MEASURING QUANTRONIUM QUBIT WITH CAVITY BIFURCATION AMPLIFIER

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W. M. KECK FOUNDATION

Monday evening seminar
September 11th 2006

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   - Quantum circuits
   - Quantronium
2. **Cavity bifurcation amplifier (CBA) :**
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   - Implementations
   - Bistability
3. **Quantronium with CBA:**
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   - Rabi/Ramsey oscillations
4. **Outlook:** - Coupled qubits (See Chad's talk)
   - Multiplexed C.B.A's

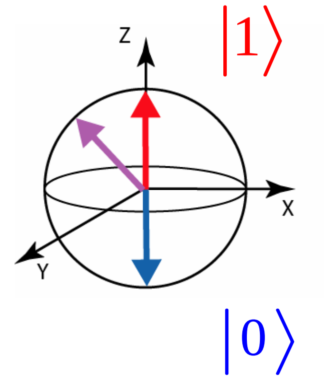
QUANTUM COMPUTATION

Quantum computation:

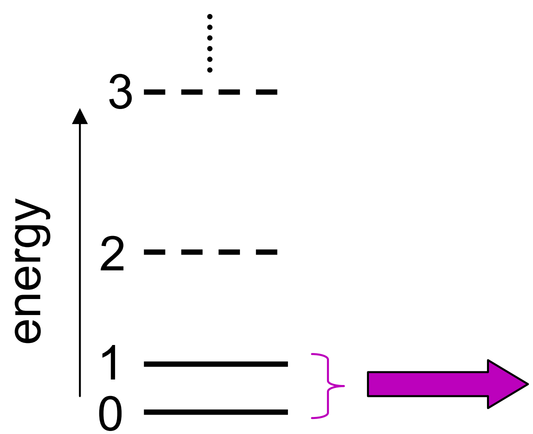
Unitary evolution of initially prepared n-qubit state and its subsequent measurement

Qubit:

Just a 2-state system
(effective spin – ½)



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



Isolate two energy levels

QUANTUM PARALLELISM

N-qubit state:

$$|\psi\rangle = \sum_{k=0}^{2^N-1} C_k |k\rangle$$

Unitary operation,U:

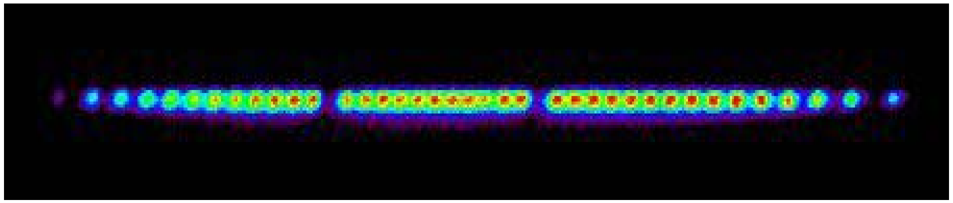
$$U|\psi\rangle = \sum_{k=0}^{2^N-1} C_k U |k\rangle$$

2^N operations in parallel!!

$$|k\rangle \left\{ \begin{array}{c} 000000000000 \\ 000000000001 \\ 000000000010 \\ \vdots \\ 111111111110 \\ 111111111111 \end{array} \right.$$

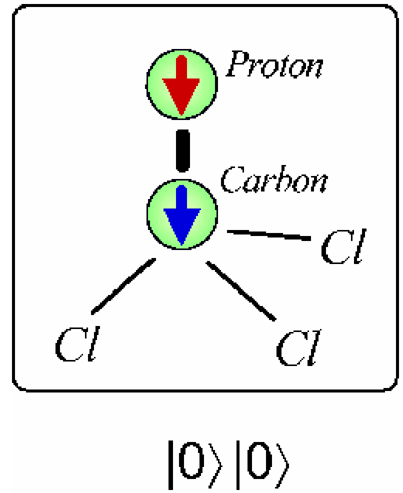
QUBIT REALIZATIONS

Trapped ions



Long qubit coherence
Low environmental coupling
Scalability difficult

NMR



chloroform molecule

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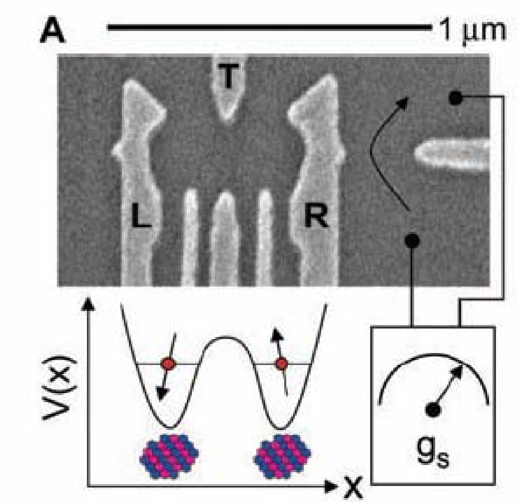
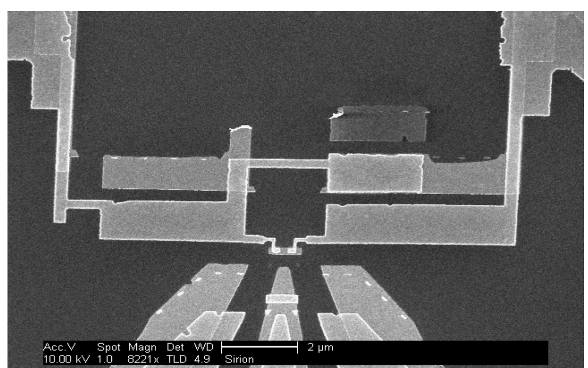
semiconductor dots

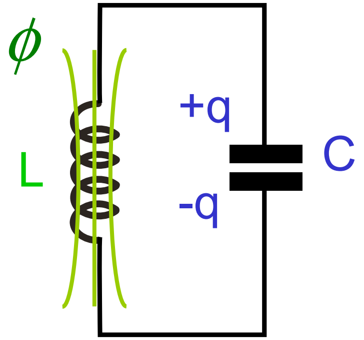


superconducting circuits



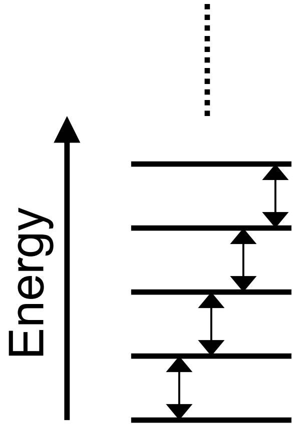
Shorter qubit coherence
Large environmental coupling
Scalability easier
Electrical access

QUANTUM CIRCUITS



$$H = \frac{\phi^2}{2L} + \frac{q^2}{2C}$$

$$[\phi, q] = i\hbar$$

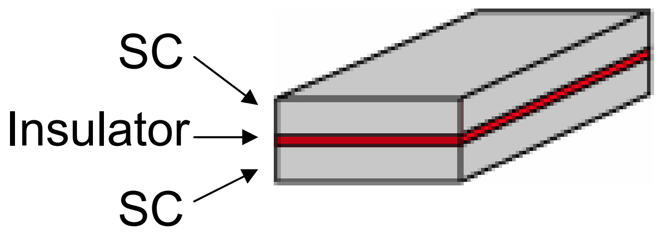


$$\Delta E = \hbar\omega \gg k_B T$$

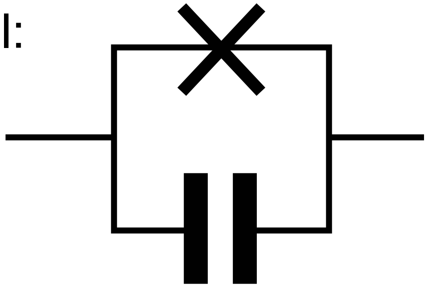
Microfabrication and cryogenics → $\omega \sim 1\text{GHz}$, $T \sim 10\text{mK}$

Equal level spacing → Need non-linear element

NON-LINEAR ELEMENT: JOSEPHSON JUNCTION



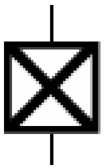
Model:



Josephson current:

$$i(t) = -I_0 \sin\left[\underbrace{\frac{2e}{\hbar}\Phi_J(t)}_{\Delta\varphi}\right]$$

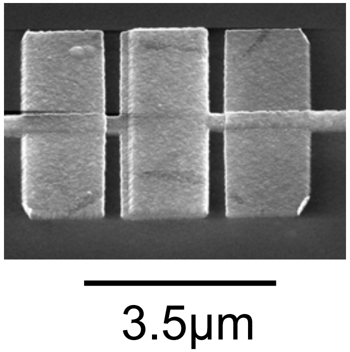
Circuit symbol:



Inductance:

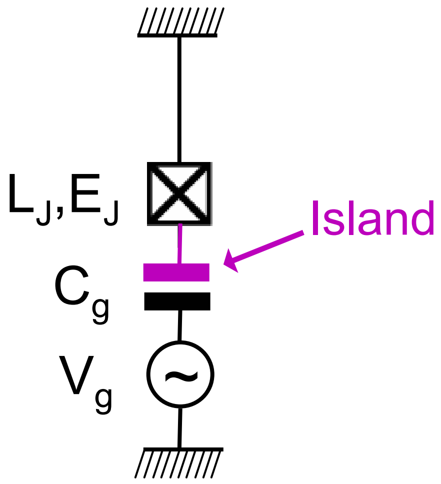
$$L = \frac{1}{\partial i / \partial \Phi} = \frac{\hbar}{2eI_0\cos(\Delta\varphi)}$$

SEM:



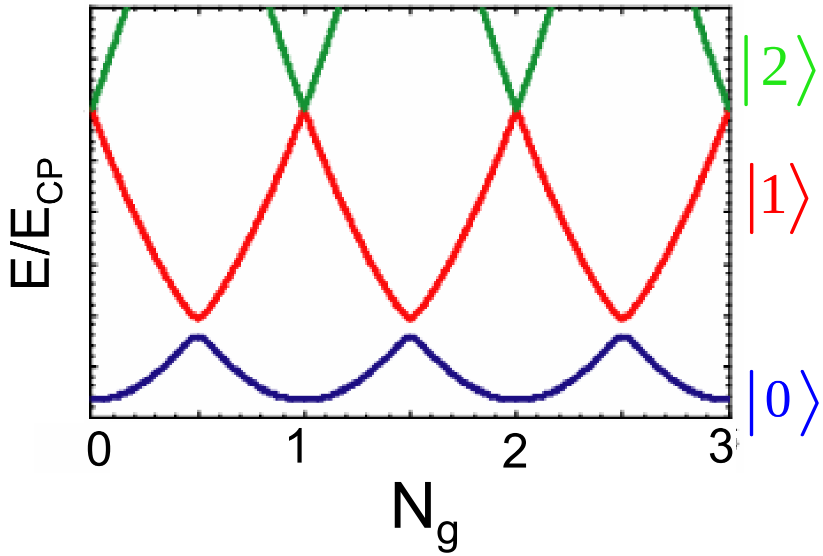
Non-Linear Inductor!

COOPER PAIR BOX

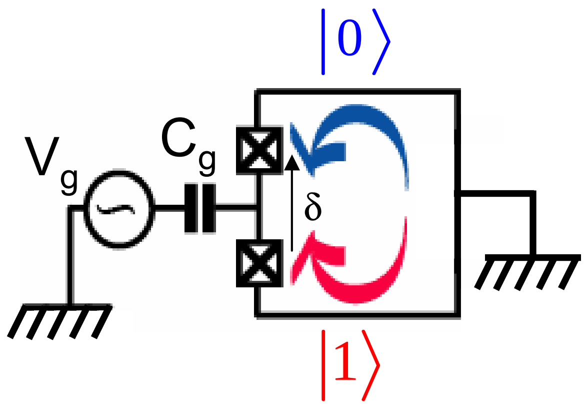


$$\hat{H}\left(N_g\right) = E_{CP}\left(\hat{N} - N_g\right)^2 - E_J \cos\left(\hat{\theta}\right)$$

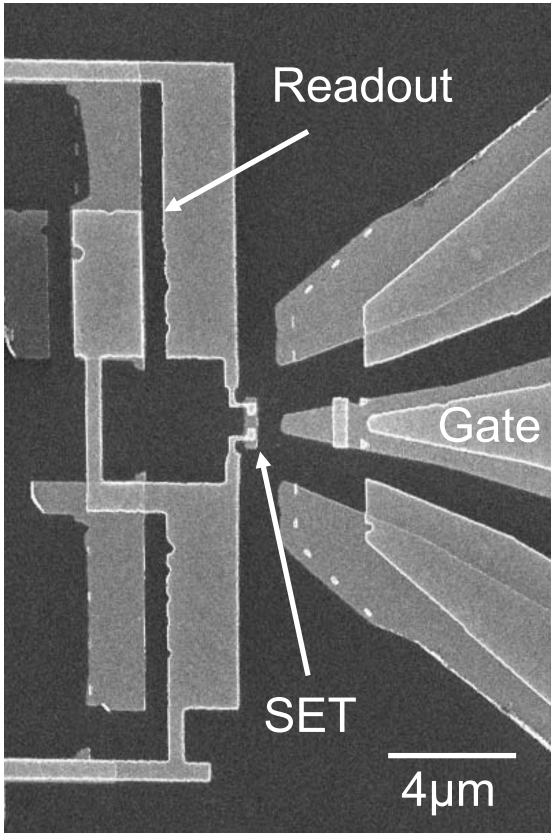
$$E_{CP} = \frac{(2e)^2}{2\left(C_g + C_J\right)} \qquad N_g = \frac{C_g V_g}{2e} \qquad \left[\hat{\theta}, \hat{N}\right] = i$$



SPLIT COOPER PAIR BOX



SEM image of Quantronium



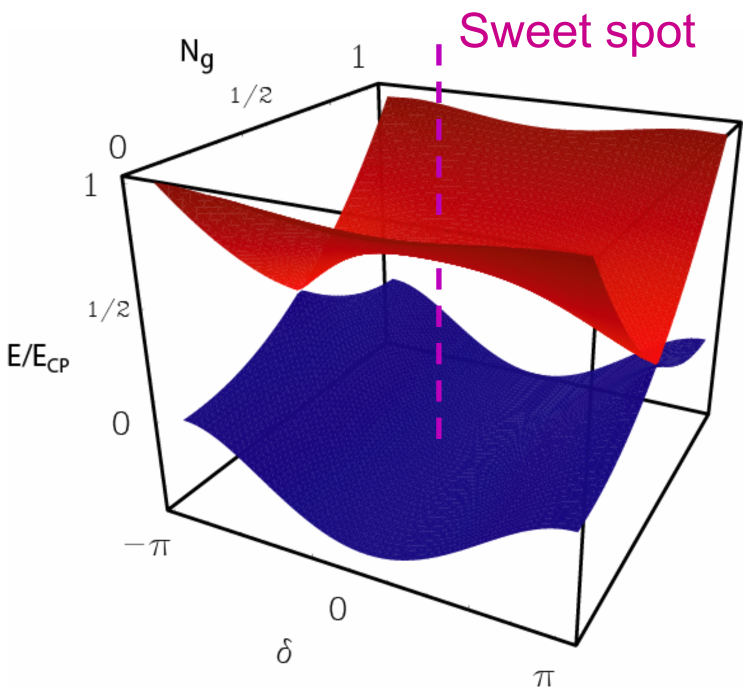
$$\hat{H}\left(N_g\right) = E_{CP}\left(\frac{1}{i}\frac{\partial}{\partial\theta} - N_g\right)^2 - E_J\left(\delta\right)\cos\left[\hat{\theta}\left(\delta\right)\right]$$

$$E_J << E_{CP} \Rightarrow H_{CPB} = h_z\left(\delta\right)\sigma_z + h_x\left(N_g\right)\sigma_x$$

$\Downarrow$

Artificial 2-level atom

ENERGY LEVELS

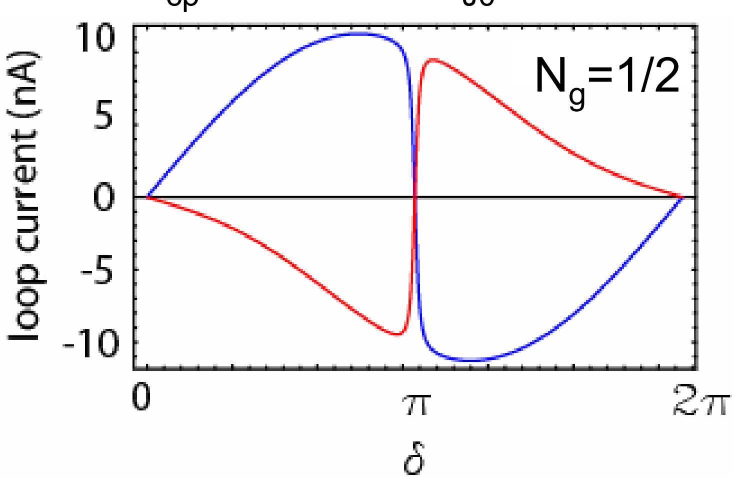


Eigenstates, E_k: Mathieu Functions

Sweet spot:

$$\frac{\partial E_k}{\partial \delta} = \frac{\partial E_k}{\partial N_g} = 0$$

E_{cp} = 17GHz, E_{J0} = 15GHz



Average loop current:

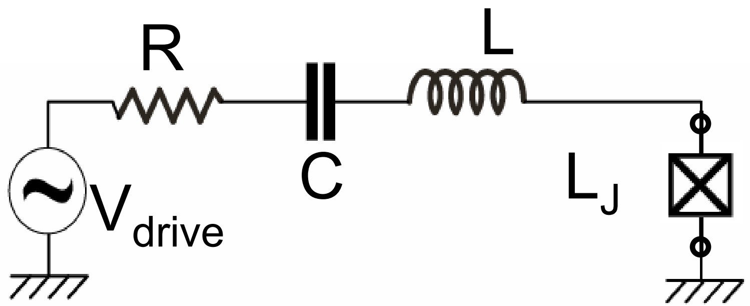
$$\mathrm{i}_k(N_g, \delta) = \frac{1}{\varphi_0} \frac{\partial E_k(N_g, \delta)}{\partial \delta}$$

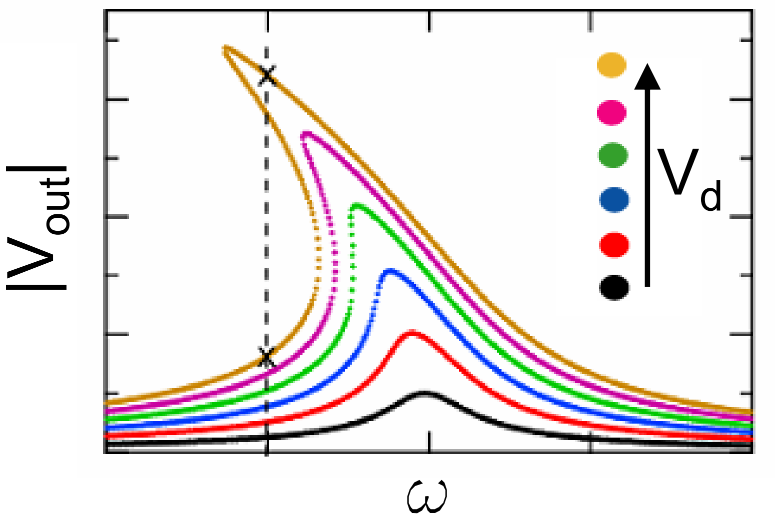
With inductance:

$$L(N_g, \delta) = \left[\frac{1}{\varphi_0} \left(\frac{\partial I}{\partial \delta} \right) \right]^{-1} = \left[\frac{1}{\varphi_0^2} \left(\frac{\partial^2 E_k(N_g, \delta)}{\partial \delta^2} \right) \right]^{-1}$$

NON-LINEAR READOUT

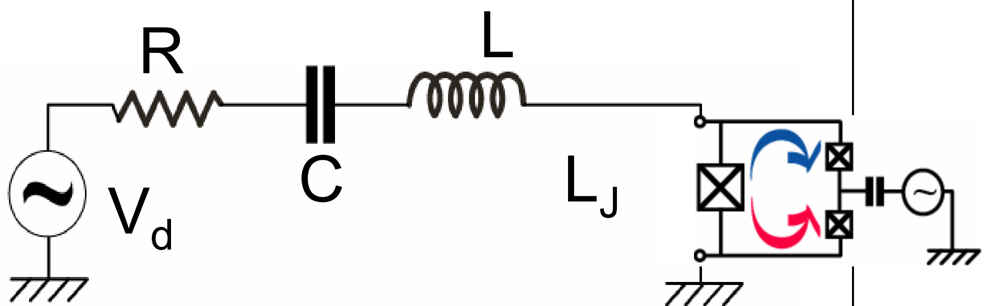
Non-linear LC oscillator



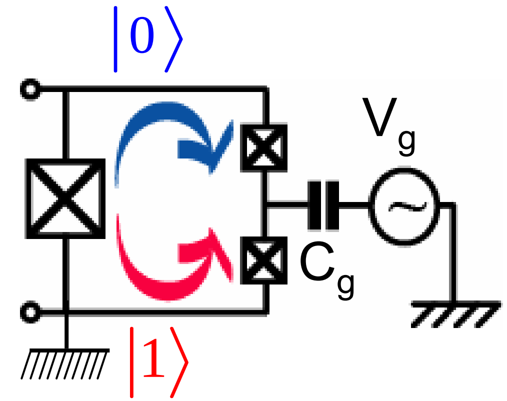


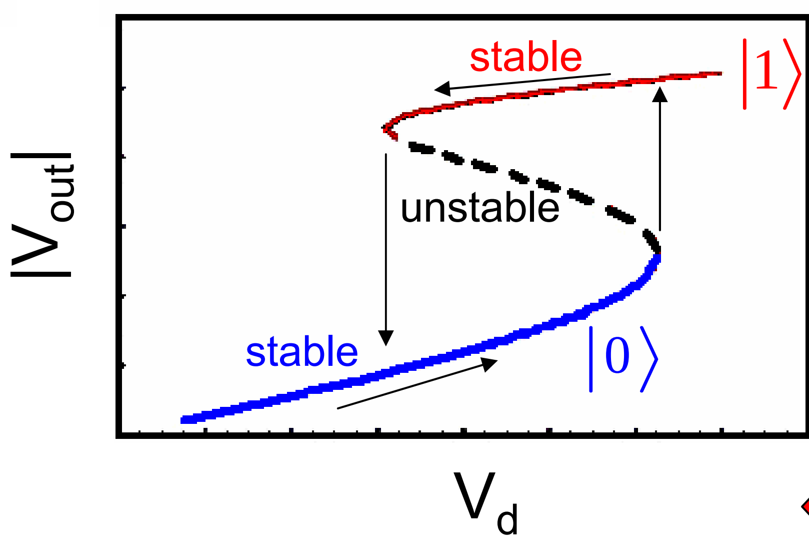
NON-LINEAR READOUT

Non-linear LC oscillator

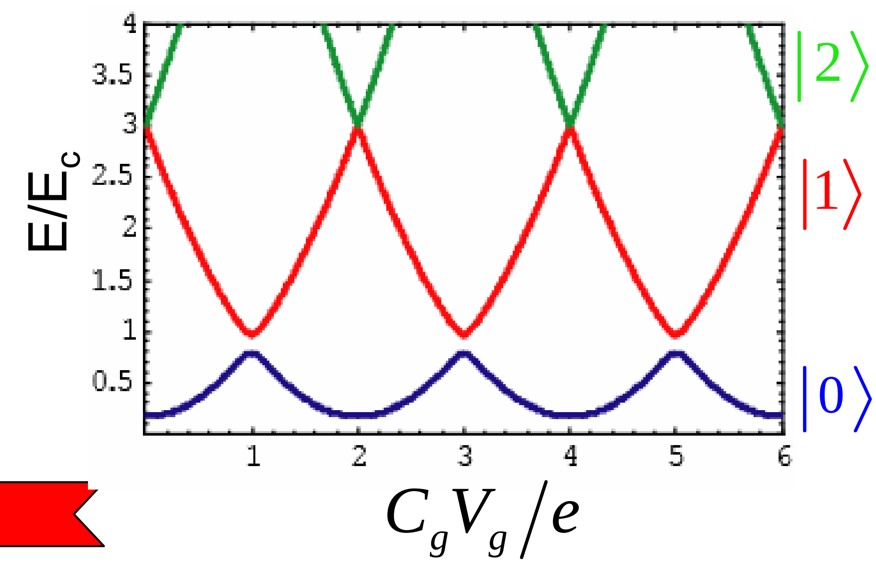


Quantronium Qubit





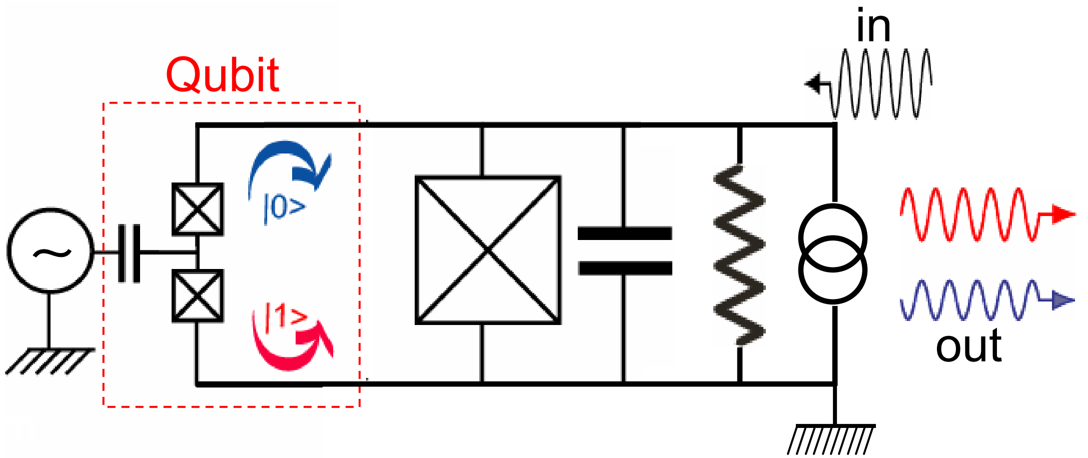
Energy levels



Mapping

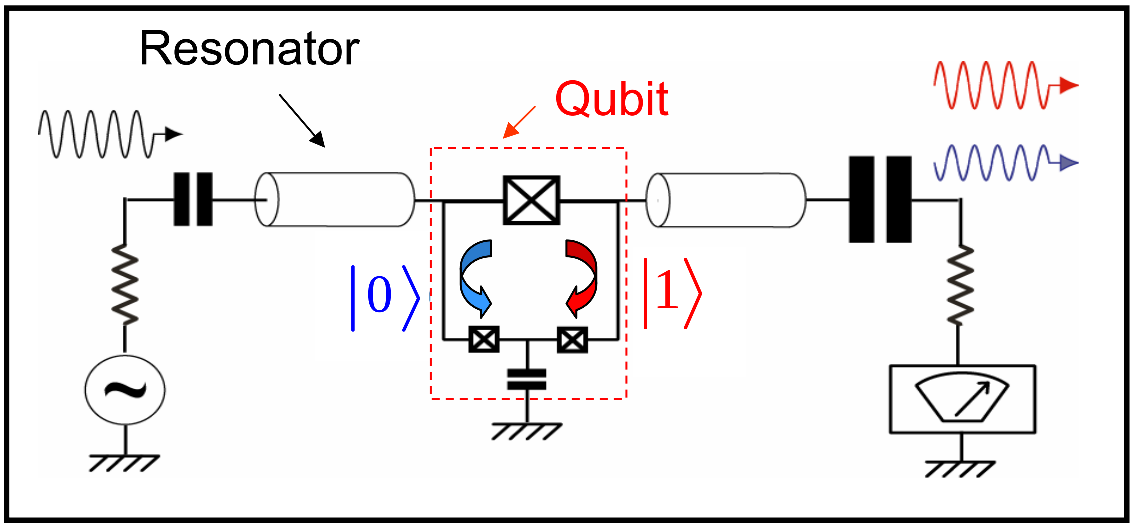
IMPLEMENTATIONS

Quantronium qubit with Josephson bifurcation amplifier (JBA)



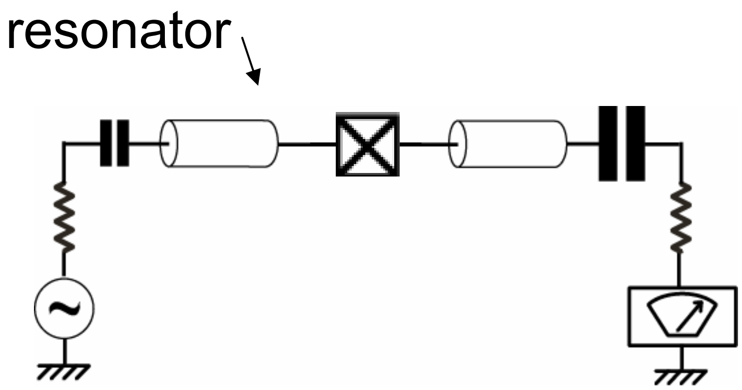
(I. Siddiqi et. al, PRB 2006)

Quantronium qubit with cavity bifurcation amplifier (CBA)

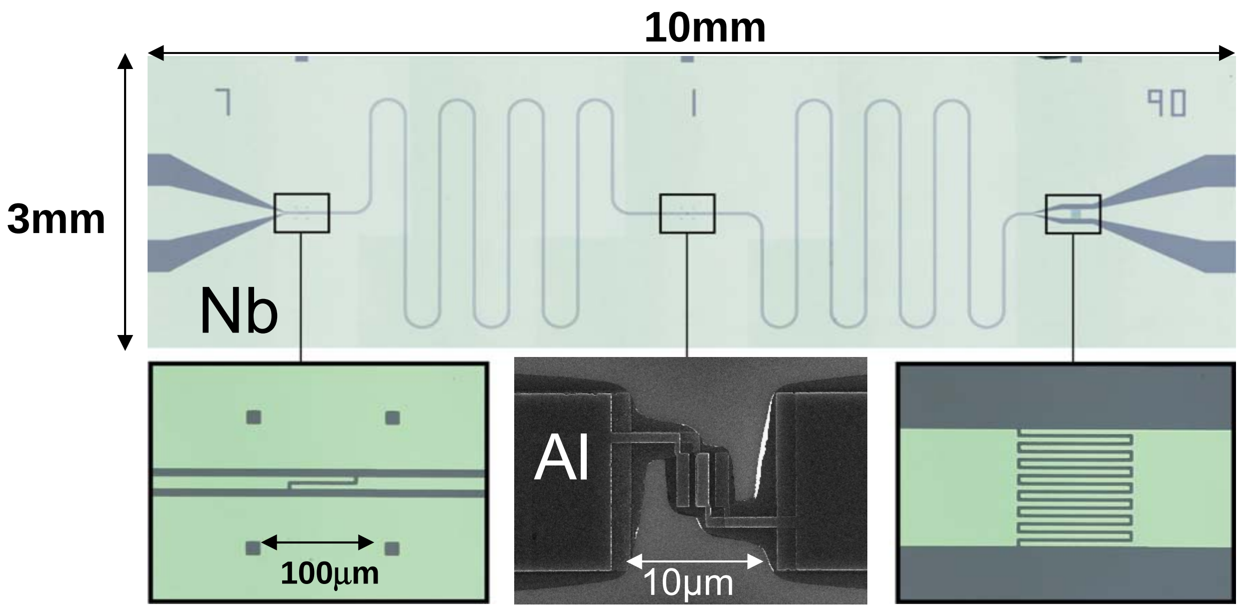


NEW

SAMPLE

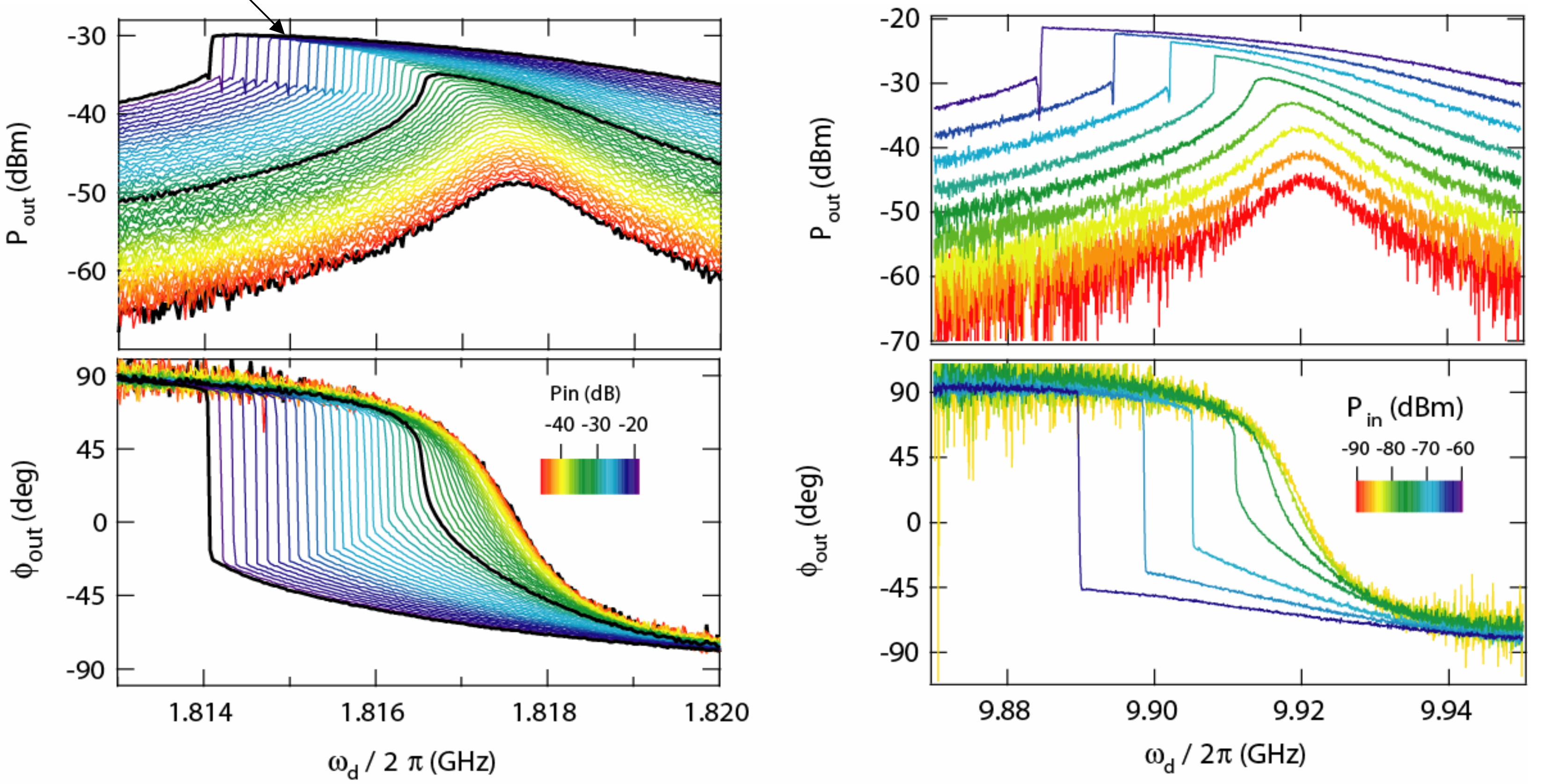


1) Precisely control non-linearity
2) Engineer freq, Q
3) No dissipation on-chip



MICROWAVE RESPONSE

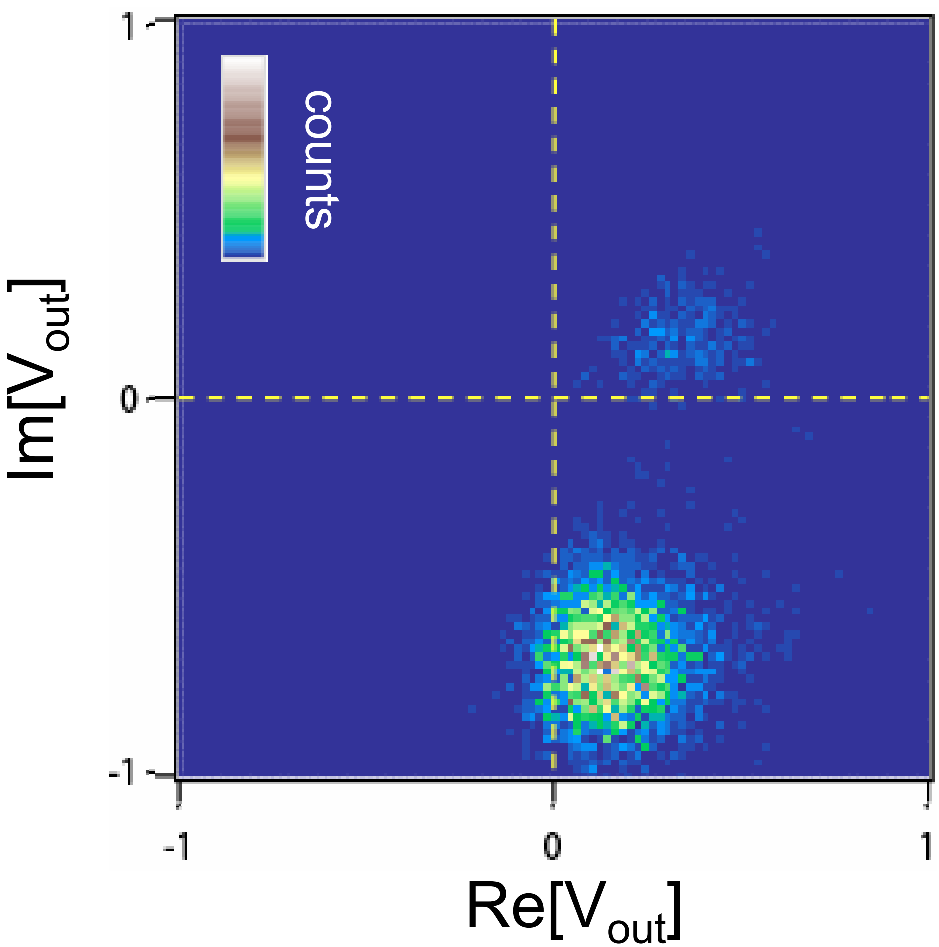
Bistable states

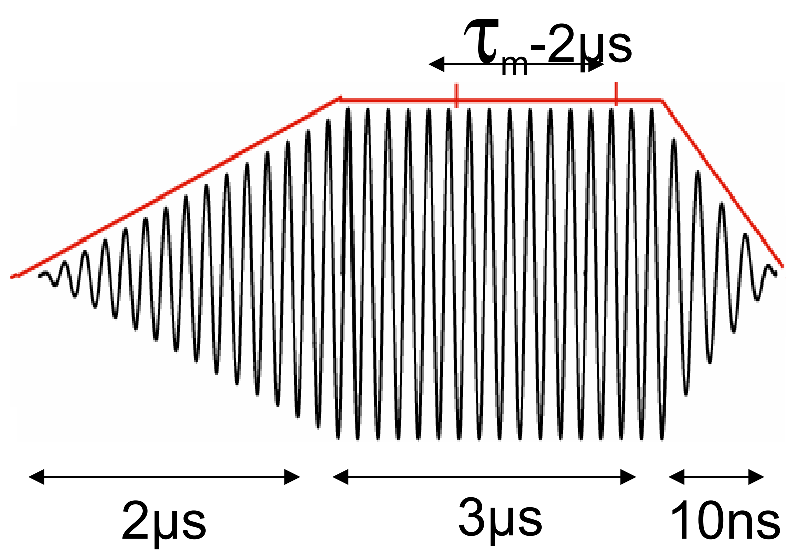


1.8 GHz

9.8 GHz

OBSERVATION OF BISTABILITY

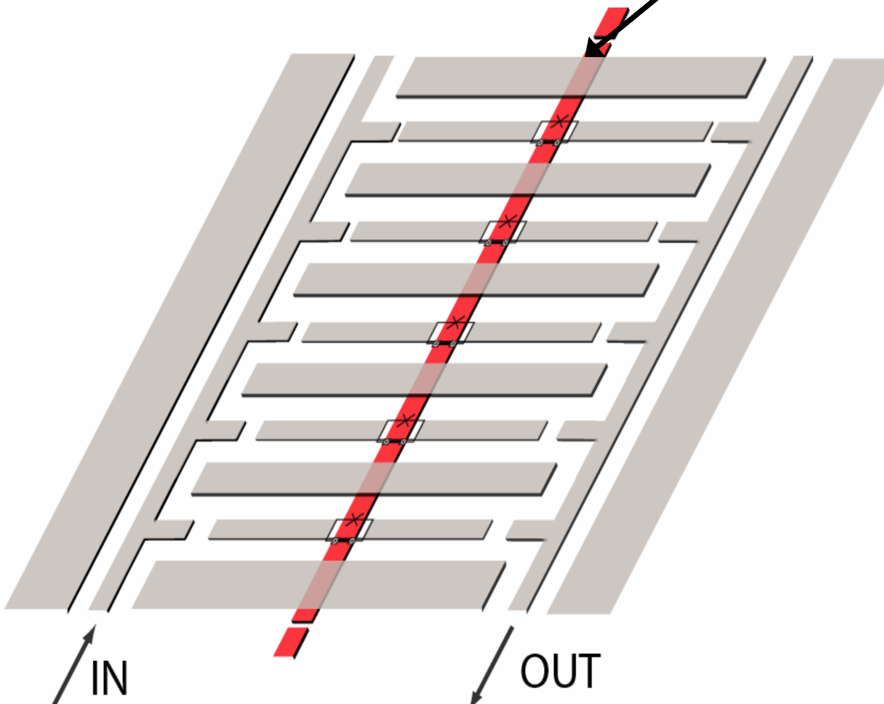




WHY: MULTIPLEXED QUBITS

Coupling line

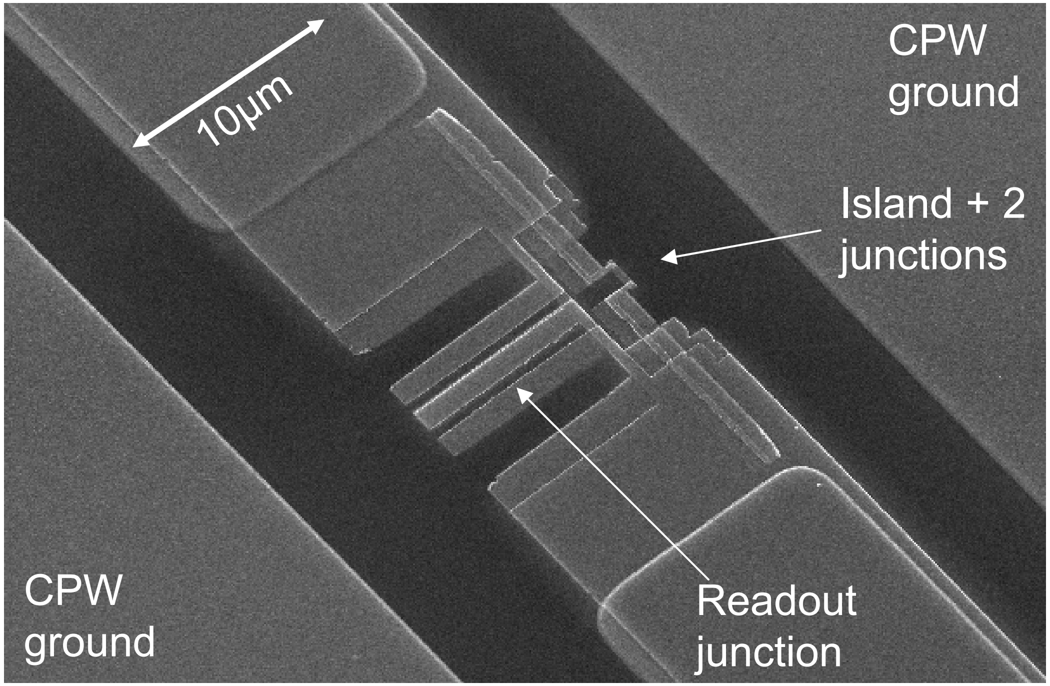
Qubit in resonator

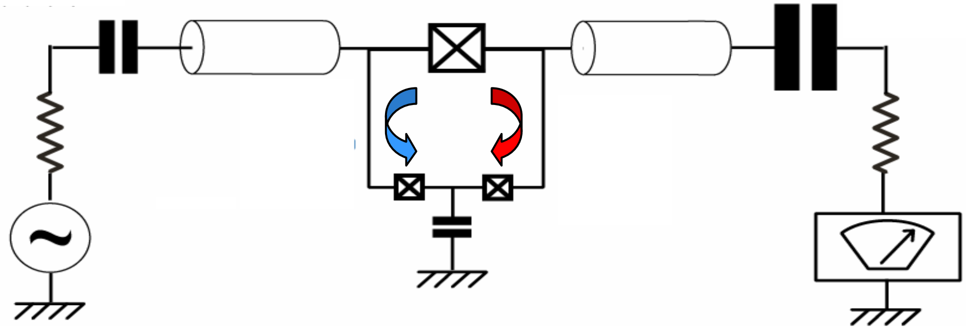


Multiplexed readout and gate lines

C.B.A. WITH QUANTRONIUM

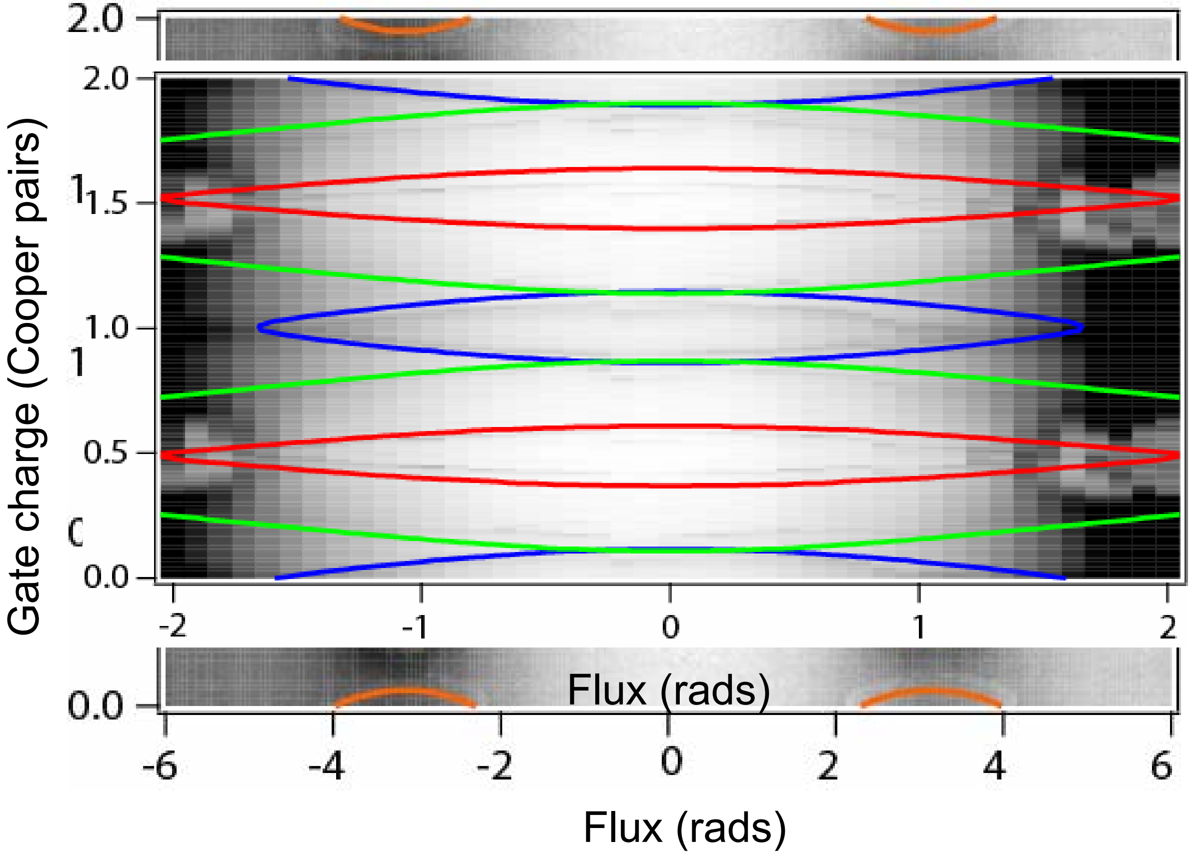
SEM image of Quantronium in CBA





GATE MODULATIONS

Fit is with E_{cp} = 17.0GHz and E_{J0} = 15.1GHz



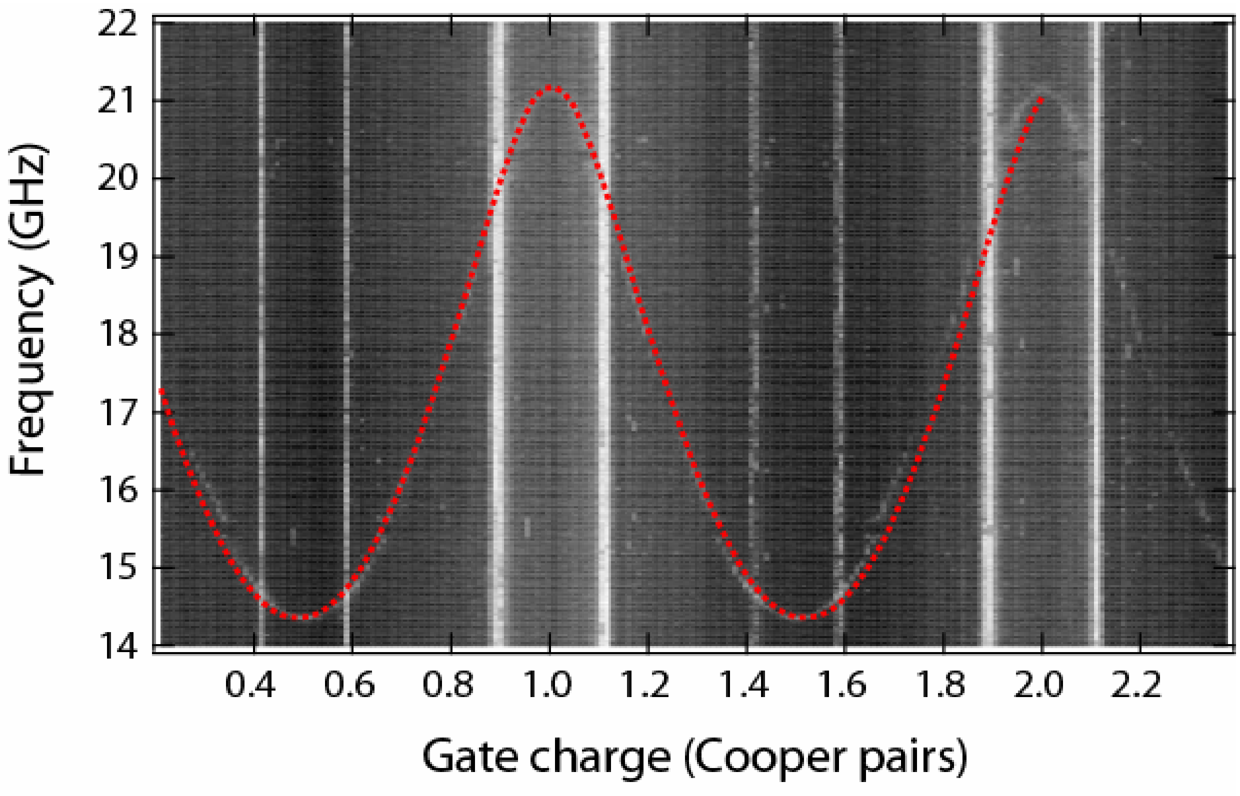
Transitions:	level1	level2	photons
blue	0	1	2
green	0	2	3
red	0	2	4

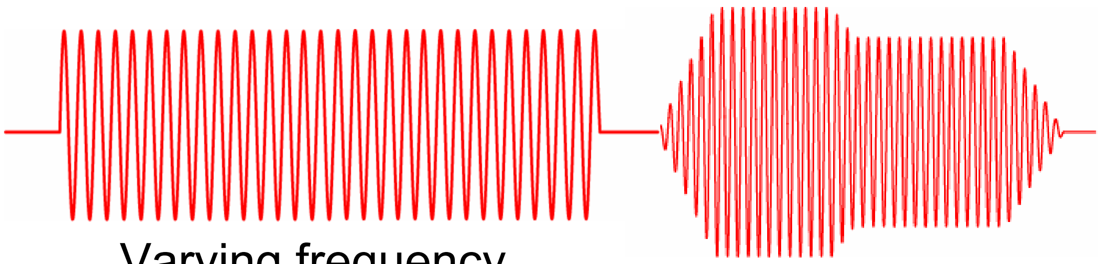
Readout in linear regime

Move to bistable regime:

→ More gain

SPECTROSCOPY

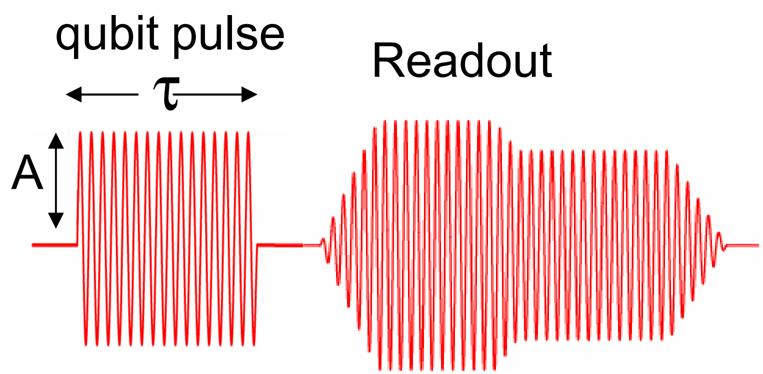


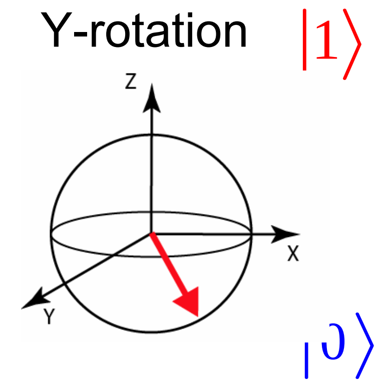


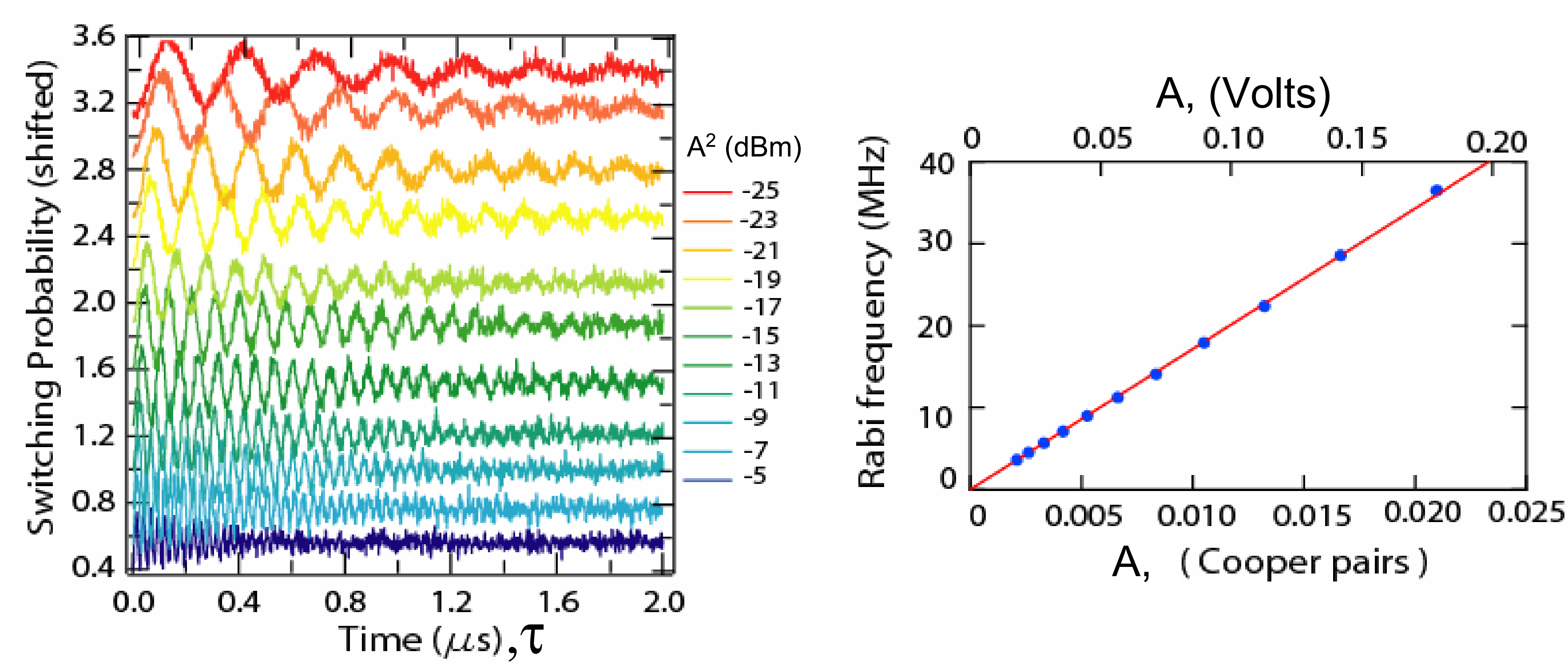
Fit: E_{cp} = 17.0GHz

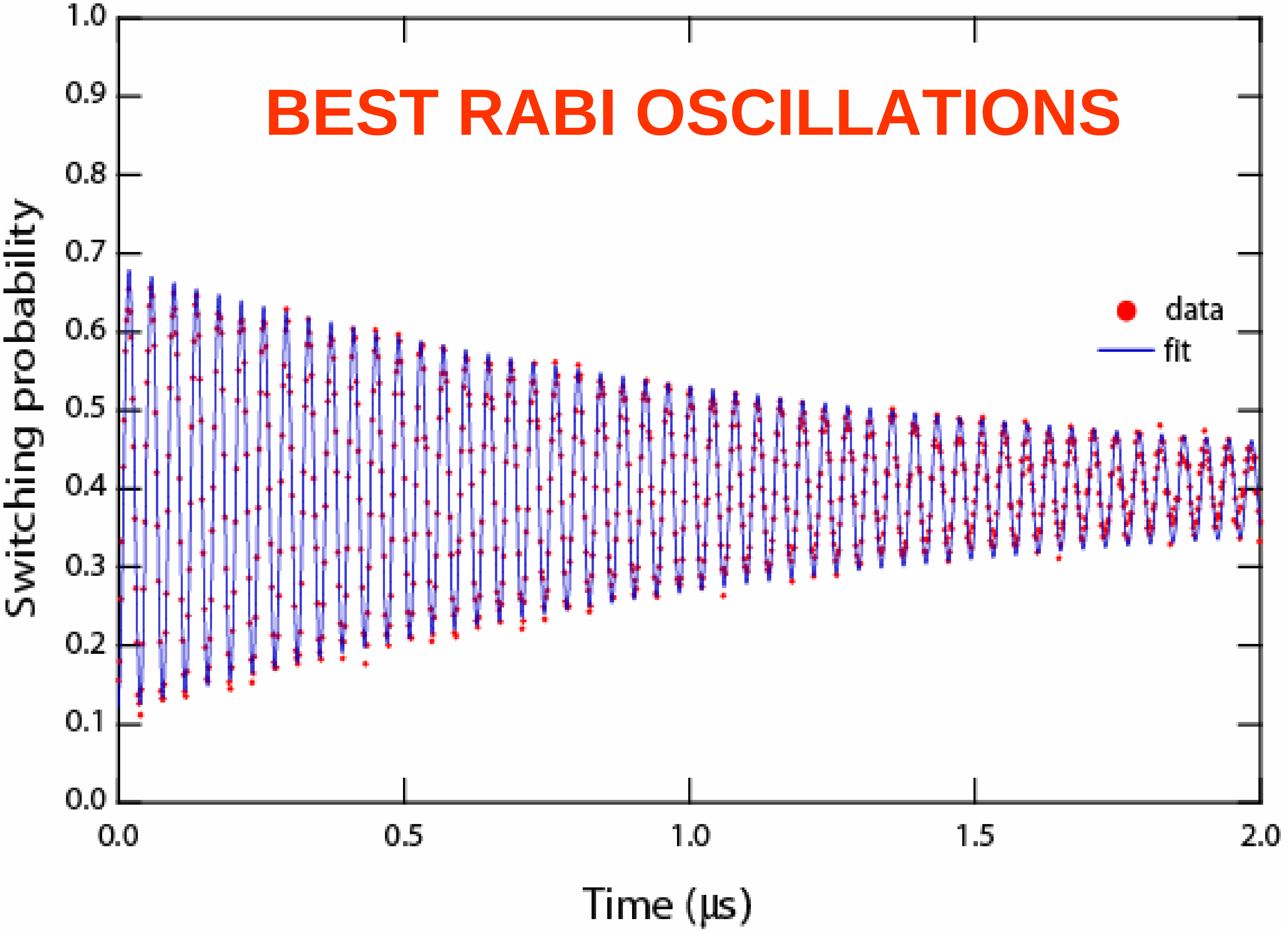
E_{J0} = 15.1GHz

RABI OSCILLATIONS

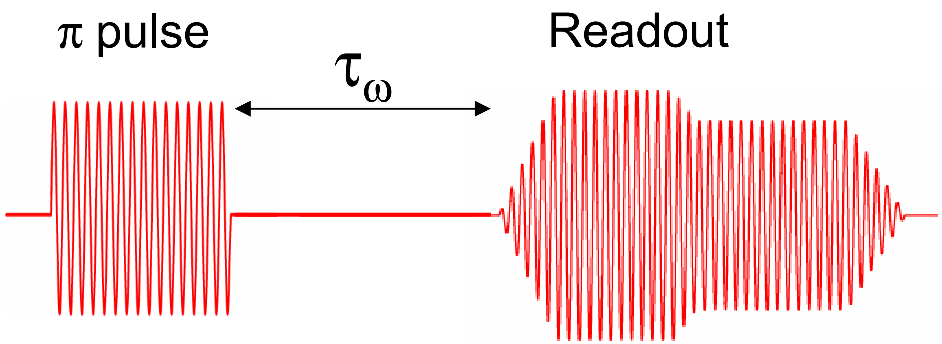


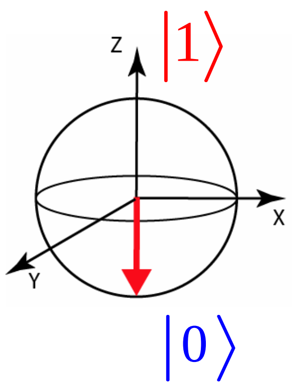


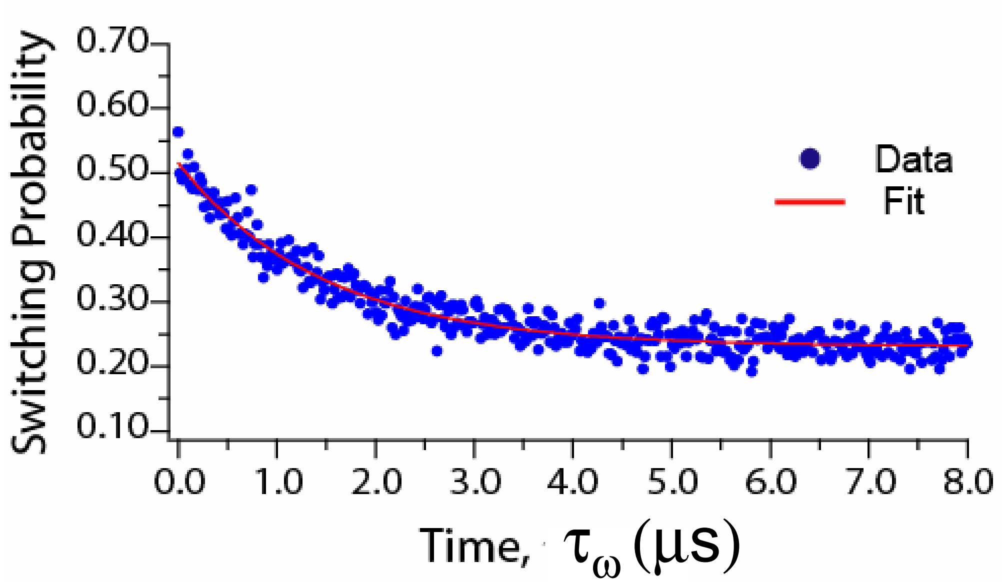



BEST RABI OSCILLATIONS
Switching probability
Time (μs)
data
fit
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.5
1.0
1.5
2.0

RELAXATION TIME, T_1

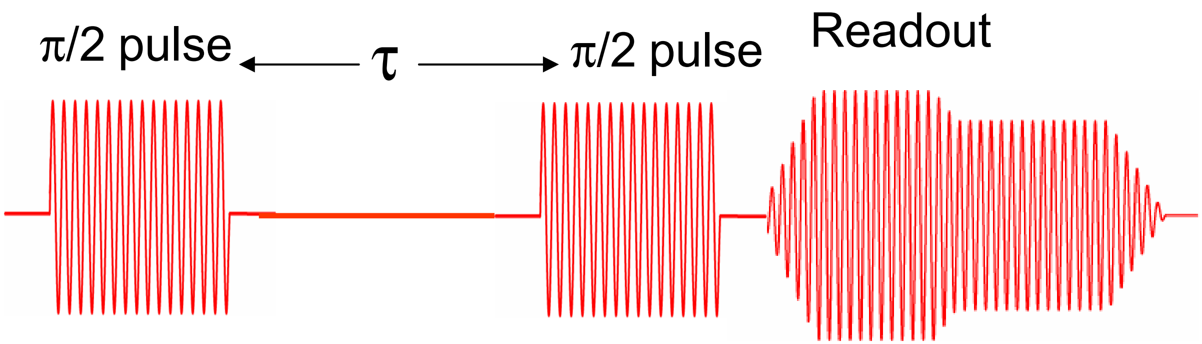


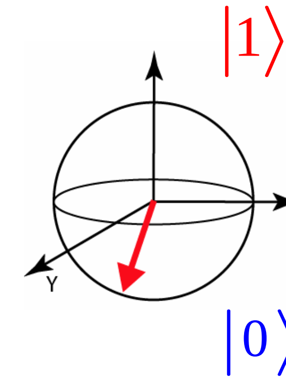


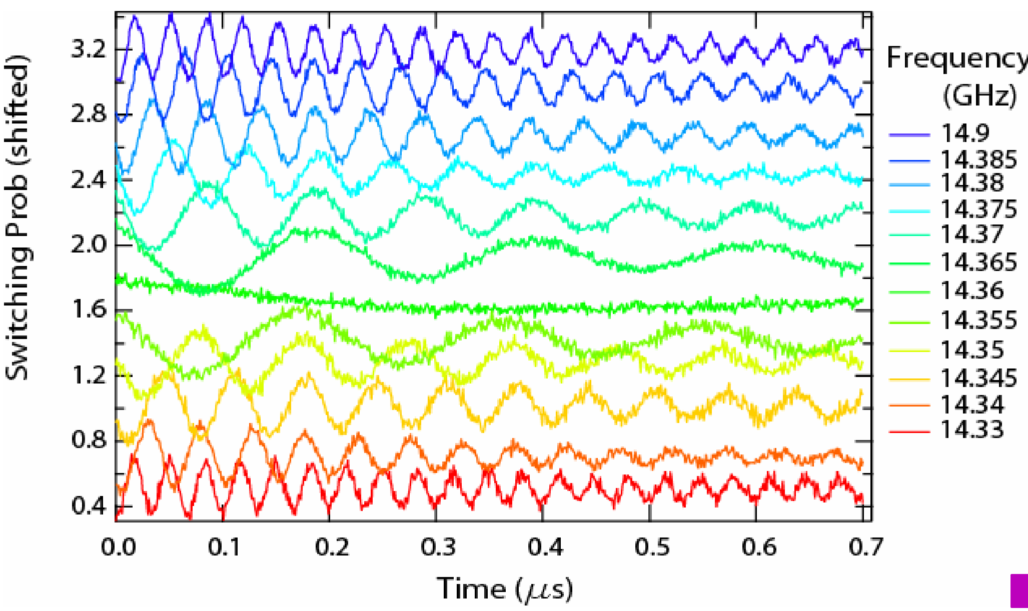


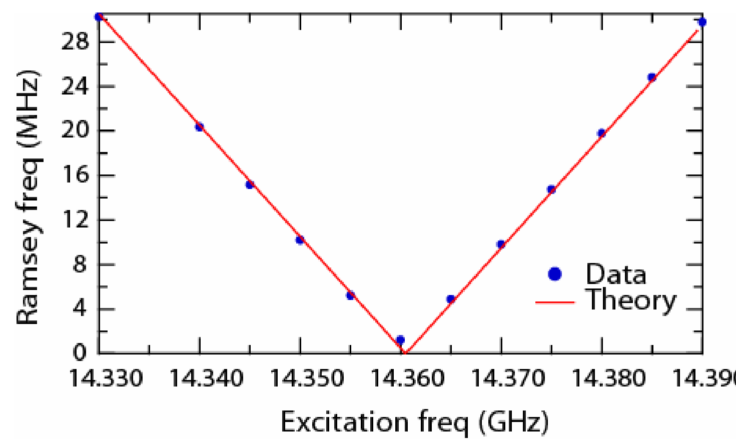
T_1=1.4μs↔1.8μs

RAMSEY FRINGES





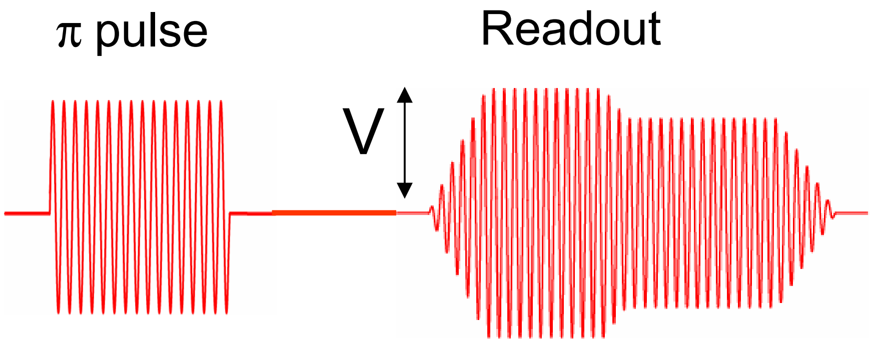


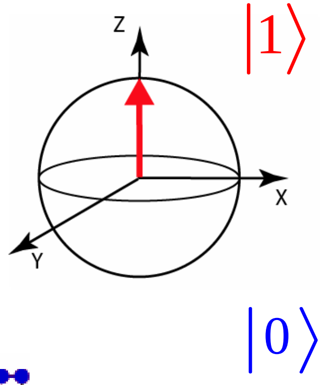


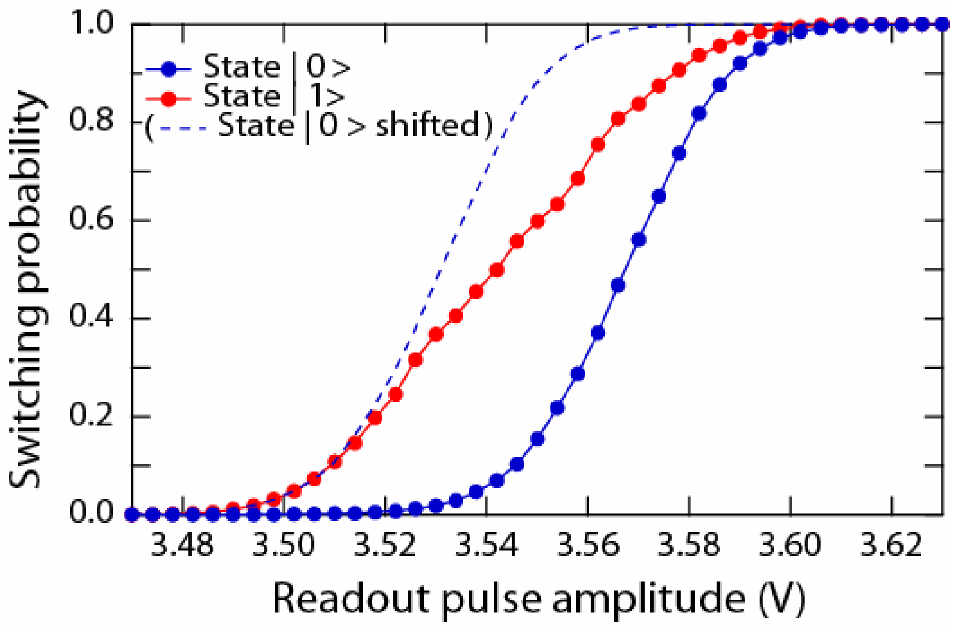
200ns ≤ T_2 ≤ 800ns

$$Q_\varphi = 2\pi\nu_{01}T_2 = 2.10^4 \leftrightarrow 7.10^4$$

MEASURED CONTRAST

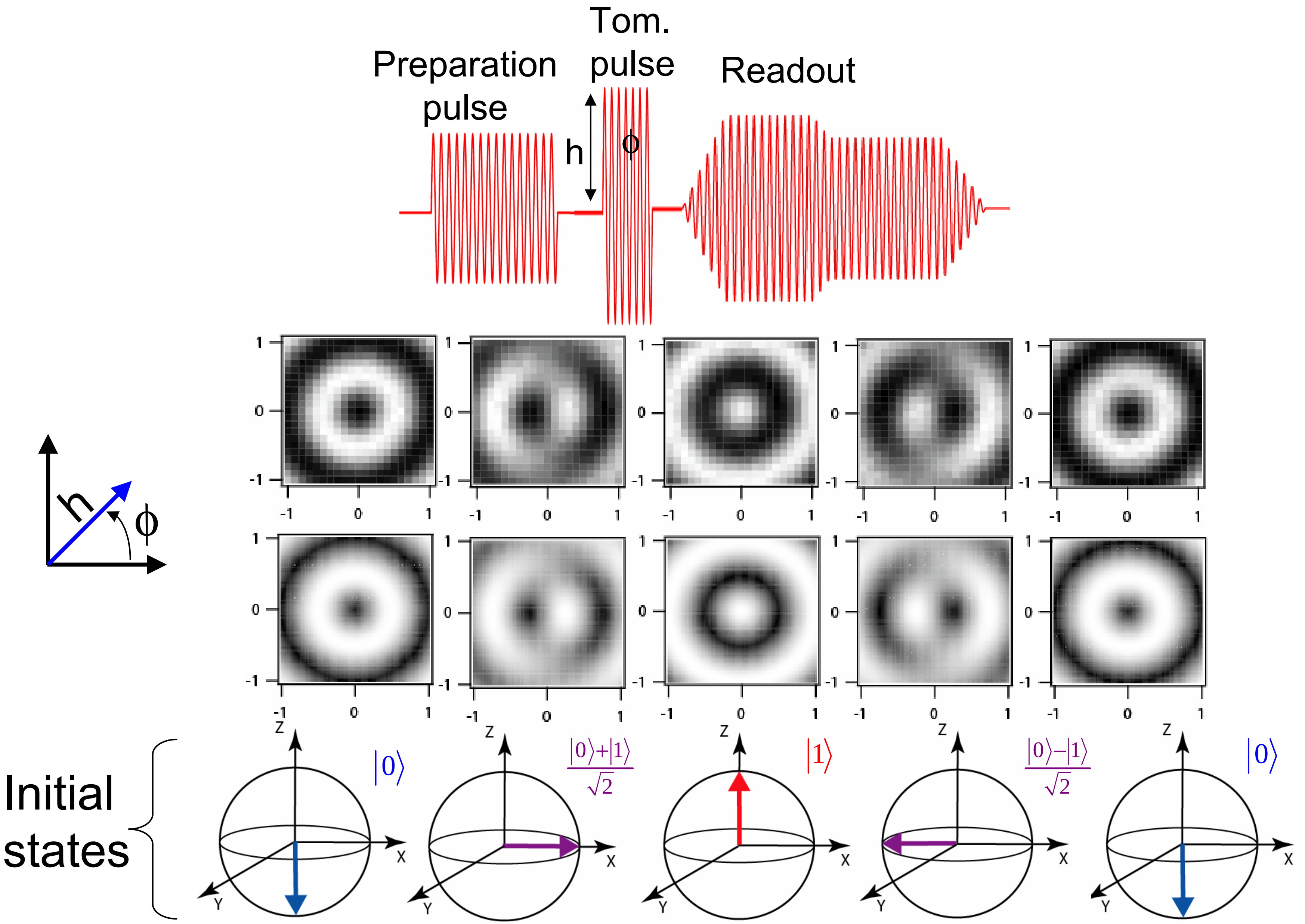






Readout relaxation → Reduced contrast

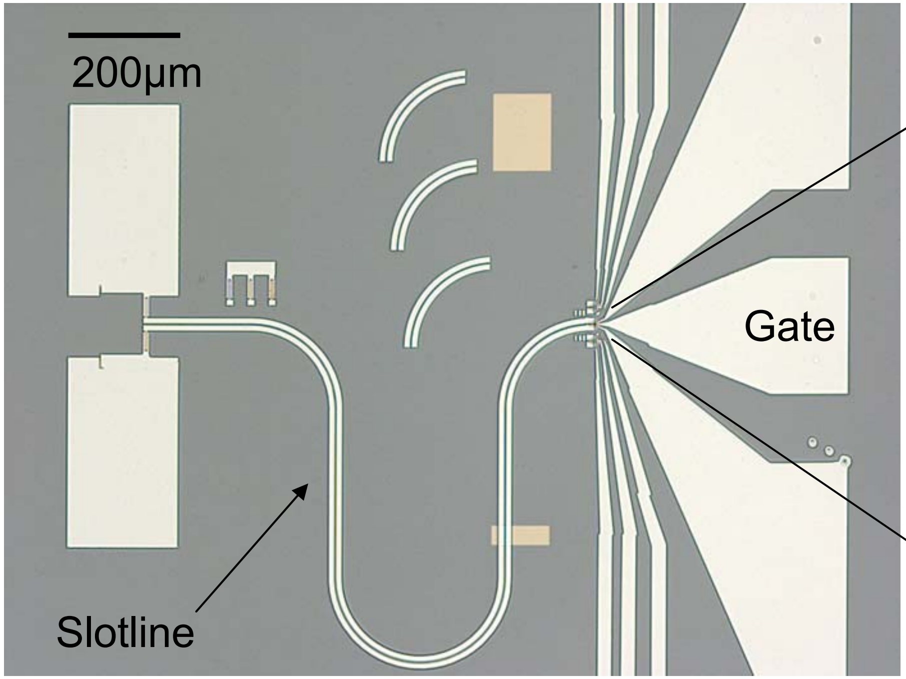
TOMOGRAPHY



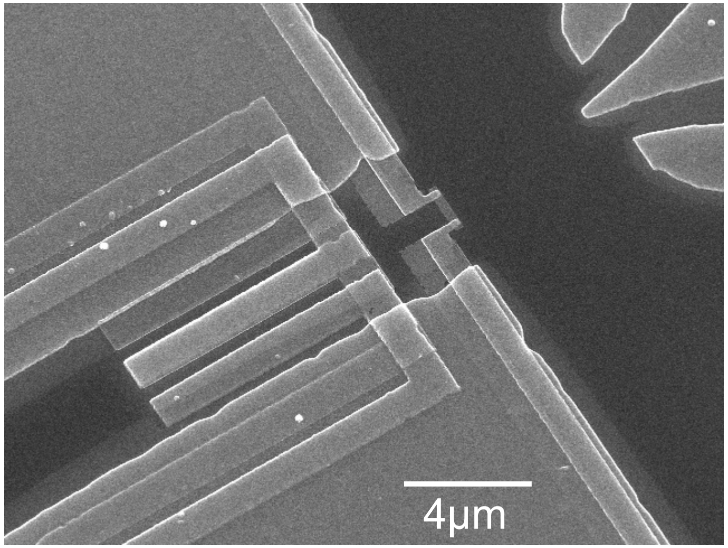
Preparation pulse
Tom. pulse
Readout
h
ϕ
Initial states
$|0\rangle$
$\frac{|0\rangle+|1\rangle}{\sqrt{2}}$
$|1\rangle$
$\frac{|0\rangle-|1\rangle}{\sqrt{2}}$
$|0\rangle$
X
Y
Z

NOW: SLOTLINE NON-LINEAR RESONATOR

Optical image of device



SEM image of qubit

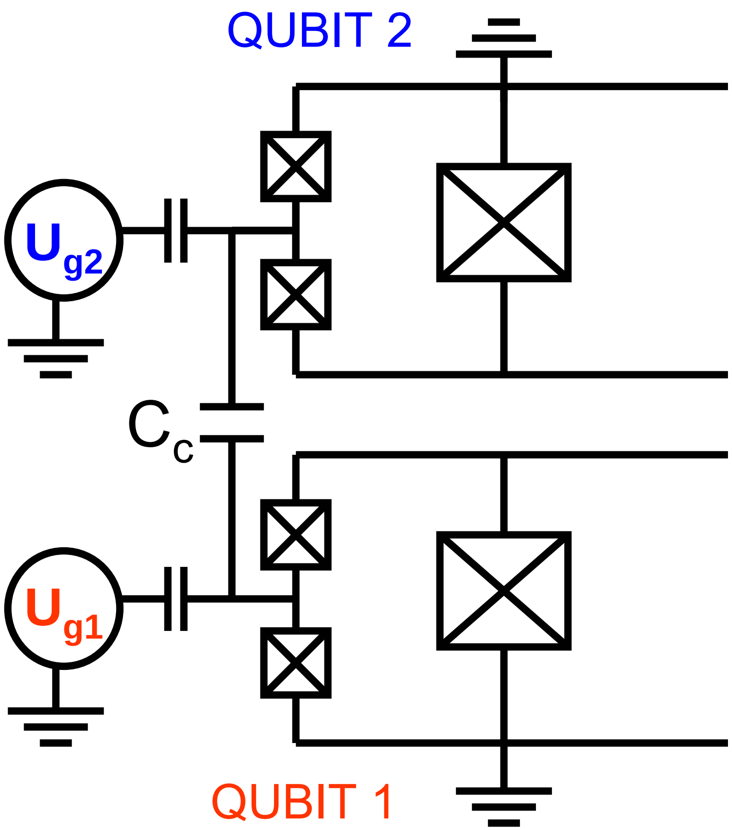


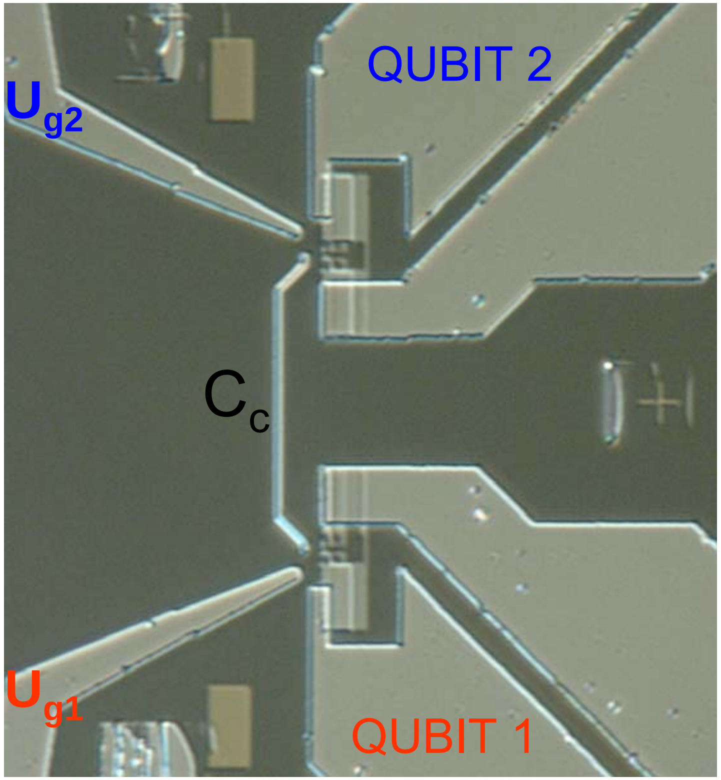
Advantages: 1. Completely fabricated using e-beam lithography

2. Gate and readout lines separated

3. Excite ± mode in slotline for readout

NEAR FUTURE: COUPLED QUBITS

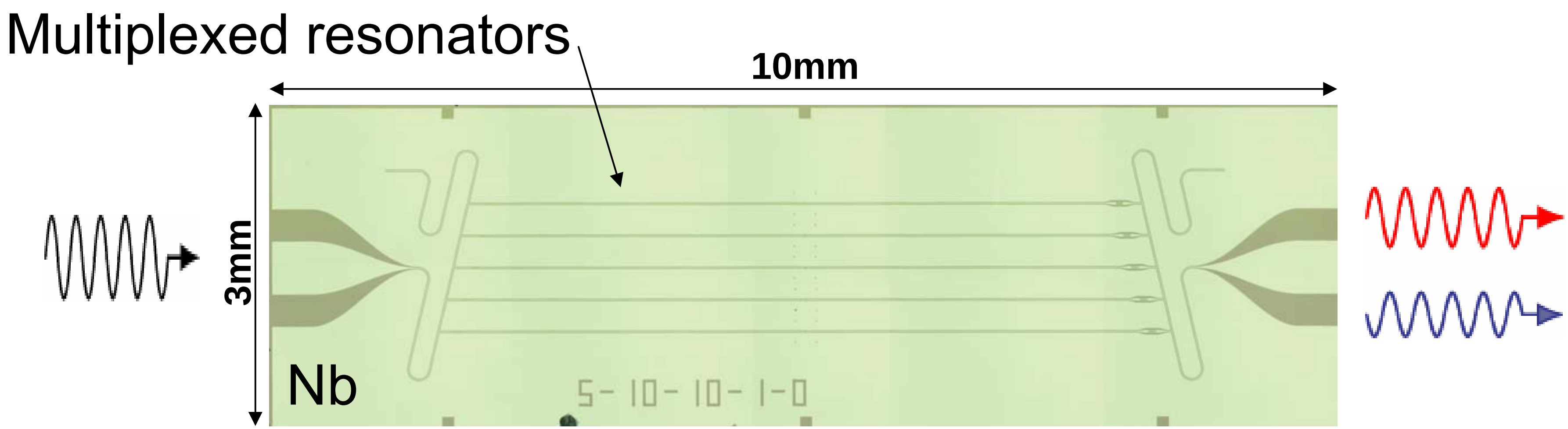




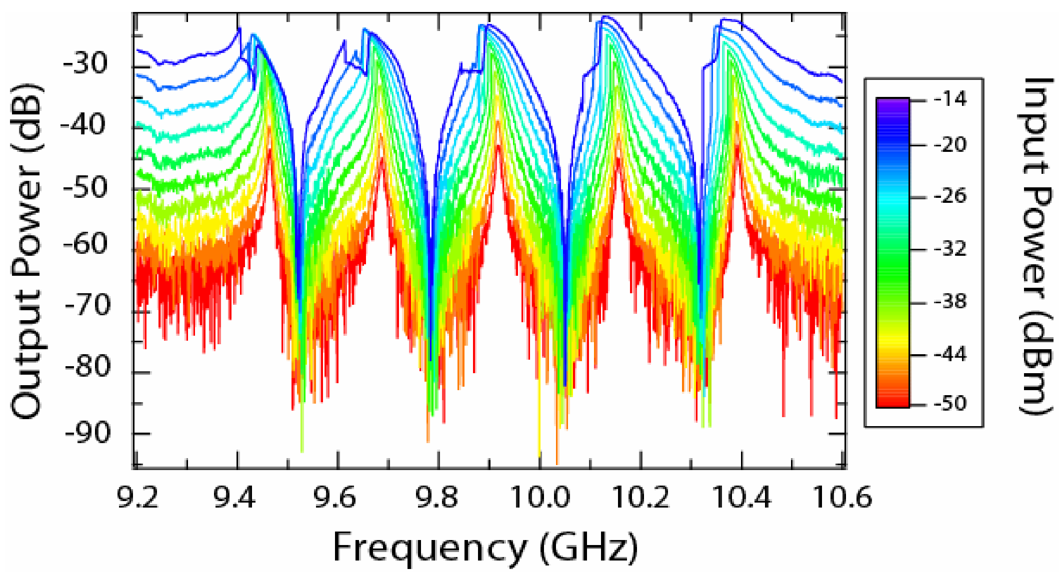
Optical image of coupled qubit with slotline readout

See Chad's MES upcoming…..

LONGER TERM: MANY COUPLED MULTIPLEXED QUIBTS



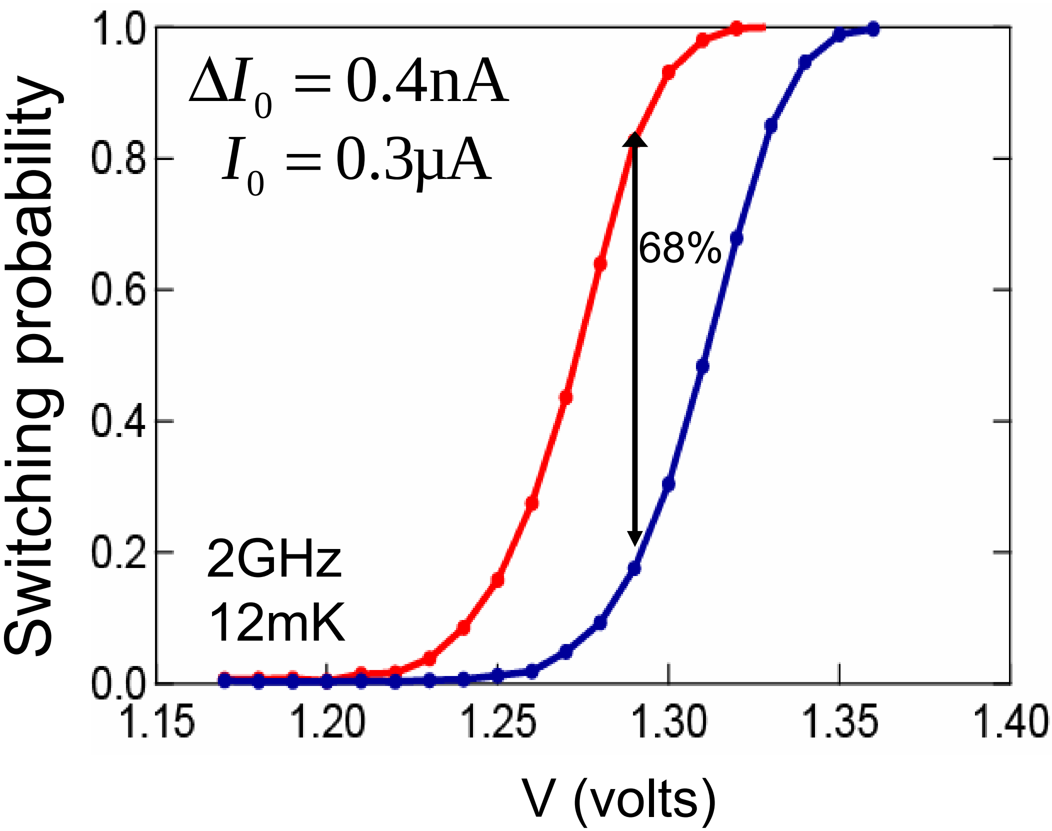
preliminary data: amplitude response

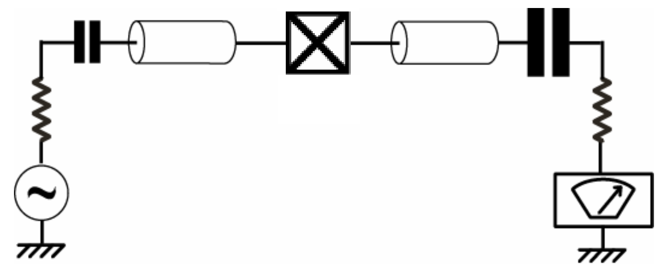


CONCLUSION

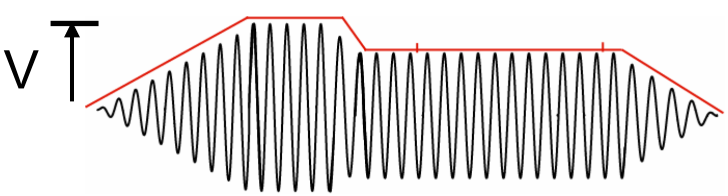
- Developed fast, non-dissipative RF readout
- Single shot qubit readout feasible
- Scalable architecture
- Coupled qubit experiments in progress…

PREDICTED CONTRAST





Freq	$\Delta\omega$	ΔI_0^{meas}	ΔI_0^{theory}
2GHz	1.4MHz	0.4nA	0.5nA
10GHz	20MHz	6.4nA	5nA



Single shot possible

RAMSEY TOMOGRAPHY

Map of state during Ramsey experiment (c.f. Martinis, PRL)

Slides after this are additional

RANDOM EQUATIONS

Josephson Junction:

Charge tunneling through JJ:

$Q = 2eN$

Flux associated with SC phase diff across JJ:

$\Phi = \varphi_0 \theta$

$[\theta, N] = i$

Hamilton of JJ:

$$\mathrm{H} = \mathrm{E_{CJ}}\left(N - Q_r/2e\right)^2 - E_J \cos\theta$$

where

$$\mathrm{E_{CJ}} = \frac{(2e)^2}{2C_J}$$

Cooper Pair box:

$$\hat{H}(N_g) = E_c\left(\frac{1}{i}\frac{\partial}{\partial\theta} - N_g\right)^2 - E_J \cos(\hat{\theta})$$

$$N = \frac{1}{i}\frac{\partial}{\partial\theta}$$

$$E_J \ll E_{CP}$$

$$H_{CPB} = -E_z(\sigma_z + X_{cont}\sigma_x)$$

where

$$\mathrm{E_z} = E_J/2$$

$$X_{cont} = 2E_{CP}/E_J\left(1/2 - N_g\right)$$

$E_J \leftrightarrow$ Zeeman field

$\mathrm{E_{CP}} \leftrightarrow$ transverse field

$X_{cont} = 0 \Rightarrow$ Sweet spot

Loop current/Inductances:

$$\hat{I}(Ng,\delta) = -2e\frac{d\hat{K}}{dt}$$

where number of cooper pairs tunnelling onto island

$$\hat{\hat{\mathrm{K}}} = \left(\hat{\hat{N}}_1 + \hat{N}_2\right)/2$$

$$\hat{I}(Ng,\delta) = -\frac{1}{i\varphi_0}[\hat{K},\hat{H}] = \frac{1}{\varphi_0}\frac{\partial\hat{H}}{\partial\delta}$$

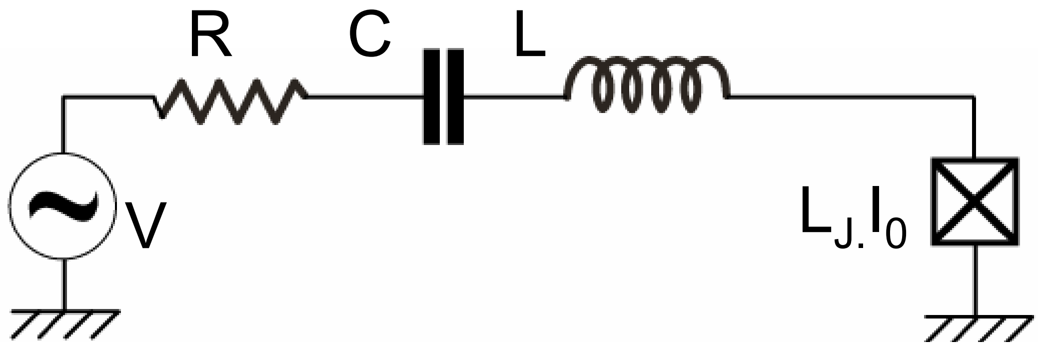
Hence the average loop current is:

$$\mathrm{i_k}(N_g,\delta) = \frac{1}{\varphi_0}\frac{\partial E_k(Ng,\delta)}{\partial\delta}$$

with inductance:

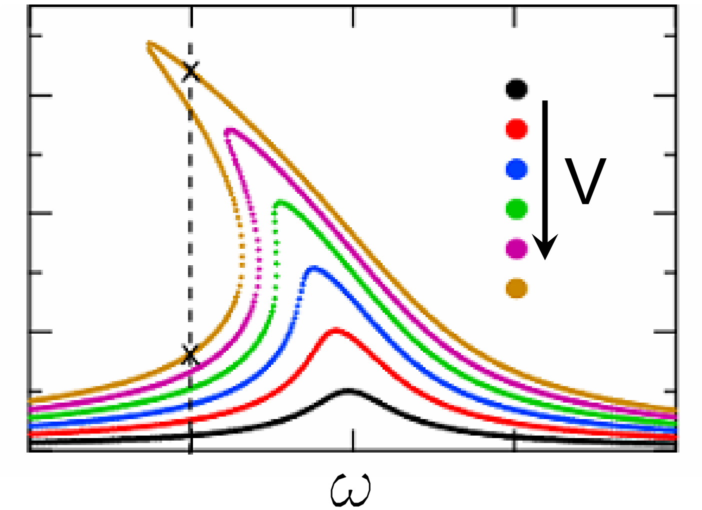
$$\mathrm{L}(Ng,\delta) = \left[\frac{1}{\varphi_0}\left(\frac{\partial I}{\partial\delta}\right)\right]^{-1} = \left[\frac{1}{\varphi_0^2}\left(\frac{\partial^2 E_k(N_g,\delta)}{\partial\delta^2}\right)\right]$$

NON-LINEAR OSCILLATOR

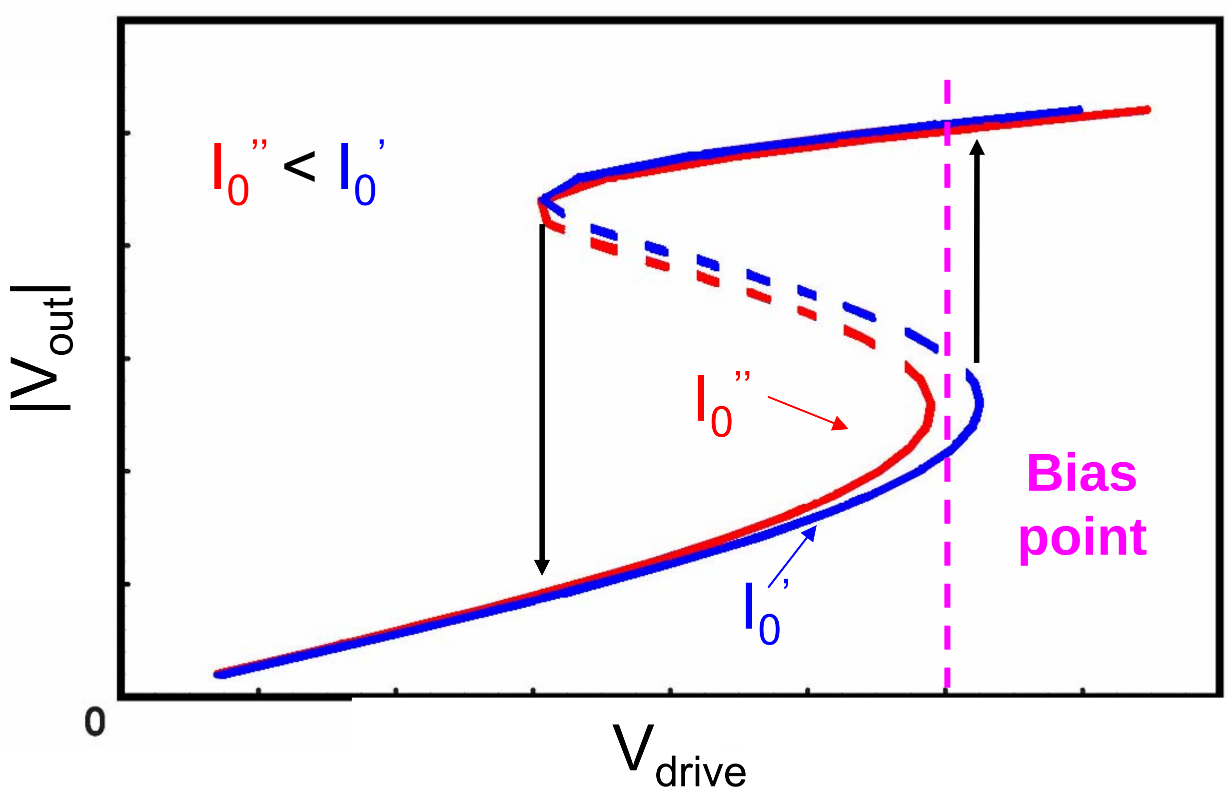


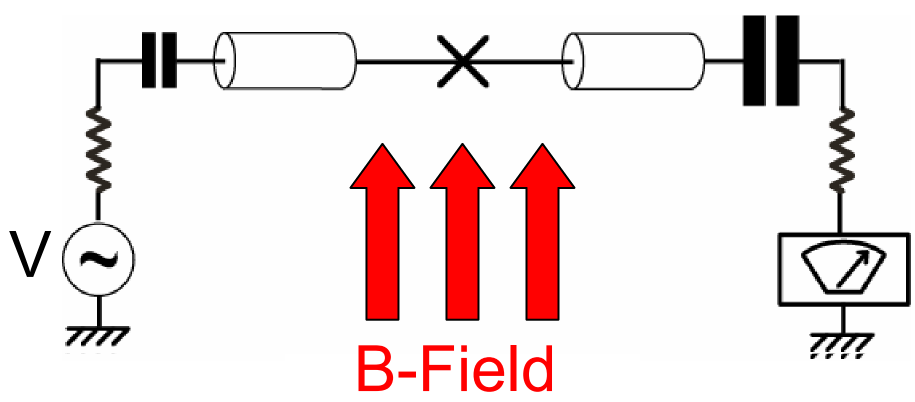
$$L_t \ddot{q} + \mathrm{R}\,\dot{q} + \frac{q}{C} + L_J \ddot{q}\left(\frac{1}{\sqrt{1-(\dot{q}/I_0)^2}} - 1\right) = V_d \cos \omega t + V_N$$

Non-Linear resonance



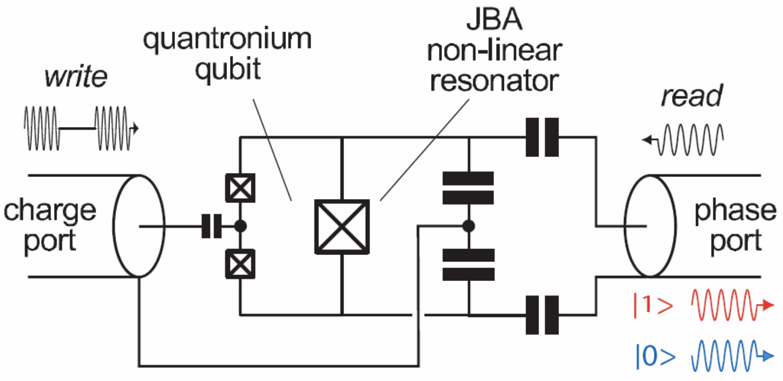
Readout scheme





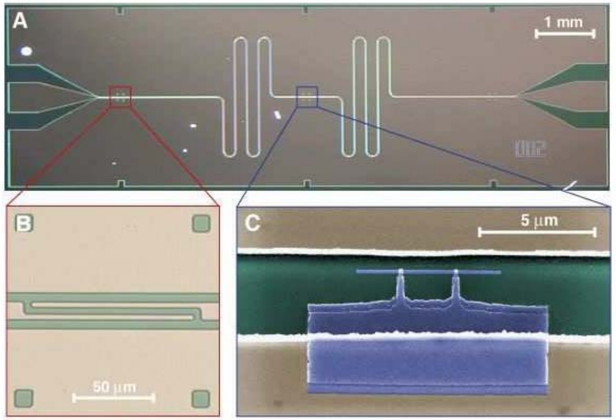
Previous work

Quantronium qubit with JBA



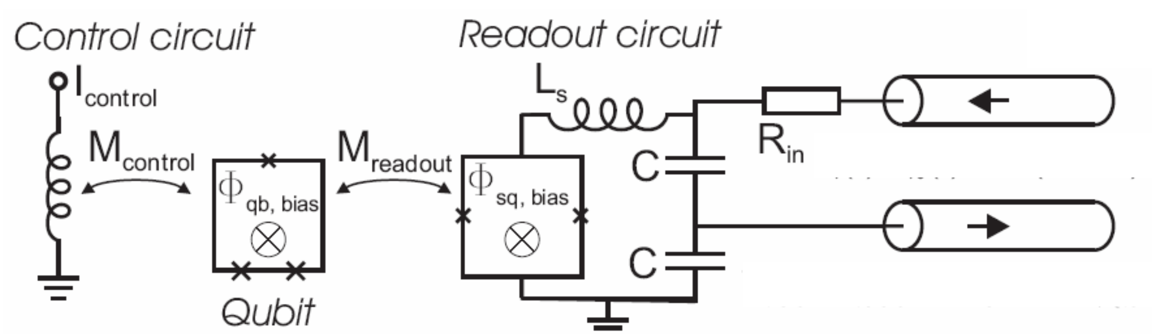
I. Siddiqi et. al, PRB 2006

CQED



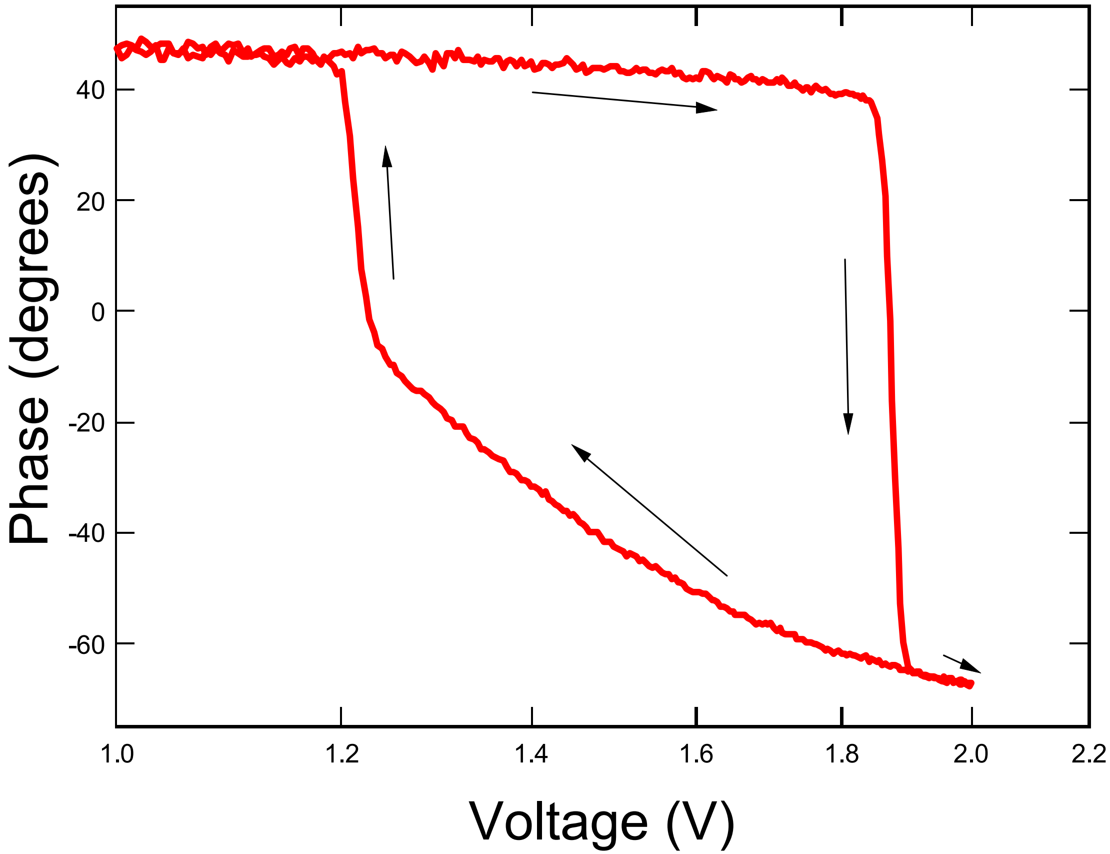
A. Wallraff et. al, Nature 2004

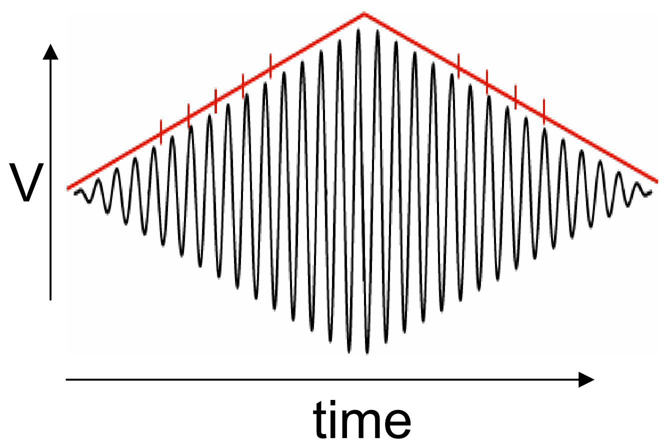
Flux qubit with linear resonator and JBA



A. Lupascu et. al cond-mat/0601634

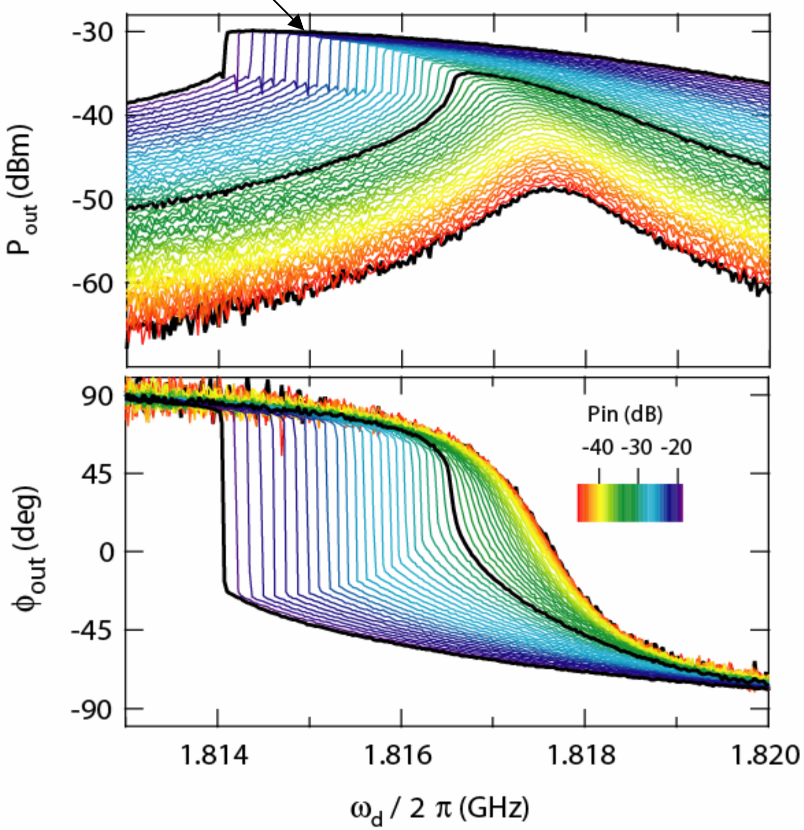
Experimental observation of two oscillator states



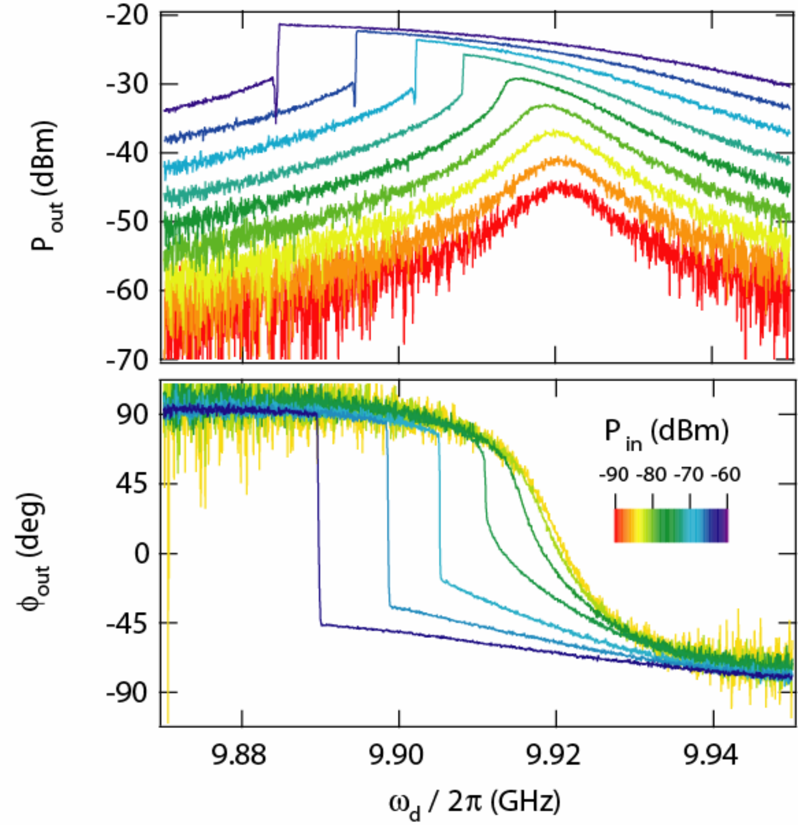


Microwave response

Bistable states

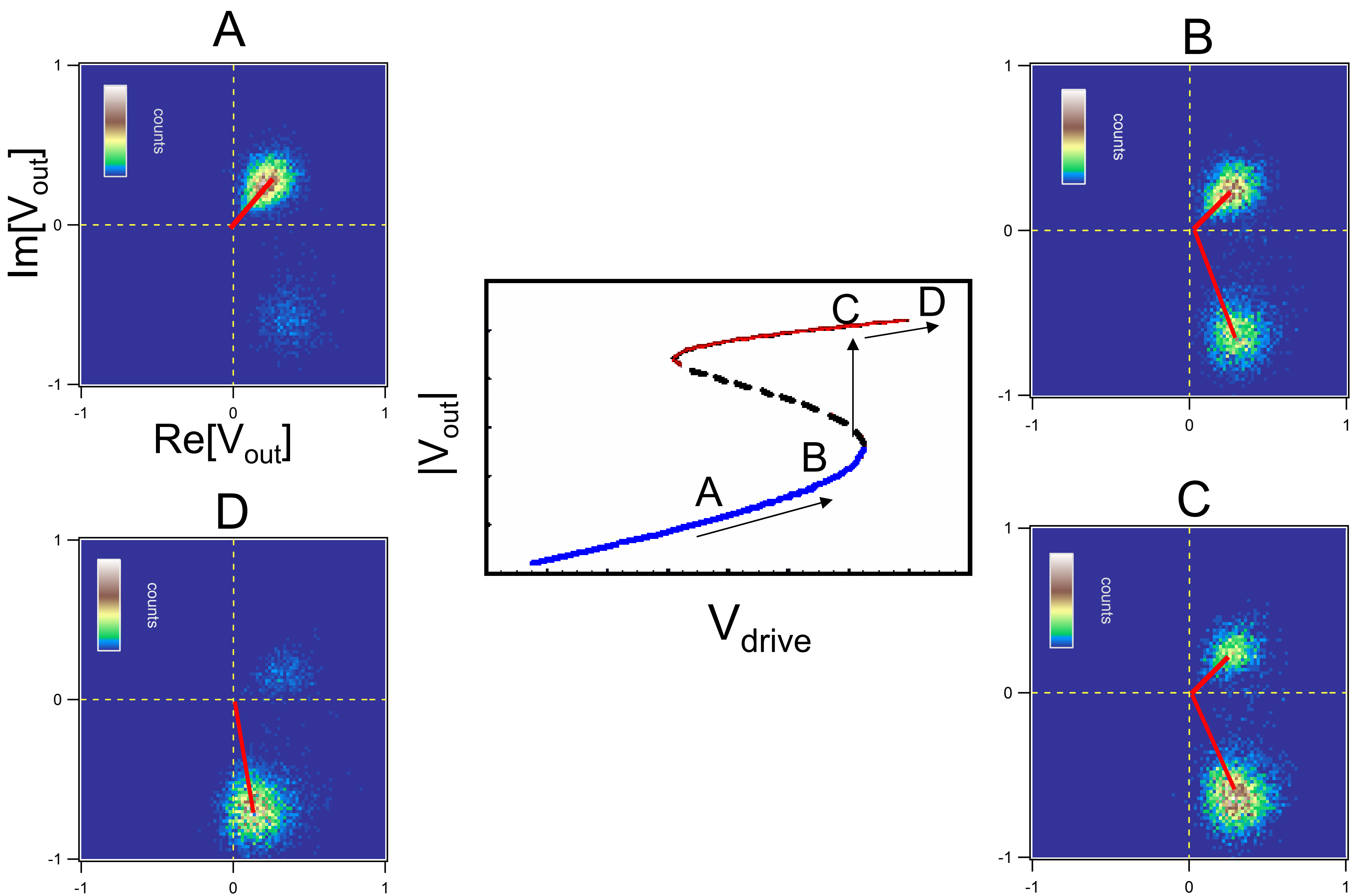


1.8 GHz

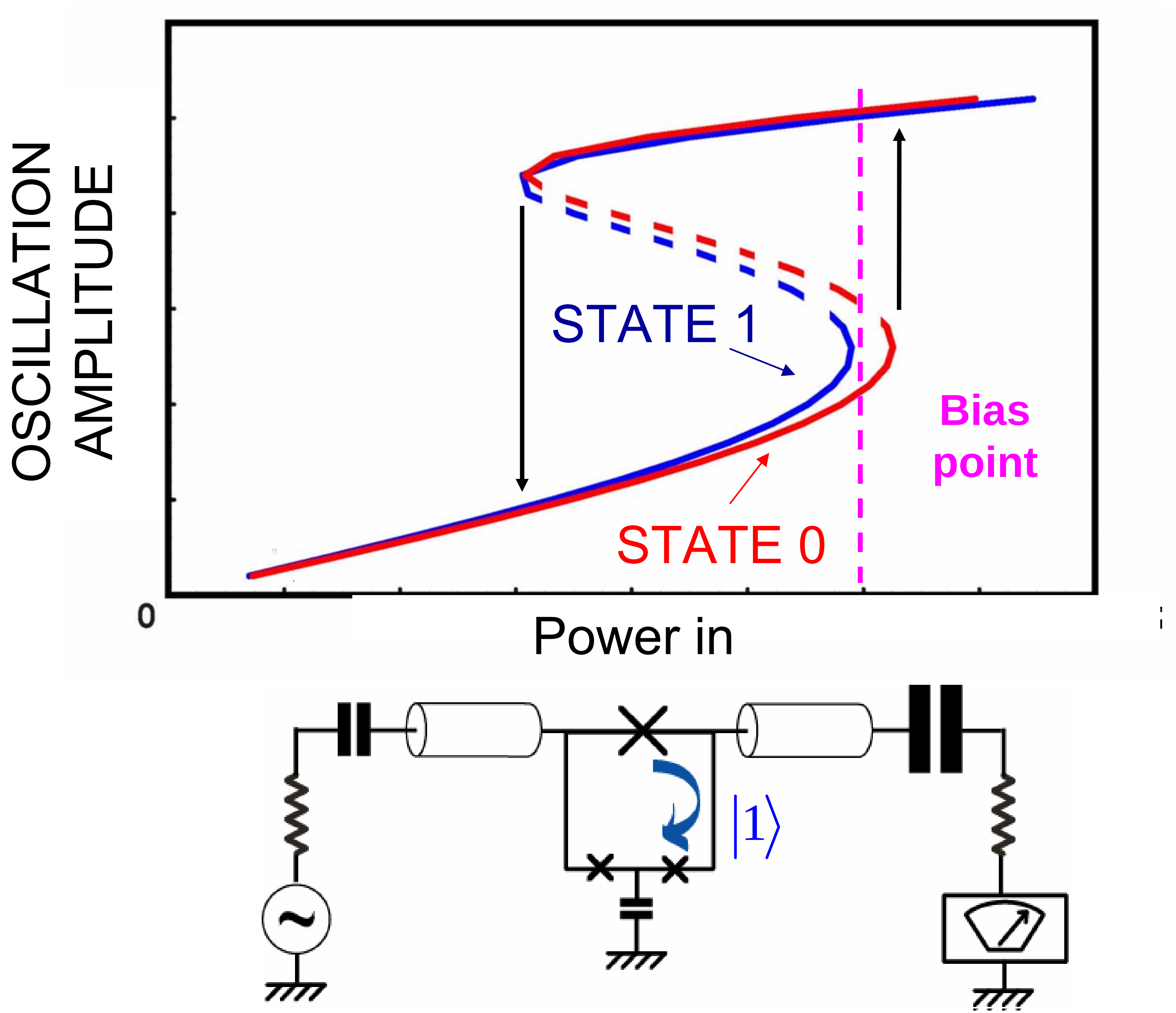


9.8 GHz

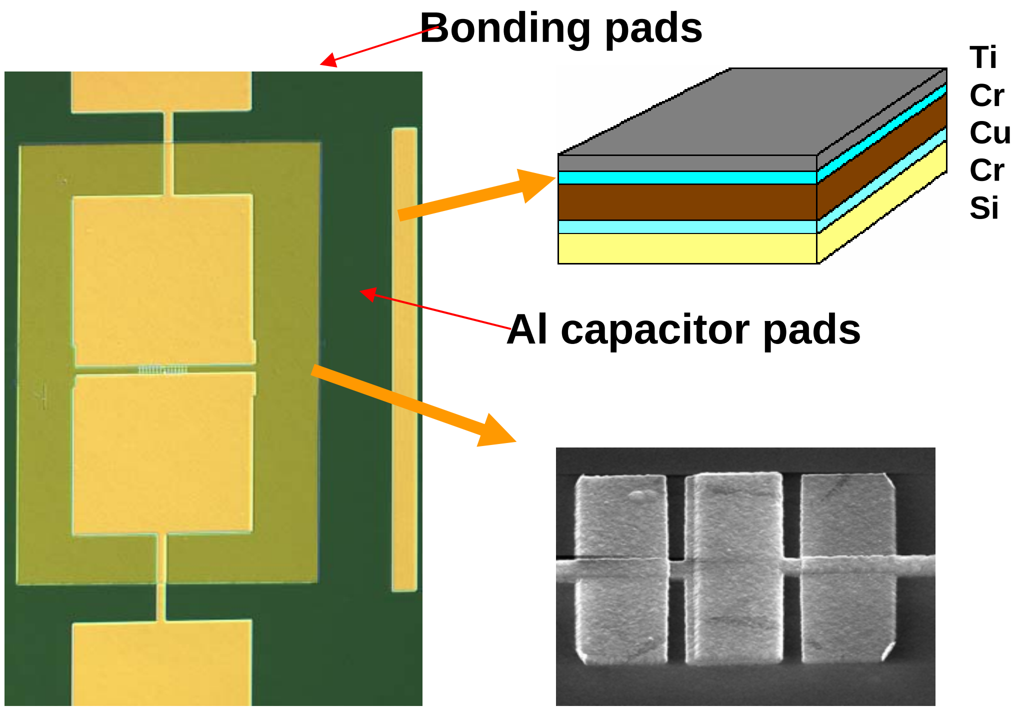
Bistability



Readout scheme

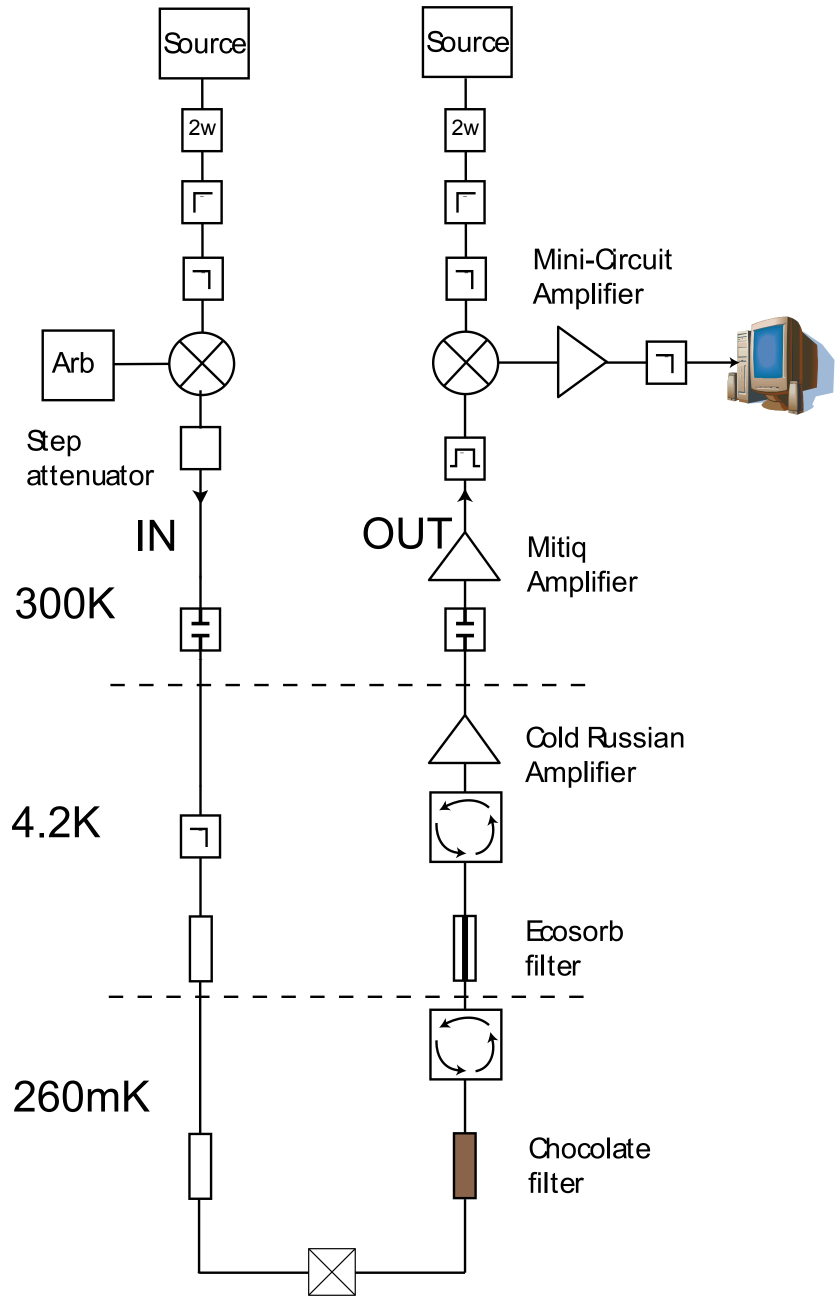


JBA



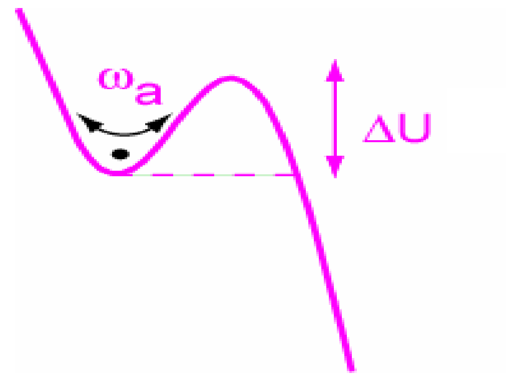
- Complicated fabrication
- Same physics

TIME RESOLVED MEASURMENT



ESCAPE RATES

For : $\omega_a \square \Gamma$



Thermally activated escape:

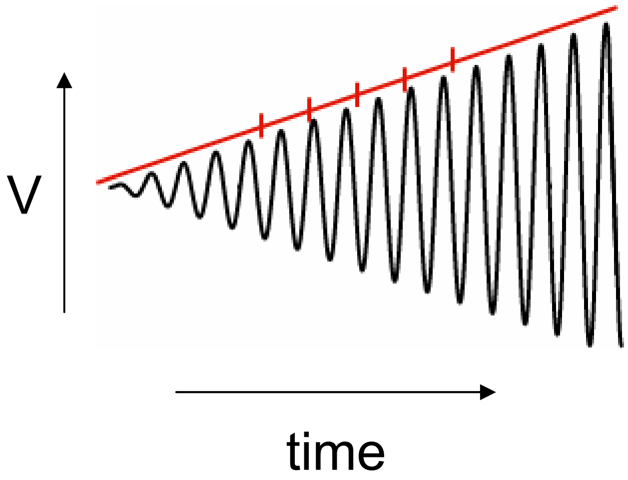
$$\gamma = \frac{\omega_a}{2\pi} \exp\left(-\frac{\Delta U}{k_B T_{esc}} \right)$$

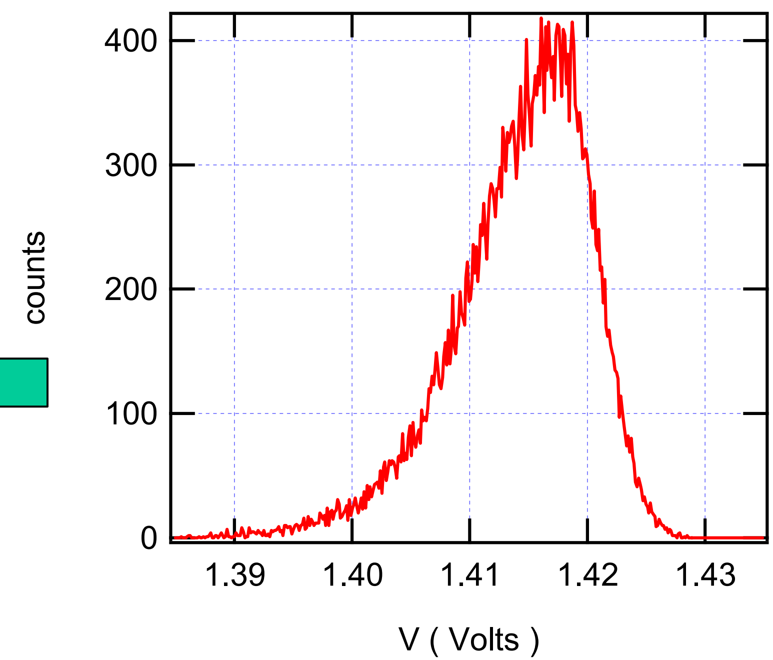
Where:

$$\omega_a = \frac{2}{3\sqrt{3}} \Gamma \Omega^2 \left|1 - \beta / \beta_b\right|^{1/2} \qquad \Delta U = \frac{64}{9\sqrt{3}} E_J \left(\frac{L_t}{L_J} \right)^2 \frac{\Omega}{Q} \left|1 - \beta / \beta_b\right|^{3/2}$$

Plot: $\left(\ln(\omega_a / 2\pi\gamma)\right)^{2/3} vs\, \beta / \beta_b \longrightarrow T_{esc}$

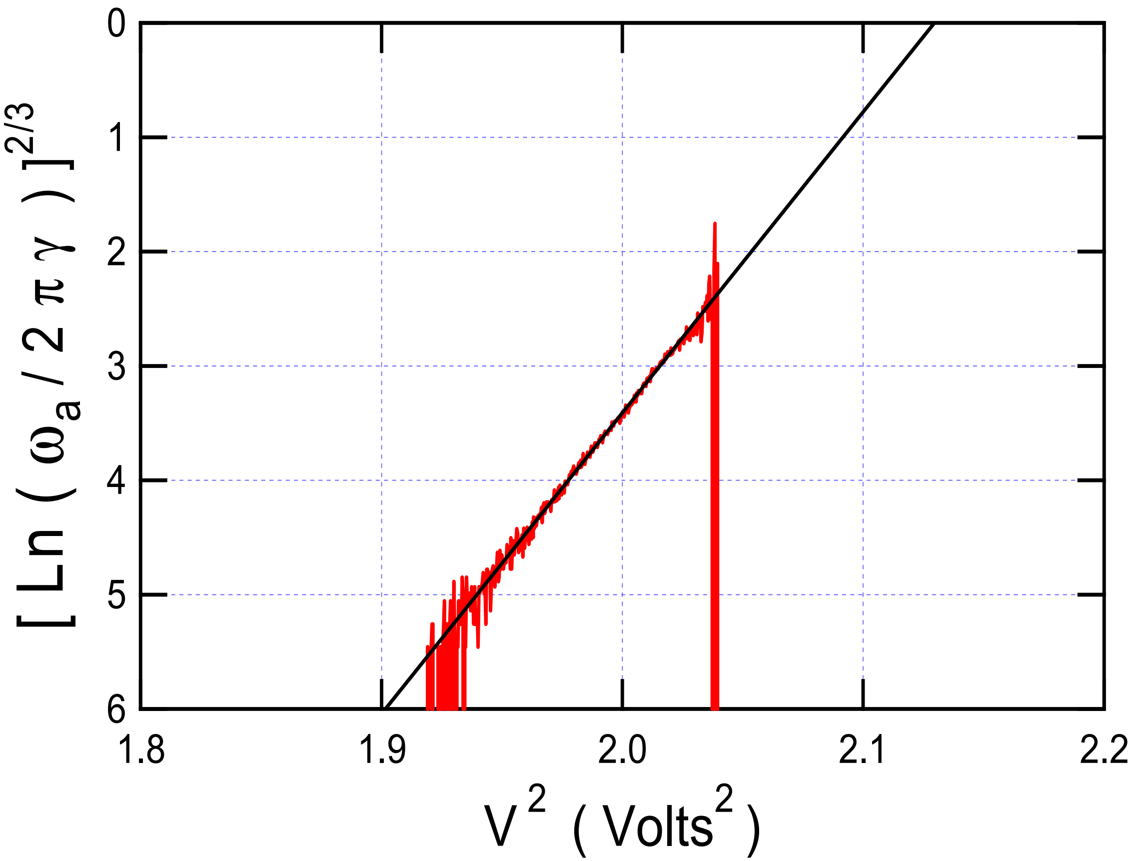
ESCAPE RATES METHOD





$$\gamma(V) = \frac{1}{\Delta V}\frac{dV}{dt} Ln\left[\frac{\sum_{v \geq V} P(v)}{\sum_{v \geq V+\Delta V} P(v)}\right]$$

ESCAPE RATES



Intercept: V_b

Slope: T_{esc}

$U_0/K_BT = 420$

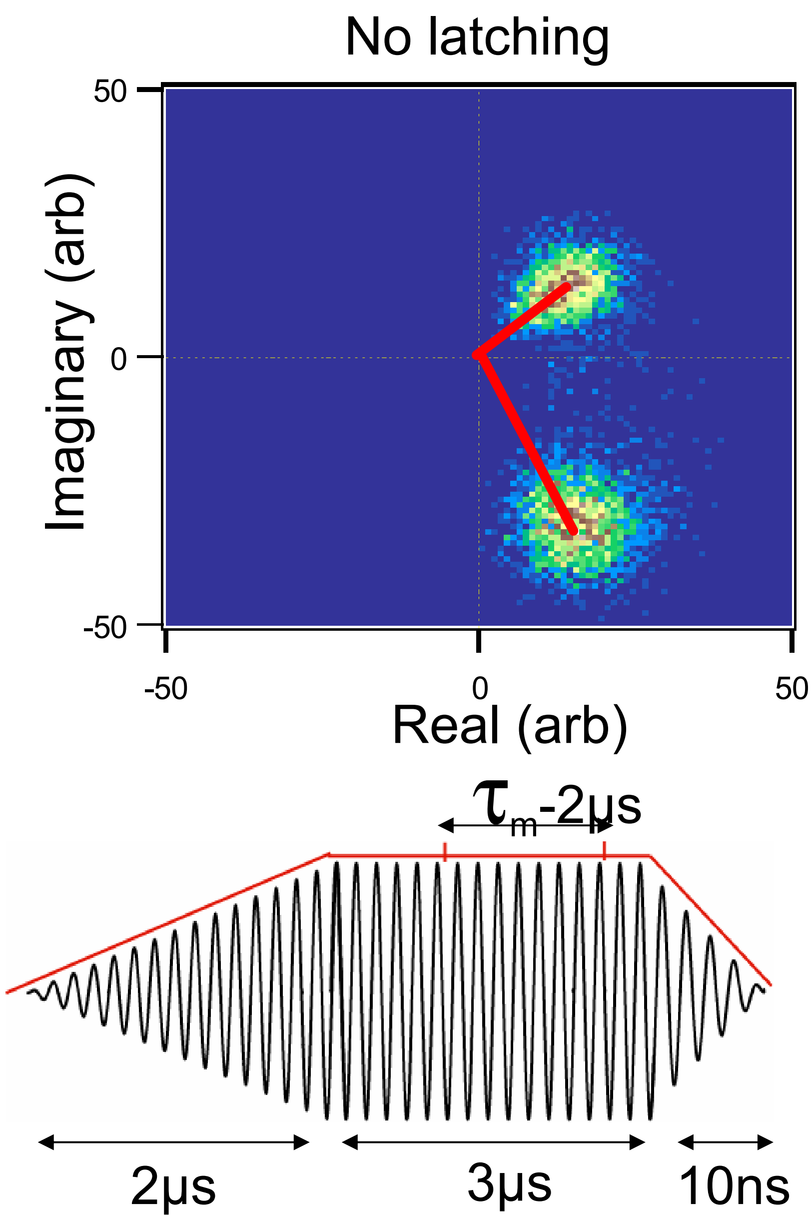
$U_0 = 220K$

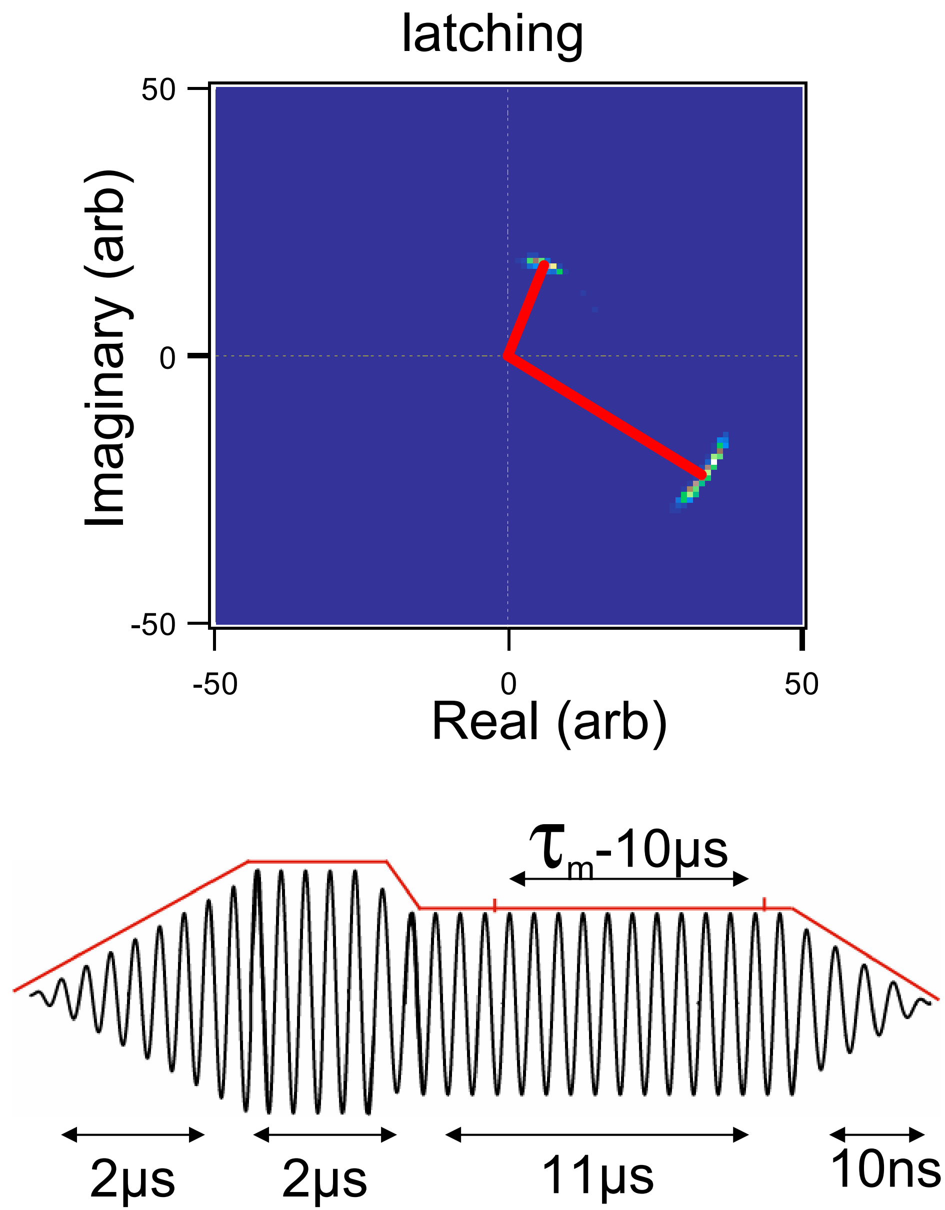
$T_{esc} = 520mK$

$T_{physical} = 260mK$

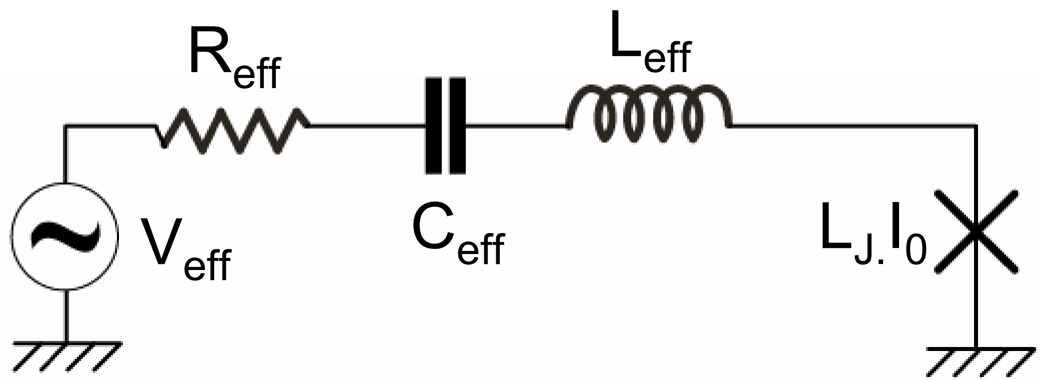
Useful tool

2D-HISTOGRAMS





CAVITY BIFURCATION AMPLIFIER



Parameters: $Z_0 = 50\Omega$;

$\omega_0 \sim (1.8\text{Ghz})2\pi$;

$C_{OUT} \sim 50\text{fF}$;

→

$L_{eff} \sim 7\text{nH}$;

$C_{eff} \sim 1.5\text{pF}$;

$R_{eff} \sim 0.03\Omega$;

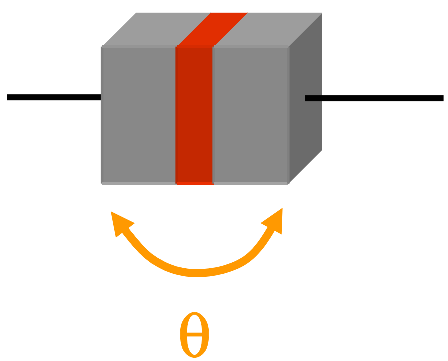
$Q \sim 2000$

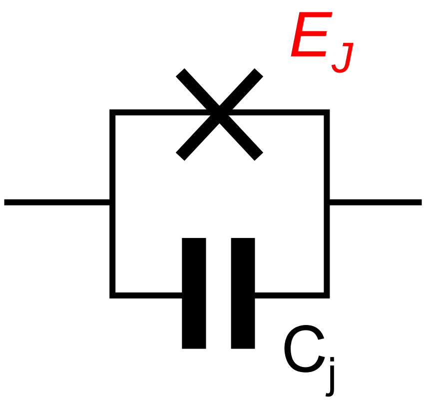
$$L_t \ddot{q} + R_{eff}\,\dot{q} + \frac{q}{C_{eff}} + L_J \ddot{q}\left(\frac{1}{\sqrt{1-(\dot{q}/I_0)^2}} - 1\right) = V_d \cos\omega t + V_N$$

THE JOSEPHSON TUNNEL JUNCTION: AN ATOM-LIKE CIRCUIT ELEMENT TO WHICH YOU CAN ATTACH WIRES ...

S I S
TUNNEL
JUNCTION

$-N(2e) \quad +N(2e)$

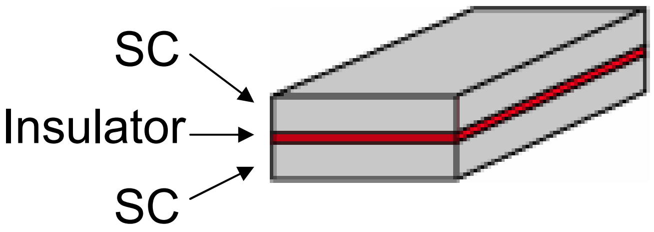




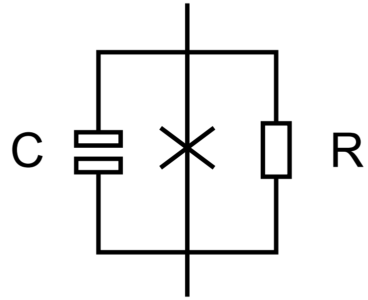
$$[\hat{\theta}, \hat{N}] = i$$

NON-LINEAR INDUCTOR

JOSEPHSON JUNCTION



Model:



Zero voltage supercurrent:

$$I_s = I_c \sin(\Delta\varphi)$$

$$\Delta\varphi = \frac{\Phi_J(t)}{\Phi_0} \qquad \Phi_0 = \frac{\hbar}{2e} \qquad \Phi_J = \int_{-\infty}^{t} v(t')dt'$$

Applied voltage: $\dfrac{d(\Delta\varphi)}{dt} = \dfrac{2eV}{\hbar}$ $\rightarrow$ alternating current

Free energy stored in junction: $W = \int I_s V dt$

$$F = -E_J \cos(\Delta\varphi) + const \qquad E_J = \frac{\hbar I_C}{2e}$$

$$L_J = \frac{\hbar}{2eI_0}$$

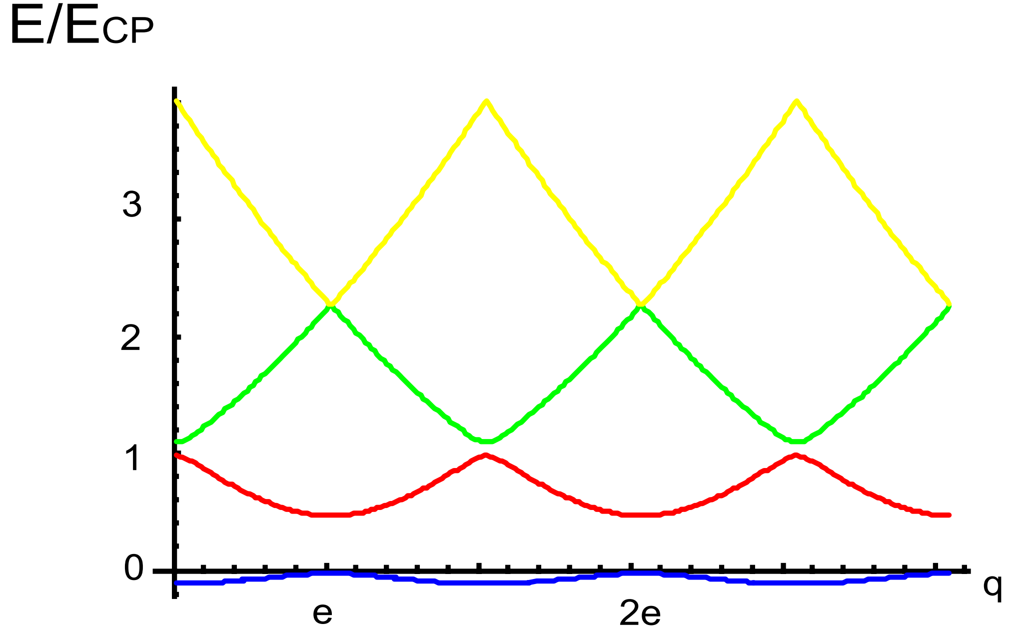
Non-Linear Inductor!

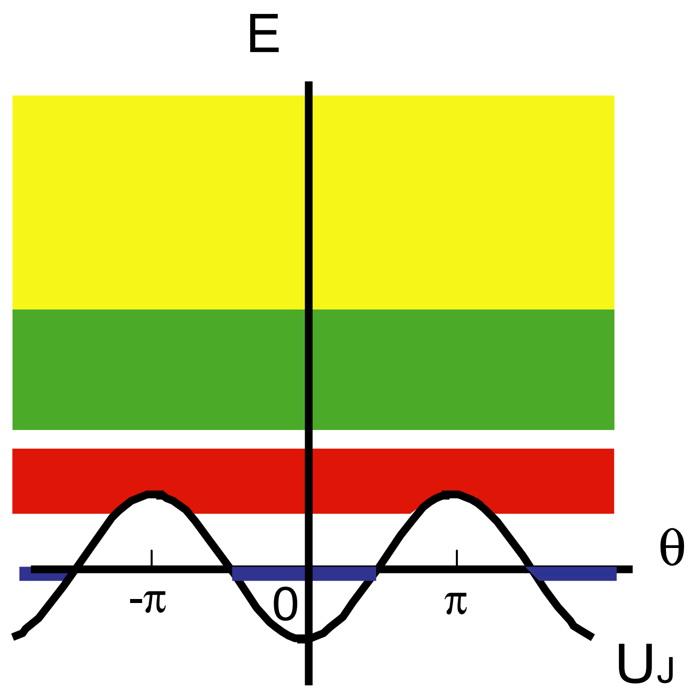
ENERGY LEVELS OF AN ISOLATED JUNCTION

HAMILTONIAN: $H = E_{CP}\left(\hat{N} - q/2e\right)^2 - E_J \cos(\hat{\theta})$ $Z >> R_Q = h/4e^2$

CHARGING ENERGY

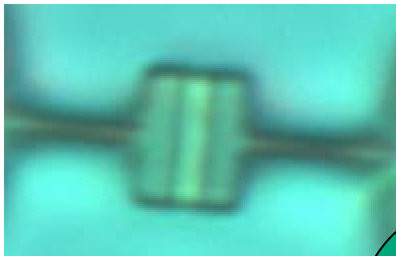
COUPLING ENERGY, U_J





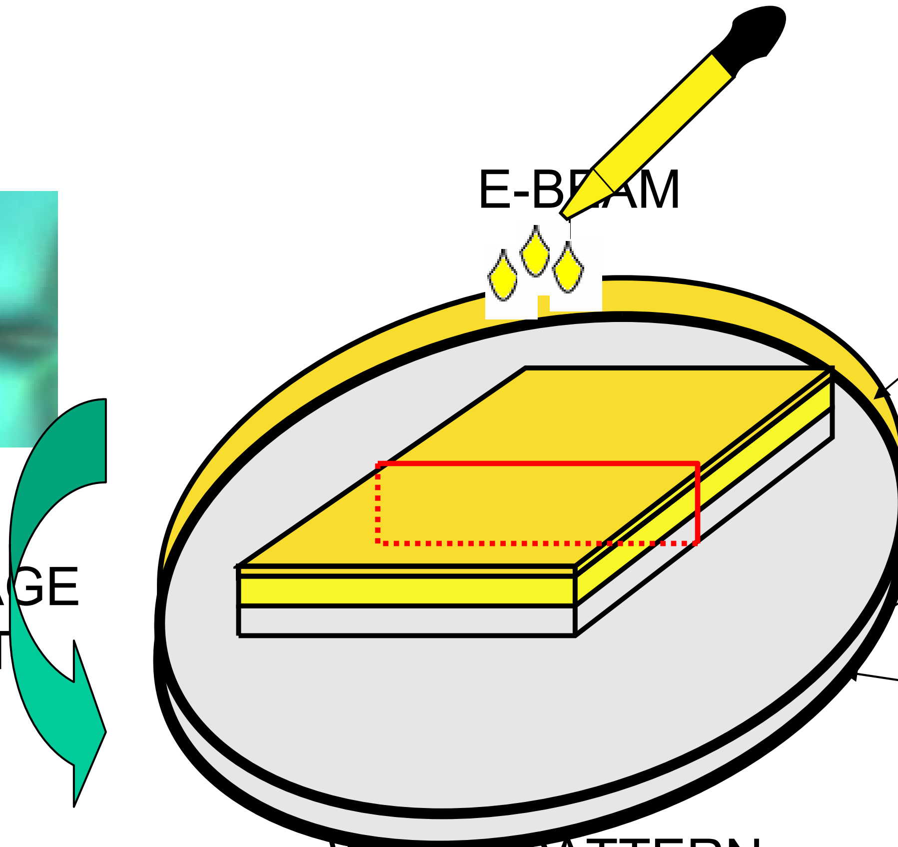
BLOCH WAVEFUNCTIONS

SHADOW-MASK EVAPORATION



3.5μm

OPTICAL IMAGE OF RESIST



WRITE PATTERN WITH SEM

DICE WAFER INTO SMALL CHIPS

2" SI WAFER

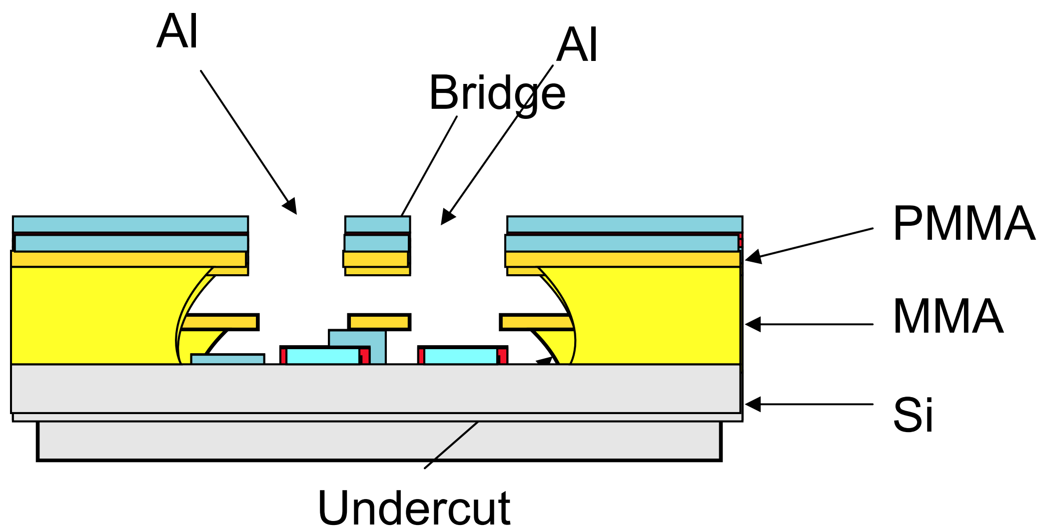
2" SI WAFER

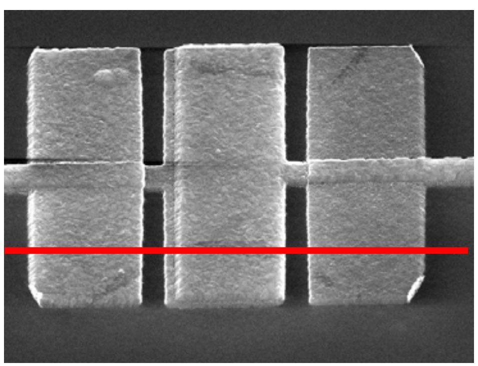
SPIN ON RESIST

SPIN ON RESIST

SHADOW-MASK EVAPORATION

CROSS SECTION:





3.5µm

SEM IMAGE OF $AL/AL_2O_3/AL$ JUNCTION

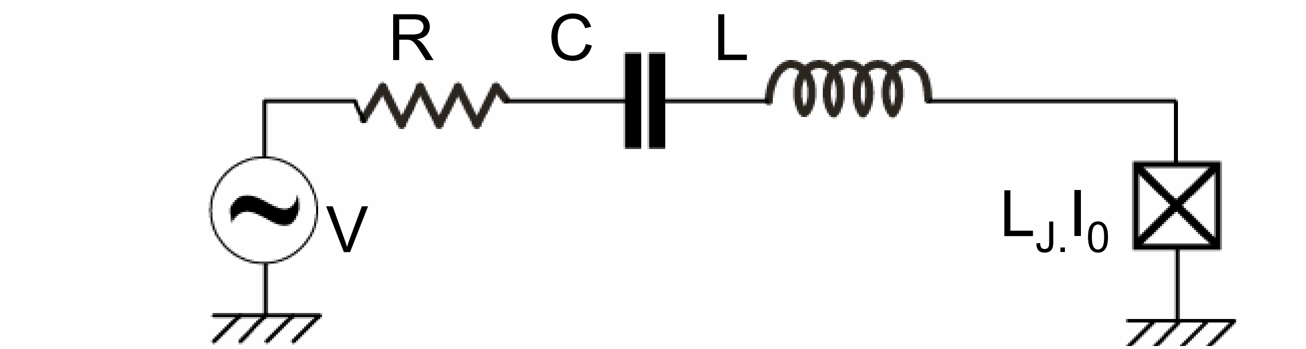
Develop in MIBK:IPA, 1:3, for ~40s and rinse in IPA

Oxidation: 15% O_2 with 85% Ar, 1-10T, 5-20mins

2^{nd} Al evaporation

Lift off resist with unwanted Al with Acetone (60-90°C)

NON-LINEAR OSCILLATOR



$$L_t \ddot{q} + \mathrm{R}\,\dot{q} + \frac{q}{C} + L_J \ddot{q}\left(\frac{1}{\sqrt{1-(\dot{q}/I_0)^2}} - 1\right) = V_d \cos \omega t + V_N$$

Non-Linear resonance