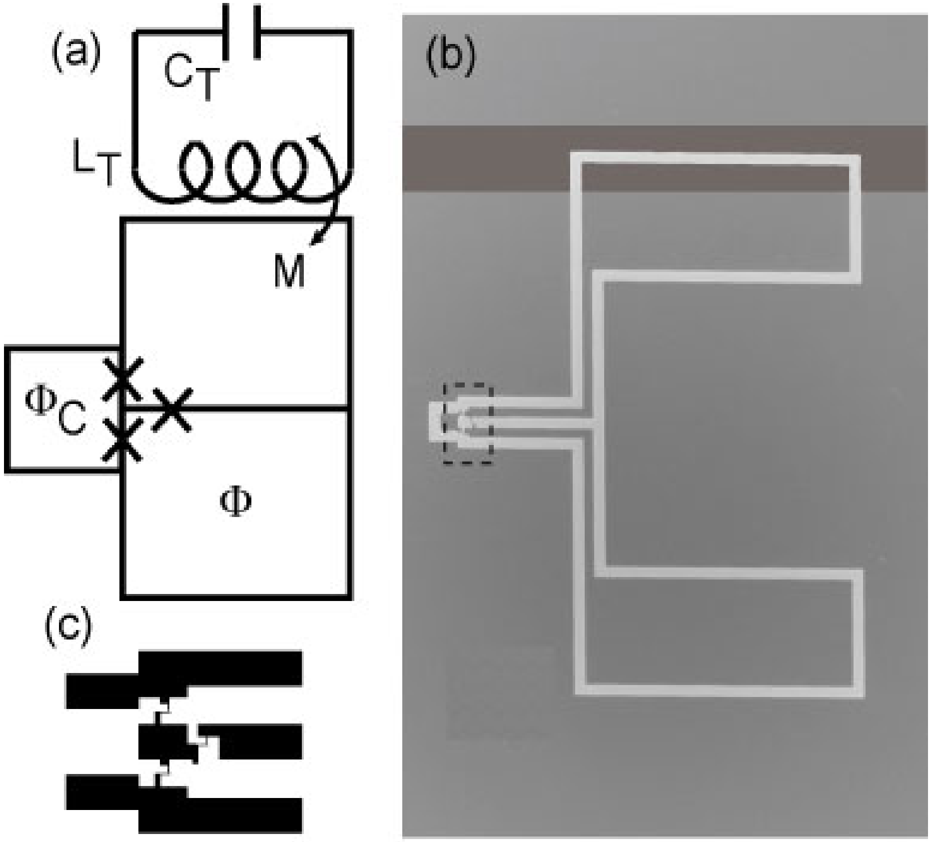
$$\frac{1}{\sqrt{2}}\left(|S\rangle + e^{i\theta}|A\rangle\right)$$

--in the original basis, this corresponds to rotating between L and R:

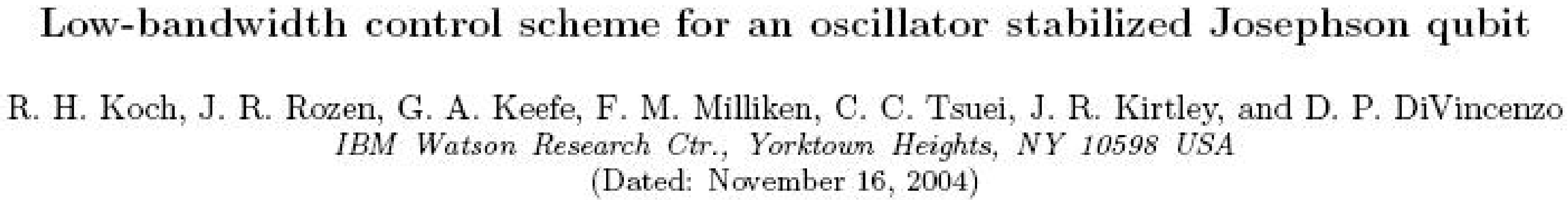
$$\cos\theta|L\rangle + i\sin\theta|R\rangle$$



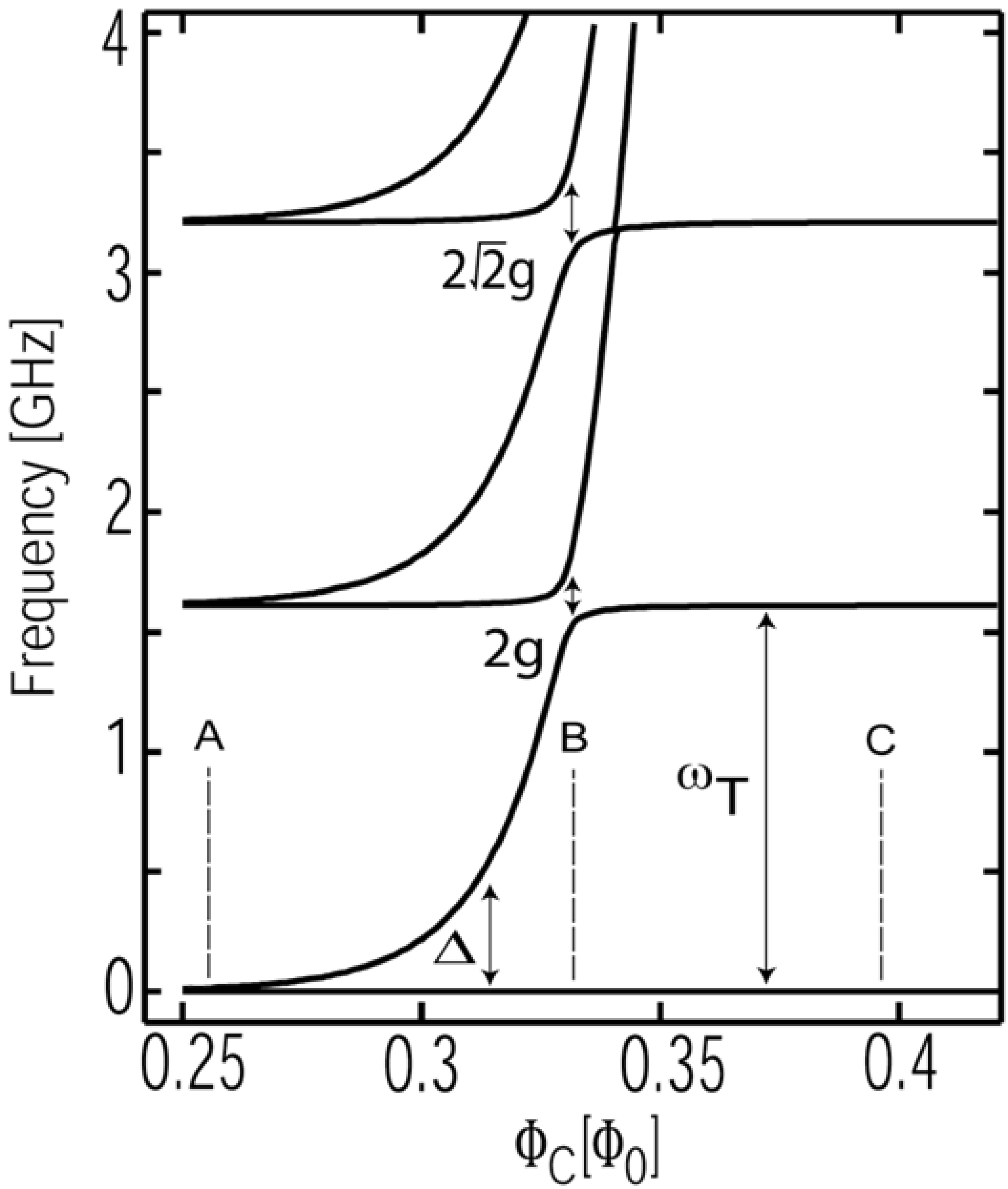
IBM Josephson junction qubit



"qubit" = circulation of electric current in one direction or another (????)



Energy diagram of qubit coupled to transmission line



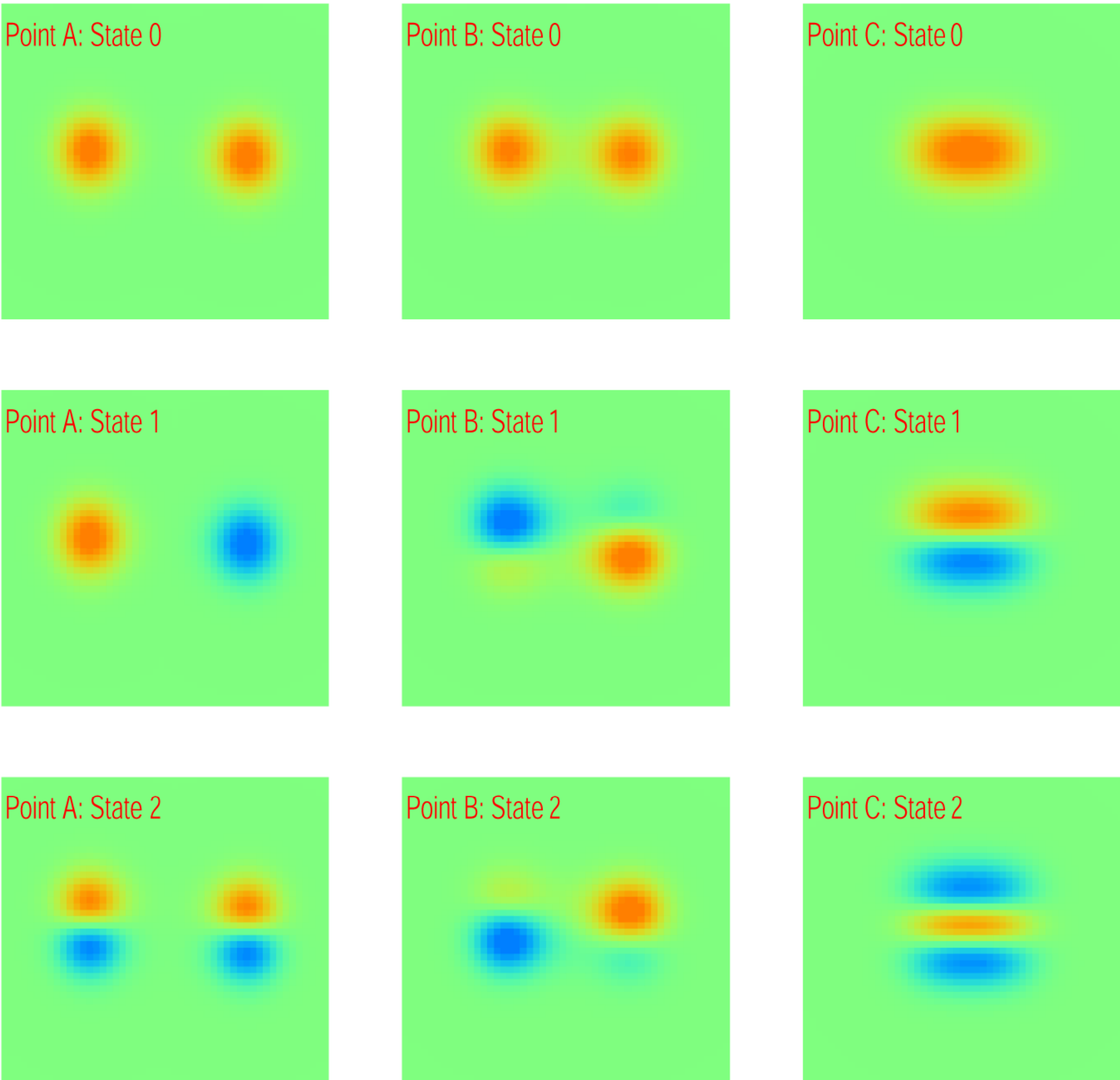
2g = 270 MHz
for C = 10 fF

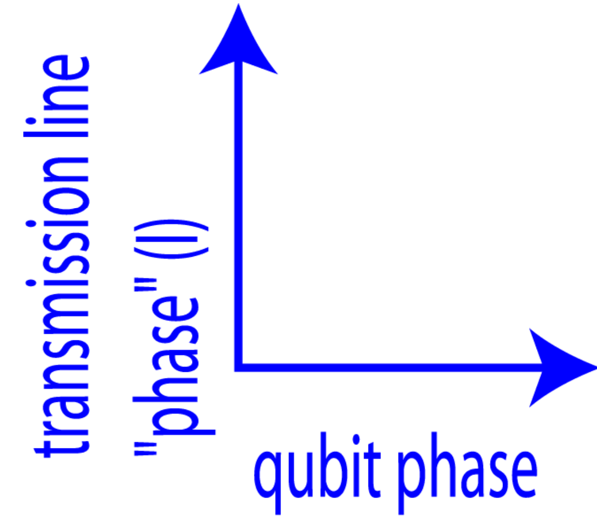
2g = 220 MHz
for C = 50 fF

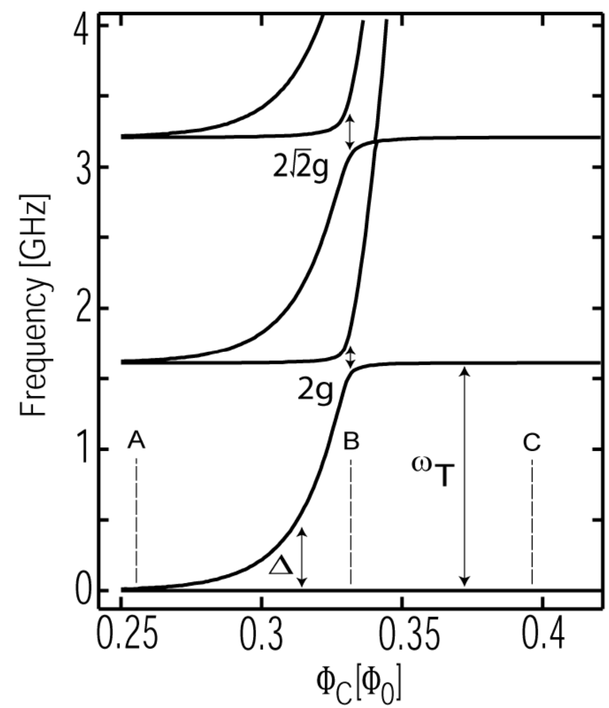
Need 2g of about 1000 MHz for 100% visibility and good independence of operating parameters on junction critical current Io.

Have ~980 MHz today
2000+ MHz is achievable.

Coupled wave functions at three points



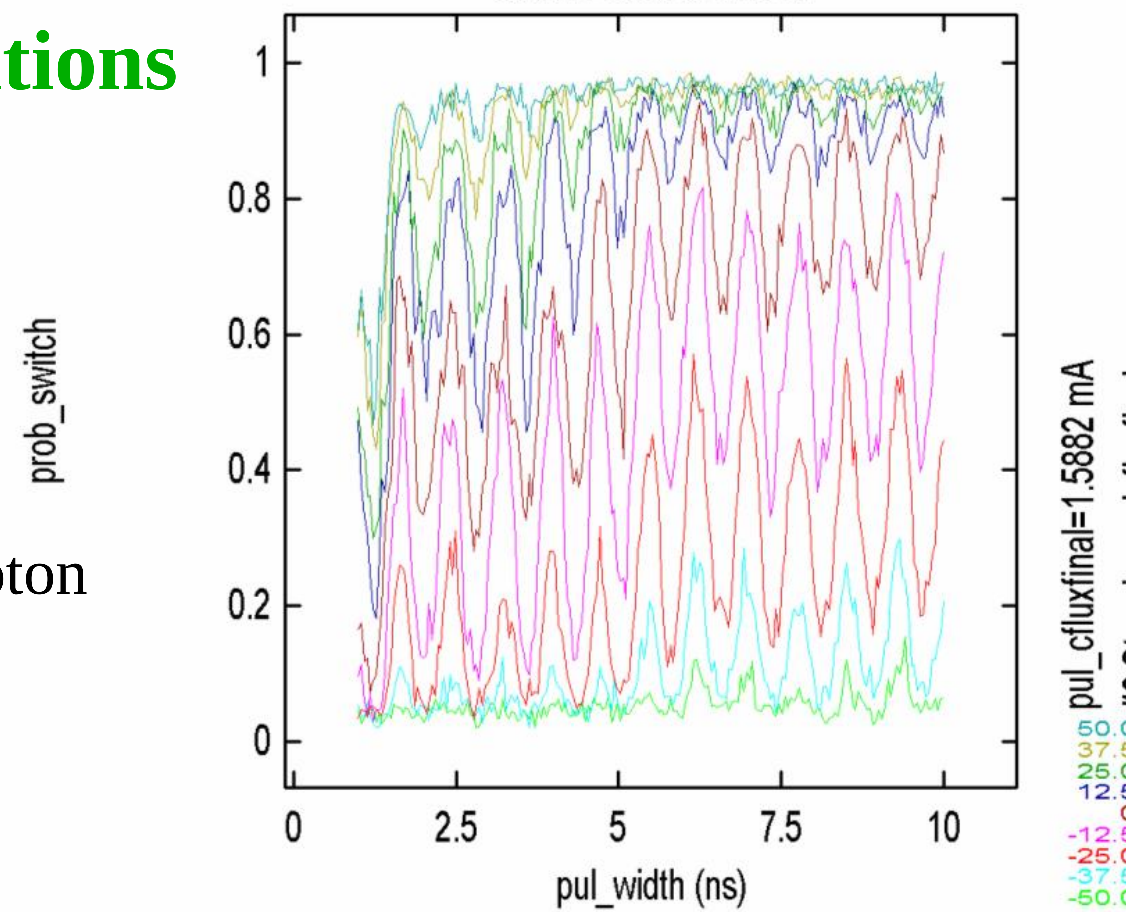


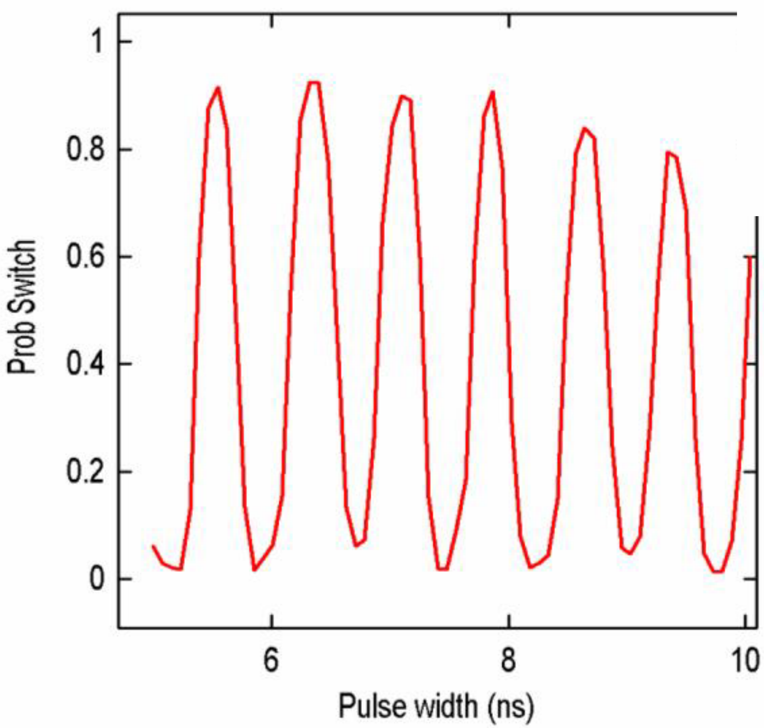


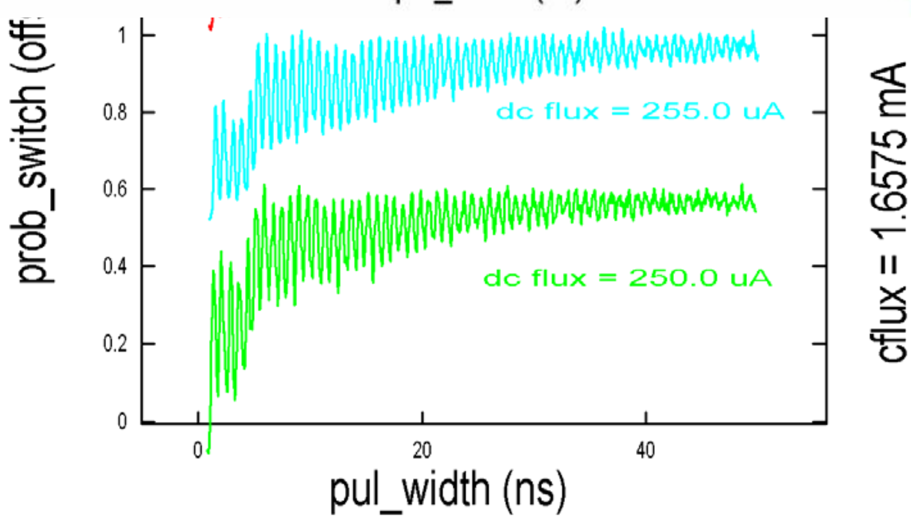
Good Larmor oscillations
IBM qubit

-- Up to 90% visibility
-- 40nsec decay
-- reasonable long term stability

They are actually 0/1 photon oscillations of trans. line.

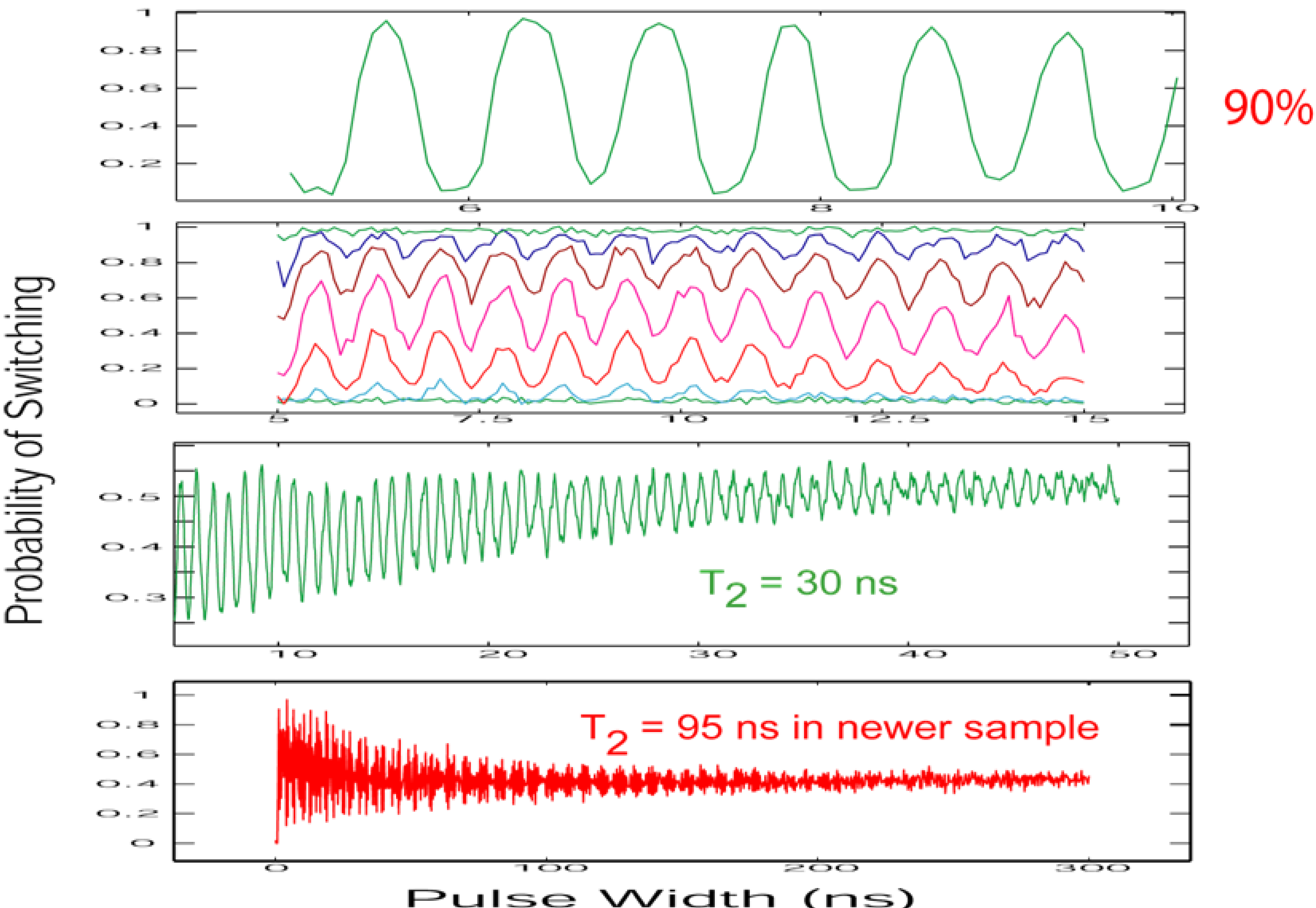






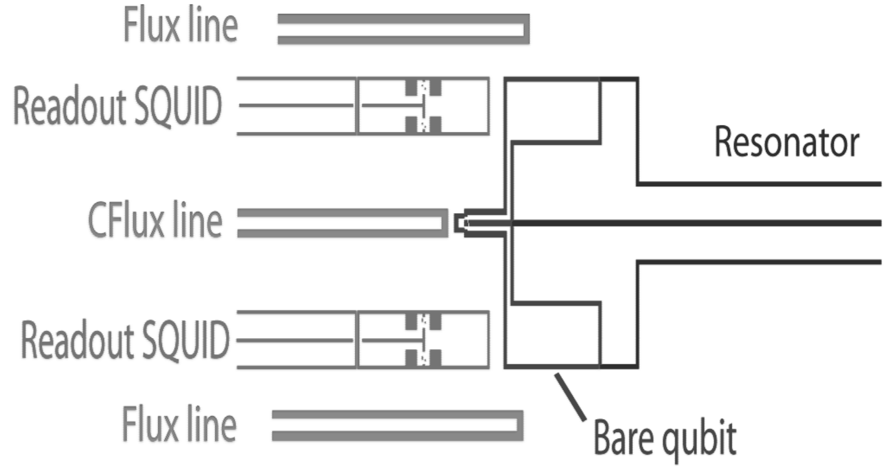
Experimental Demonstration of an Oscillator Stabilized Josephson Flux Qubit

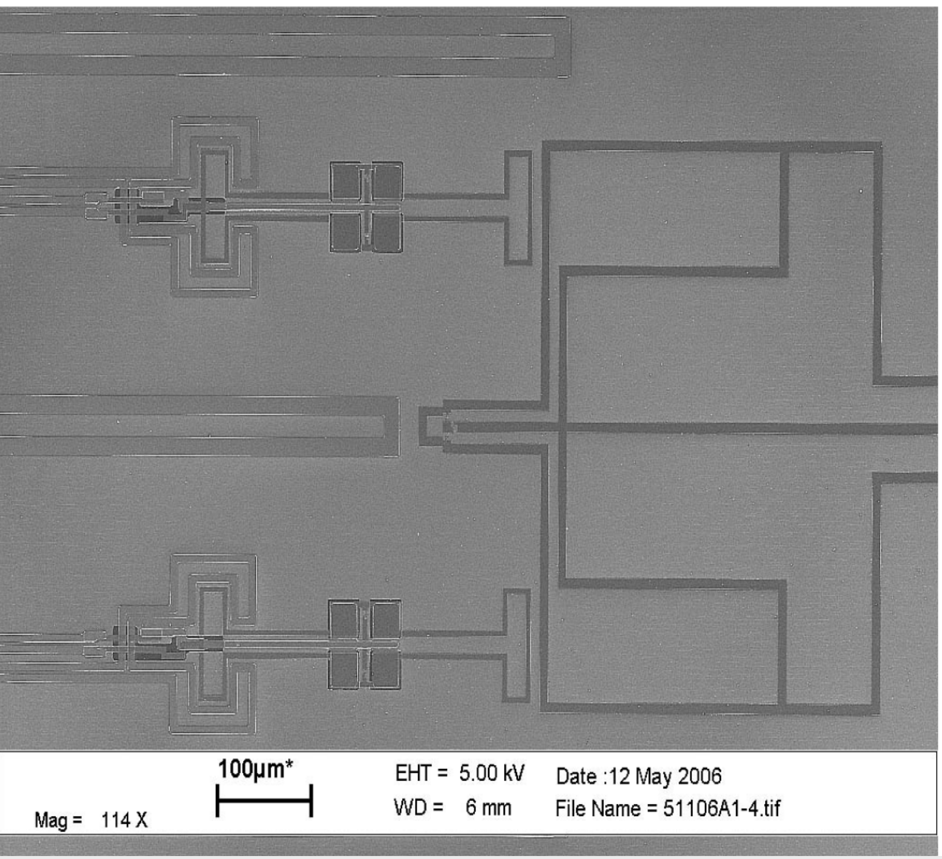
R. H. Koch, G. A. Keefe, F. P. Milliken, J. R. Rozen, C. C. Tsuei, J. R. Kirtley, and D. P. DiVincenzo
IBM Watson Research Center, Yorktown Heights, New York 10598, USA

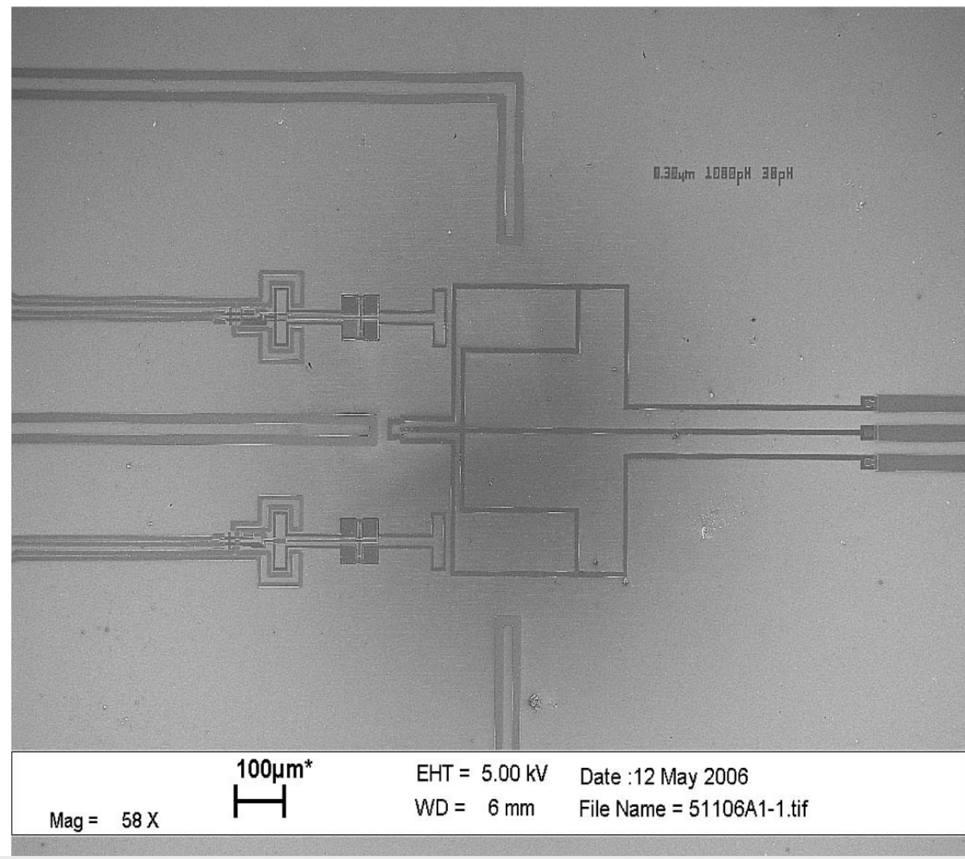


Integrated IBM qubit
May 2006 version

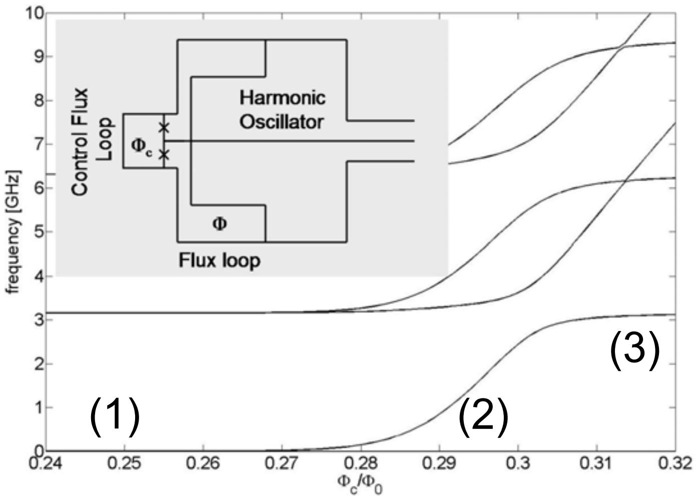
All components including junctions are integrated.
Stack has two levels of metal and one crossover.
Test fabrications on ordinary silicon wavers and wafers with embedded superconducting ground plane 60 um into the silicon.

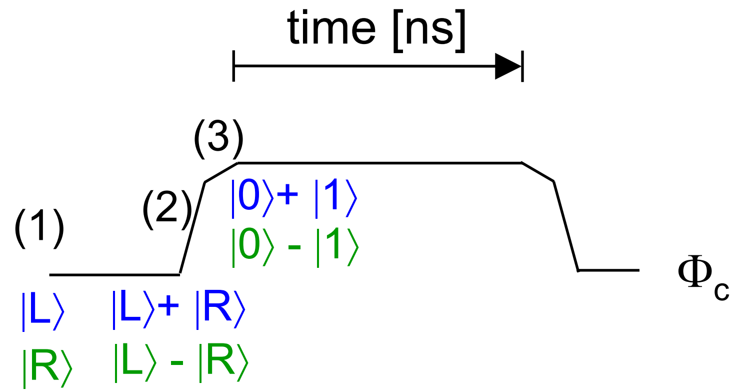




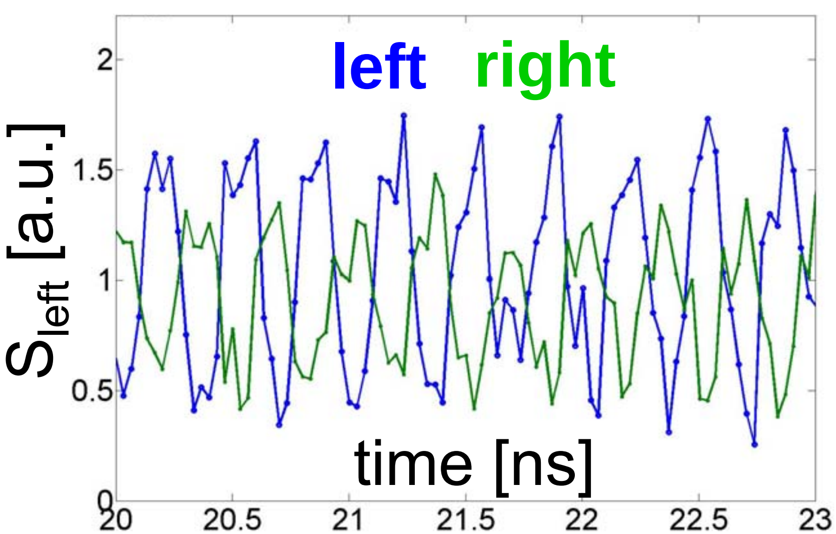


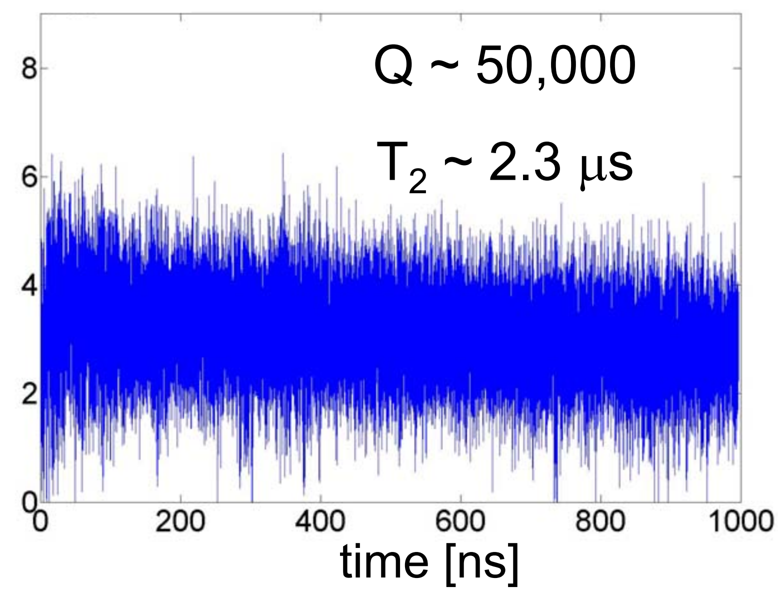
Follow-up Experiment, March 2007 (unpublished)





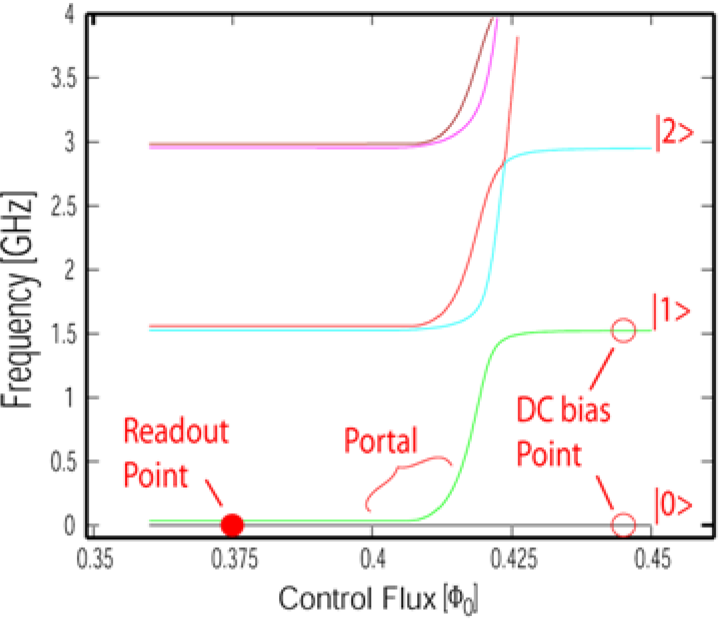
Should observe "Larmor precessions" which measure quality of harmonic oscillator

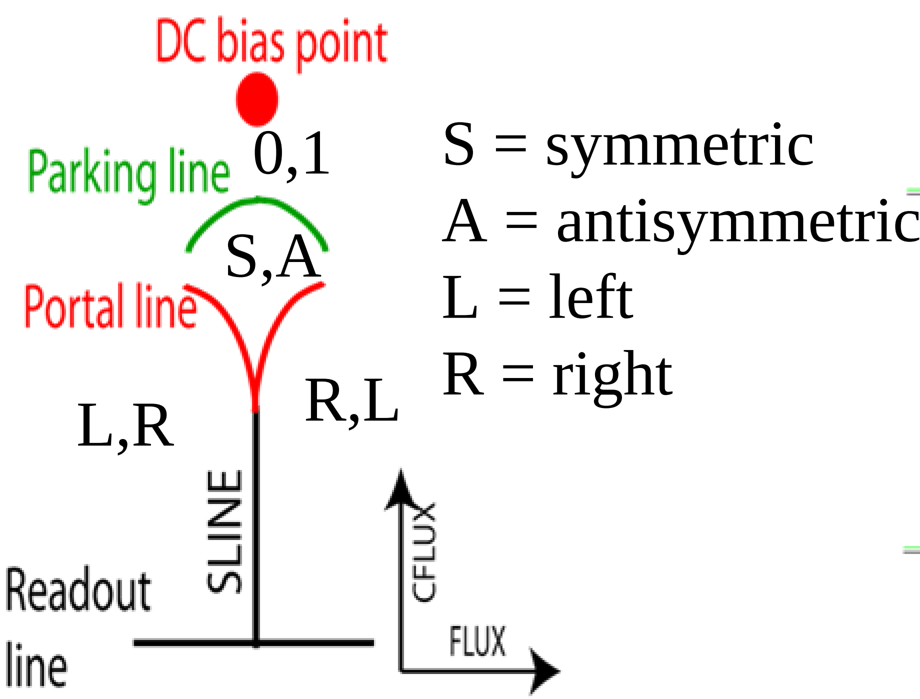


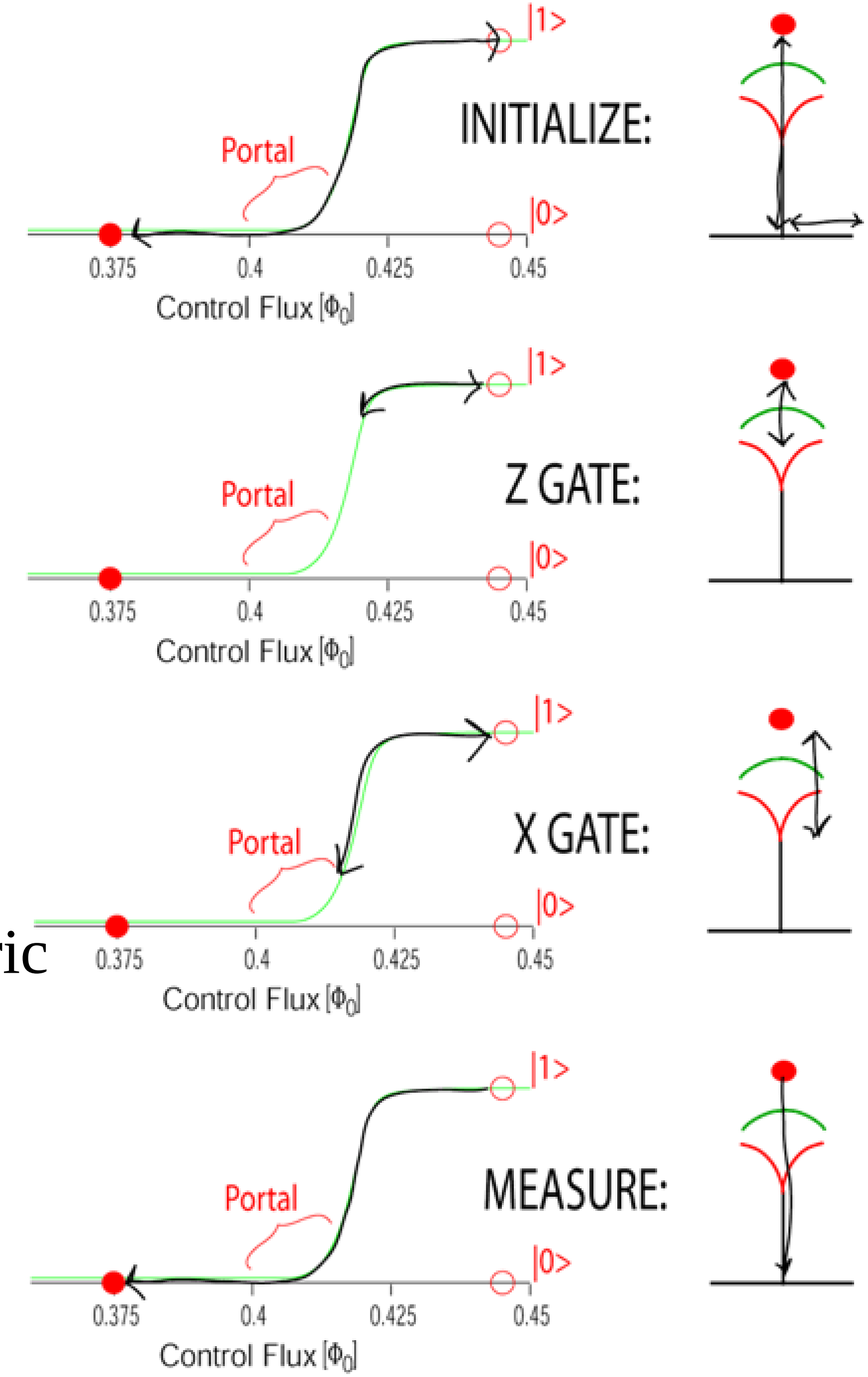


T_2 increased by 300x !!

Gate operations

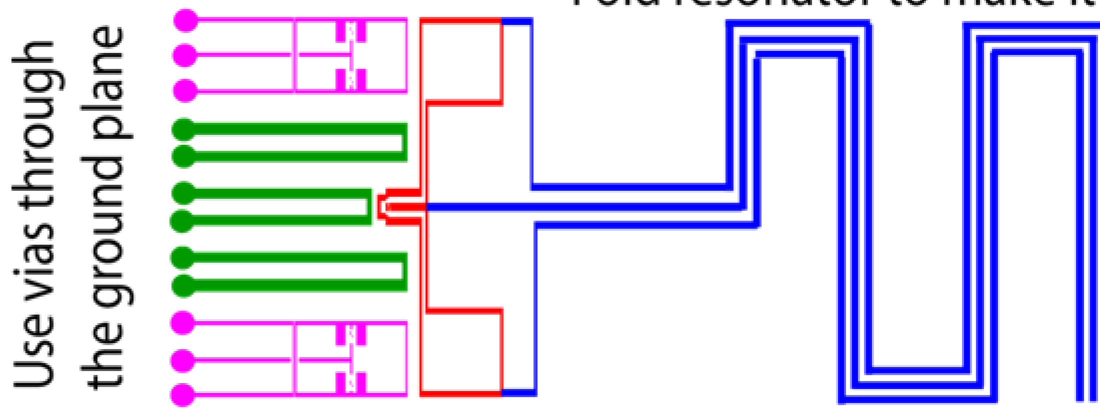


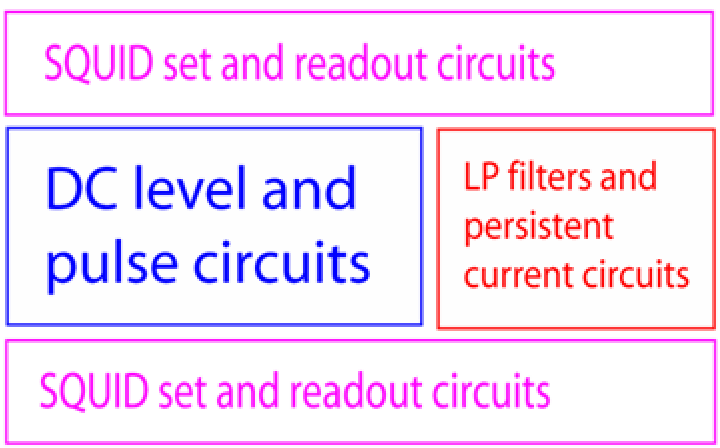


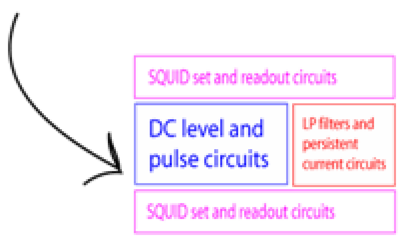


Some of the design and testing demos needed to build a 2-D array of qubits:

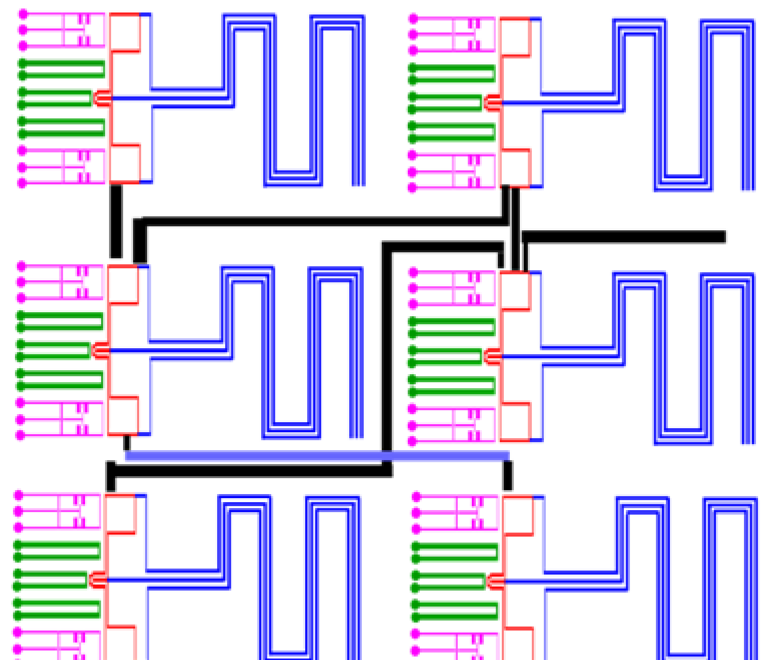
Fold resonator to make it smaller







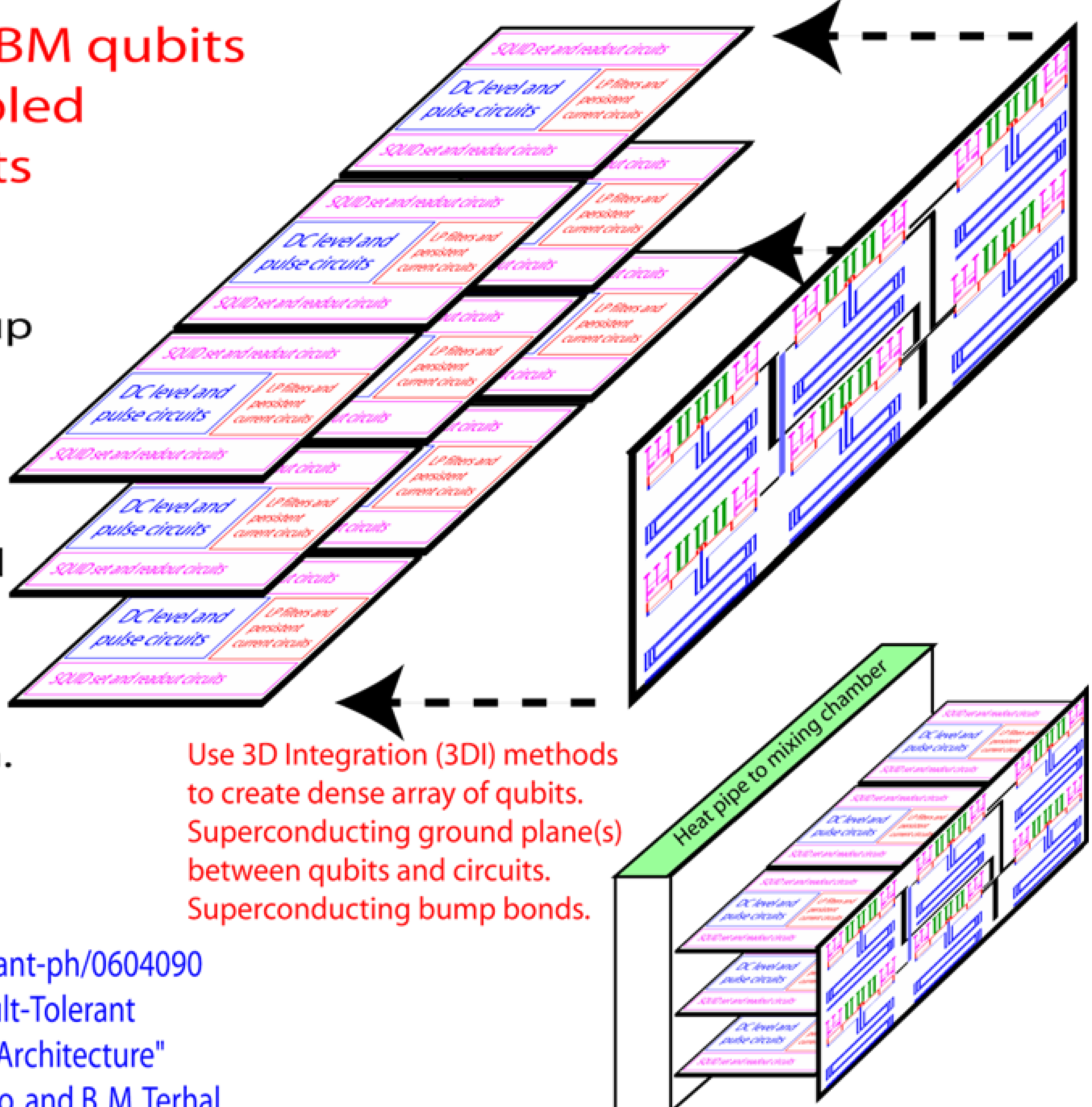
Make circuits smaller and make control circuit choices (CMOS vs SFQ and dc pulse vs microwaves)



Allow multiple qubit-to-qubit coupling, long range, and "coupling crossovers"

2-D array of IBM qubits to form Coupled Logical Qubits

IBM theory group has shown that a 2-d plane of qubits will have a much better threshold when compared to a 1-d or fractal design.



Use 3D Integration (3DI) methods to create dense array of qubits.
Superconducting ground plane(s) between qubits and circuits.
Superconducting bump bonds.

Following the ideas of quant-ph/0604090
"Noise Threshold for a Fault-Tolerant Two-Dimensional Lattice Architecture"
K. M. Svore, D. P. DiVincenzo, and B. M. Terhal

IBM Josephson Junction Qubit

- Many basic principles in hand theoretically and experimentally
- Good ideas:
  - oscillator stabilization
  - adiabatic interconversion
- Unclear in our work so far:
  - essential to use microwaves?
  - (All-baseband pulses work in principle.)
- Noise avoidance is everything, technically
- It is now possible, just barely, to discuss systems issues.

Five criteria for physical implementation of a quantum computer

1. Well defined extendible qubit array -stable memory
2. Preparable in the "000…" state
3. Long decoherence time (>10^4 operation time)
4. Universal set of gate operations
5. Single-quantum measurements

D. P. DiVincenzo, in Mesoscopic Electron Transport, eds. Sohn, Kowenhoven, Schoen (Kluwer 1997), p. 657, cond-mat/9612126; "The Physical Implementation of Quantum Computation," Fort. der Physik 48, 771 (2000), quant-ph/0002077.