Quantum Information Processing with Superconducting Circuits

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Collaborations:
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M. da Silva *(Raytheon, USA)*
K. Ensslin, F. Merkt, V. Wood *(ETH Zurich)*

SEVENTH FRAMEWORK PROGRAMME

CIRCUIT AND CAVITY QUANTUM ELECTRODYNAMICS

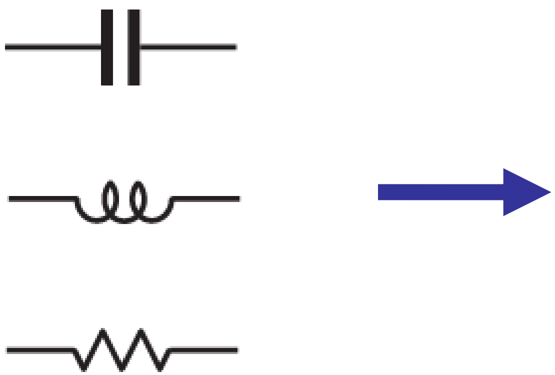
QSIT Quantum Science and Technology
National Centre of Competence in Research

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

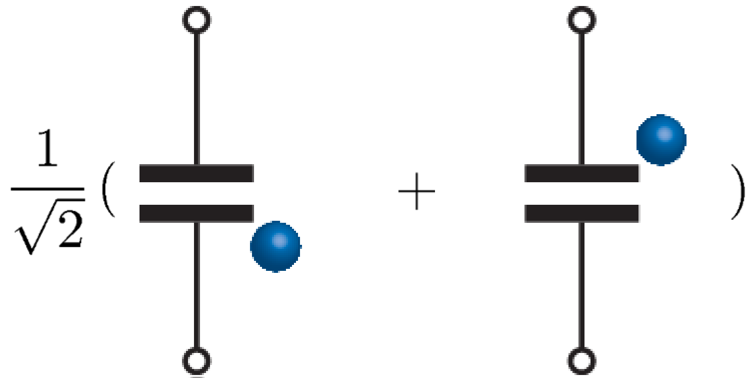
SWISS NATIONAL SCIENCE FOUNDATION

Classical and Quantum Electronic Circuit Elements

basic circuit elements:



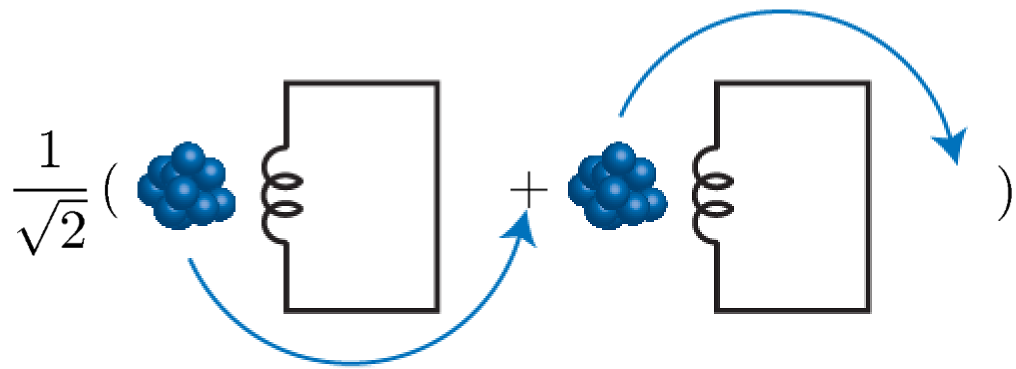
charge on a capacitor:



quantum superposition states:

- charge q
- flux ϕ

current or magnetic flux in an inductor:

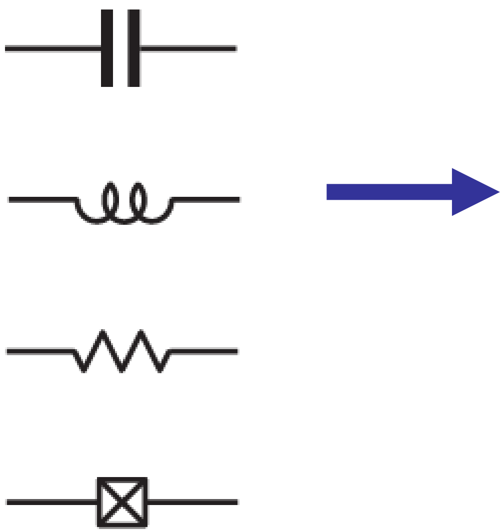


commutation relation (c.f. *x*, *p*):

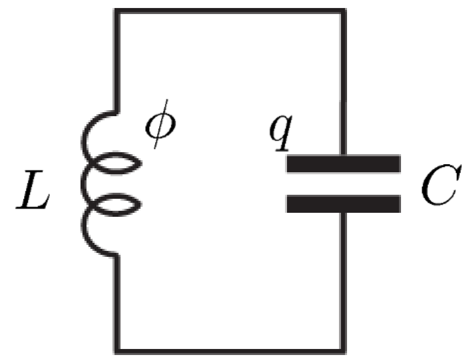
$$\left[\hat{\phi}, \hat{q}\right] = i\hbar$$

Constructing Linear Quantum Electronic Circuits

basic circuit elements:



harmonic LC oscillator:



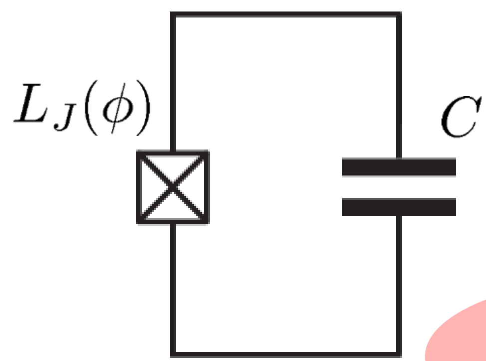
energy:

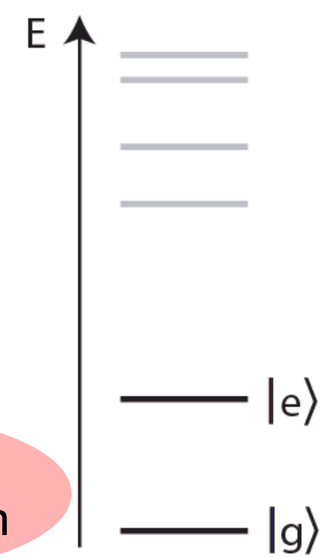
electronic photon

Josephson junction:

a non-dissipative nonlinear element (inductor)

anharmonic oscillator:





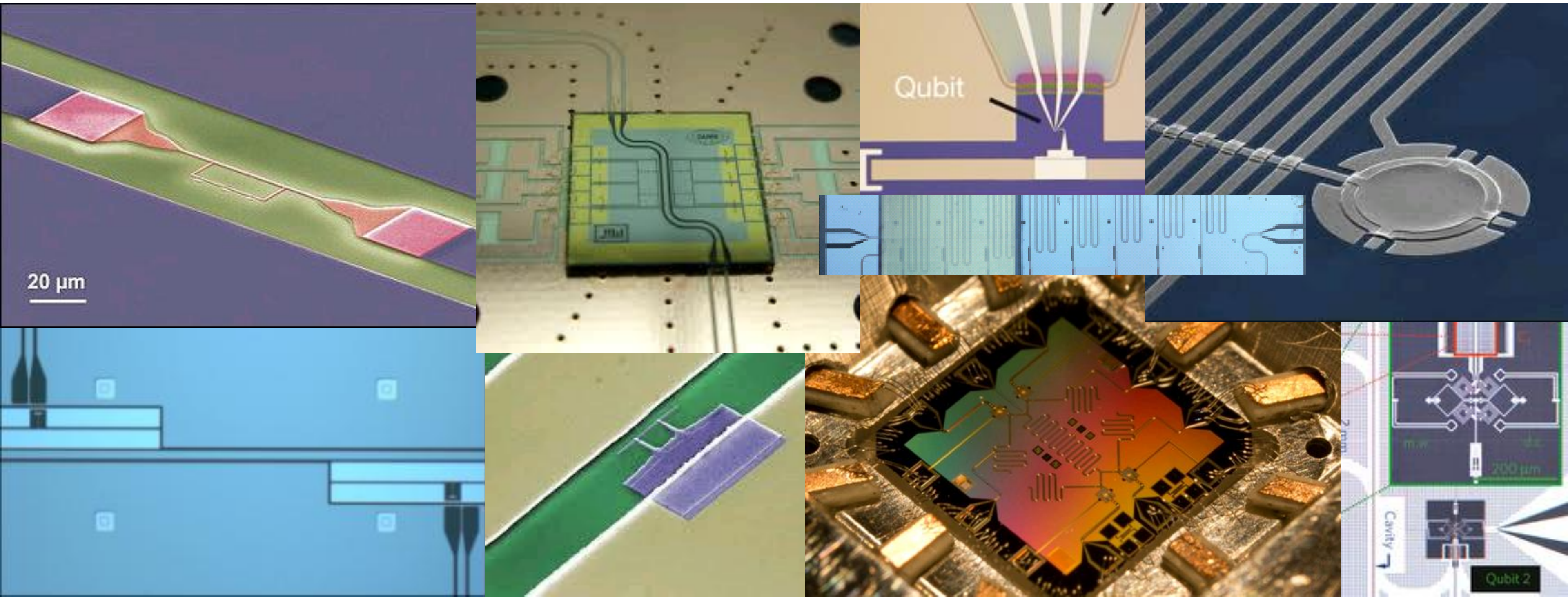
electronic artificial atom

Review: M. H. Devoret, A. Wallraff and J. M. Martinis, *condmat/0411172* (2004)

Superconducting Quantum Electronic Circuits

single or multiple superconducting qubits coupled to harmonic oscillators

- investigated in a few dozen labs around the world
- for basic science and applications

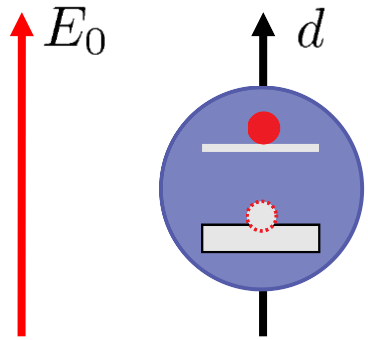


reviews:

R. J. Schoelkopf, S. M. Girvin, *Nature* **451**, 664 (2008)
J. Clarke and F. Wilhelm, *Nature* **453**, 1031 (2008)
J. Q. You and F. Nori, *Nature* **474**, 589 (2011)

Controlling the Interaction of Photons and Qubits

challenging on the level of single particles



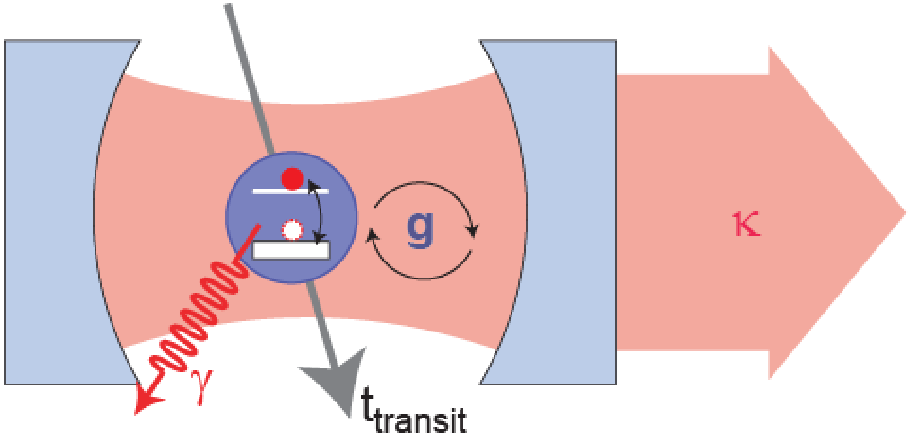
- dipole moment *d* in microscopic systems (usually small ~ ea_o)
- single photon fields E_o (small in 3D)
- photon/qubit interaction $\hbar g \sim dE_0$ (usually small)

What to do?

- confine qubit and photon in a cavity (cavity QED)
- engineer qubit/light interaction in solid state circuits

D. Walls, G. Milburn, Quantum Optics (Spinger-Verlag, Berlin, 1994)

Cavity QED with Superconducting Circuits

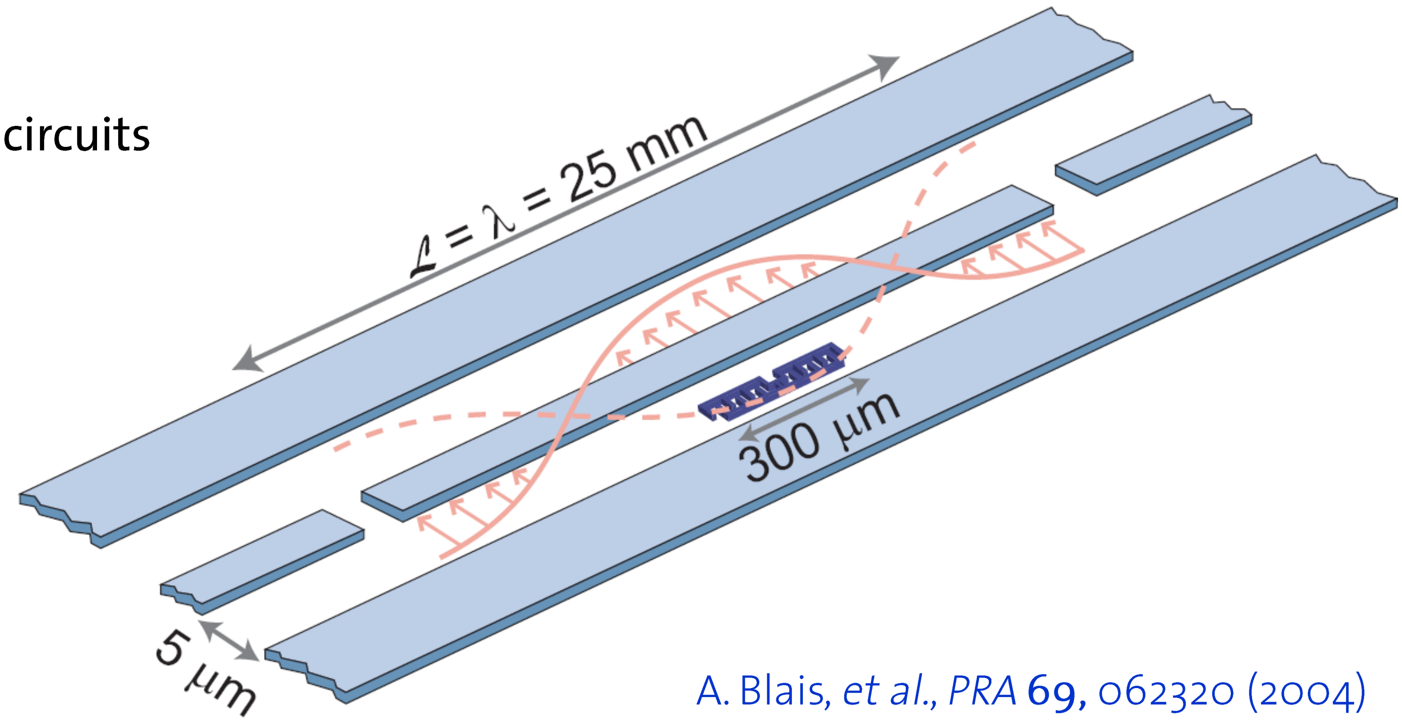


coherent interaction of photons with quantum two-level systems ...

J. M. Raimond *et al.*, *Rev. Mod. Phys.* **73**, 565 (2001)
S. Haroche & J. Raimond, *OUP Oxford* (2006)
J. Ye., H. J. Kimble, H. Katori, *Science* **320**, 1734 (2008)

... in superconducting circuits

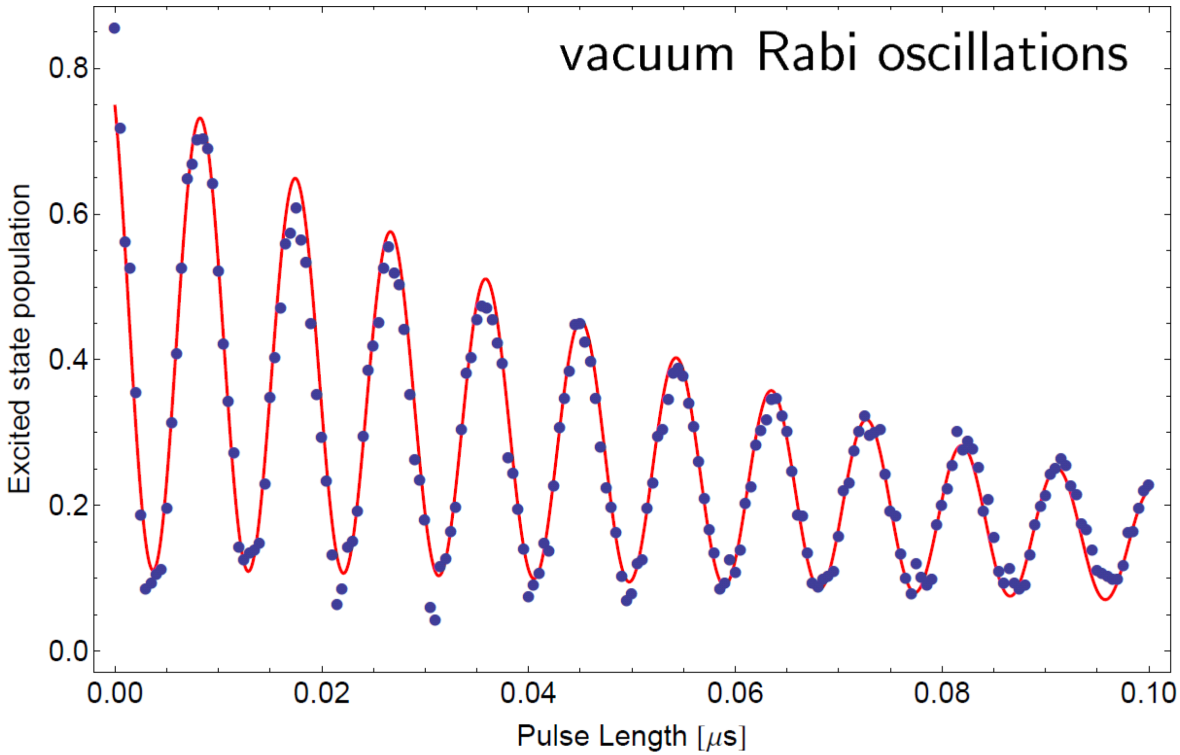
circuit quantum electrodynamics



A. Blais, *et al.*, *PRA* **69**, 062320 (2004)
A. Wallraff *et al.*, *Nature (London)* **431**, 162 (2004)
R. J. Schoelkopf, S. M. Girvin, *Nature (London)* **451**, 664 (2008)

Resonant Vacuum Rabi Mode Splitting ...

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

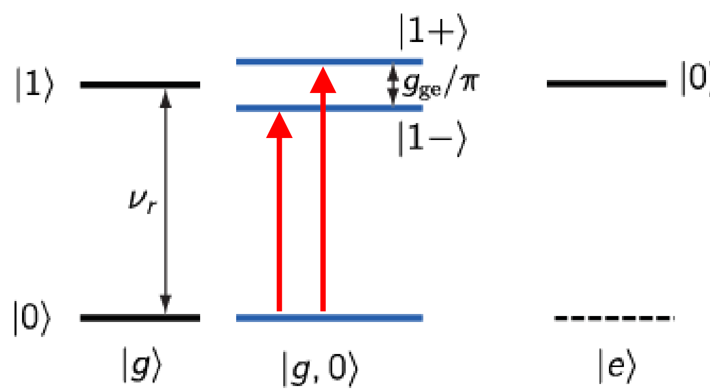


very strong coupling:

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

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

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



forming a 'molecule' of a qubit and a photon

first demonstration in a solid: A. Wallraff *et al.*, *Nature (London)* **431**, 162 (2004)

this data: J. Fink et al., *Nature (London)* **454**, 315 (2008)

R. J. Schoelkopf, S. M. Girvin, *Nature (London)* **451**, 664 (2008)

Quantum Physics with Circuit QED ... some examples

Vacuum Rabi Mode Splitting
A. Wallraff *et al.*, *Nature* **431**, 162 (2004)

Coherent Flux-Qubit / SQUID Coupling
I. Chiorescu *et al.*, *Nature* **431**, 159 (2004)

Quantum AC-Stark Shift
D. Schuster *et al.*, *Nature* **445**, 515 (2007)

Lamb Shift
A. Fragner *et al.*, *Science* **322**, 1357 (2008)

Fock and Arbitrary Photon States
M. Hofheinz *et al.*, *Nature* **454**, 310 (2008)
M. Hofheinz *et al.*, *Nature* **459**, 546 (2009)

Root n Nonlinearity
J. Fink *et al.*, *Nature* **454**, 315 (2008)

Two Photon Nonlinearities
F. Deppe *et al.*, *Nat. Phys.* **4**, 686 (2008)

Parametric Amplification
Castellanos-Beltran *et al.*, *Nat. Phys.* **4**, 928 (2008)

Super Splitting and Root n Nonlinearity
L. Bishop *et al.*, *Nat. Phys.* **5**, 105 (2009)

Ultrastrong Coupling
T. Niemczyk *et al.*, *Nat. Phys.* **6**, 772 (2010)

Single Photon Source
A. Houck *et al.*, *Nature* **449**, 328 (2007)

Single Qubit MASER
O. Astafiev *et al.*, *Nature* **449**, 588 (2007)

Single Qubit Resonance Fluorescence
O. Astafiev *et al.*, *Science* **327**, 840 (2010)

QND Measurement of Single Photon
B. Johnson *et al.*, *Nat. Phys.* **6**, 663 (2010)

Correlation Function Measurements
D. Bozyigit et al., *Nat. Phys.* **7**, 154 (2011)

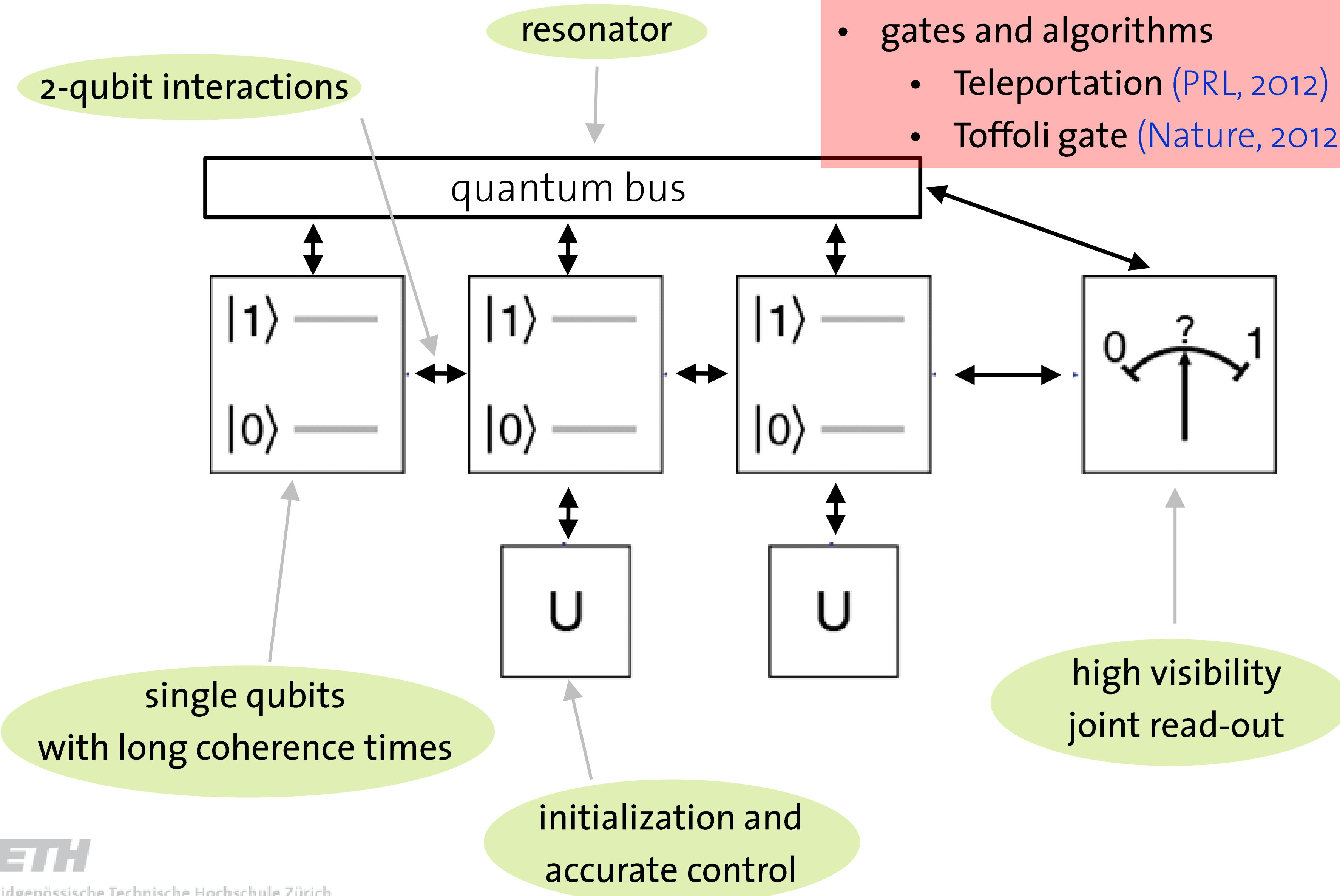
Cooling and Amplification
M. Grajcar *et al.*, *Nat. Phys.* **4**, 612 (2008)

Quantum Algorithms & Entangled States
L. DiCarlo *et al.*, *Nature* **460**, 240 (2009)
L. DiCarlo *et al.*, *Nature* **467**, 574 (2010)
A. Fedorov *et al.*, *Nature* **481**, 170 (2012)
M. Reed *et al.*, *Nature* **481**, 382 (2012)

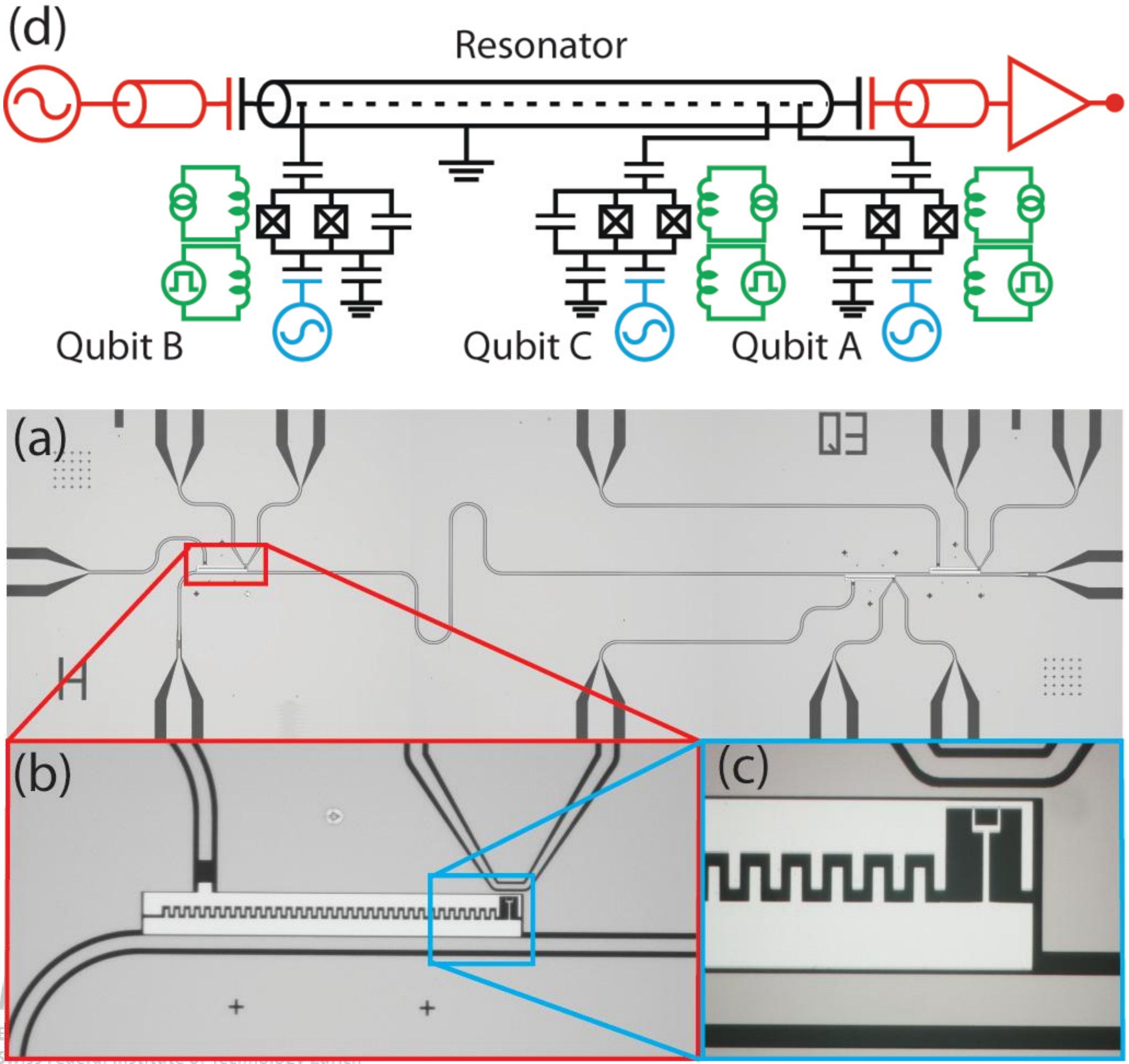
Quantum Bus
M. Sillanpaa *et al.*, *Nature* **449**, 438 (2007)
H. Majer *et al.*, *Nature* **449**, 443 (2007)
M. Mariantoni *et al.*, *Nat.Phys.* **7**, 287 (2011)
M. Mariantoni *et al.*, *Science* **334**, 61 (2011)

Quantum Information Processing

- generating 3 qubit entanglement
- gates and algorithms
  - Teleportation (PRL, 2012)
  - Toffoli gate (Nature, 2012)



Quantum Processor Platform with 3 Qubits



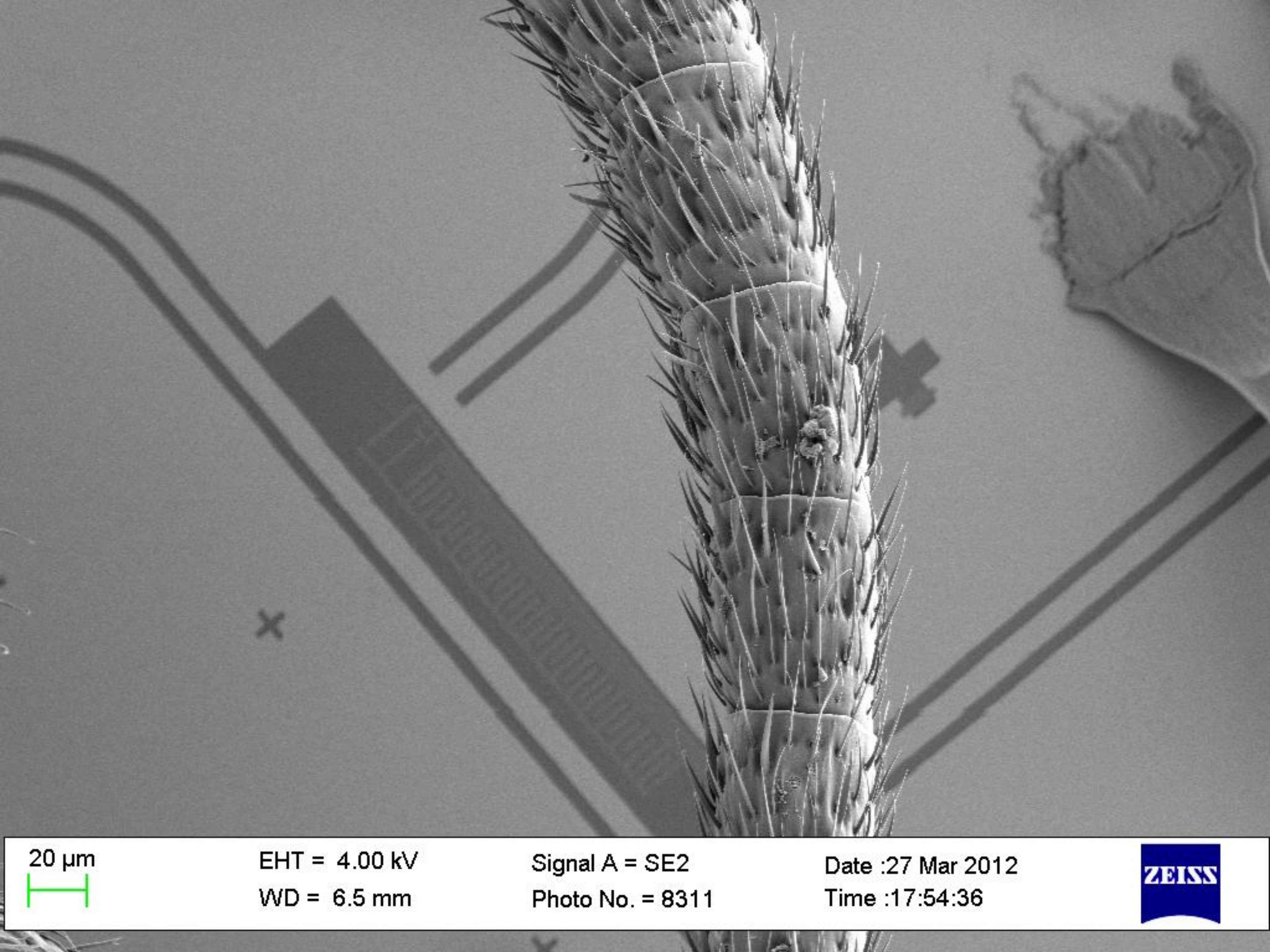
3 Transmon qubits

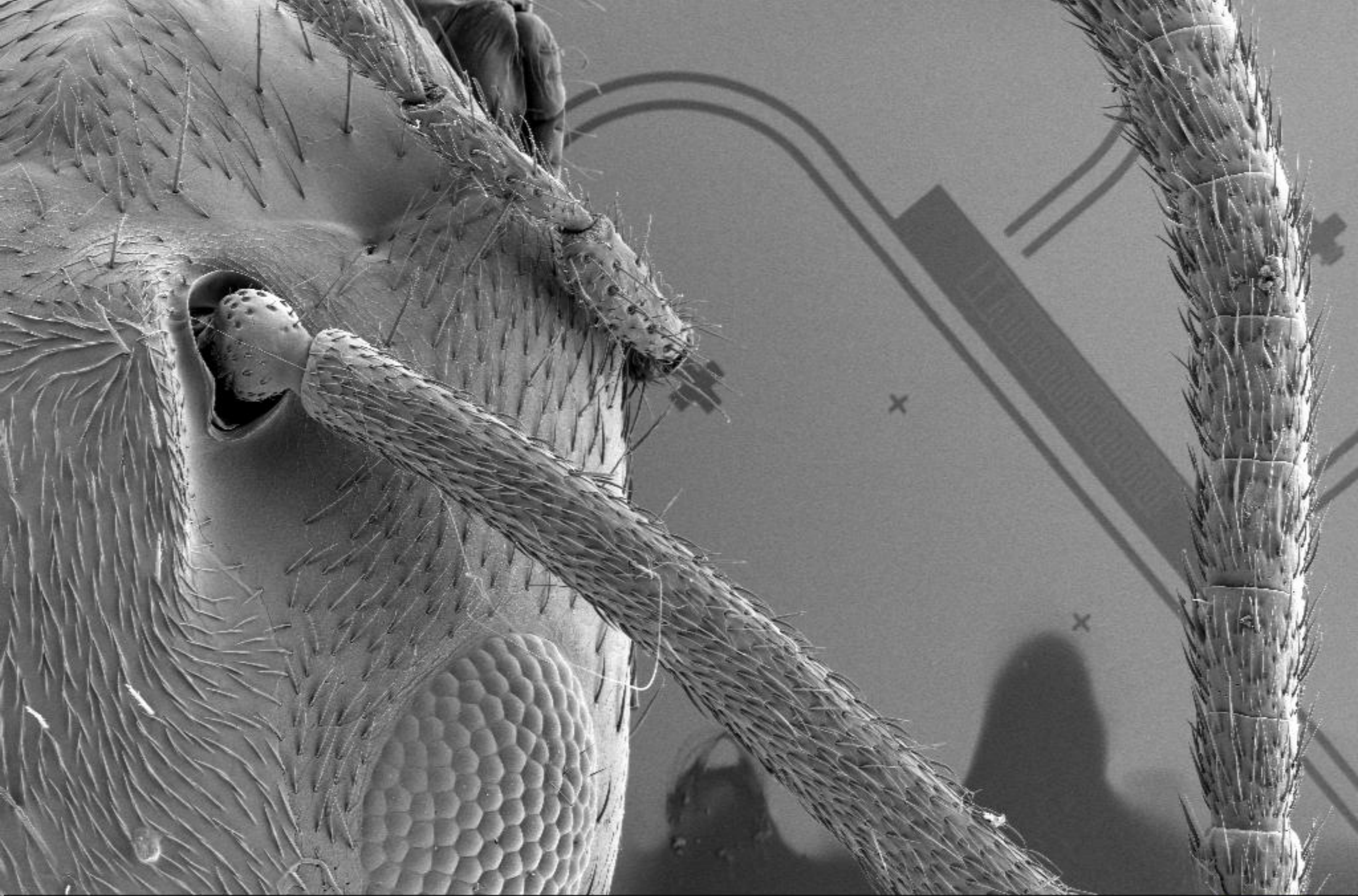
- individual control via local electric and magnetic fields
- Coherences times: $T_1 \sim 0.8 - 1.2\ \mu s$ $T_2 \sim 0.4 - 0.7\ \mu s$
- Large coupling $g/2\pi \sim 300$ MHz

Resonator

- $f_0 \sim$ 8.625 GHz for reduced density of resonator modes

M. Baur et al., *Phys. Rev. Lett.* 108, 040502 (2012)


20 µm
EHT = 4.00 kV
WD = 6.5 mm
Signal A = SE2
Photo No. = 8311
Date :27 Mar 2012
Time :17:54:36
ZEISS



100 µm

EHT = 4.00 kV

WD = 6.5 mm

Signal A = SE2

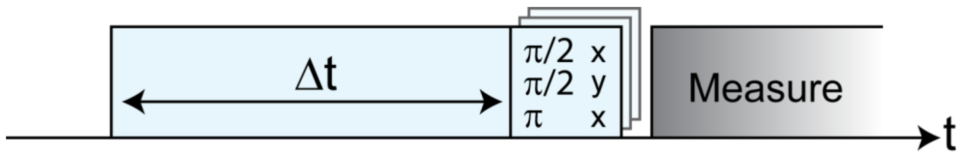
Photo No. = 8347

Date :27 Mar 2012

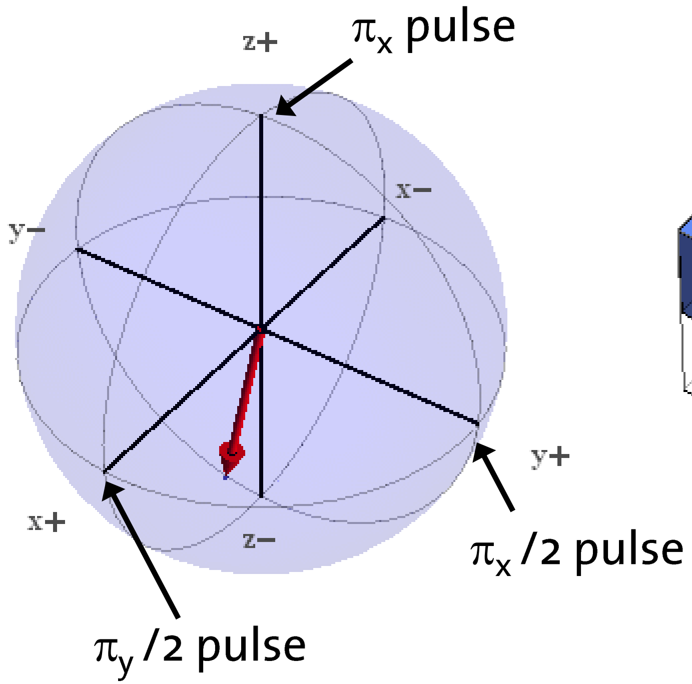
Time :18:38:14

Single Qubit Operations and Measurement

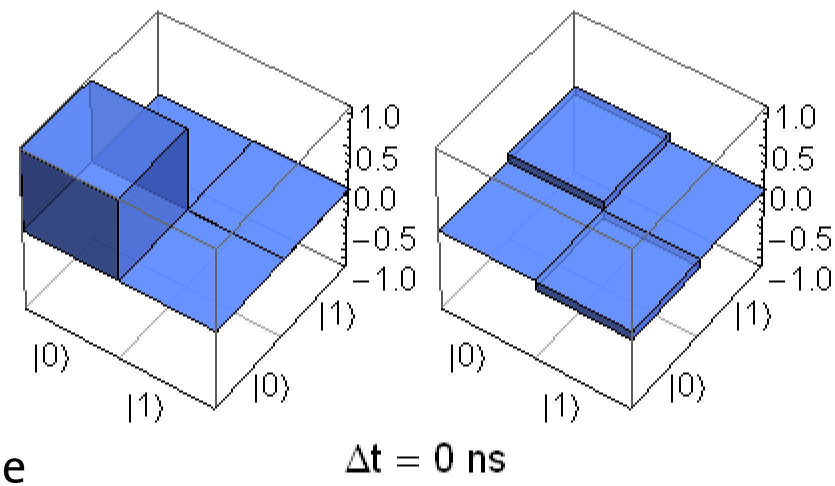
Pulse sequence for qubit rotation and readout



experimental Bloch vector



experimental density matrix



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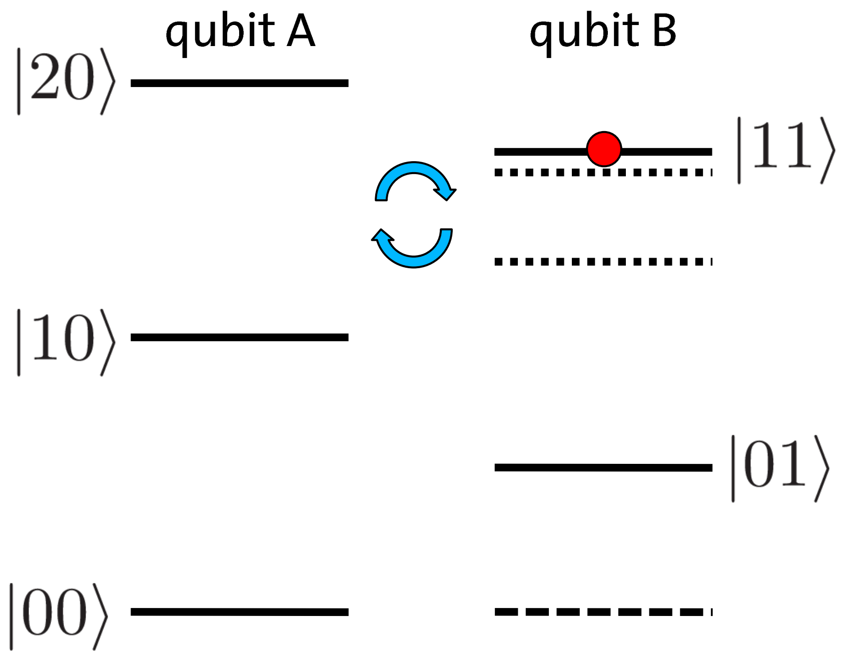
Swiss Federal Institute of Technology Zurich

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

Universal Two-Qubit Gate

Tune levels into resonance using magnetic field

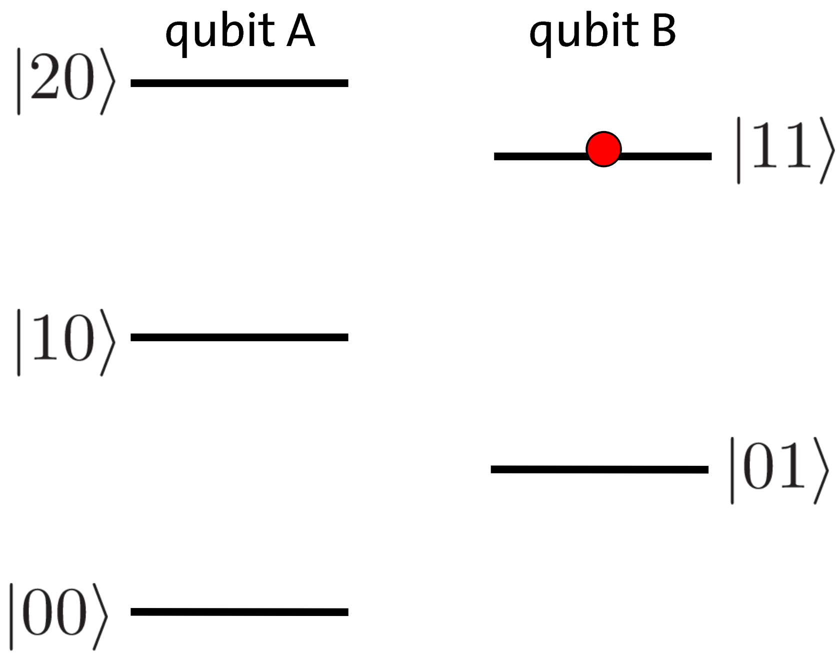


Interaction mediated by virtual photon exchange through resonator

$$|11\rangle \longrightarrow i|20\rangle \longrightarrow -|11\rangle$$

proposal: F. W. Strauch, *Phys. Rev. Lett.* **91**, 167005 (2003).
first implementation: L. DiCarlo, *Nature* **460**, 240 (2010).

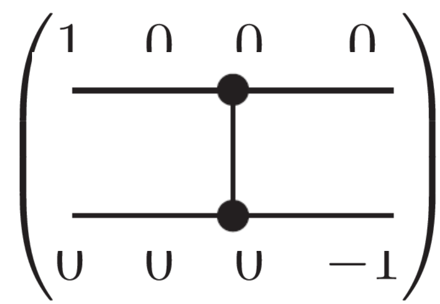
Controlled Phase Gate



Universal two-qubit gate. Used together with single-qubit gates to create any quantum operation.

$$|11\rangle \longrightarrow i|20\rangle \longrightarrow -|11\rangle$$
$$|01\rangle \longrightarrow |01\rangle$$
$$|10\rangle \longrightarrow |10\rangle$$
$$|00\rangle \longrightarrow |00\rangle$$

C-Phase gate:



proposal: F. W. Strauch, *Phys. Rev. Lett.* **91**, 167005 (2003).

first implementation: L. DiCarlo, *Nature* **460**, 240 (2010).

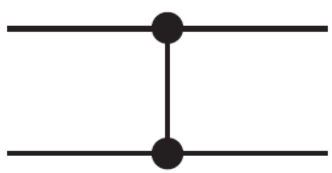
Process Tomography: C-Phase Gate

arbitrary quantum process $\rho' = \mathcal{E}(\rho)$ decomposed into $\mathcal{E}(\rho) = \sum_{mn} \tilde{E}_m \rho \tilde{E}_n^\dagger \chi_{mn}$

$\{\tilde{E}_k\}$ is an operator basis

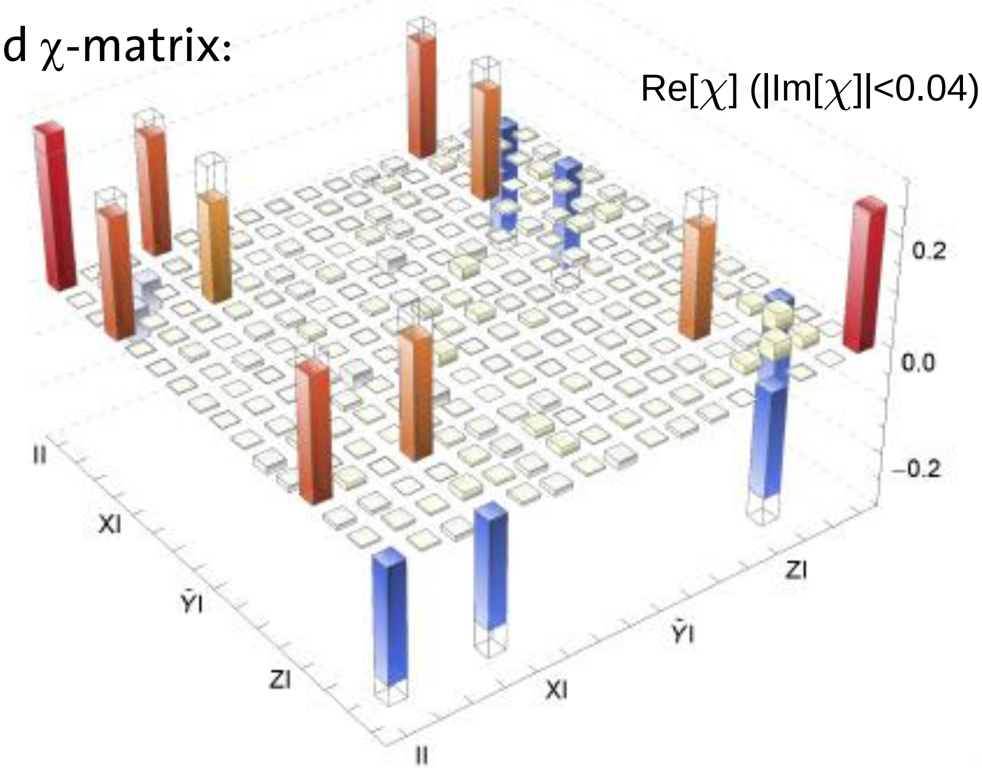
χ is a positive semi definite Hermitian matrix characteristic for the process

Controlled phase gate



$$cZ_{00} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Measured χ-matrix:

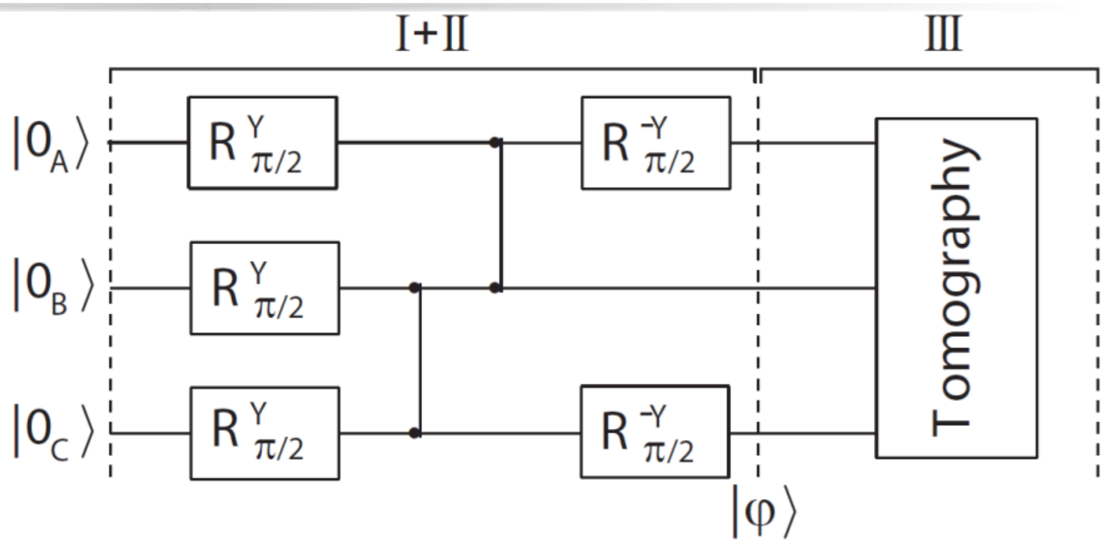


$F = \mathrm{Tr}[\chi_{\mathrm{meas}} \chi_{\mathrm{ideal}}] = 0.86$

Maximally Entangled Three Qubit States

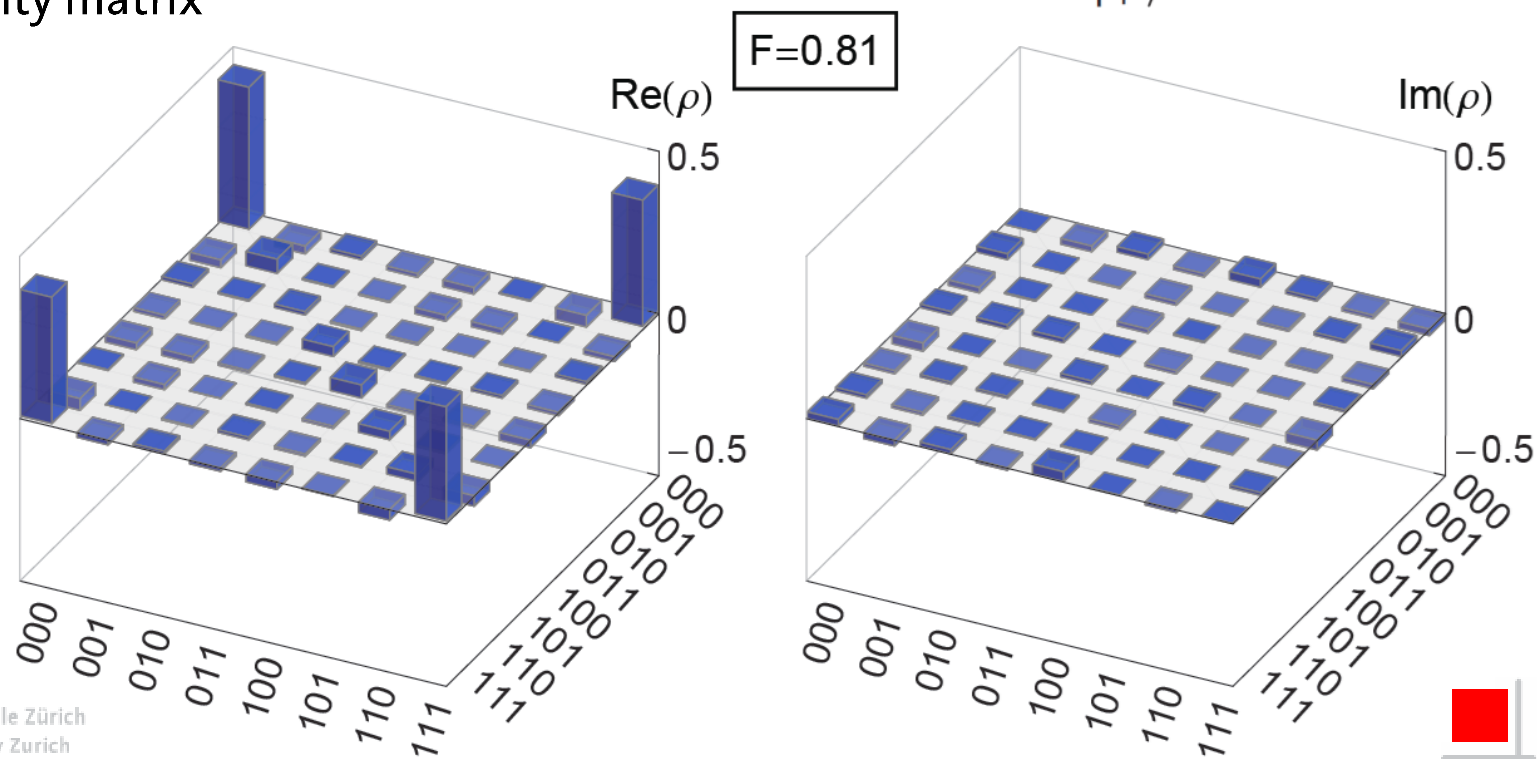
Generation of GHZ class, e.g. |000>+|111>, states:

- single qubit gates
- C-PHASE gates



Measured density matrix

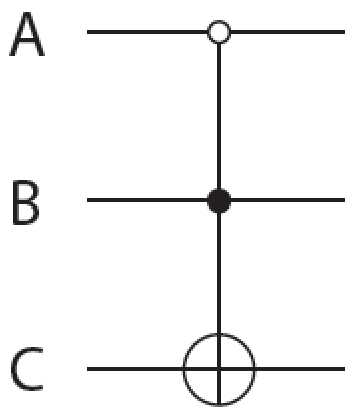
- high fidelity



The Toffoli Gate

proposed by ***Tommaso Toffoli*** in 1980

- *any* reversible computation can be performed with *only* the Toffoli gate



function:

- inverts qubit C only if qubits A and B are in selected basis states

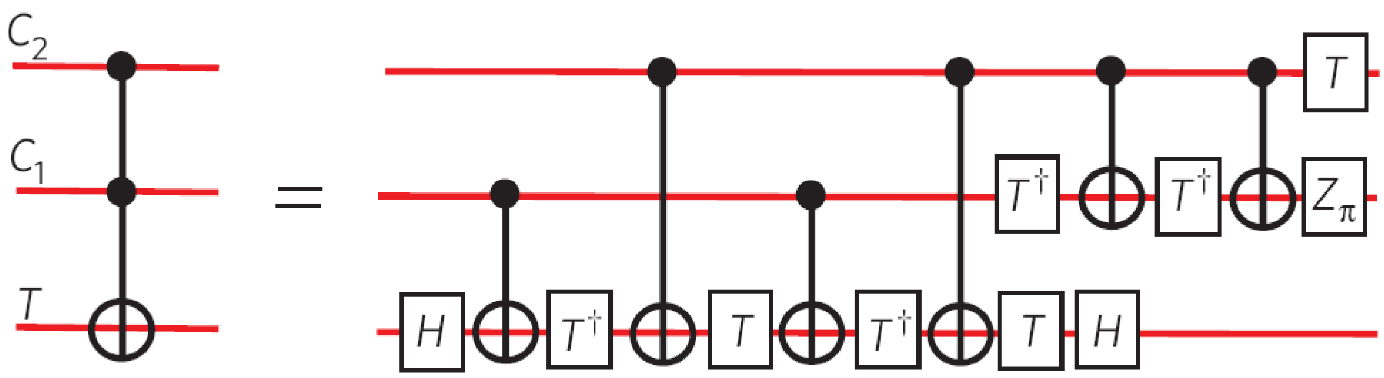
applications:

- for universal reversible classical computation
- for simplification of complex quantum circuits
- used in quantum error-correction schemes (essential for any practical quantum processor)

Implementation of a Toffoli Gate

with only single and two-qubit gates requires:

- 6 CNOT gates
- 10 single qubit gates



Inefficient decomposition not feasible with any solid state system yet!

Idea by T. C. Ralph *et. al., PRA* 75, 022313 (2007):

- use higher levels (qutrits) for efficient decomposition

Circuit Diagram

New approach: use qubit-qutrit gates for the *more efficient* decomposition!

CC-PHASE – inverts the sign for only one basis state

Equivalent to Toffoli up to single qubit rotations

same amount of resources, more efficient

ETH
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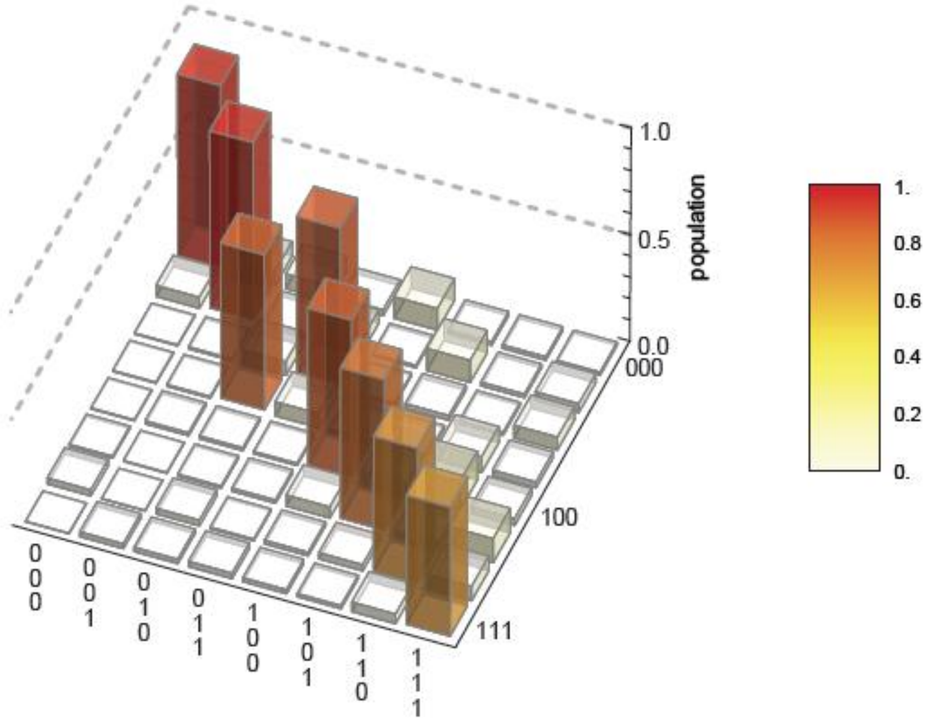
Swiss Federal Institute of Technology Zurich

A. Fedorov et al., *Nature (London)* **481**, 170 (2012)

Truth Table

- characterizes the action of the Toffoli gate on the basis input states
- Fidelity

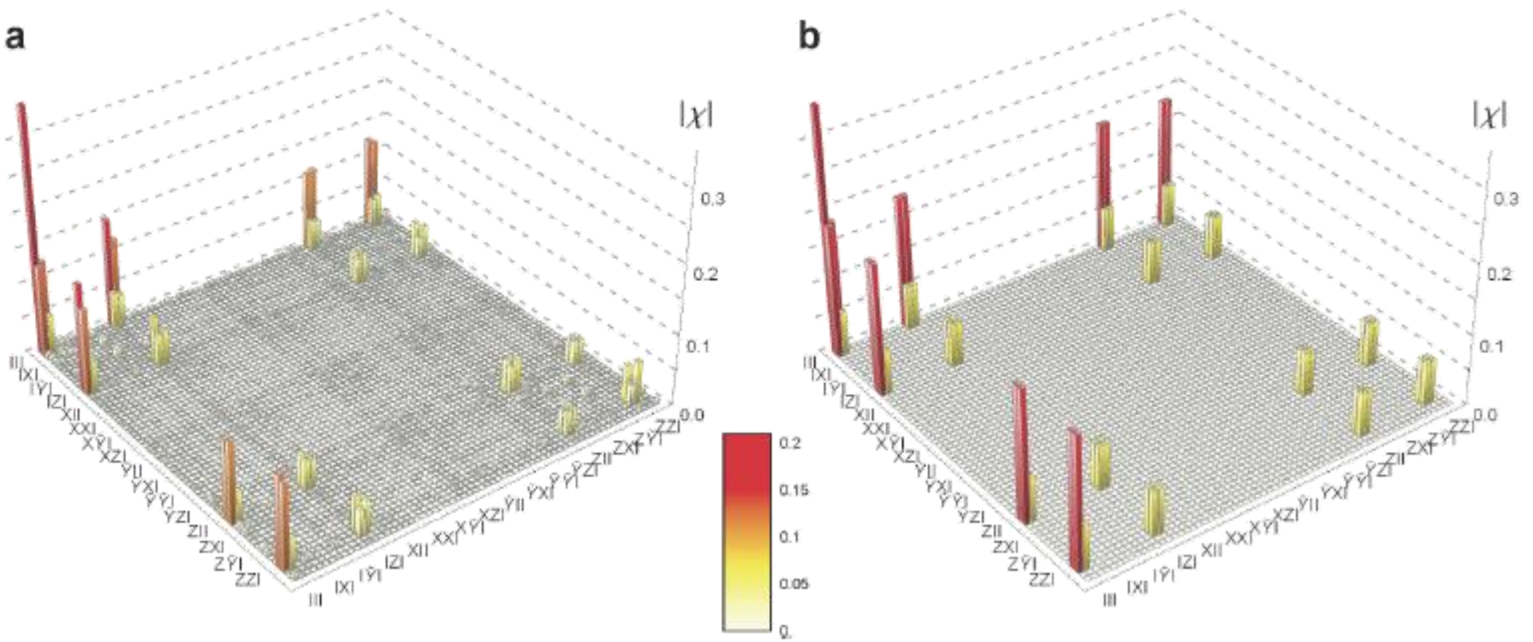
$$F = \frac{1}{8}\mathrm{Tr}\left[U_{\mathrm{exp}}^{T} U_{\mathrm{ideal}}\right] = 76\%$$



A. Fedorov et al., *Nature (London)* **481**, 170 (2012)

Process Tomography

- Fully characterizes the process by evaluating χ-matrix (ML)



- Fidelity $$F = \frac{1}{8}\mathrm{Tr}\left[\chi_{\mathrm{exp}}^{T}\chi_{\mathrm{ideal}}\right] = 69 \text{ +- } 3\ \%$$

- Monte Carlo process certification does not rely on maximum-likelihood procedures [da Silva et al., *PRL* **107**, 210404 (2011), Steffen et al., arXiv:1202.5196]

$$F = \quad 68.5 \text{ +- } 0.5\ \%$$

A. Fedorov et al., *Nature (London)* **481**, 170 (2012)

Toffoli Gate and Error Correction in Circuits

- Realization and full characterization of 3 qubit Toffoli gate also with efficient process certification
  A. Fedorov et al., *Nature (London)* **481**, 170 (2012)
  L. Steffen et al., arXiv:1202.5196 (2012)

- Realization of Toffoli-class gate with only two qubits (used resonator as 3rd qubit) and limited characterization (phase fidelity)
  M. Mariantoni et al., *Science* **334**, 61 (2011)

- First use of Toffoli gate for correcting an induced error
  M. D. Reed et al., Nature (London) **482**, 382 (2012)

Teleportation

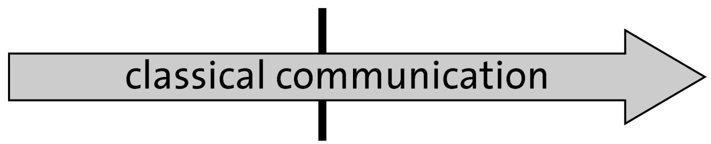
Task:

- transmit state of unknown qubit (A) from Alice to Bob

Resources:

- a pair of entangled qubits (B+C)
- a small quantum computer
- classical communication

Alice



Bob

Features:

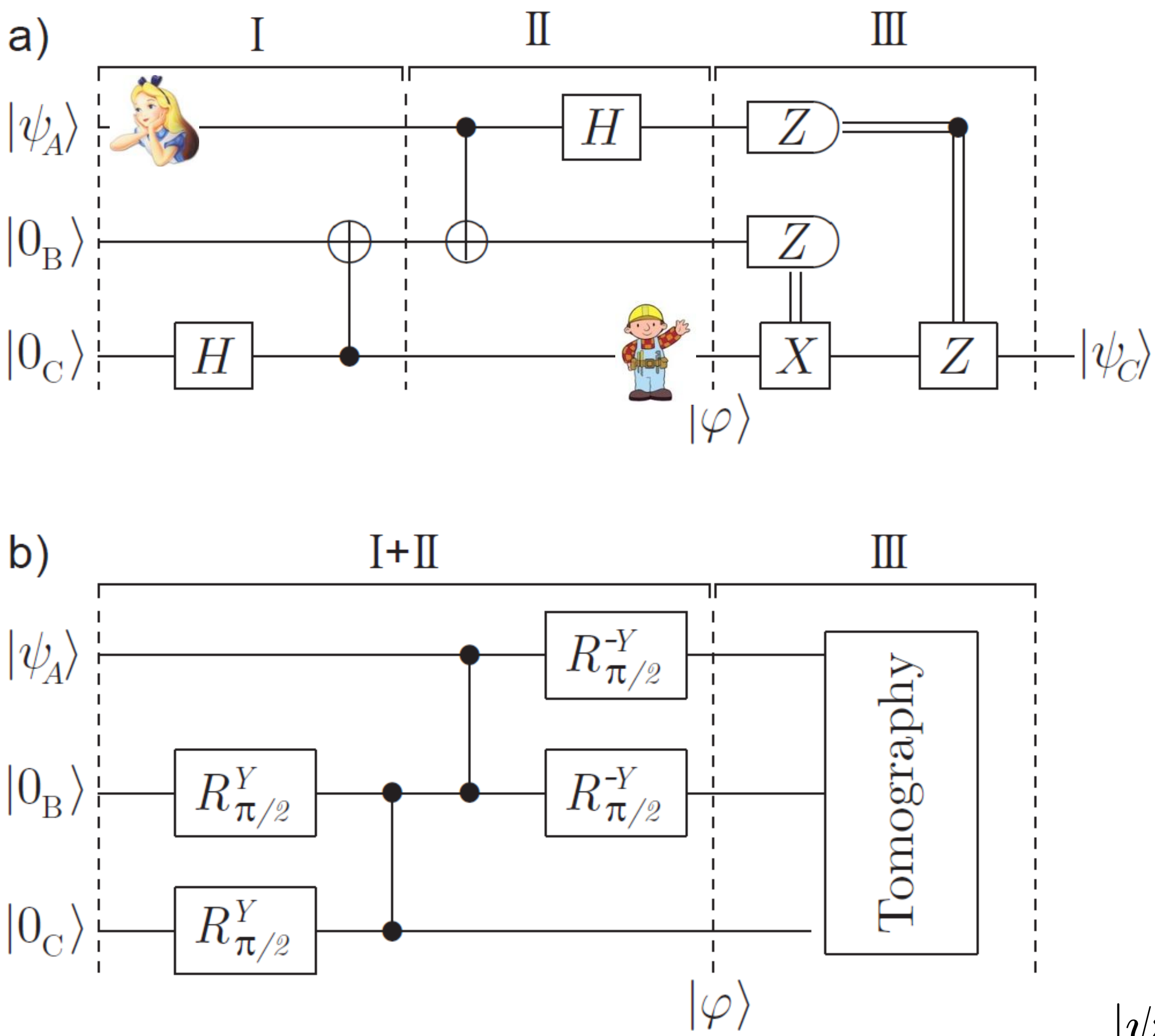
- exploits non-local quantum correlations
- contains the same essential steps as for realizing a quantum computer: important benchmark to pass!

Applications:

- quantum repeaters
- simplification of quantum circuits
- universal computation

Has been demonstrated for photons and ions, but not yet in any solid state system!

Quantum Circuit for Teleportation



teleportation scheme with single shot measurement and feed-back

here: demonstrate scheme without use of feed-back

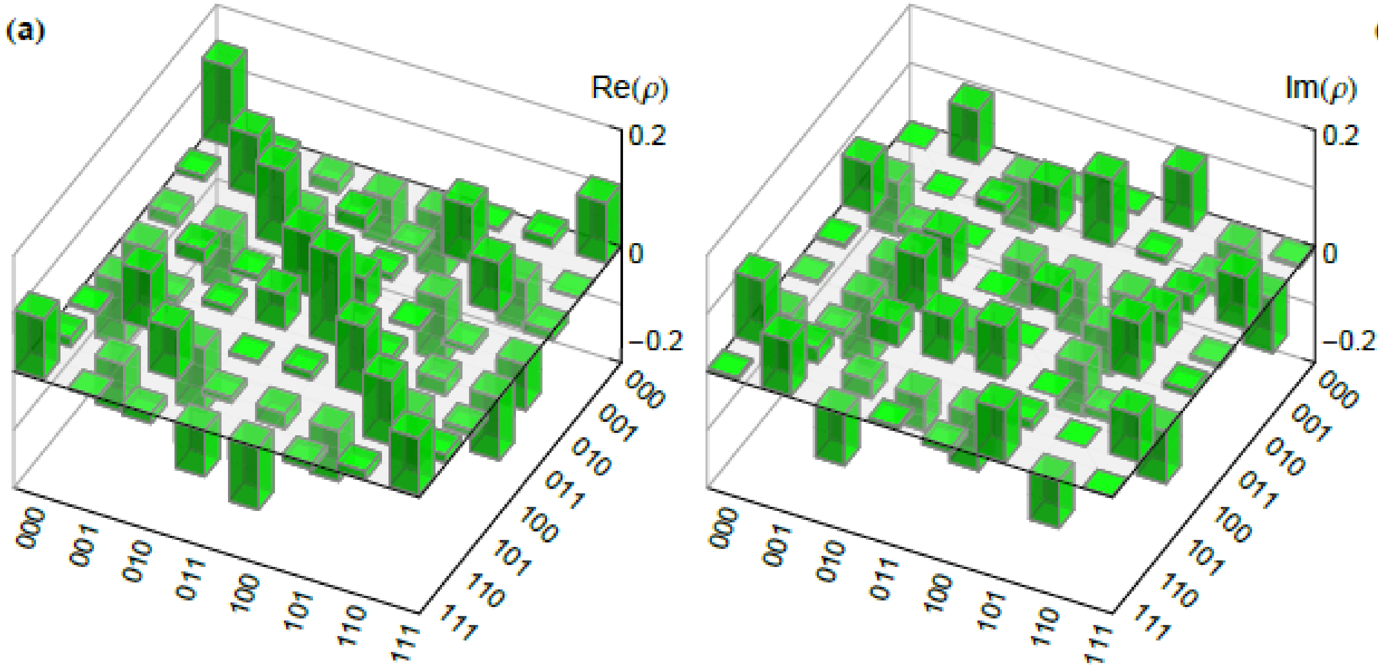
implemented three qubit tomography at step III

projection on A and B to recover density matrix of teleported state

$$|\psi\rangle\langle\psi| = \langle 0_A 0_B|\rho_{A,B,C}|0_A 0_B\rangle$$

M. Baur *et al.*, *Phys. Rev. Lett.* **108**, 040502 (2012)

Characterizing the Full System State



measured 3-qubit entangled state after execution of circuit:

input state: $|\psi\rangle = (|0\rangle - i|1\rangle)/\sqrt{2}$

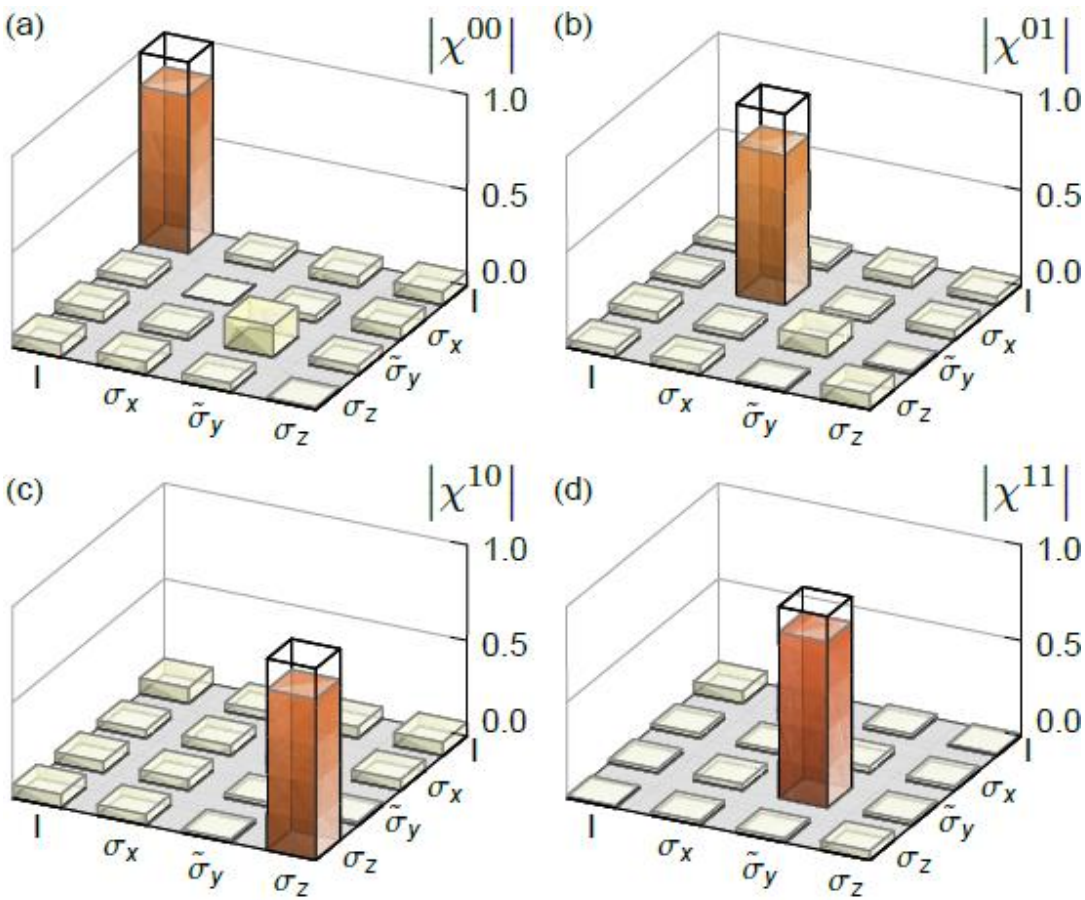
density matrix of teleported state when projecting qubits A & B onto |00>

M. Baur *et al.*, *PRL* **108**, 040502 (2012)

Benchmarking the Teleportation Process

procedure:

- prepare set of input states
- run circuit
- perform tomography on full system state
- project on basis states for qubits A and B
- analyze process acting on qubit C (see a-d)
- average fidelity of teleportation 83%

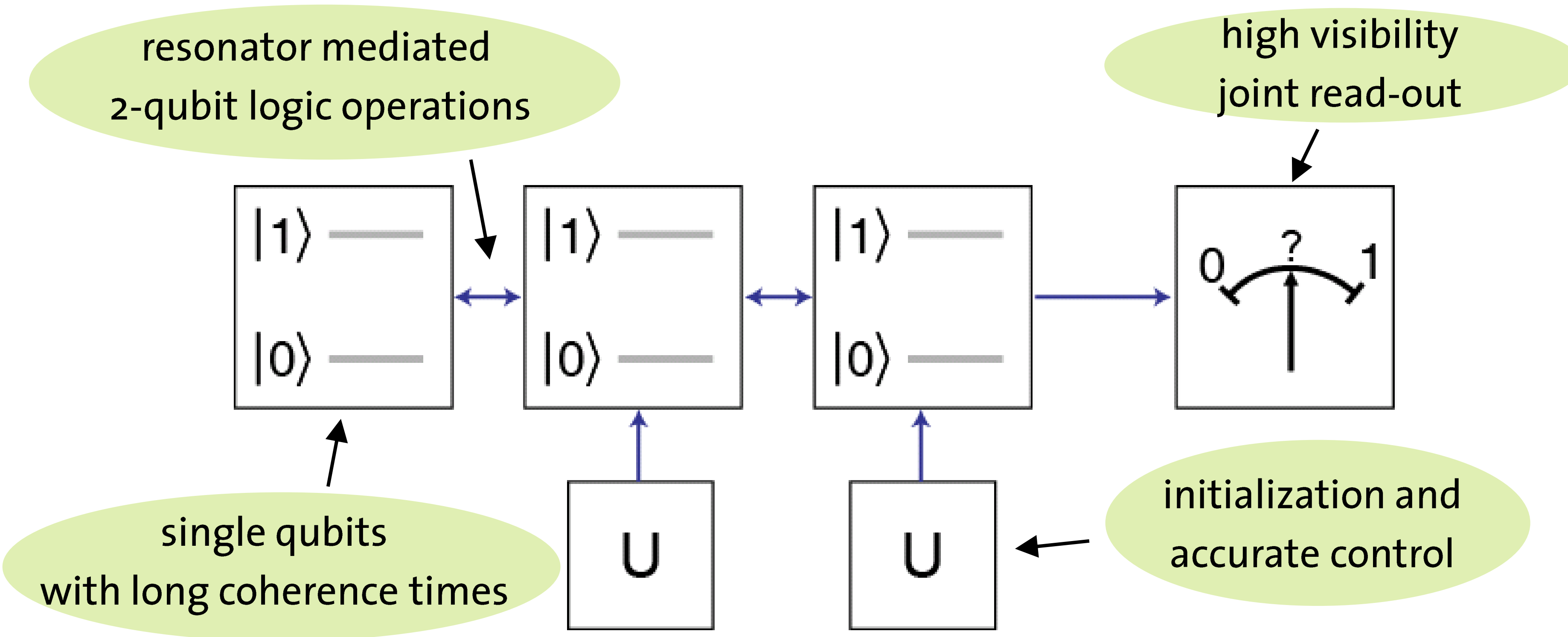


summary:

- verified operation of teleportation circuit & demonstrated 3-qubit quantum processor
- without single-shot projective read-out or feed-back

M. Baur *et al.*, *Phys. Rev. Lett.* **108**, 040502 (2012)

Quantum Computing using Circuit QED



Recently:

- Toffoli gate for error correction
  A. Fedorov et al., *Nature* **481**, 170 (2012)
- benchmarking of teleportation circuit
  M. Baur *et al.*, *PRL* **108**, 040502 (2012)

Future challenges:

- improve coherence times
- address scalability questions
- realize feed-back
- solve interesting problems (quantum simulation, error correction)


The ETH Zurich Quantum Device Lab
Postdoc and PhD positions available
FNSNF
Swiss National Science Foundation
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
QSIT Quantum Science and Technology
National Centre of Competence in Research
QED
CIRCUIT AND CAVITY
QUANTUM ELECTRODYNAMICS
aqute
SOLID
erc
GEOMDISS

Selected Circuit QED Publications

Circuit QED Proposal:

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

Strong Coupling & Vacuum Rabi Mode Splitting:

- Wallraff et al., *Nature* **431**, 162 (2004)
- Fink et al., *Nature* **454**, 315 (2008)
- Fink et al., *PRL* **105**, 163601 (2010)

Tavis-Cummings Multi-Atom QED:

- Fink et al., *PRL* **103**, 083601 (2009)

AC-Stark & Lamb Shift, Autler-Townes and Mollow Transitions

- Schuster et al., *PRL* **94**, 123062 (2005)
- Gambetta et al., *PRA* **74**, 042318 (2006)
- Schuster et al., *Nature* **445**, 515 (2007)
- Fragner et al., *Science* **322**, 1357 (2008)
- Baur et al., *PRL* **102**, 243602 (2009)

Itinerant Photons, Tomography, Photon Blockade

- da Silva et al., *PRA* **82**, 043804 (2010)
- Bozyigit et al., *Nat. Phys.* **7**, 154(2011)
- Eichler et al., *PRL* **106**, 220503 (2011)
- Lang et al., *PRL* **106**, 243601 (2011)
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