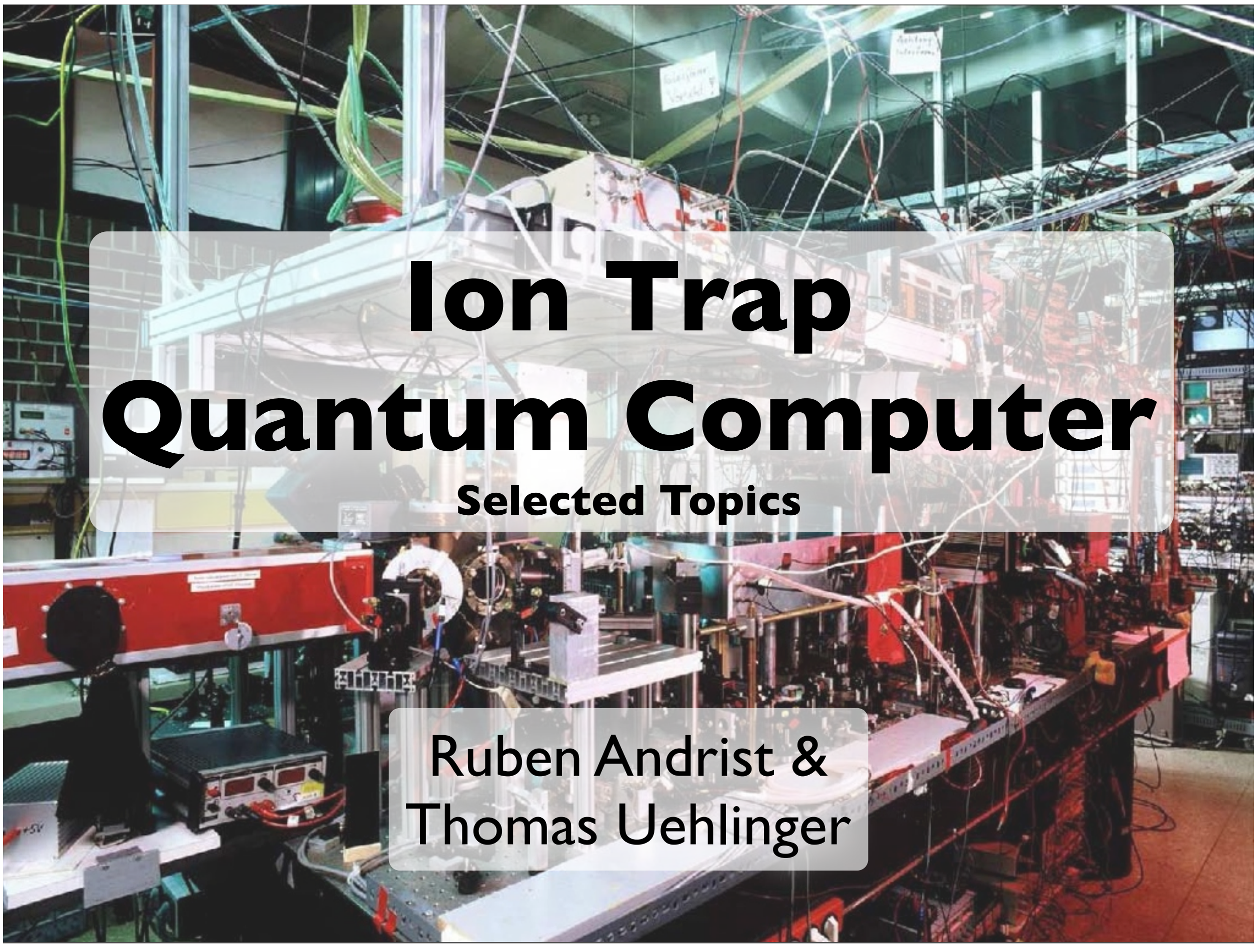


Ion Trap Quantum Computer

Selected Topics

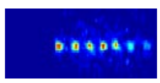
Ruben Andrist &
Thomas Uehlinger

Outline

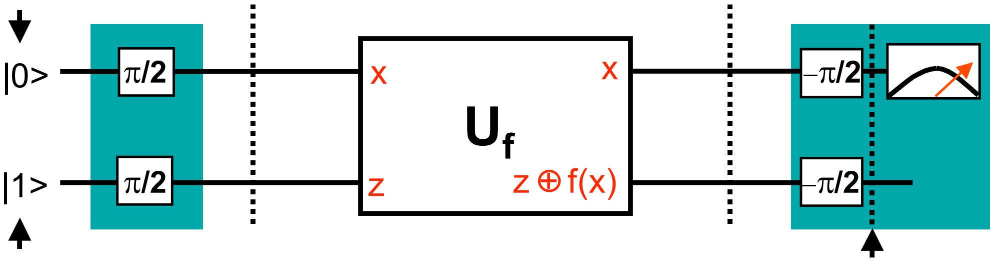
Part I
Deutsch-Josza algorithm

Part II
Scalability of ion trap quantum computers

Part III
Roundup & Outlook



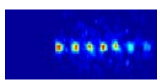
Part I
Quantum Algorithms



Implementation of the Deutsch-Josza algorithm using trapped ions

- show suitability of ion traps
- relatively simple algorithm
- using only one trapped ion

Paper: Nature 421, 48-50 (2 January 2003), doi:10.1038/nature01336;
- Institut für Experimentalphysik, Universität Innsbruck
- MIT Media Laboratory, Cambridge, Massachusetts



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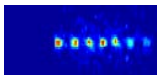
The two problems

The Deutsch-Josza Problem:

- Bob uses constant or balanced function
- Alice has to determine which kind

The Deutsch Problem:

- Bob uses a fair or forged coin
- Alice has to determine which kind



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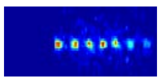
Four different types of coins

Constant functions		Balanced functions	
Case 1	Case 2	Case 3	Case 4
0	1	0	1
0	1	1	0
ID	NOT	CNOT	Z-CNOT

The third line shows addition modulo 2: $w \oplus f(a)$



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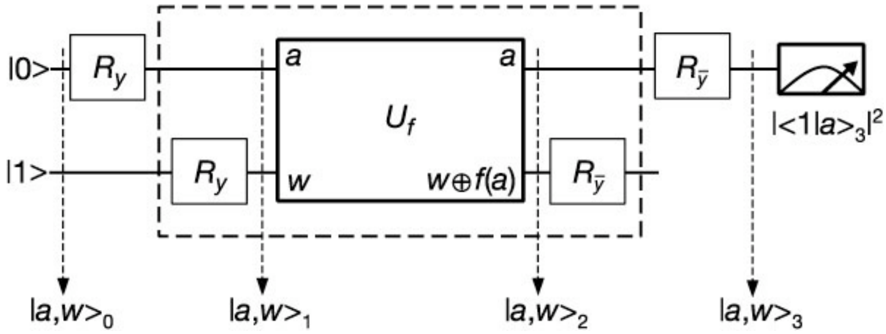
Deutsch-Jozsa Algorithm I



$$U_f : |x\rangle|y\rangle \mapsto |x\rangle|f(x) \oplus y\rangle$$

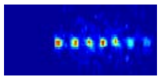
$$\begin{aligned}|x\rangle|y\rangle &\leftarrow H|0\rangle H|1\rangle \\ &= \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \cdot \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) \\ &= \frac{1}{2}(|0\rangle|0\rangle - |0\rangle|1\rangle + |1\rangle|0\rangle - |1\rangle|1\rangle)\end{aligned}$$

Ion Traps

Deutsch-Josza
Problem
Algorithm
Implementation

Scalability
Problem
Move ions
Microtraps
Photons
Charges

Roundup



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Deutsch-Josza Algoritm II

$$\begin{aligned}|x\rangle|y\rangle &\leftarrow U_f|x\rangle|y\rangle \\ &= \frac{1}{2}(|0\rangle|0 \oplus f(0)\rangle - |0\rangle|1 \oplus f(0)\rangle + |1\rangle|0 \oplus f(1)\rangle - |1\rangle|1 \oplus f(1)\rangle) \\ &= \frac{1}{2}(|0\rangle \cdot (|f(0)\rangle - |1 \oplus f(0)\rangle) + |1\rangle \cdot (|f(1)\rangle + |1 \oplus f(1)\rangle)) \\ &= \frac{1}{2}((-1)^{f(0)}|0\rangle \cdot (|0\rangle - |1\rangle) + (-1)^{f(1)}|1\rangle \cdot (|0\rangle - |1\rangle)) \\ &= \frac{1}{2}((-1)^{f(0)}|0\rangle + (-1)^{f(1)}|1\rangle) \cdot (|0\rangle - |1\rangle)\end{aligned}$$

$$\frac{1}{2}(\pm(|0\rangle + |1\rangle)) \cdot (|0\rangle - |1\rangle) \qquad \frac{1}{2}(\pm(|0\rangle - |1\rangle)) \cdot (|0\rangle - |1\rangle)$$

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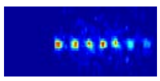

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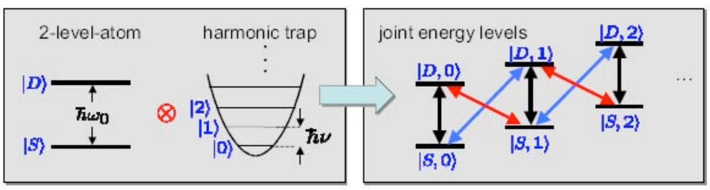
Implementation using trapped ions

- $^{40}Ca^{+}$ ion in a Linear Paul Trap
- Relabel the states of the motional degree of freedom
- Doppler / Sideband cooling prepares groundstate

Qubits

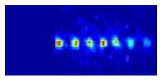
Two qubits are involved:

- electronic quantum state of the ion
- phonon number of the axial vibrational mode
- states can be swapped (by a pulse sequence)



Manipulation of the trapped ion

- Resonant pulses perform single-qubit rotations
- Detuned pulses perform two-qubit rotations
- Manipulation by a sequence of pulses



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Main sources of errors

Ion Traps

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Problem
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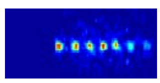
Roundup

- phases introduced by light shifts of the lasers
- system may leave the computational subspace



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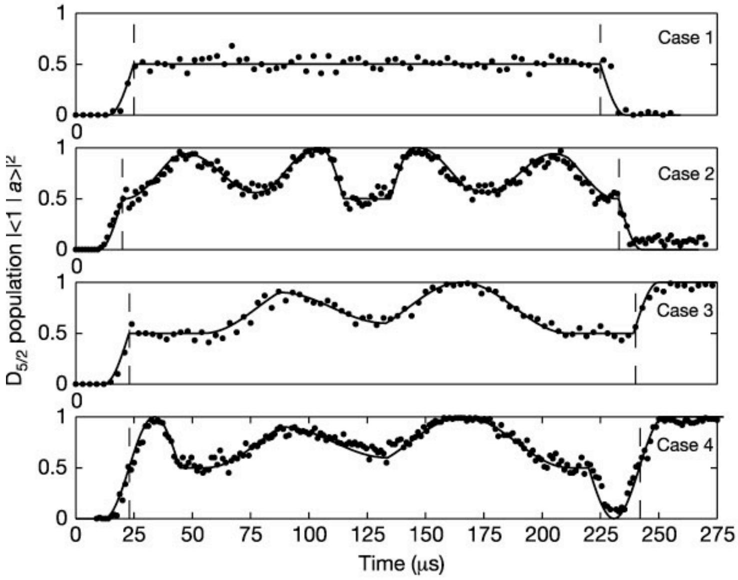
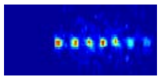
Time evolution of the qubit



Ion Traps



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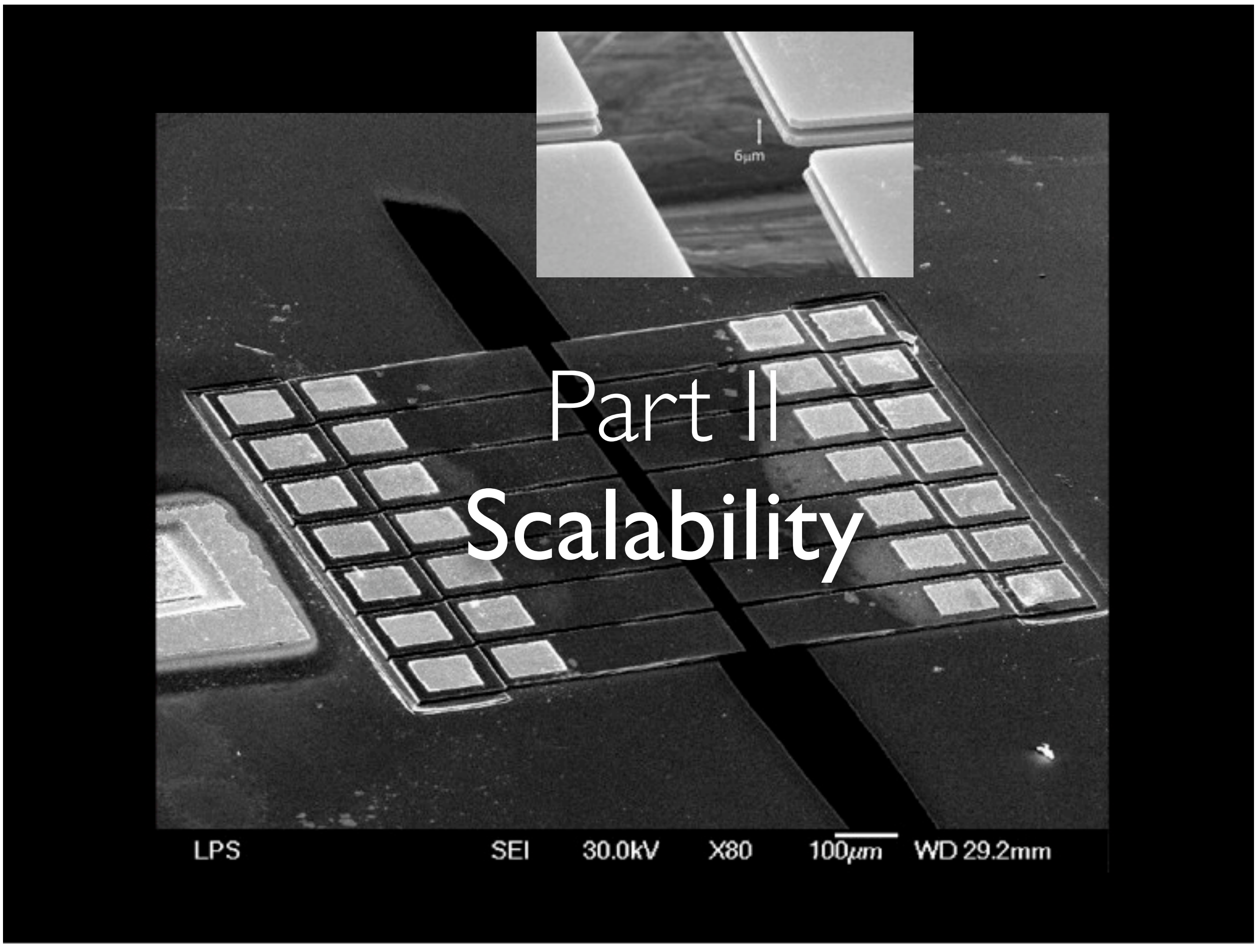

Introduction

currently: Ion Trap Quantum Computer with ~10 ions.

useful application:
factorization of a 200-digit numer:
requires 3’500 qubits (100’000 with the implementation of error correction)

from I. Cirac and P. Zoller, Nature 404, 579 (2000)

a) are the current approaches scalable?
b) what other approaches do we need?

Scalability of linear ion traps

elementary requirements for quantum computation have been demonstrated,
but...
experimental and theoretical problems limit the scalability

✓ (should be o.k.)

- addressing
- generation of entangled states with many ions
  (H. Häffner et al., Nature 438, 639 (2005)
- error correction
  (J. Chiaverini et al., Nature 432, 602 (2004)

✗ (problem)

- control over the interaction of the qubits

Ion Traps

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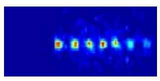

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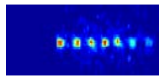
Problem



- with adding more and more ions the chain gets heavier but on the other hand the coupling strength decreases as $\eta \propto \frac{1}{\sqrt{N}}$
  - ➡ need more time for gate operations
- harder to cool all ions to the ground state
- ions get closer to each other
  - ➡ addressing more difficult
- driving transitions between single modes gets more difficult (more stray excitations)

~ some 10 ions at a maximum

Solutions

Ion Traps

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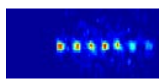


General idea:

use multiple ion traps with few ions
\+ couple these traps together

Implementations:

❶ Move the atoms between traps

❷ Array of microtraps

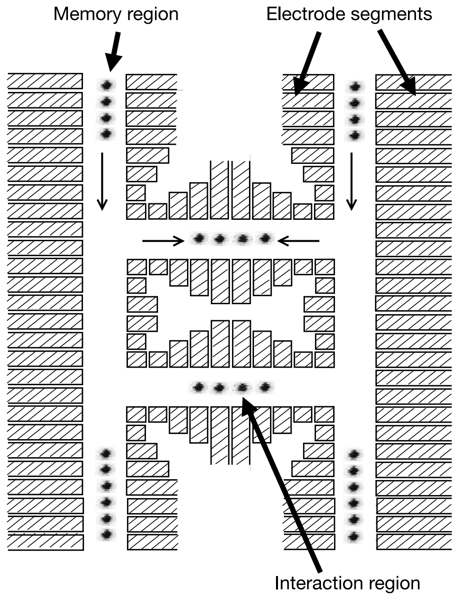
❸ Coupling via photons

❹ Coupling via image charges

❶ Move the ions around

D. Kielpinksi, C. Monroe & D. J. Wineland, Nature 417, 709 (2002)
three layer T-junction trap: W. K. Hensinger et al., Appl. Phys. Lett. 88, 034101 (2006)

proposal: quantum-charge-coupled-deivce (QCCD)
= ion chip



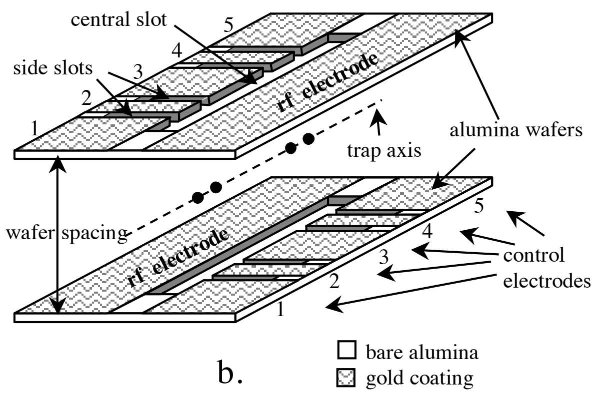
idea: move the ions between memory and interaction region by changing the fields on the electrodes

two more layers of rf electrodes above and below the static electrodes shown

T-junction trap demonstrated in 2006

Transport of quantum states and separation of ions in a dual rf trap

M. A. Rowe et al., Quantum Info. Comput. 2, 257 (2002)



trap distance: 1.2 mm

transfer of the ion by continuously changing the potentials on the five pairs of control electrodes

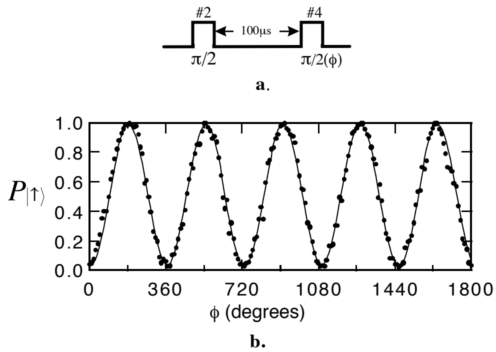
transfer time T=54 μs: gain of 0.01±0.03 motional quanta

robust: same ion transferred 10^6 times

Transport of quantum states and separation of ions in a dual rf trap (2)

Measure coherence: Ramsey-type experiment

1. preparation (π/2 pulse) $|\downarrow\rangle \rightarrow \frac{1}{\sqrt{2}}(|\downarrow\rangle + |\uparrow\rangle)$
2. transfer (T=55 µs)
3. π/2 pulse with phase ϕ to first
4. transfer back
5. measure state



$$P_{|\uparrow\rangle} = \frac{1}{2}(1 + C\cos(\phi + \phi'))$$

fringe contrast C measured as 95.8 ± 0.8%

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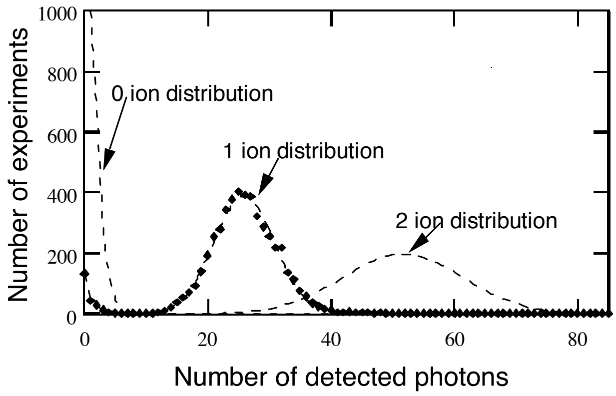
Transport of quantum states and separation of ions in a dual rf trap (3)

Separation of two ions



in 95 ± 1% of the experiments one ion correctly transferred,
4 ± 1% both ions transferred,
less than 1% no ion transferred

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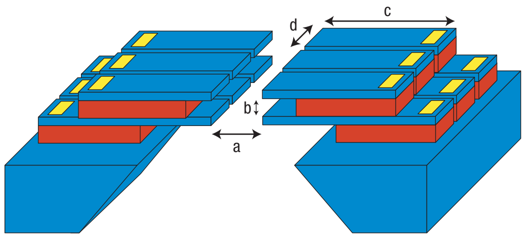
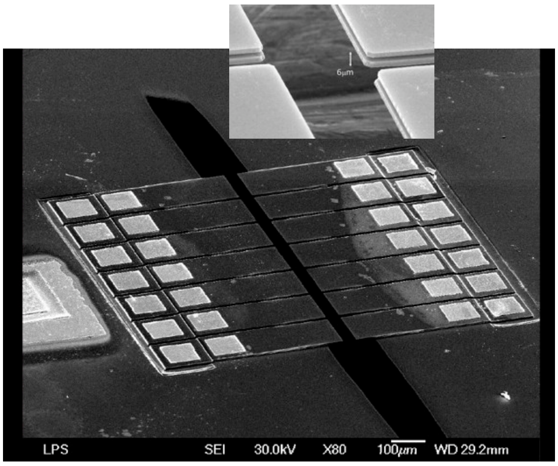
Ion trap in a semiconductor chip

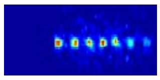
D. Stick, W. K. Hensinger, S. Olmschenk, M. J. Madsen, K. Schwab and C. Monroe, Nature Physics 2, 36 (2006)



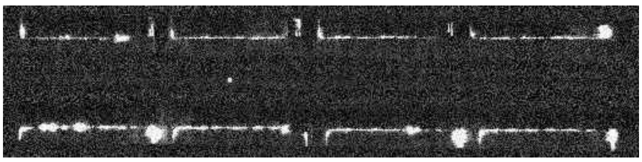
4 layers of alternating AlGaAs and GaAs epitaxially grown on a GaAs substrate

trap segment width: 130 μm / trap height: 60 μm

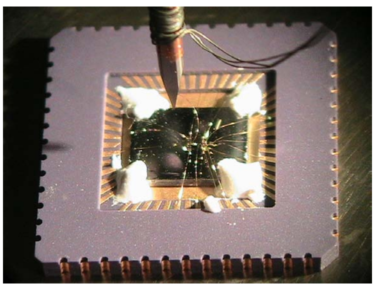




Ion trap in a semiconductor chip (2)

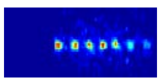


single Cd^{+} ion in the trap



the chip being wired up
size is a about that of a postage stamp

- trap depth 0.08 eV
- storage time 10 min
- could not load more than one ion



Surface-Electrode Ion Trap

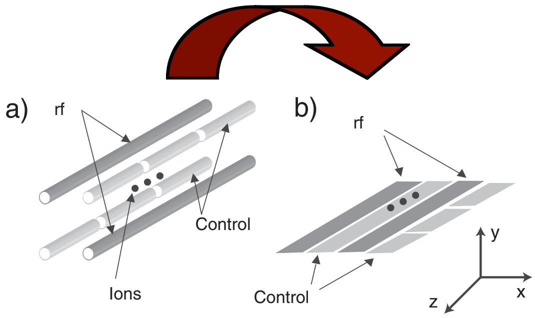
S. Seidelin et al., PRL 96, 253003 (2006)

trap constructed with standard an scalable microfabrication processes, substrate: fused quartz, copper seed layer, gold

stable confinement demonstrated

all electrodes reside in a single plane

ions are trapped 40 μm above this plane



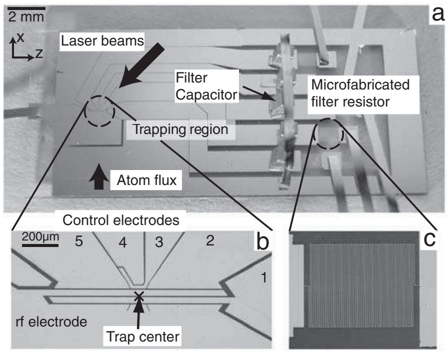


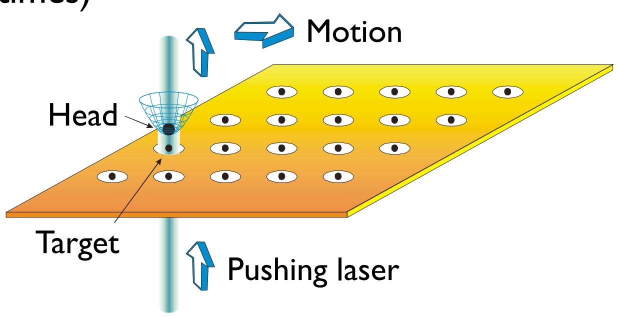
FIG. 2. Pictures of the surface-electrode trap. (a) The complete trap structure, including lead-out wires (ribbons) and filter capacitors. The directions of the laser beams (cooling and photo-ionization) and atom flux are indicated. (b) Expanded view of the trap region (center marked by ×). The control electrodes are numbered for reference in the text. (c) On-board meander line resistor.

- up to 12 ions
- trap depth 0.17 eV
- storage for several hours

❷ Array of microtraps

I. Cirac and P. Zoller, Nature 404, 579 (2000)

model that combines scalability (from solid state systems) with the advantages of quantum optical systems (good control and coherence times)

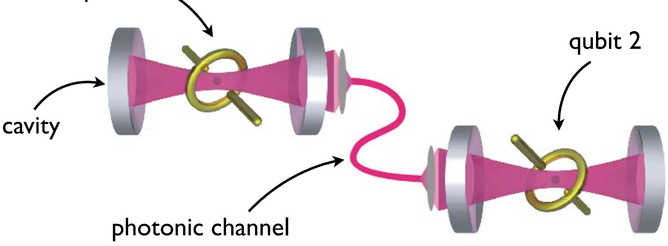


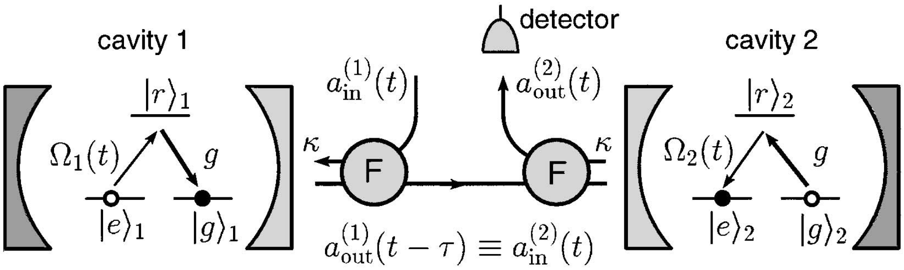
- two-dimensional array of trapped ions (electric or laser fields)
- different ion (Head) that can be moved above the plane
- perform two qubit gate with pushing laser
- can swap the states of Head and Target
- entanglement operations between distant ions

but... technical problems for this approach unsolved at current time

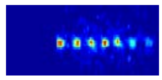
❸ Coupling via photons

Protocol: J. I. Cirac, P. Zoller, H. J. Kimble, and H. Mabuchi, PRL 78, 3221 (1997)
Part of an implementation: A. Kuhn, M. Hennrich, and G. Rempe, *Deterministic Single-Photon Source for Distributed Quantum Networking*, PRL 89, 067901 (2002)
(related e.g. D.L. Moehring, P. Maunz, S. Olmschenk et. al, *Entanglement of single-atom quantum bits at a distance*, Nature 449, 68 (2007))





use STIRAP (Stimulated Raman Adiabatic Passage)
coupling can be chosen by STIRAP detuning



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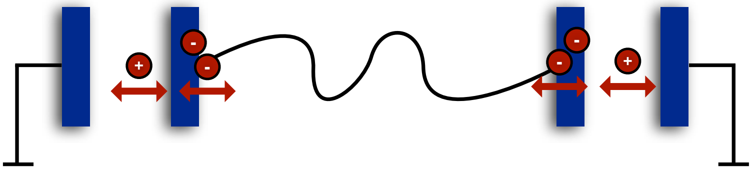
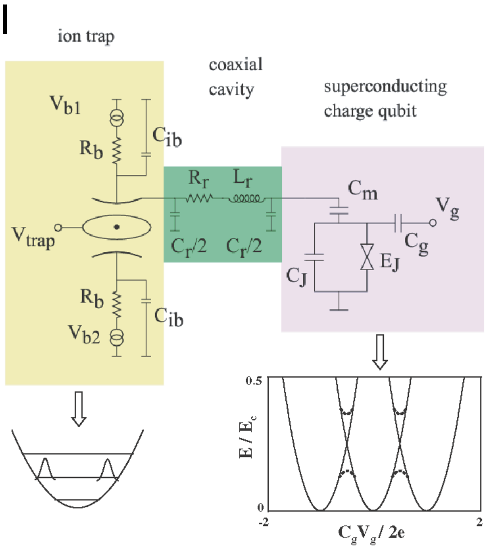
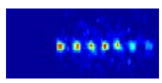
❹ Coupling via image charges

L. Tian, P. Rabl, R. Blatt, and P. Zoller, PRL 92, 247902 (2004)
L. Tian, R. Blatt, and P. Zoller, Eur. Phys. J. D 32, 201 (2005)



- idea: couple quantum-optical and solid-state qubits
  - memory: ion trap
  - processor: superconducting charge qubit (logic gates in the ns time scale)
  - coupling controlled by a switch
- fast swap gate





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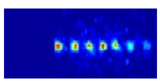
Part III
Roundup & Outlook

Summary

DiVincenzo criteria

criterion	*physical implementation*	*status*
scalable qubits	linear traps, arrays, coupled traps	several promising possibilities: ion chips, coupling to different types of qubits via photonic or charge channels (hybrid systems)
initialization	laser pulses	arbitrary state preparation
long coherence times	narrow transitions	coherence times up minutes
universal quantum gates	Cirac-Zoller CNOT	high fidelity, but slow (μs time scale)
qubit measurement	quantum jump detection	individual ion fluorescence (almost 100%)
convert qubits to flying qubits	coupling of ions with cavity	promising progress in CQED, recent advances (Deterministic Single-Photon Source)
faithfully transmit flying qubits	connect cavities with fibers	



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