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)
In tribute to Hans 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

IBM Watson Research Ctr., Yorktown Heights, NY 10598 USA
(Dated: November 16, 2004)
IBM qubit with associated

$I_c = 1.3 \, \mu\text{A}$
$L_1 = 32\,\text{pH}$
$L_3 = 680\,\text{pH}$
$M_{1cf} = 0.8\,\text{pH}$
$M_{3\text{flux}} = 0.5\,\text{pH}$
$
\omega_T = 2\pi \, 3.1 \, \text{GHz}$
$Z_0 = 110 \, \Omega$
$L_T = 5.6 \, \text{nH}$
$M_{qT} = 200 \, \text{pH}$
“No power is required to perform computation.”
CH Bennett

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

“Quantum computers can operate autonomously.”
N Margolus

(inventor of “computronium”)
Quantum SQUID characteristic: the “washboard”

1. Loop: inductance $L$, energy $\omega^2/L$
2. Josephson junction: critical current $I_c$, energy $I_c \cos \omega$
3. External bias energy (flux quantization effect): $\omega \Phi/L$

Quantum energy levels

Junction capacitance $C$, plays role of particle mass
Equation of motion of a complex circuit:

\[
C \ddot{\phi} = -L_j^{-1} \sin \phi - R^{-1} \dot{\phi} - M_0 \phi - M_d \varphi - \frac{2\pi}{\Phi_0} N \Phi_x - \frac{2\pi}{\Phi_0} S I_B
\]

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

\[
\frac{1}{2} Q_C^T C^{-1} Q_C + U(\phi)
\]

\[
U(\phi) = - \sum_i L_{j;i}^{-1} \cos \phi_i
\]

\[
+ \frac{1}{2} \varphi^T M_0 \varphi + \frac{2\pi}{\Phi_0} \varphi^T (N \Phi_x + S I_B)
\]

the equation of motion (continued):

\[ C \ddot{\varphi} = -L_J^{-1} \sin \varphi - R^{-1} \dot{\varphi} - M_0 \varphi - M_d \ast \varphi - \frac{2\pi}{\Phi_0} N \Phi x - \frac{2\pi}{\Phi_0} S I_B \]

\[ M_0 = F_{CL} \tilde{L}_L^{-1} \bar{L} L_{LL}^{-1} F_{CL}^T, \]
\[ N = F_{CL} \tilde{L}_L^{-1} \bar{L} L_{LL}^{-1}, \ldots \]

\[ \bar{N}(\omega = 0) = F_{CL} \left[ 1_L + L^{-1} L_{LK} \left( L_K - L_{LK}^T L_{LK} L^{-1} L_{LK} \right)^{-1} \right. \]
\[ \left. \left( 1_K - L_K (F_{KL} - L_K^{-1} L_{LK}^T) L^{-1} L_{LK} (L_K - L_{LK}^T L_{LK} L^{-1} L_{LK})^{-1} \right)^{-1} L_K (F_{KL} - L_K^{-1} L_{LK}^T) \right] \]
\[ \left[ L - L_{LK} L_K^{-1} L_{LK}^T + F_{KL}^T \left( 1_K - L_K (F_{KL} - L_K^{-1} L_{LK}^T) L^{-1} L_{LK} (L_K - L_{LK}^T L_{LK} L^{-1} L_{LK})^{-1} \right)^{-1} L_K (F_{KL} - L_K^{-1} L_{LK}^T) \right]^{-1}. \]

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

Linear electric circuit
The physics of the coupling matrices

Linear electric circuit

Cut out the Josephson junctions…
The physics of the coupling matrices

Multiport Electric circuit

Green function:

\[ I_j(\omega) = Y_{ij}(\omega) V_i(\omega), \quad Y_{ij}(\omega) = \frac{1}{i\omega} (L^{-1})_{ij} + K = \frac{\dot{M}_0}{i\omega} + K \]

small-loop noise: gradiometrically protected
Large-loop noise: bad, but heavily filtered

FIG. 2: Contour plot of the potential $U'(f)$ 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.

FIG. 20: The total relaxation, dephasing and decoherence times ($T_1$, $T_\phi$ and $T_2$, respectively) along the S line. We can see that $T_\phi$ ($T_1$) strongly increases (decreases) as a function of $\Phi_c$. These facts cause there to be a window of desirable operating parameters for the qubit.
IBM Josephson junction qubit: scheme of operation:

-- fix $\varepsilon$ to be small
-- initialize qubit in state
$|L\rangle = \frac{1}{\sqrt{2}}(|S\rangle + |A\rangle)$
-- pulse small loop flux, reducing barrier height $h$

$\varepsilon = \text{asymmetry of double well}$

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

$\text{splitting} \approx \exp(\alpha \Phi_C)$

control flux $\Phi_C$
IBM Josephson junction qubit: scheme of operation:

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$$splitting \approx \exp(\alpha \Phi_C)$$
IBM Josephson junction qubit: scheme of operation:

--fix $\varepsilon$ to be small
--initialize qubit in state
$$|L\rangle = \frac{1}{\sqrt{2}}(|S\rangle + |A\rangle)$$
--pulse small loop flux, reducing barrier height $h$
--state acquires phase shift
$$\frac{1}{\sqrt{2}}(|S\rangle + e^{i\theta}|A\rangle)$$
--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 (????)

Low-bandwidth control scheme for an oscillator stabilized Josephson qubit

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(Dated: November 16, 2004)
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 I0.

Have ~980 MHz today. 2000+ MHz is achievable.
Coupled wave functions at three points

Point A: State 0
Point B: State 0
Point C: State 0

Point A: State 1
Point B: State 1
Point C: State 1

Point A: State 2
Point B: State 2
Point C: State 2

transmission line
"phase" (l)
qubit phase

Frequency [GHz]
0 1 2 3 4

0.25 0.3 0.35 0.4

A 2/2g 2g
B ω_T C
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


IBM Watson Research Center, Yorktown Heights, New York 10598, USA

90%

\[ T_2 = 30 \text{ ns} \]

\[ T_2 = 95 \text{ ns in newer sample} \]
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.

\[ |L\rangle, |L\rangle + |R\rangle, |R\rangle, |L\rangle - |R\rangle \]

\[ Q \sim 50,000 \]
\[ T_2 \sim 2.3 \, \mu s \]

\[ T_2 \text{ increased by 300x !!} \]
Gate operations

\[ S = \text{symmetric} \]
\[ A = \text{antisymmetric} \]
\[ L = \text{left} \]
\[ R = \text{right} \]

INITIALIZE:

Z GATE:

X GATE:

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

- SQUID set and readout circuits
- DC level and pulse circuits
- LP filters and persistent current circuits

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

Fold resonator to make it smaller

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
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