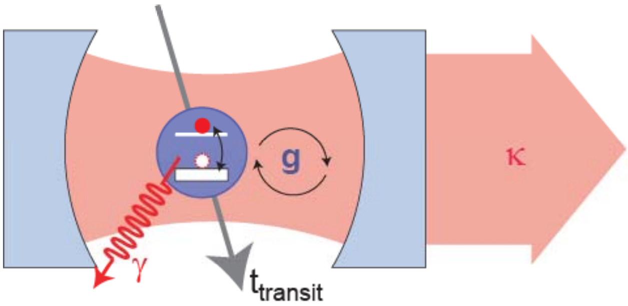
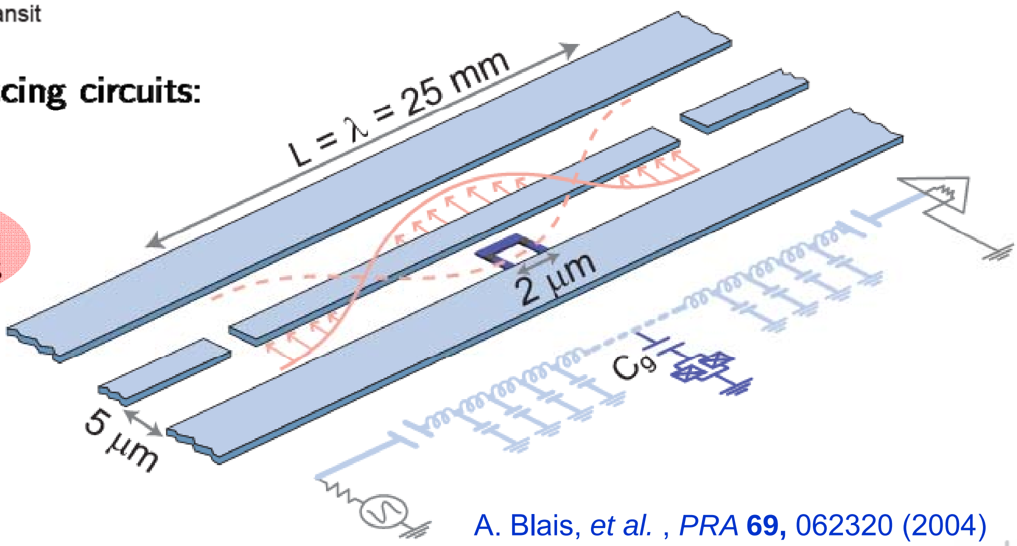
Cavity QED with Superconducting Circuits



coherent quantum mechanics
with individual photons and qubits ...

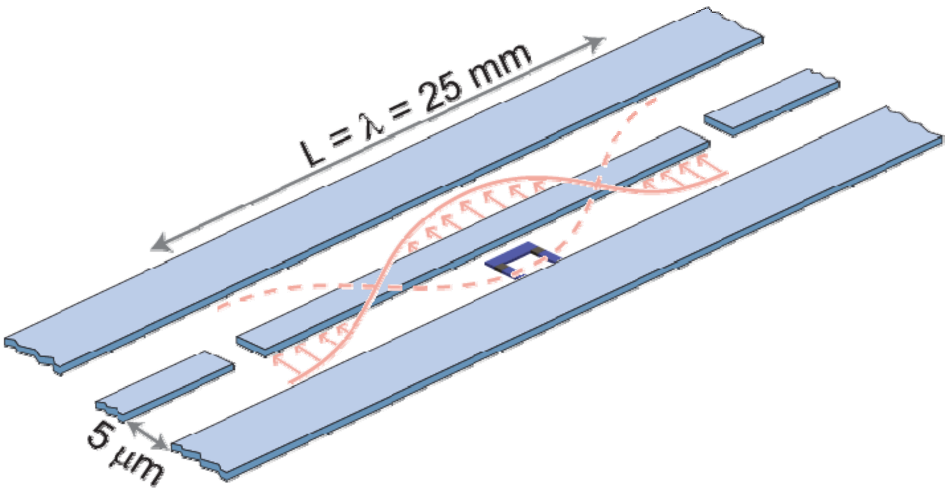
... in superconducing circuits:

circuit quantum electrodynamics



A. Blais, *et al.* , *PRA* **69,** 062320 (2004)
A. Wallraff *et al.*, *Nature (London)* **431**, 162 (2004)

Circuit Quantum Electrodynamics



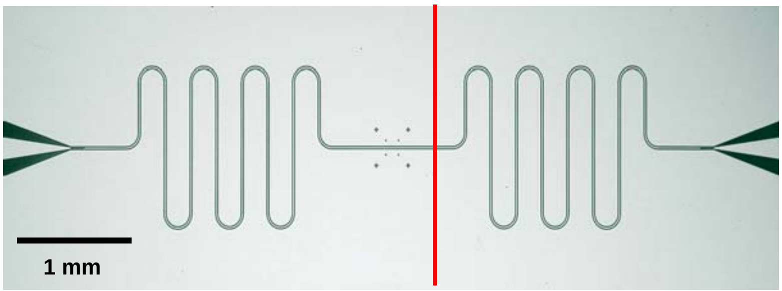
elements

- the cavity: a superconducting 1D transmission line resonator with large vacuum field E_0 and long photon life time $1/\kappa$
- the artificial atom: a Cooper pair box with large E_J/E_C with large dipole moment d and long coherence time $1/\gamma$

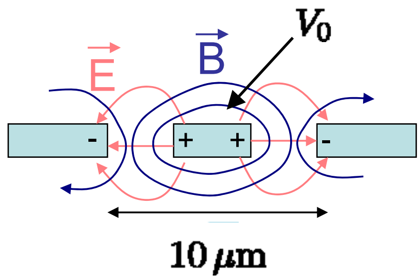
A. Blais *et al.*, *PRA* **69,** 062320 (2004)

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Vacuum Field in 1D Cavity



cross-section of transm. line (TEM mode):



voltage across resonator in vacuum state $(n = 0)$

$$V_{0,\text{rms}} = \sqrt{\frac{\hbar\omega_r}{2C}} \approx 1\,\mu\text{V}$$

harmonic oscillator

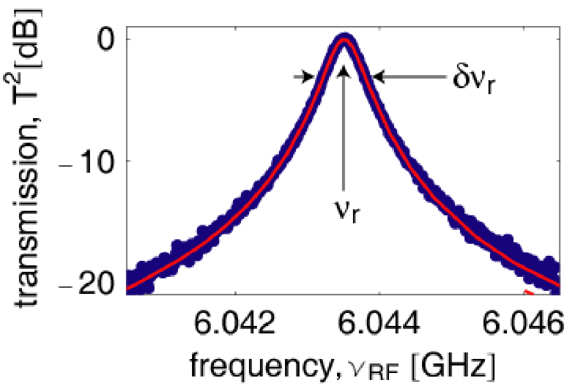
$$H_r = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right)$$

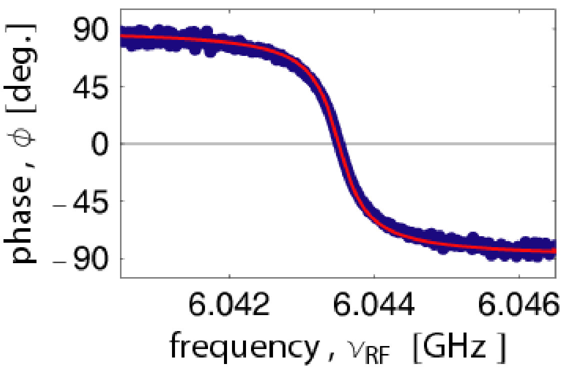
$$E_0 = \frac{V_{0,\text{rms}}}{b} \approx 0.2\,\text{V/m}$$

$\times 10^6$ larger than E_0 in 3D microwave cavity

for $\omega_r/2\pi \approx 6\,\text{GHz}$ $(C \sim 1\,\text{pF})$, $b \approx 5\,\mu\text{m}$

Resonator Quality Factor and Photon Lifetime





resonance frequency:

$$\nu_r = 6.04\,\text{GHz}$$

quality factor:

$$Q = \frac{\nu_r}{\delta\nu_r} \approx 10^4$$

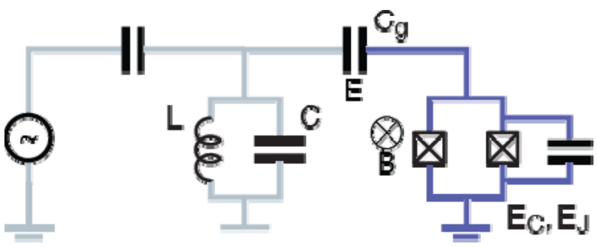
photon decay rate:

$$\frac{\kappa}{2\pi} = \frac{\nu_r}{Q} \approx 0.8\,\text{MHz}$$

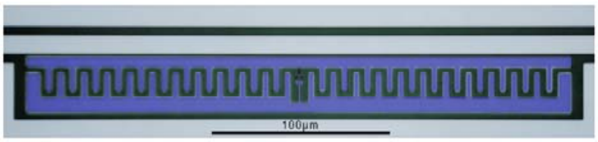
photon lifetime:

$$T_\kappa = 1/\kappa \approx 200\,\text{ns}$$

Qubit/Photon Coupling in a Circuit



qubit coupled to resonator



coupling strength:

$$\hbar g = eV_{0,\mathrm{rms}} \frac{C_g}{C_\Sigma}$$

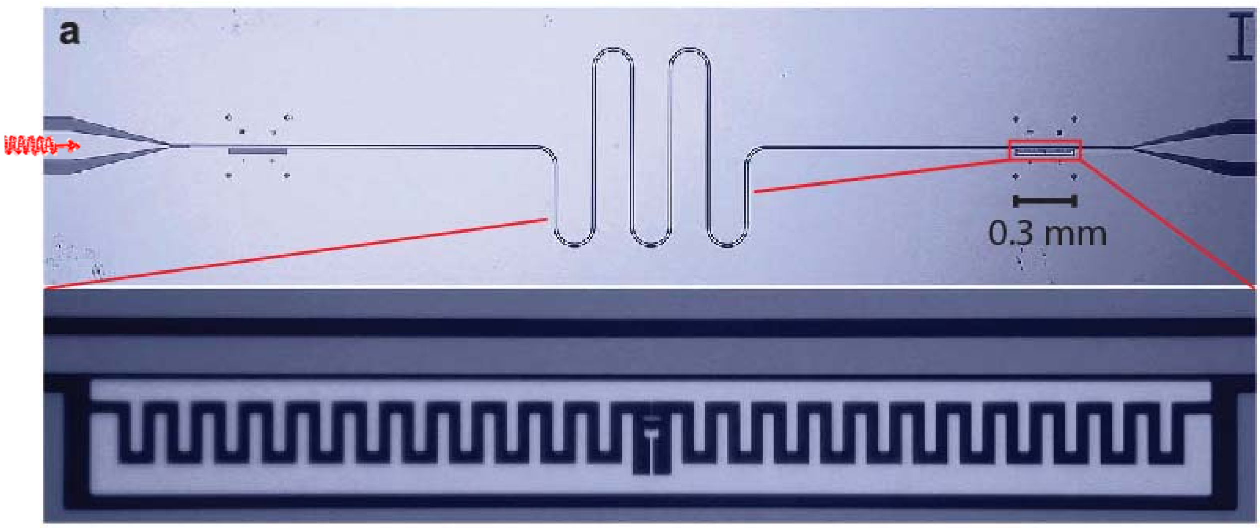
$$\Longrightarrow \nu_{\mathrm{vac}} = \frac{g}{\pi} \approx 1 \ldots 300\,\mathrm{MHz}$$

$g \gg [\kappa, \gamma]$ possible!

large effective dipole moment

$$d = \frac{\hbar g}{E_0} \sim 10^2 \ldots 10^4\, e a_0$$

Circuit QED with One Photon

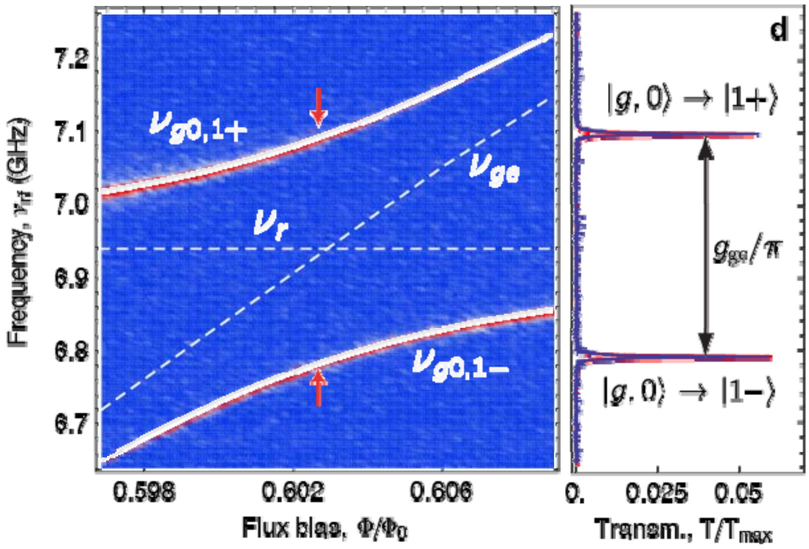


superconducting cavity QED circuit

A. Wallraff, …, R. J. Schoelkopf, *Nature (London)* **431**, 162 (2004)

Resonant Vacuum Rabi Mode Splitting ...

... with one photon ($n = 1$):

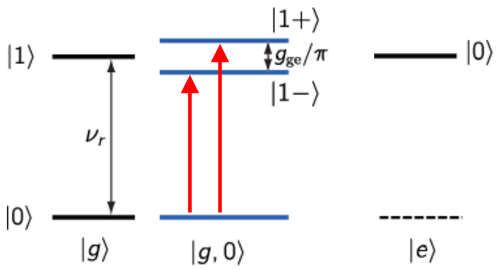


very strong coupling:

$g_{ge}/\pi = 308\,\mathrm{MHz}$

$\kappa, \gamma < 1\ \mathrm{MHz}$

$g_{ge} \gg \kappa, \gamma$



forming a 'molecule' of a qubit and a photon

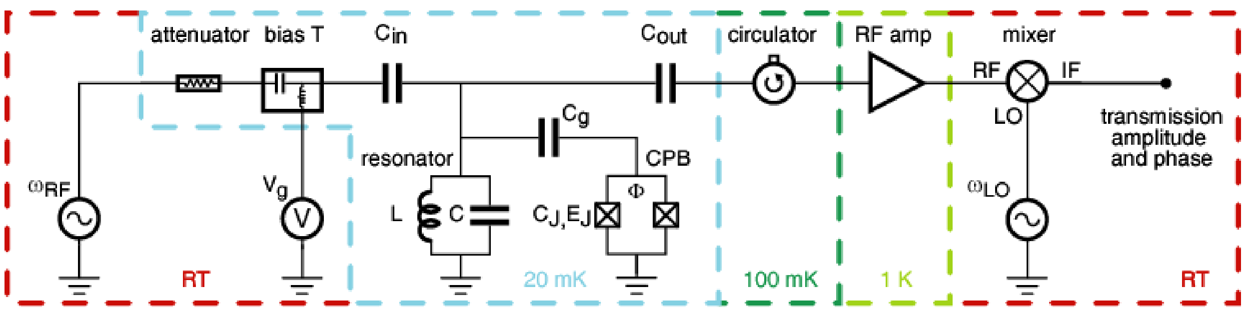
$$|1\pm\rangle = (|g,1\rangle \pm |e,0\rangle)/\sqrt{2}$$

first demonstration: A. Wallraff, … and R. J. Schoelkopf, *Nature (London)* **431**, 162 (2004)
this data: J. Fink et al., *Nature (London)* **454**, 315 (2008)

How to Measure Single Microwave Photons

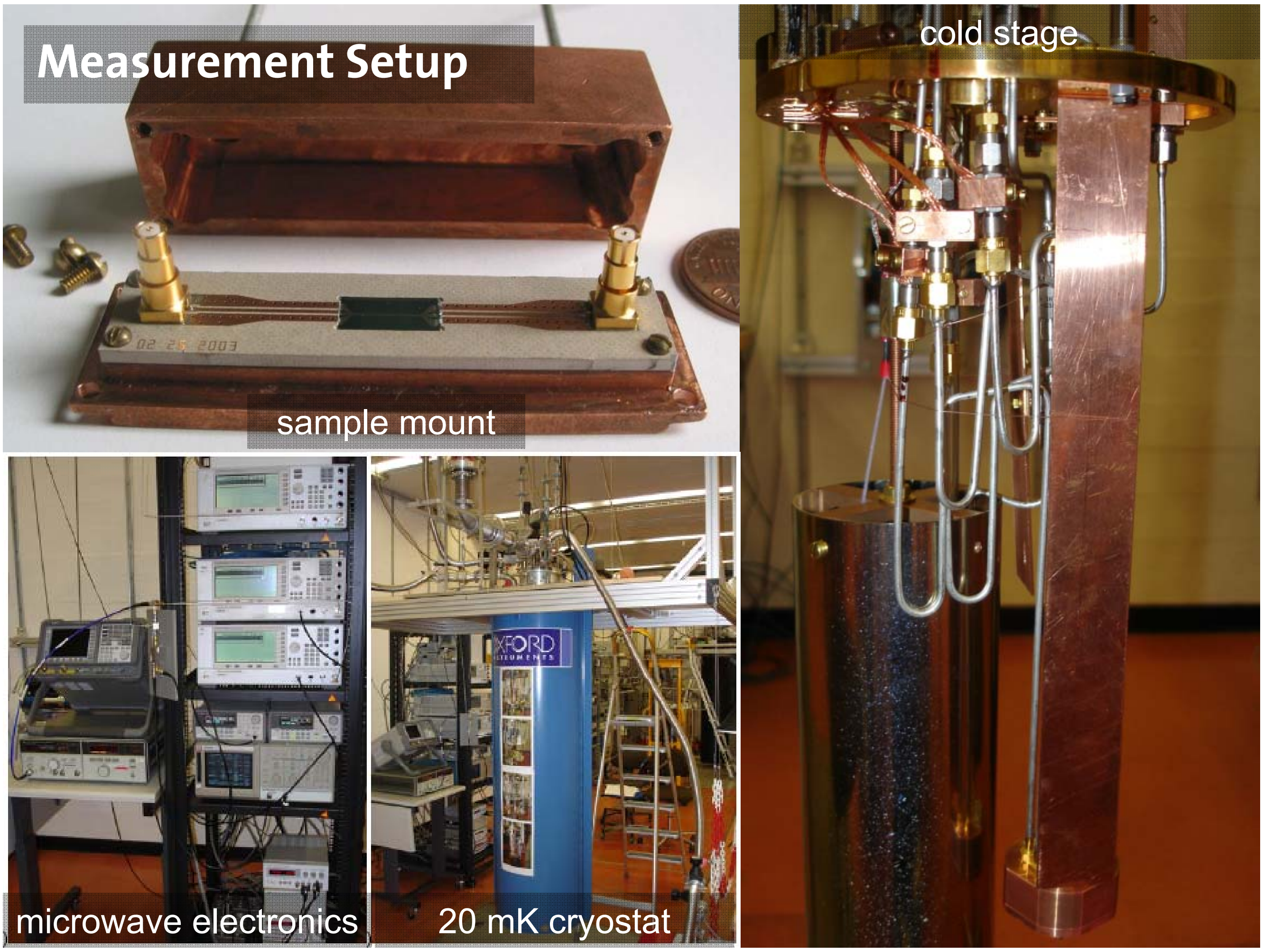
- average power to be detected

$$\rightarrow \langle n = 1\rangle \hbar\omega_r\kappa/2 \approx P_{RF} = -140\,\mathrm{dBm} = 10^{-17}\,\mathrm{W}$$



- efficient with cryogenic low noise HEMT amplifier ($T_N = 6\,\mathrm{K}$)
- prevent leakage of thermal photons (cold attenuators and circulators)

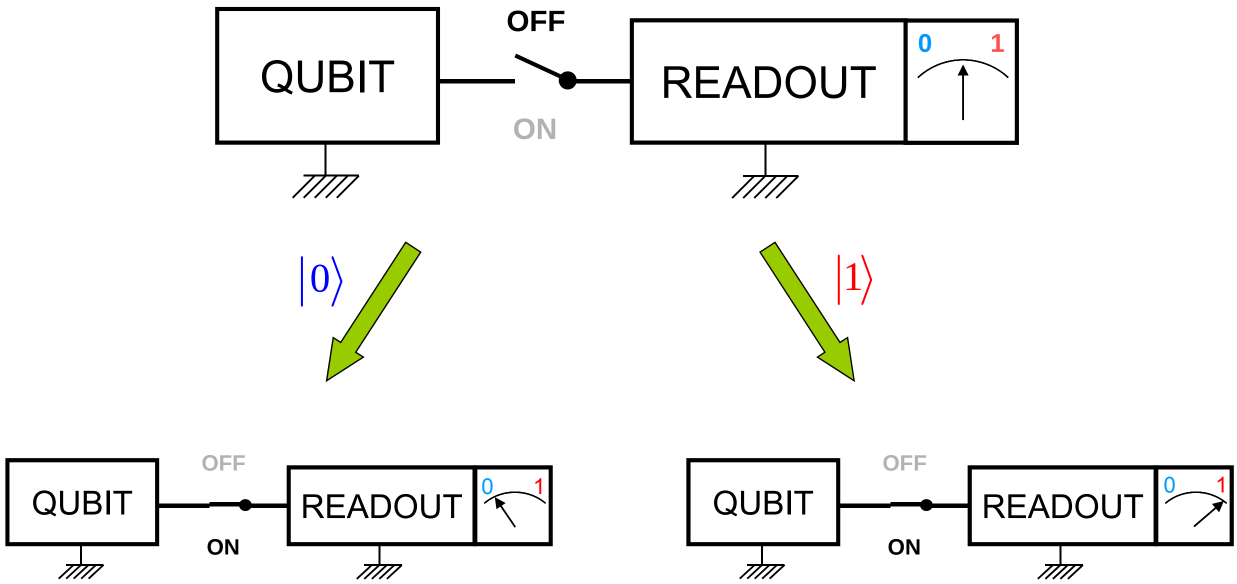
Measurement Setup



Read-Out ...

... of a superconducting charge qubit

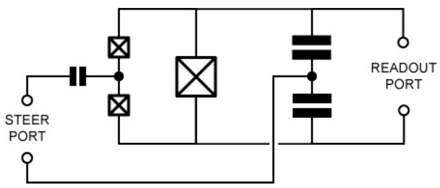
Qubit Read Out



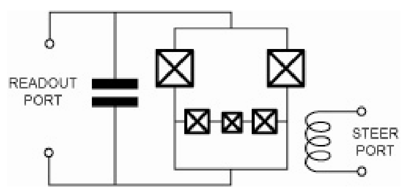
desired: good on/off ratio
no relaxation in on state (QND)

Read Out Strategies

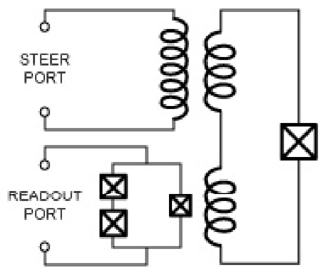
demolition measurements (switching/latching measurements)



Quantronium (Saclay, Yale)

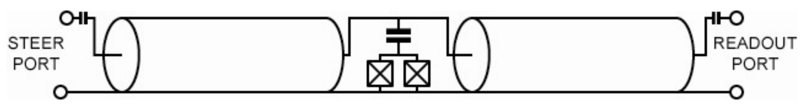


Flux Qubit (TU Delft, NEC)



Phase Qubit (NIST, UCSB)

quantum non-demolition (QND) measurements



Yale (circuit QED)

also: Chalmers, Delft, Yale (JBA)

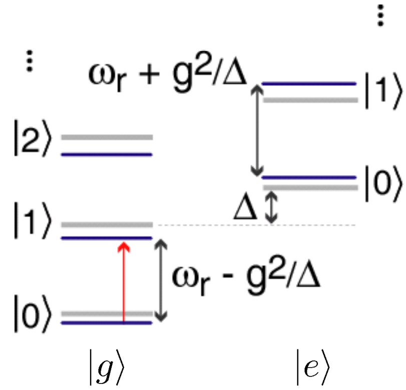
Non-Resonant Qubit-Photon Interaction

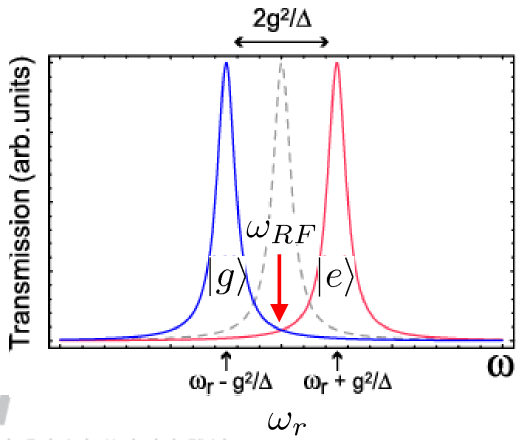
approximate diagonalization in the dispersive limit $|\Delta| = |\omega_a - \omega_r| \gg g$

$$H \approx \hbar \left(\omega_r + \frac{g^2}{\Delta} \sigma_z \right) a^\dagger a + \frac{1}{2} \hbar \left(\omega_a + \frac{g^2}{\Delta} \right) \sigma_z$$

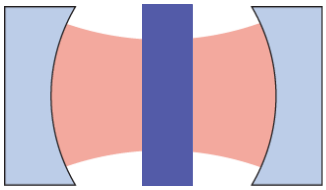
cavity frequency shift *and* qubit ac-Stark shift

Lamb shift





$|g\rangle : \epsilon > 1$



$|e\rangle : \epsilon < 1$

A. Blais *et al.*, *PRA* **69,** 062320 (2004)

Non-Resonant Qubit-Photon Interaction

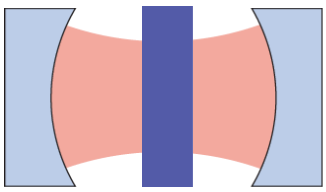
approximate diagonalization in the dispersive limit $|\Delta| = |\omega_a - \omega_r| \gg g$

$$H \approx \hbar \left(\omega_r + \frac{g^2}{\Delta} \sigma_z \right) a^\dagger a + \frac{1}{2} \hbar \left(\omega_a + \frac{g^2}{\Delta} \right) \sigma_z$$

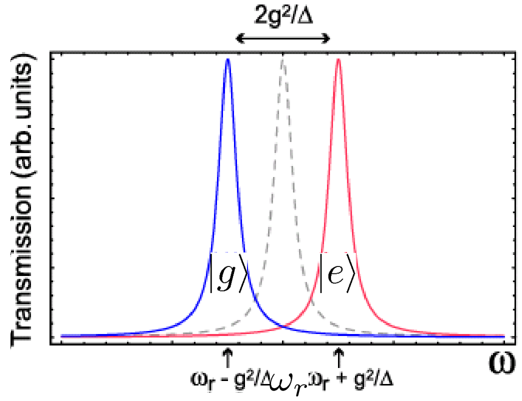
cavity frequency shift *and* qubit ac-Stark shift

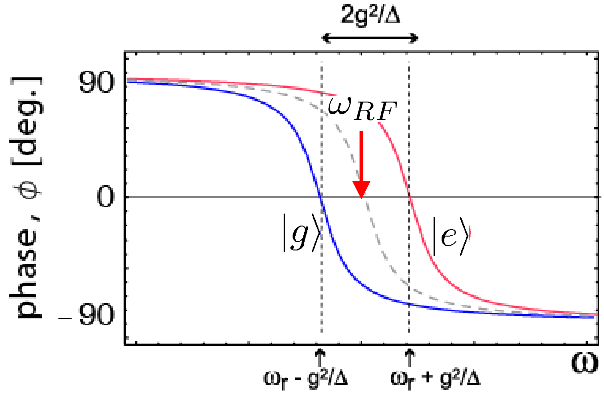
Lamb shift

$|g\rangle : \epsilon > 1$



$|e\rangle : \epsilon < 1$



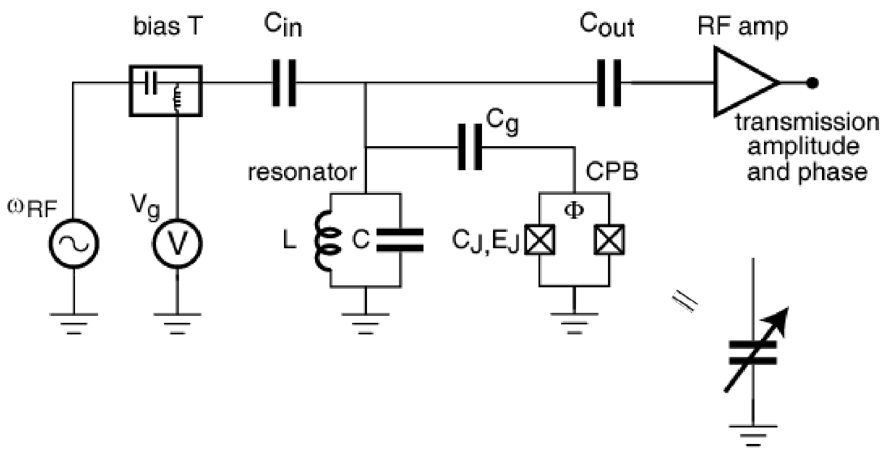


A. Blais *et al.*, *PRA* **69,** 062320 (2004)

Qubit Spectroscopy with Dispersive Read-Out ...

... additional material

Measurement Technique

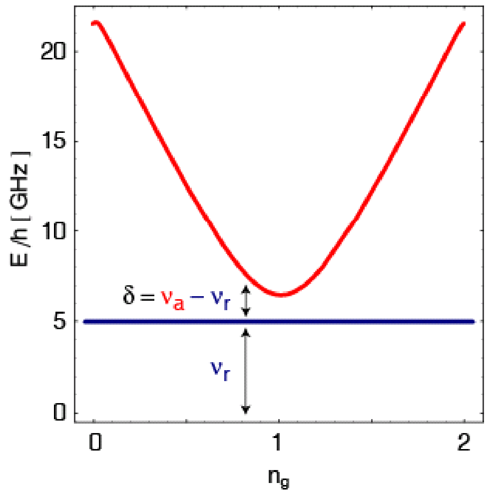


- measurement of microwave transmission amplitude T and phase ϕ
- intra-cavity photon number controllable from $n \sim 10^3$ to $n \ll 1$

Dispersive Shift of Resonance Frequency

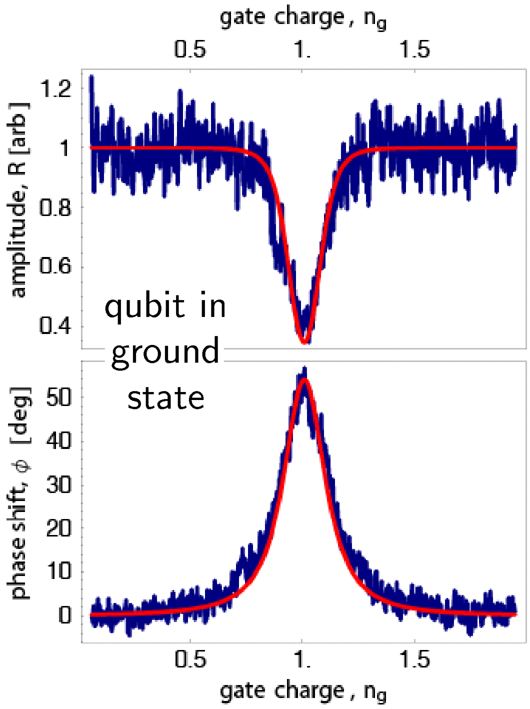
sketch of qubit level separation:

$$\Delta = 2\pi\delta > g$$

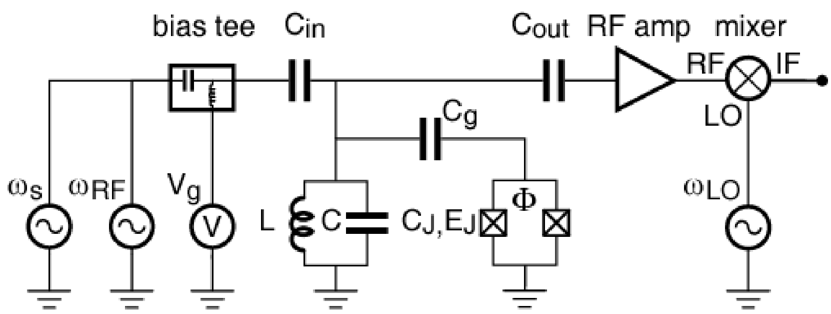


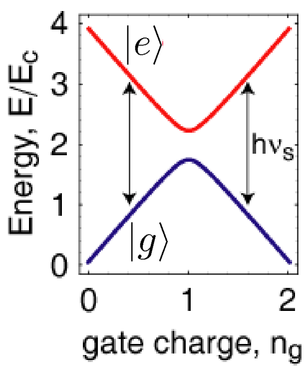
$$g/\pi = \nu_{vac} = 11\,\text{MHz}$$
$$\Delta(n_g = 1)/2\pi = 66\,\text{MHz}$$
$$n = 10$$

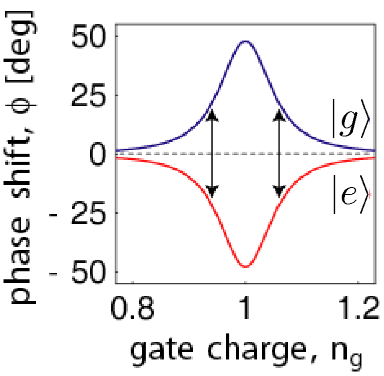
measured resonator transmission amplitude and phase:



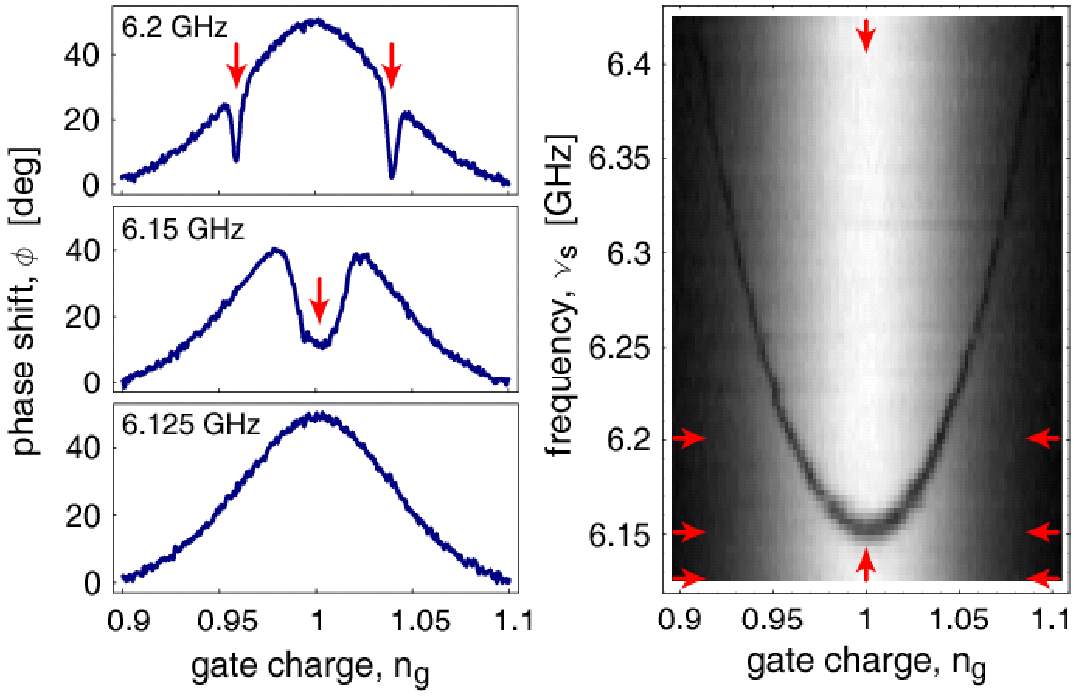
Qubit Spectroscopy with Dispersive Read-Out







CW Spectroscopy of Cooper Pair Box



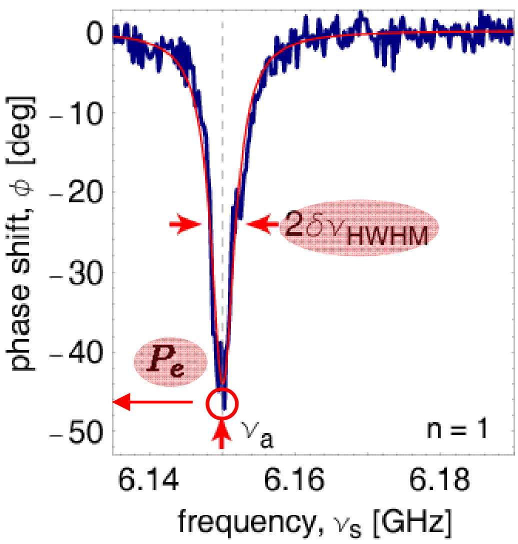
detuning $\Delta_{\mathrm{r,a}}/2\pi \sim 100\,\mathrm{MHz}$ extracted: $E_J = 6.2\,\mathrm{GHz},\ E_C = 4.8\,\mathrm{GHz}$

D. I. Schuster *et al.*, *Phys. Rev. Lett.* **94,** 123062 (2005)

Line Shape

excited state population (steady-state Bloch equations):

$$P_e = 1 - P_g = \frac{1}{2}\frac{\Omega_R^2 T_1 T_2}{1 + (T_2\Delta_{\mathrm{s,a}})^2 + \Omega_R^2 T_1 T_2}$$

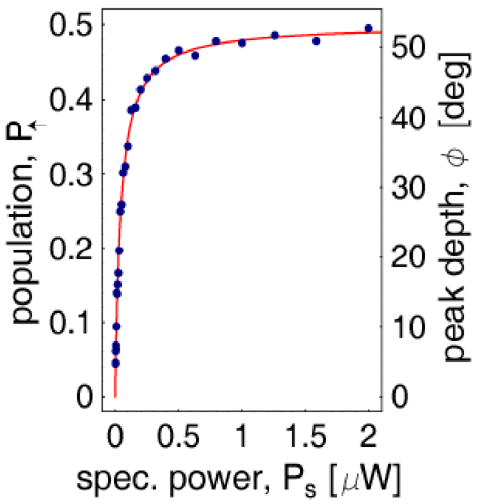


- fixed drive $P_s \propto \Omega_R^2 = n_s \omega_{\mathrm{vac}}^2$
- varying $\Delta_{\mathrm{s,a}} = \omega_s - \widetilde{\omega}_a$
- weak continuous measurement $(n \sim 1)$
- at charge degenracy $(n_g = 1)$

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Abragam, Oxford University Press (1961)

Excited State Population

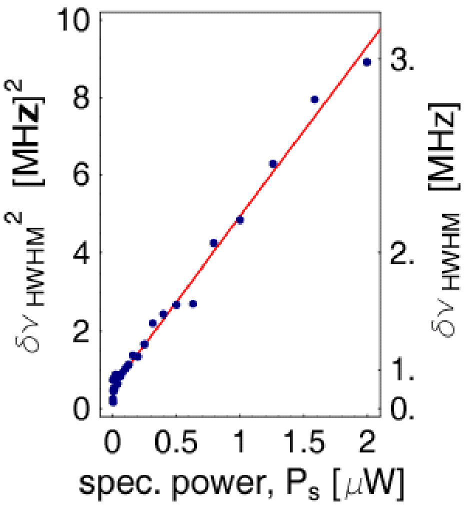


peak depth → population (saturation):

$$P_e = 1 - P_g = \frac{1}{2}\frac{\Omega_R^2 T_1 T_2}{1 + \Omega_R^2 T_1 T_2}$$

D. I. Schuster, A. Wallraff, A. Blais, L. Frunzio, R.-S. Huang, J. Majer, S. Girvin, and R. J. Schoelkopf, *Phys. Rev. Lett.* **94,** 123062 (2005)

Line Width



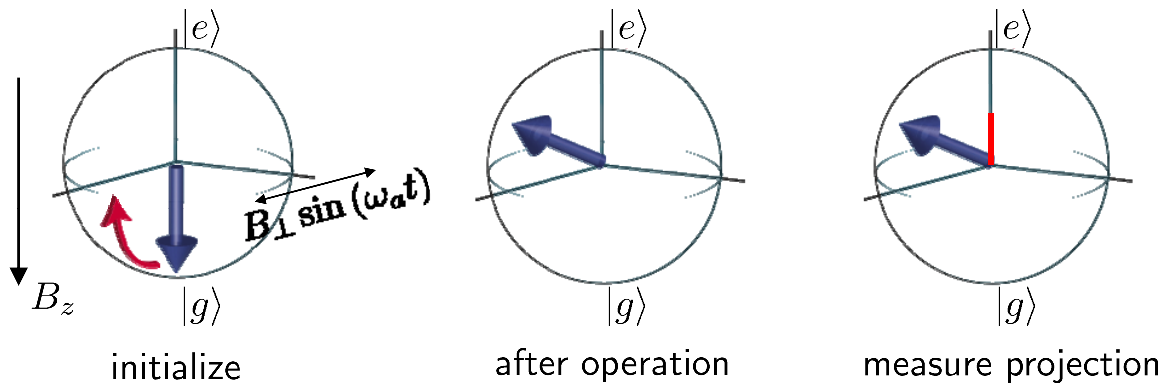
line width → coherence time:

$$2\pi\delta\nu_{\mathrm{HWHM}} = \frac{1}{T_2'} = \sqrt{\frac{1}{T_2^2} + \Omega_R^2 \frac{T_1}{T_2}}$$

$$\mathrm{Min}(\delta\nu_{\mathrm{HWHM}}) \sim 750\,\mathrm{kHz} \rightarrow \mathrm{T}_2 > 200\,\mathrm{ns}$$

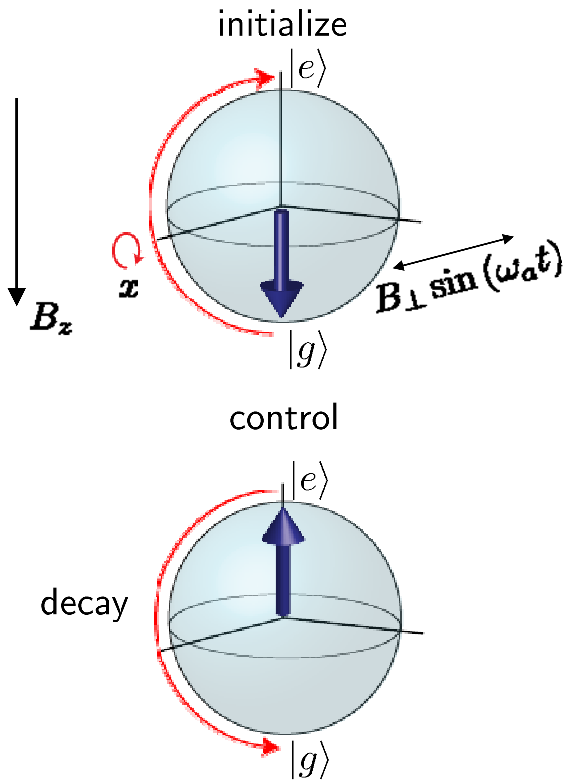
D. I. Schuster, A. Wallraff, A. Blais, L. Frunzio, R.-S. Huang, J. Majer, S. Girvin, and R. J. Schoelkopf, *Phys. Rev. Lett.* **94,** 123062 (2005)

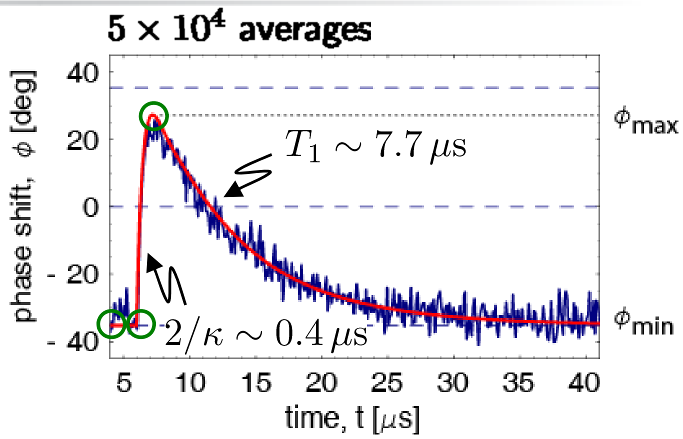
Coherent Control of a Qubit in a Cavity



- qubit state represented on a Bloch sphere
- vary length, amplitude and phase of microwave pulse to control qubit state

Qubit Control and Readout



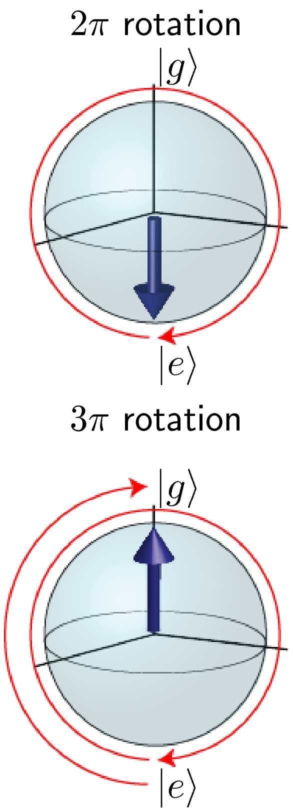


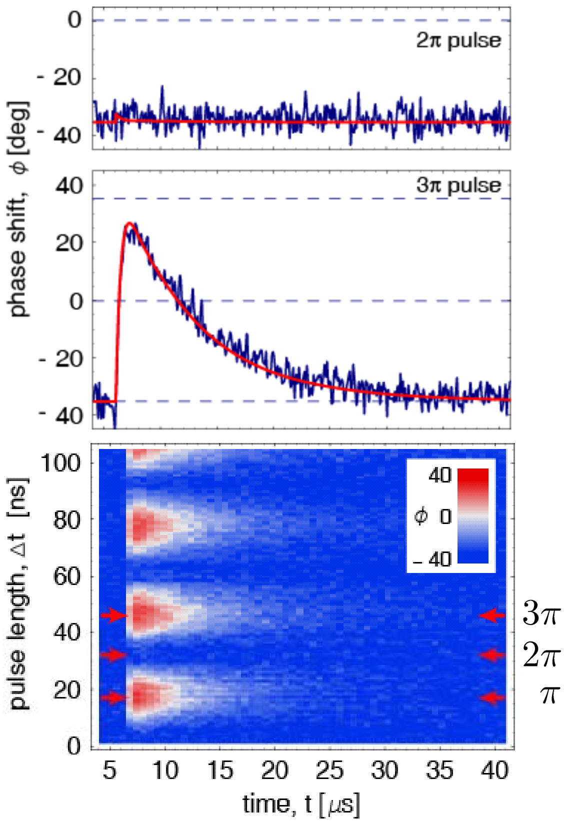
measurement properties:

- continuous
- dispersive
- quantum non-demolition
- in good agreement with predictions

Wallraff, Schuster, Blais, ... Girvin, and Schoelkopf, *Phys. Rev. Lett.* **95**, 060501 (2005)

Varying the Control Pulse Length



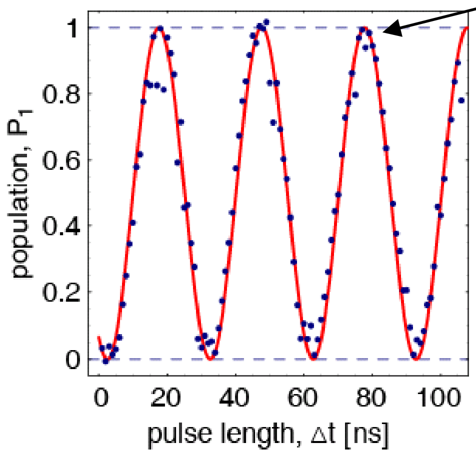


Wallraff, Schuster, Blais, ... Girvin, Schoelkopf, *PRL* **95**, 060501 (2005)

High Visibility Rabi Oscillations

Rabi oscillations:

visibility $95 \pm 5\%$



for superconducting qubits:

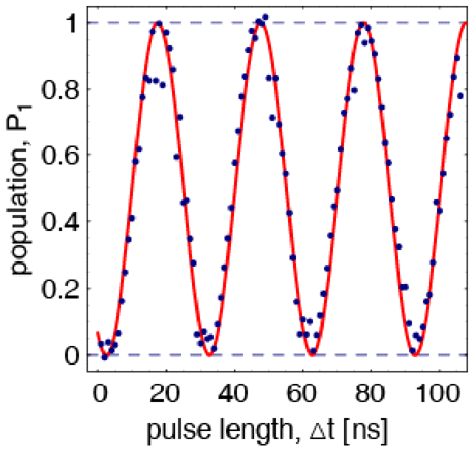
- **high visibility**
- **well characterized and understood measurement**
- **good control accuracy**

A. Wallraff, D. I. Schuster, A. Blais, L. Frunzio, J. Majer, S. M. Girvin, and R. J. Schoelkopf, *Phys. Rev. Lett.* **95**, 060501 (2005)

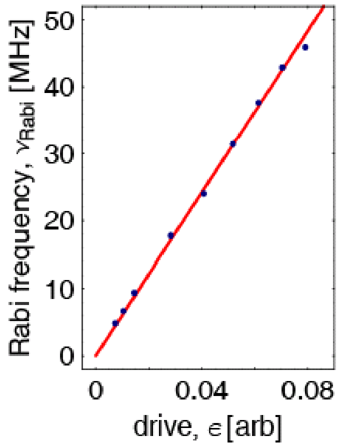
Rabi Frequency

pulse scheme:

Rabi oscillations:

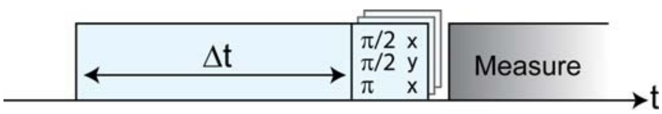


Rabi frequency:

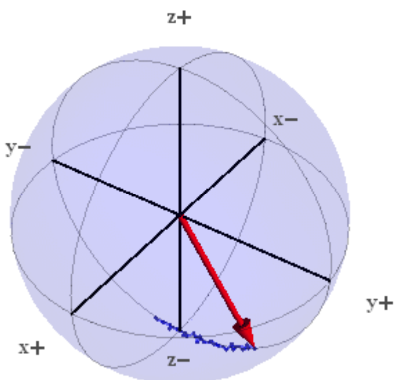


- **linear dependence of Rabi frequency on microwave amplitude**

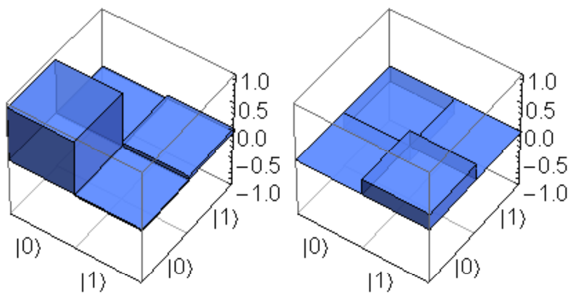
Rabi rotation pulse sequence:



experimental Bloch vector:



experimental density matrix:



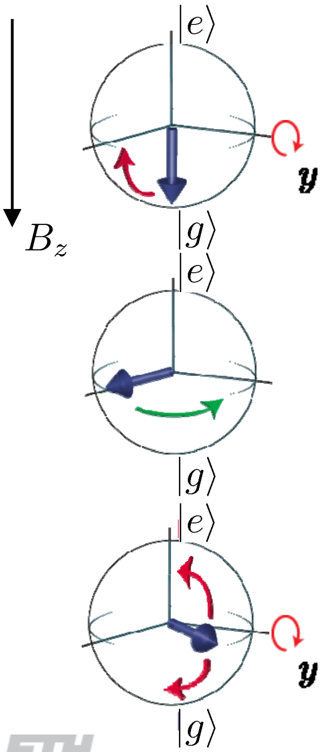
Δt = 36 ns

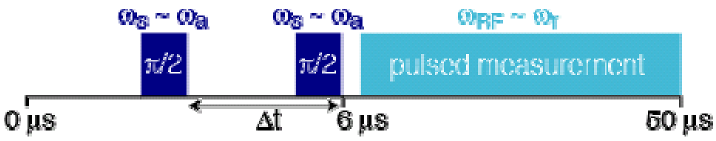
L. Steffen *et al.*, Quantum Device Lab, ETH Zurich (2008)

Measurements of Coherence Time

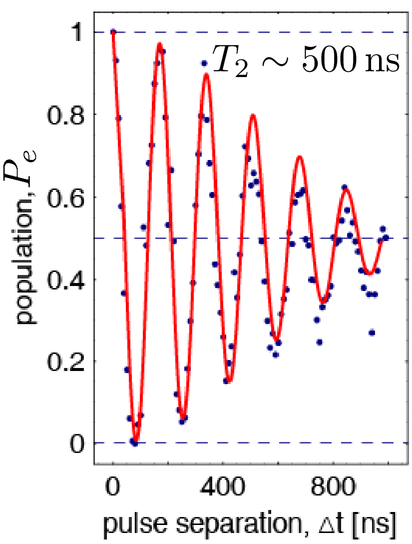
Coherence Time Measurement: Ramsey Fringes

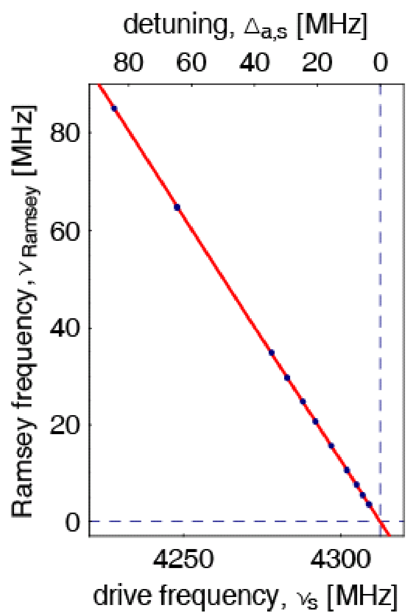
pulse scheme:





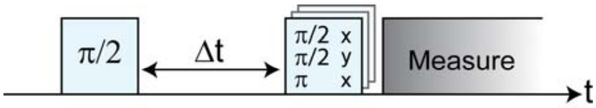
Ramsey fringes:

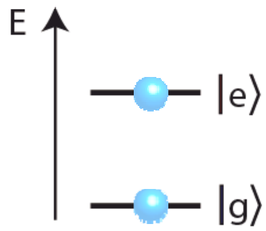




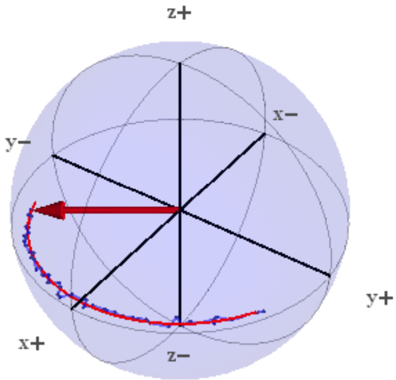
A. Wallraff *et al.*, *Phys. Rev. Lett.* **95**, 060501 (2005)

pulse sequence:

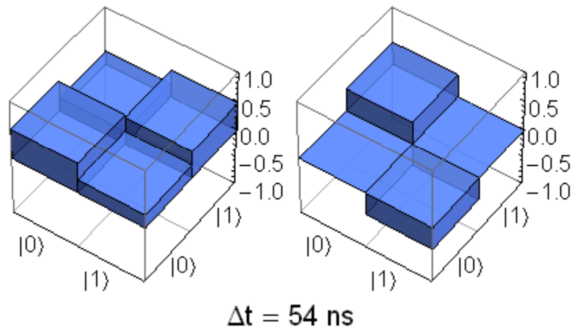




experimental Bloch vector:



experimental density matrix:



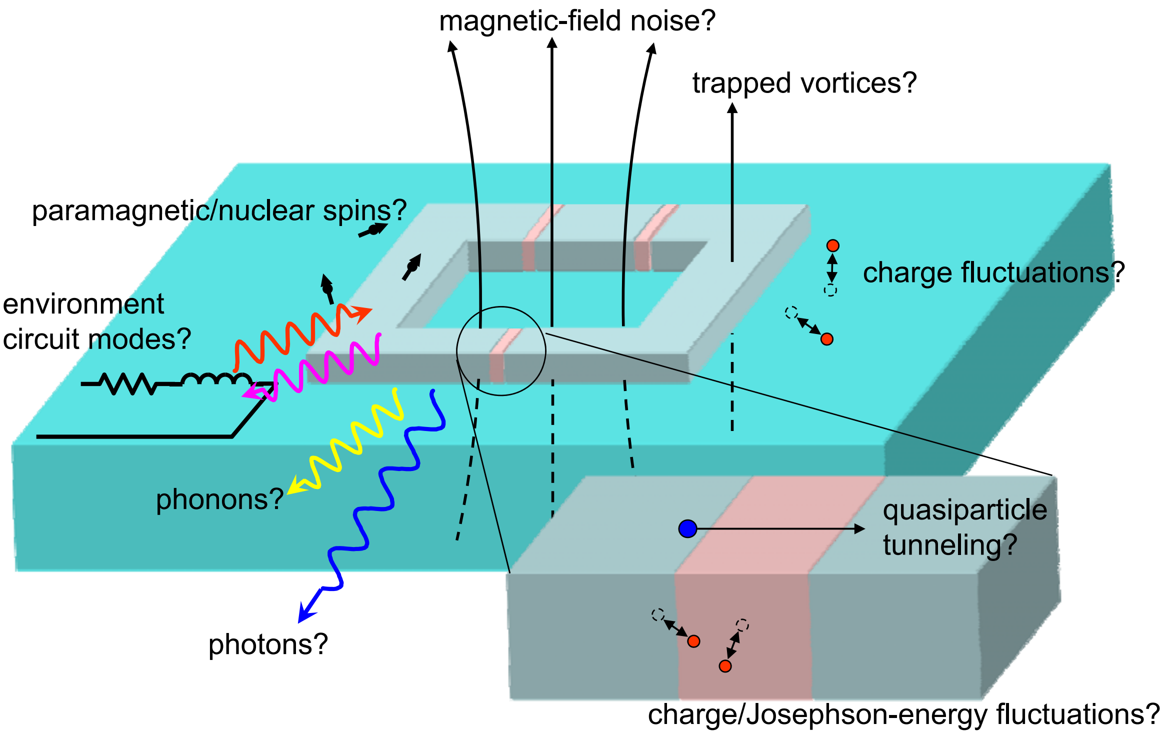
L. Steffen *et al.*, Quantum Device Lab, ETH Zurich (2008)

Decoherence ...

... additional material

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

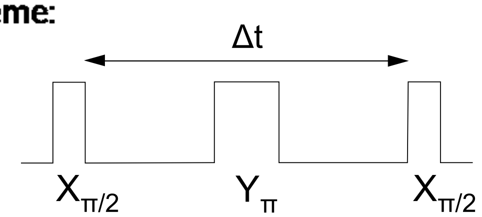
Sources of Decoherence

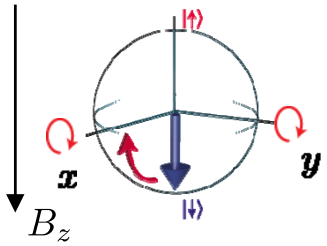


G. Ithier *et al.*, *Phys. Rev. B* **72**, 134519 (2005)

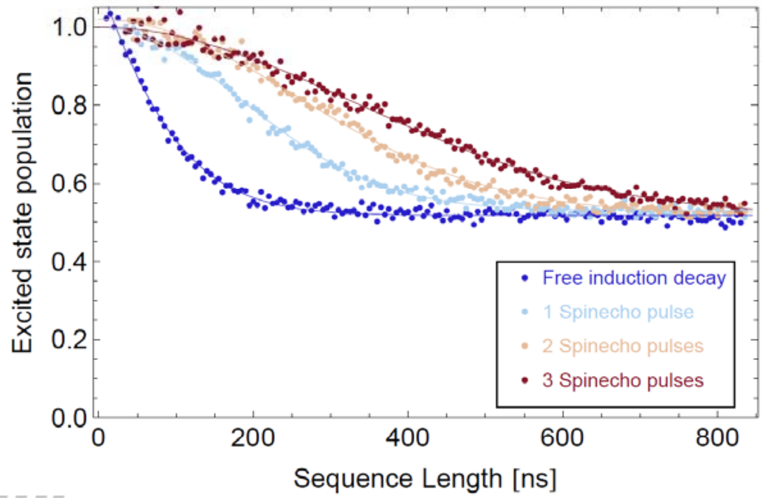
- remove sources of decoherence
  - improve materials
- use dynamic methods to counteract specific sources of decoherence
  - spin echo
  - geometric manipulations
- reduce sensitivity of quantum systems to specific sources of decoherence
  - make use of symmetries in design and operation

pulse scheme:





result:



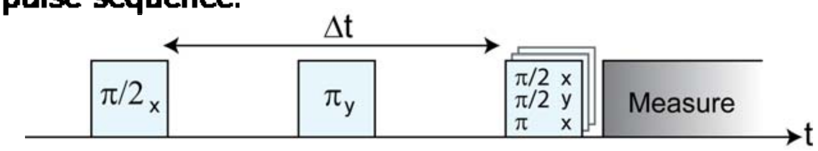
- refocusing
- elimination of low frequency fluctuations
- increased effective coherence time

Lars Steffen *et al.* (2009)

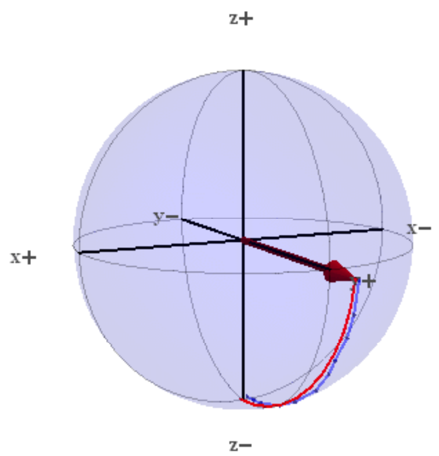
P. J. Leek, J. Fink *et al., Science* 318, 1889 (2007)

Tomography of a Spin Echo

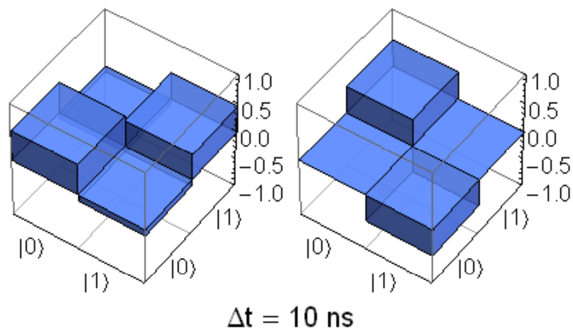
pulse sequence:



experimental Bloch vector:



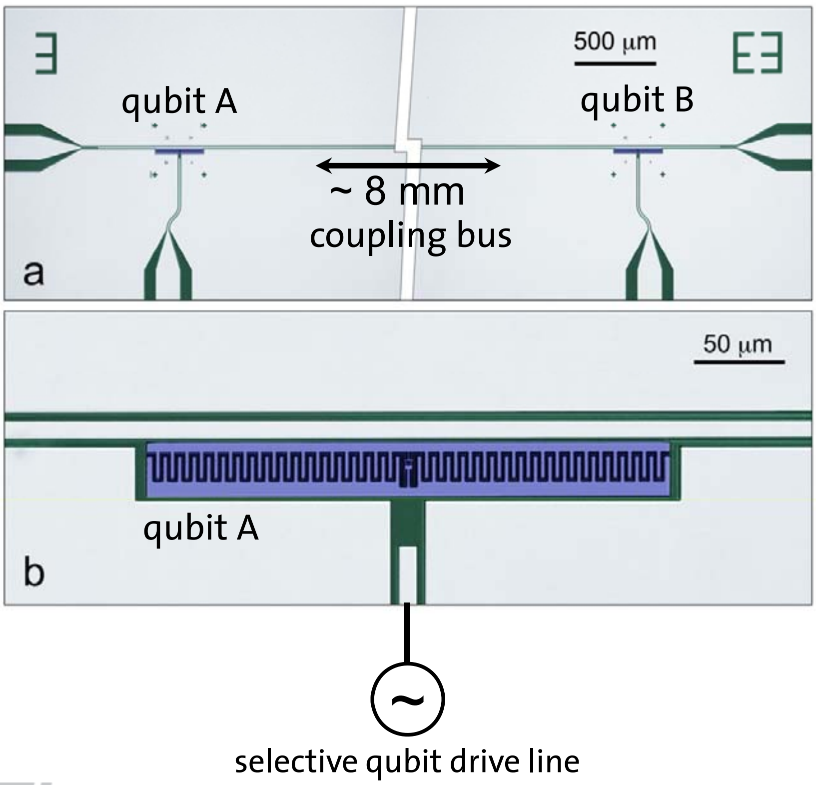
experimental density matrix:



L. Steffen *et al.,* Quantum Device Lab, ETH Zurich (2008)

Coupling Superconducting Qubits and Generating Entanglement using Sideband Transitions

2-Qubit Chip



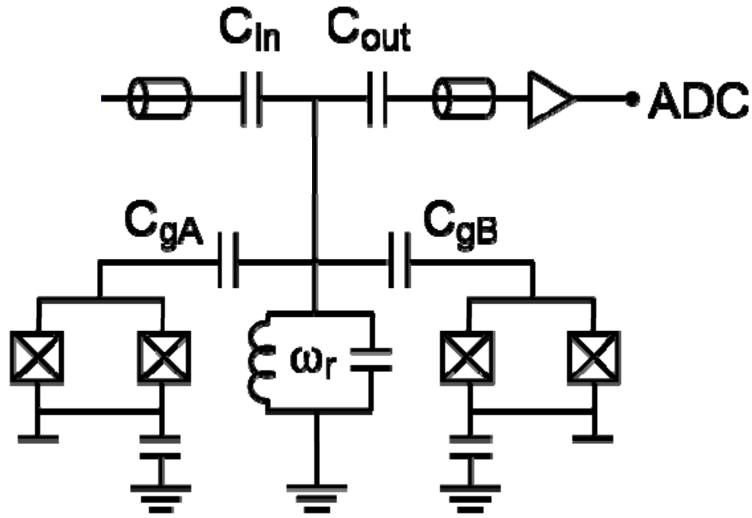
- Two near identical superconducting qubits
- Local control of magnetic flux allows independent selection of qubit transition frequencies
- Local drive lines allow selective excitation of individual qubits

et al., Phys. Rev. B **79**, 180511(R) (2009)

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

2-Qubit Circuit with Selective Control

joint dispersive read-out

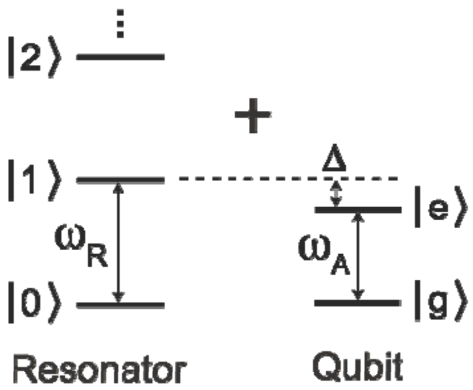


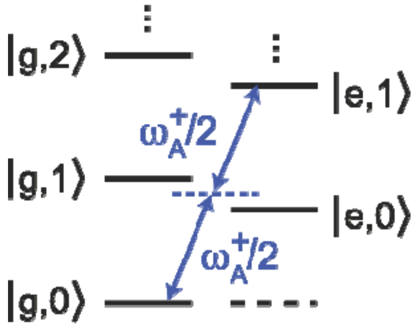
Local magnetic fields created using small inductively coupled coils

Selective qubit excitation using locally capacitively coupled drive lines

P. Leek *et al.*, *Phys. Rev. B* **79**, 180511(R) (2009)

Sideband Transitions in Circuit QED

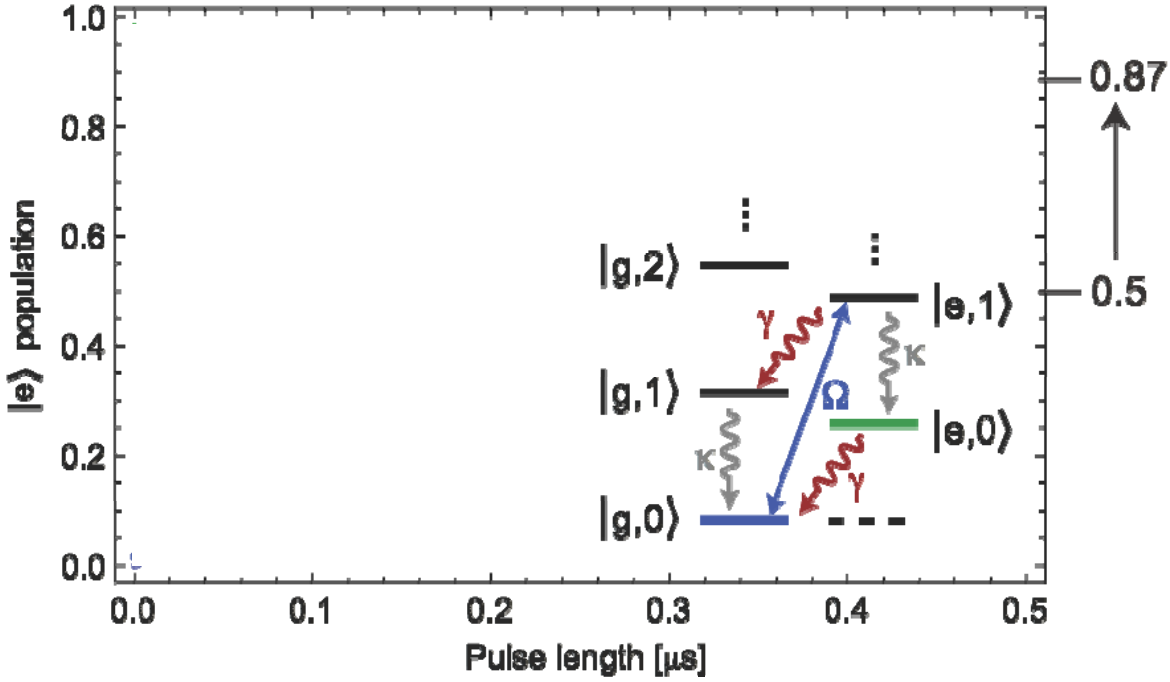




$$\omega_A/2 = (\omega_R + \omega_A)/2$$

- dispersive coupling allows joint excitations to be driven
- sideband transitions forbidden to first order: use two photon transition

Wallraff et al., *PRL* **99**, 050501 (2007)

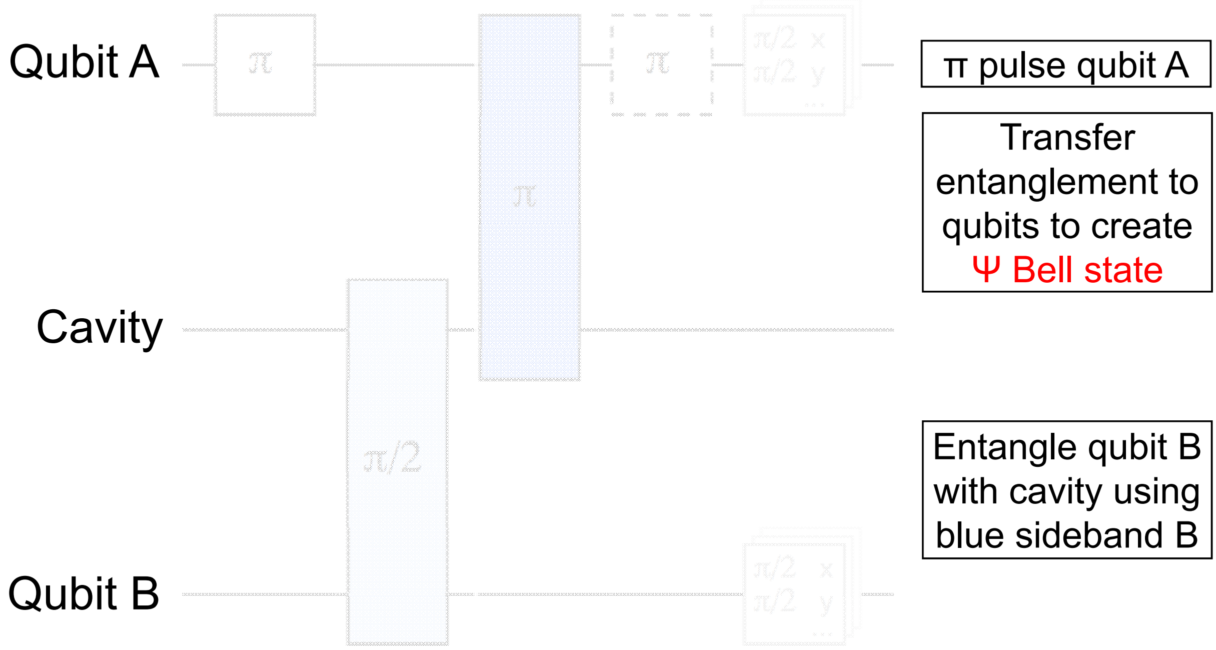


simultaneous excitation of qubit and resonator: |g,0> → |e,1>

entangle a qubit with a photon on the bus: |g,0> → |g,0> + |e,1>

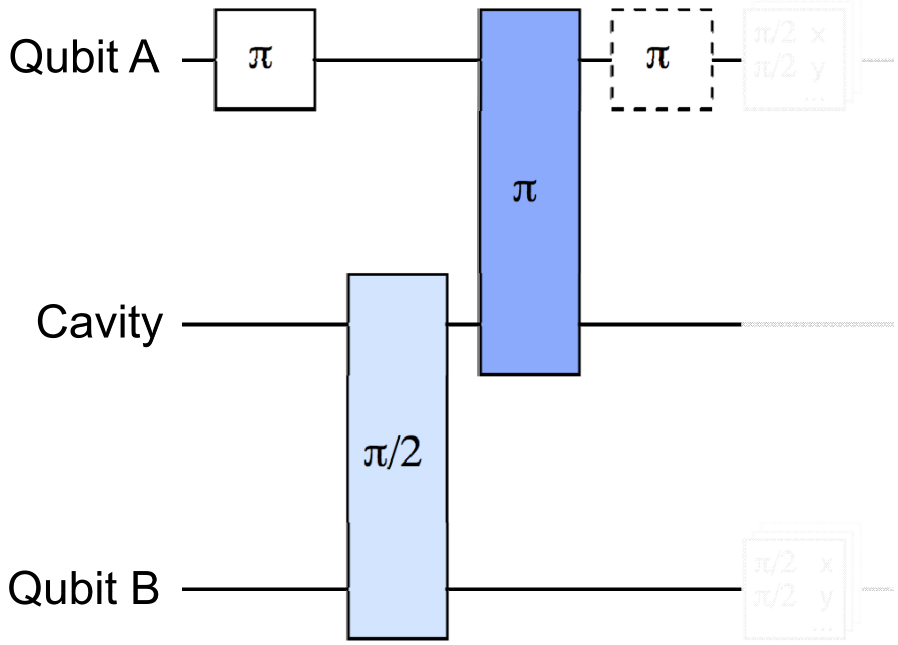
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Bell State Preparation



$$|gg0\rangle \longrightarrow |eg0\rangle \longrightarrow \frac{1}{\sqrt{2}}(|eg0\rangle + |ee1\rangle) \longrightarrow \boxed{\frac{1}{\sqrt{2}}(|eg\rangle + |ge\rangle)} \otimes |0\rangle$$

Bell State Preparation



π pulse qubit A to convert to Φ Bell state

π pulse qubit A

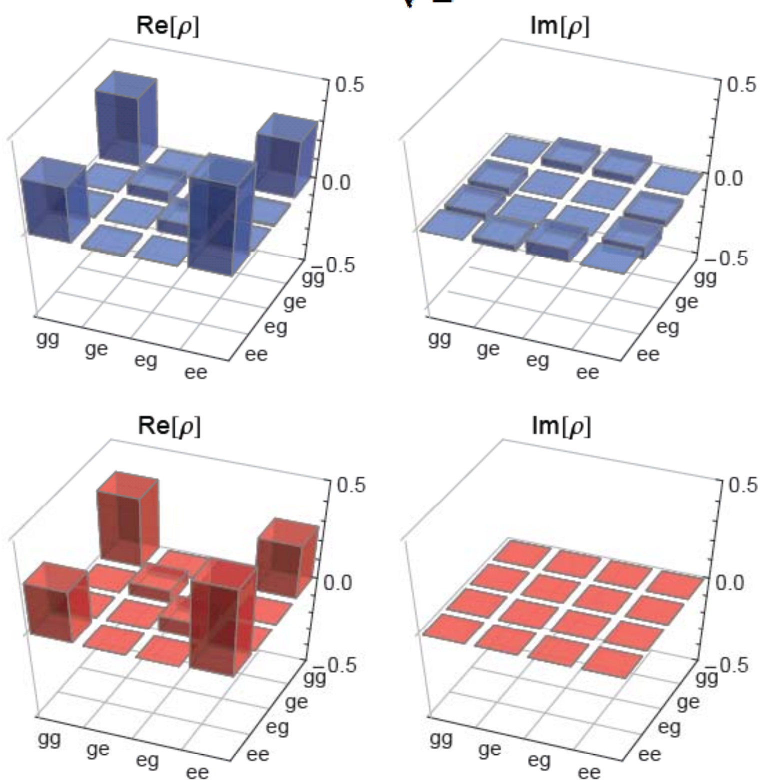
Transfer entanglement to qubit A to create Ψ Bell state

Entangle qubit B with cavity using blue sideband

Characterise the final state using quantum state tomography with joint msrmnt

$$\ldots \longrightarrow \frac{1}{\sqrt{2}}(|eg\rangle + |ge\rangle) \otimes |0\rangle \longrightarrow \frac{1}{\sqrt{2}}(|gg\rangle + |ee\rangle) \otimes |0\rangle$$

$$|\Phi_+\rangle = \frac{1}{\sqrt{2}}(|gg\rangle + |ee\rangle)$$

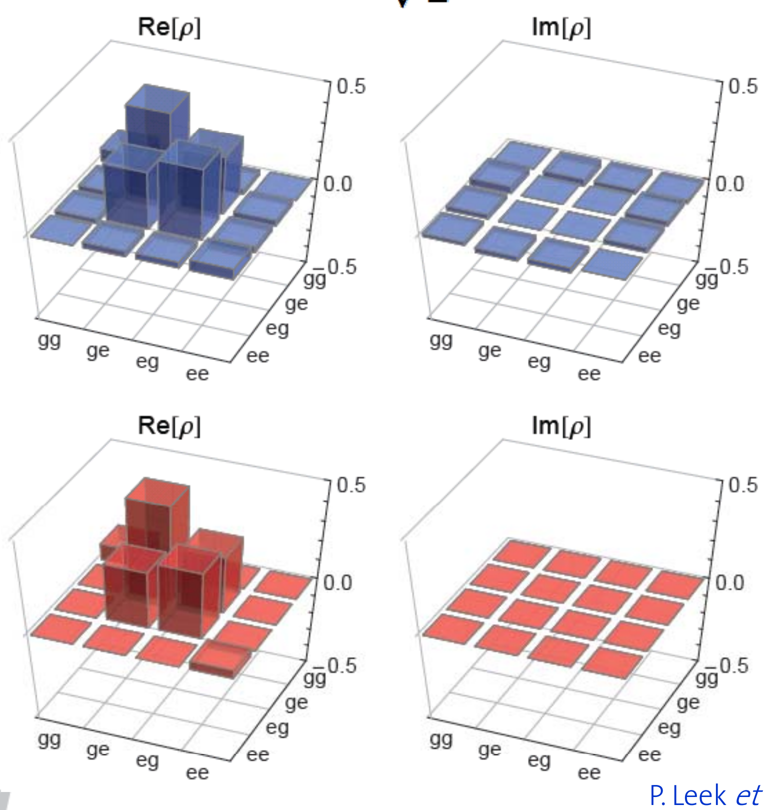


experimental state fidelity: F = 86%
concurrence: 0.541
entanglement of formation : 0.371

overlap with calculation F = 99%

Filipp *et al., Phys. Rev. Lett.* **102**, 200402 (2009)

$$|\Psi_+\rangle = \frac{1}{\sqrt{2}}(|ge\rangle + |eg\rangle)$$



experimental state fidelity: F = 86%
concurrence: 0.518
entanglement of formation : 0.374

overlap with calculation F = 99%

P. Leek *et al., Phys. Rev. B* **79**, 180511(R) (2009)
S. Filipp *et al., Phys. Rev. Lett.* **102**, 200402 (2009)

DiVincenzo Criteria fulfilled for Superconducting Qubits

for Implementing a Quantum Computer in the standard (circuit approach) to quantum information processing (QIP):

#1. A scalable physical system with well-characterized qubits. ✓
#2. The ability to initialize the state of the qubits. ✓
#3. Long (relative) decoherence times, much longer than the gate-operation time. ✓
#4. A universal set of quantum gates. ✓
#5. A qubit-specific measurement capability. ✓

plus two criteria requiring the possibility to transmit information:

#6. The ability to interconvert stationary and mobile (or flying) qubits. ✓
#7. The ability to faithfully transmit flying qubits between specified locations. ✓