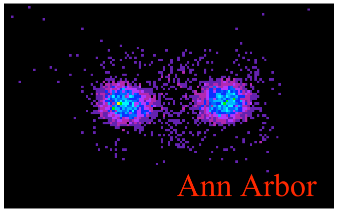
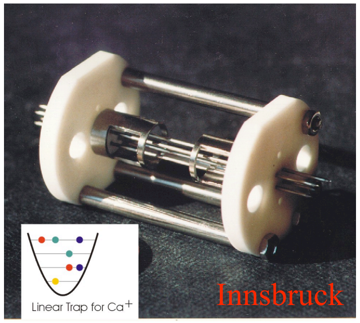
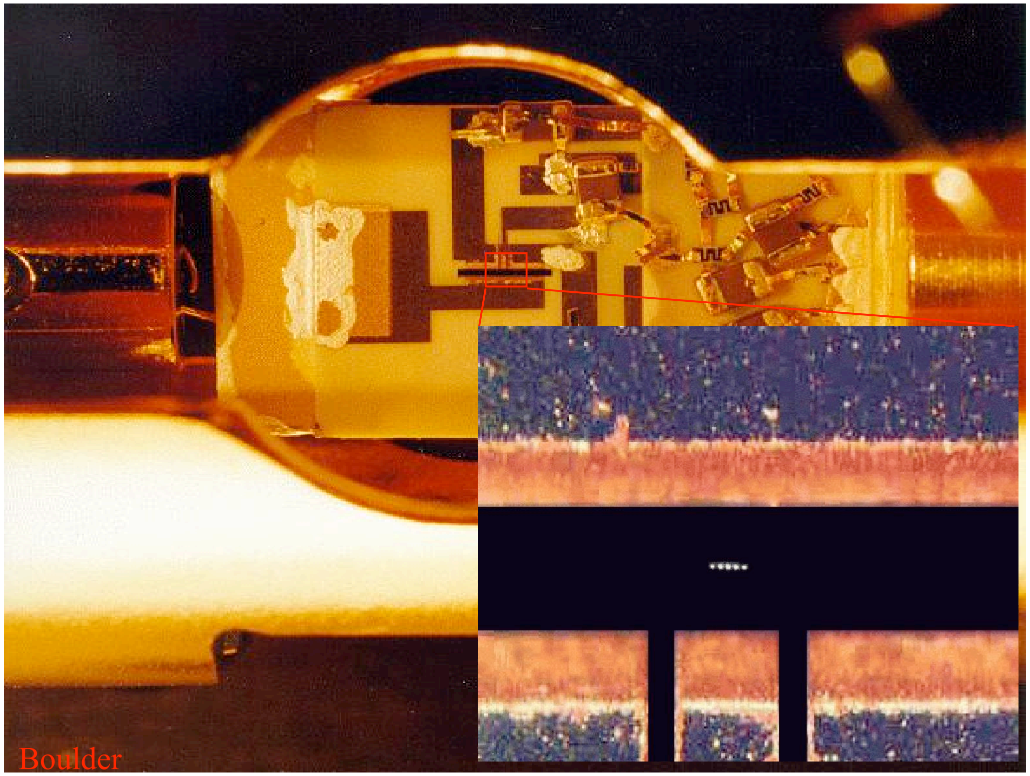
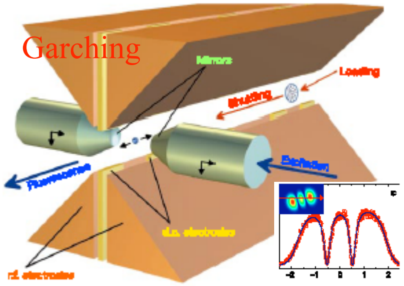
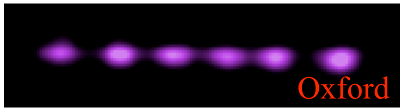
Physical “Implementations” of Quantum Computing II - Ion Traps











PIMS/MITACS summer school– June, 2003

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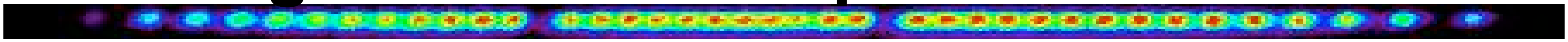
http://physserv.mcmaster.ca/~kingb/King_B_h.html

Building Quantum Computers:

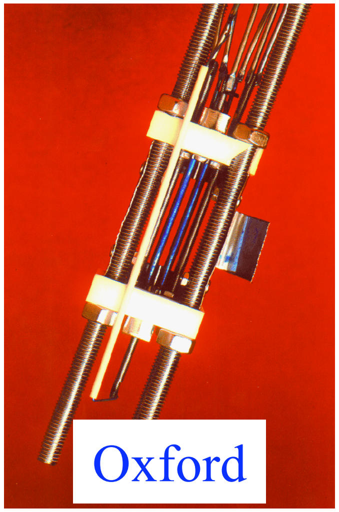


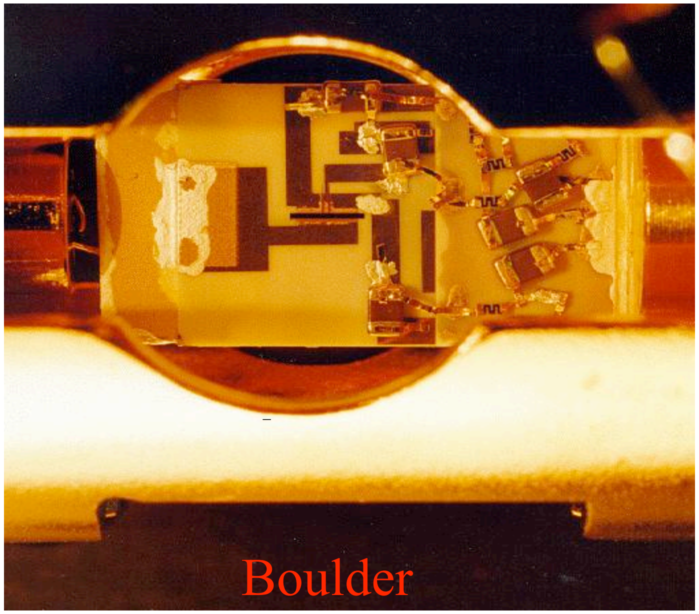
Need:

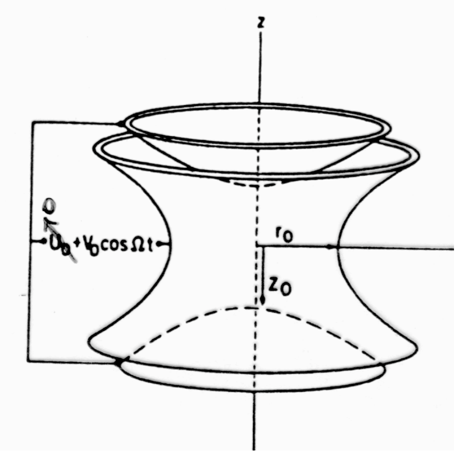
1. qubits
   - two-level quantum systems
   - *superpositions* □ isolated from outside world
   - confined, characterizable, scalable
2. preparation
   - prepare computer in standard start state
3. read-out
4. logic gates
   - controllable interactions with outside world!
   - single- and two-qubits gate sufficient (not nec.!)

Ion traps for quantum computing:

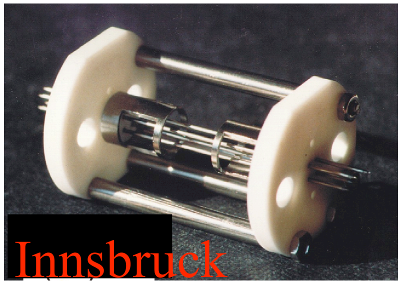
- store quantum information inside atoms
- need way to hold atoms in place and “protect” them
- ion traps:

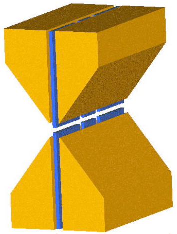

Oxford


Boulder

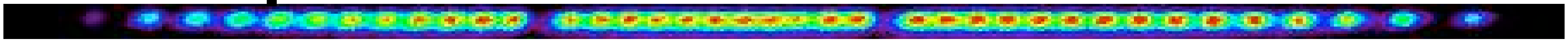


G. Werth, *Progress in Atomic Spectroscopy*,
H.J. Beyer, H. Kleinpoppen, *eds*


Innsbruck


MPQ/Garching

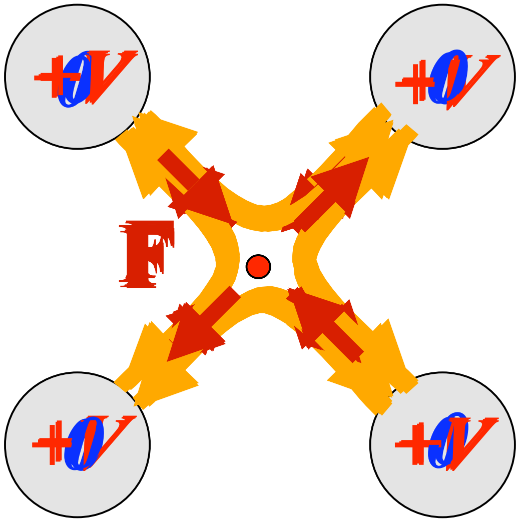
Ion Traps:



- want electric field pointing inwards everywhere

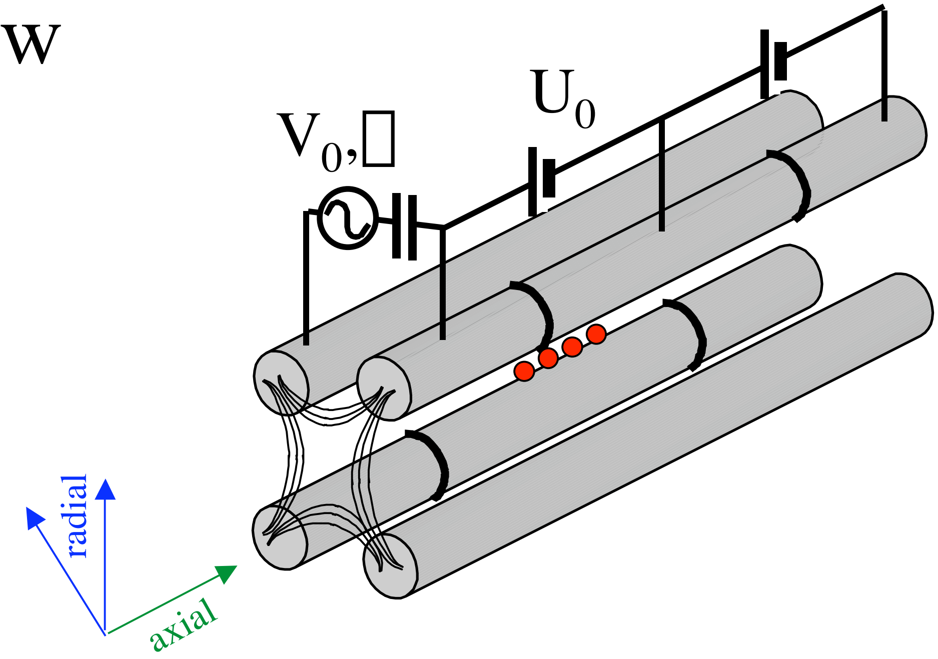
  □ positive charges trapped!

- problem: Gauss’ Law



2-D:

dynamic trapping

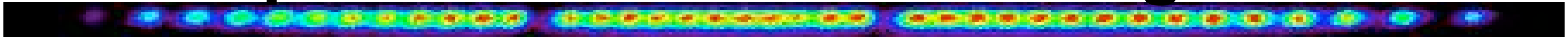


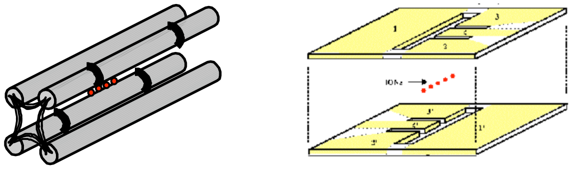
3-D:

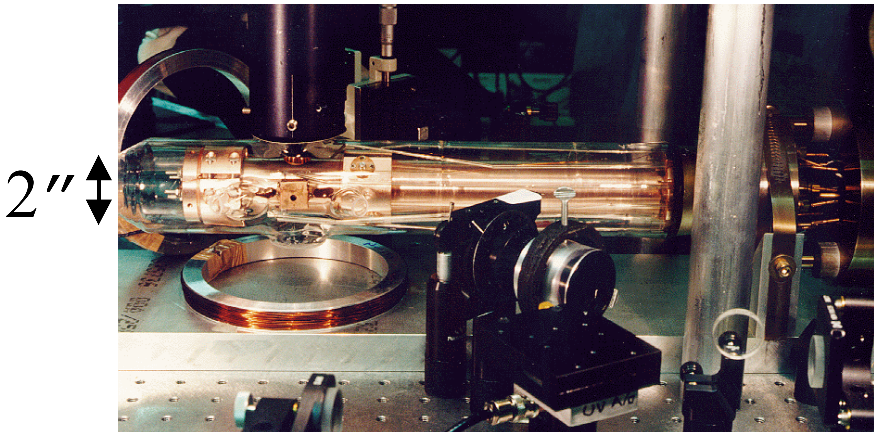
axial - static

radial - dynamic

Ion Traps - initial micromachining:







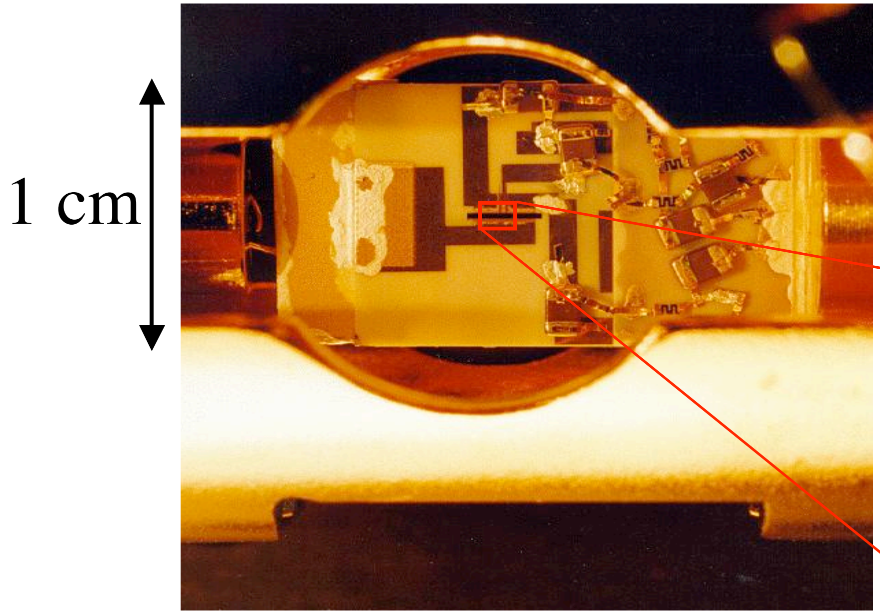
- DC: $U_0 \approx 10\ V$
- RF: $V_0 \approx 750\ V$

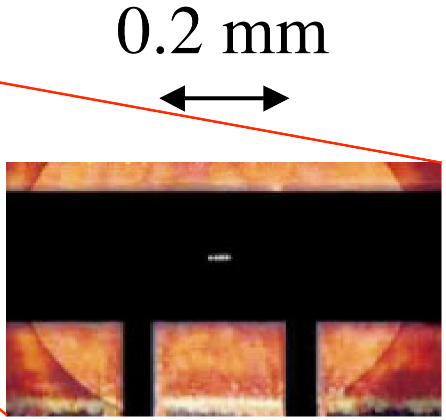
- **F = k · z :** harmonic oscillator
- $□ \approx 230\ MHz$

  $□\ \ □_{HO} \approx 10\ MHz$

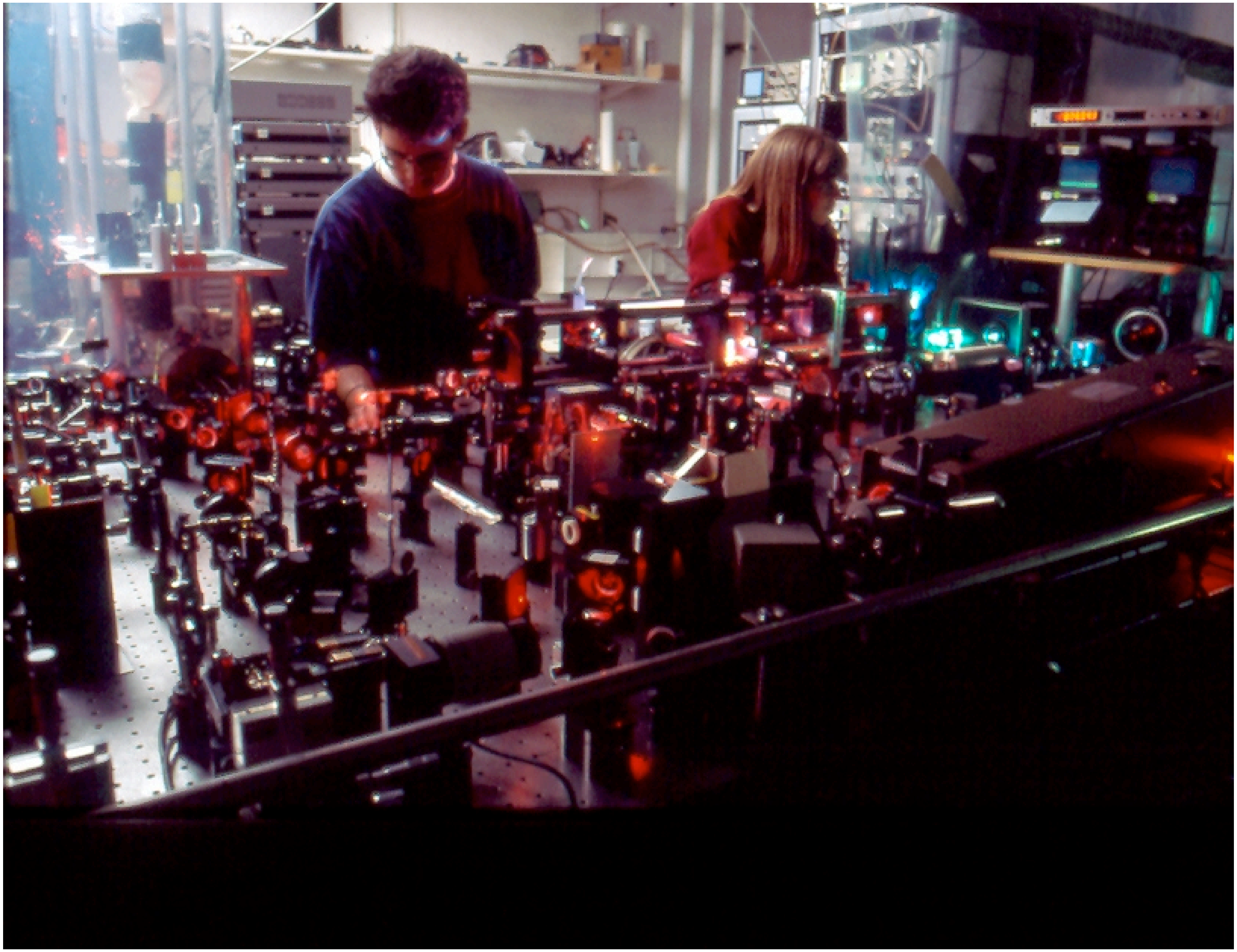
- single ion lifetime:

  $> 10\ h.$ (up to *100 days…*)

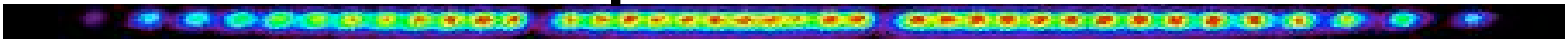




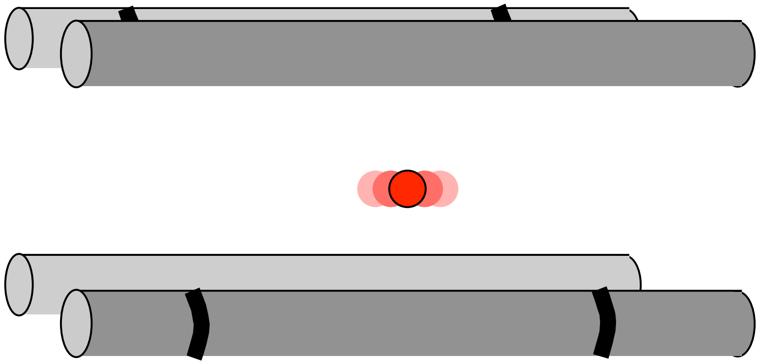
Putting it all together…



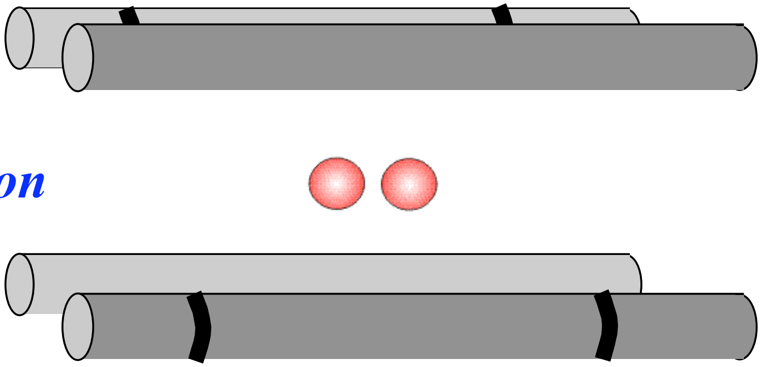
Ion Motion in Trap:



- single ion:
  - like a mass on a spring



- multiple, cold ions:
  - “normal modes” - the string moves as one...



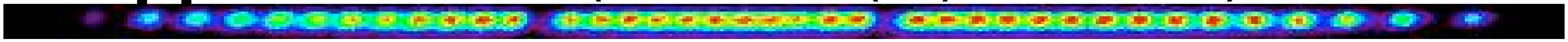
N ions:

N modes per direction

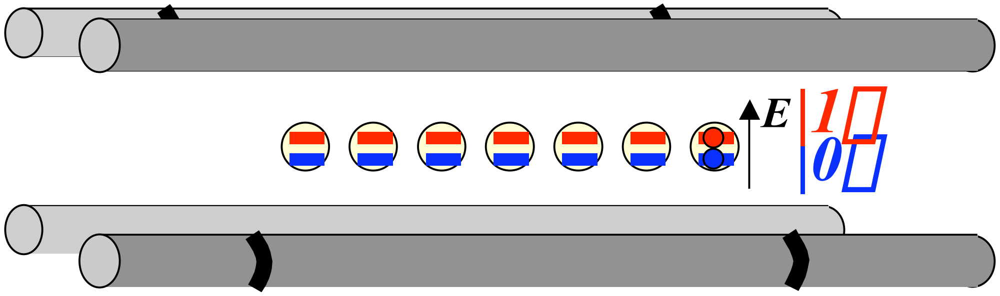
“stretch”

$2\,\square_x$

Trapped-Ion QC (Cirac, Zoller('95) Phys. Rev. Lett. **74**, 4091)

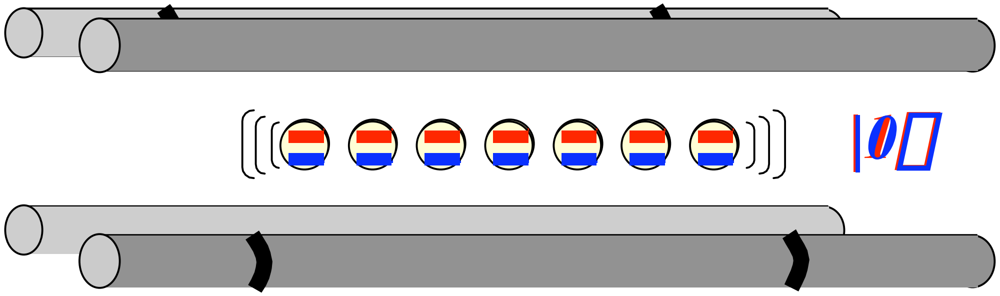


- a collection (string) of trapped atomic ions:
  - qubits: (1) internal atomic levels



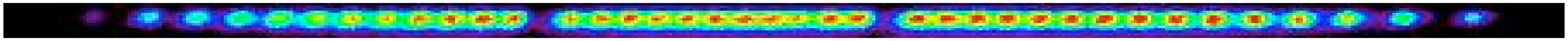
- *quantum memory*
- $t_{decoh} \gg t_{gate}$
  - $T_2 > 10$ *min.*
  - *clocks*

- “data bus:” (2) common-mode motion

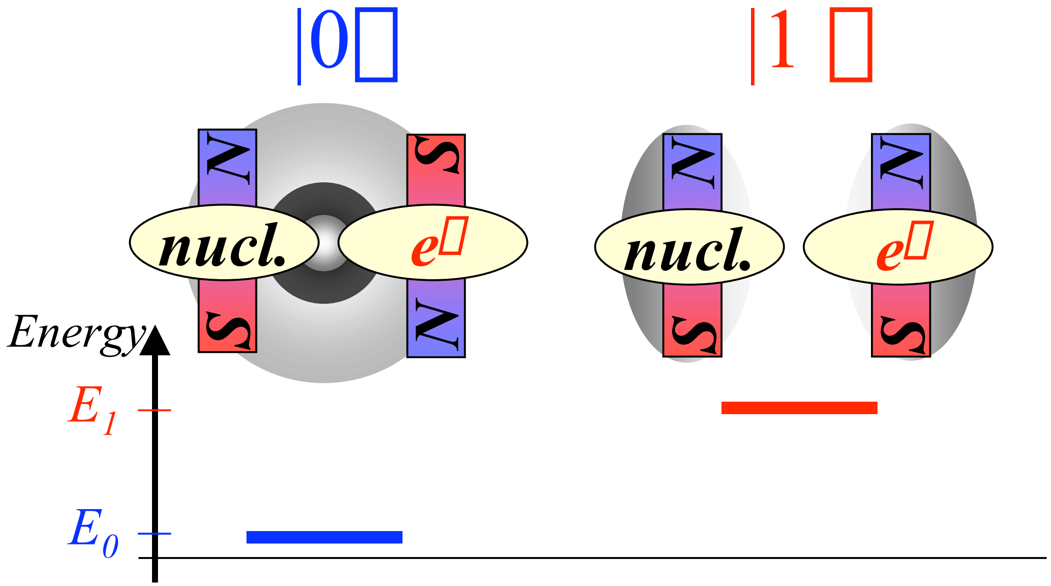


- *transitory*
- $t_{decoh} > t_{gate}$
  - $10^{-2} - 10^{-3}$

Ion Qubits:

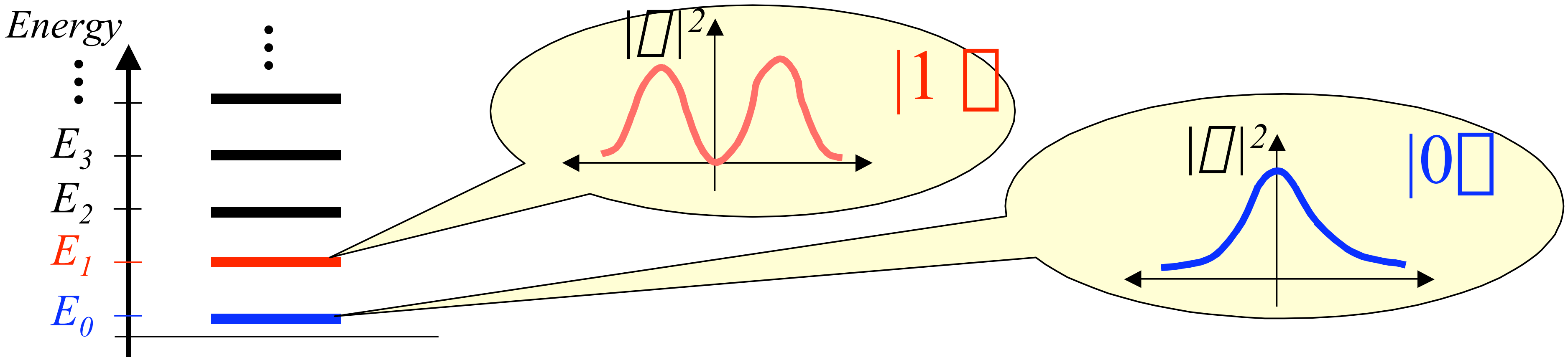


- orbital energy of outer electron: (Be^+, Mg^+, Ca^+, Sr^+, ...)

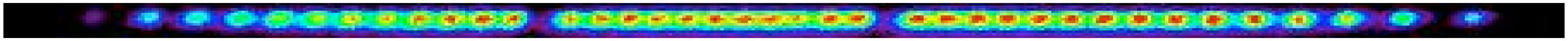


1. long-lived "electronic" levels (τ > *10 ms*)
2. long-lived hyperfine levels (τ > *10,000 y.*)

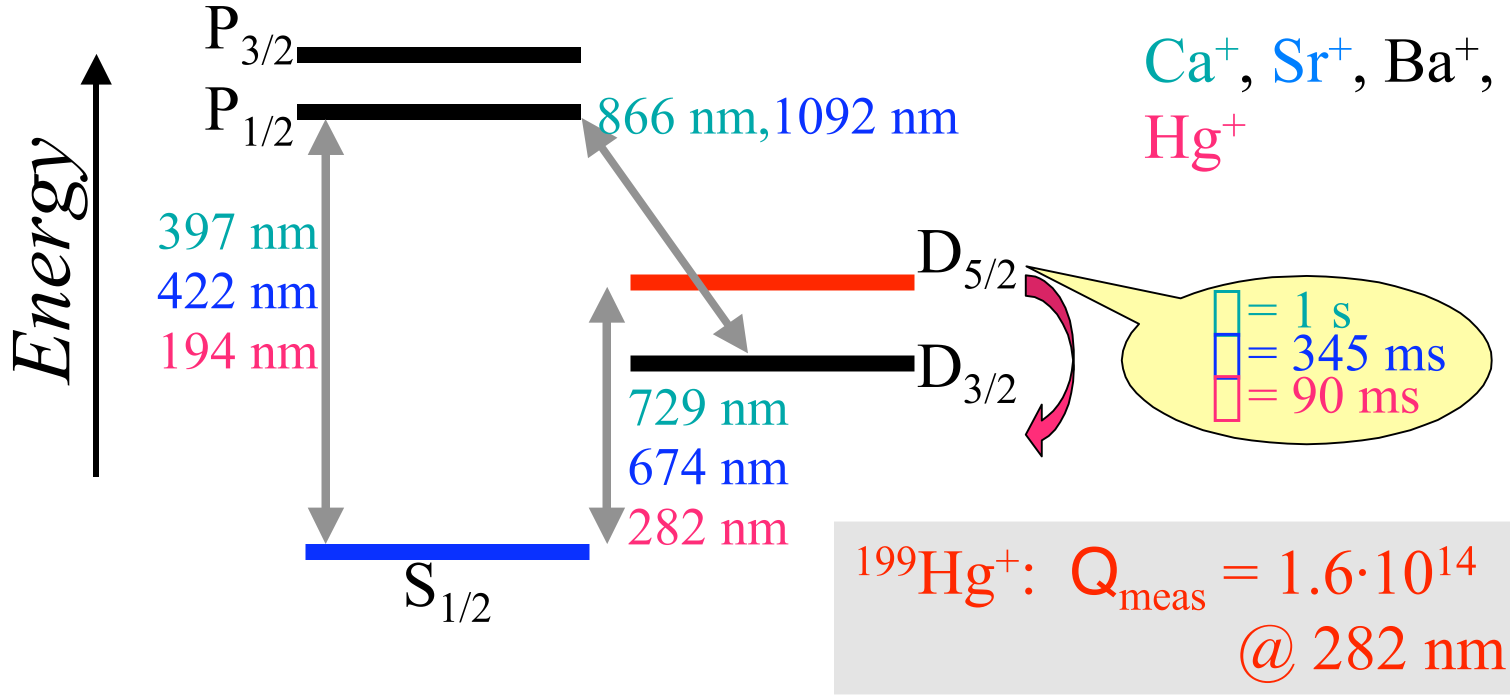
- vibrational energy of ions in trap:



Qubits:



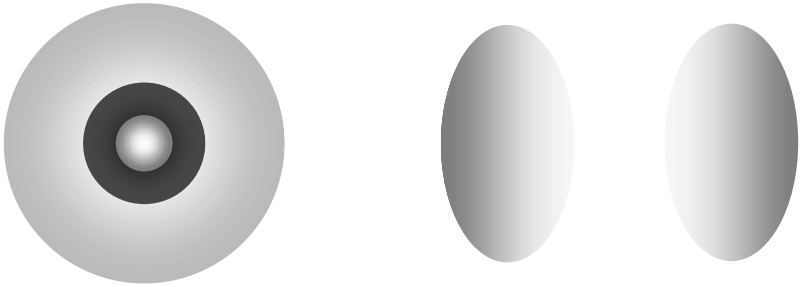
- long-lived electronic states:



Ca^+, Sr^+, Ba^+, Hg^+

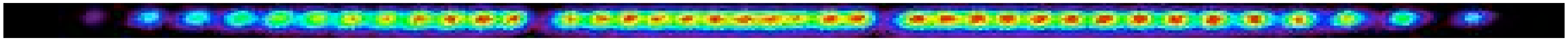
τ = 1 s
τ = 345 ms
τ = 90 ms

$^{199}Hg^+$: $Q_{meas} = 1.6 \cdot 10^{14}$ @ 282 nm

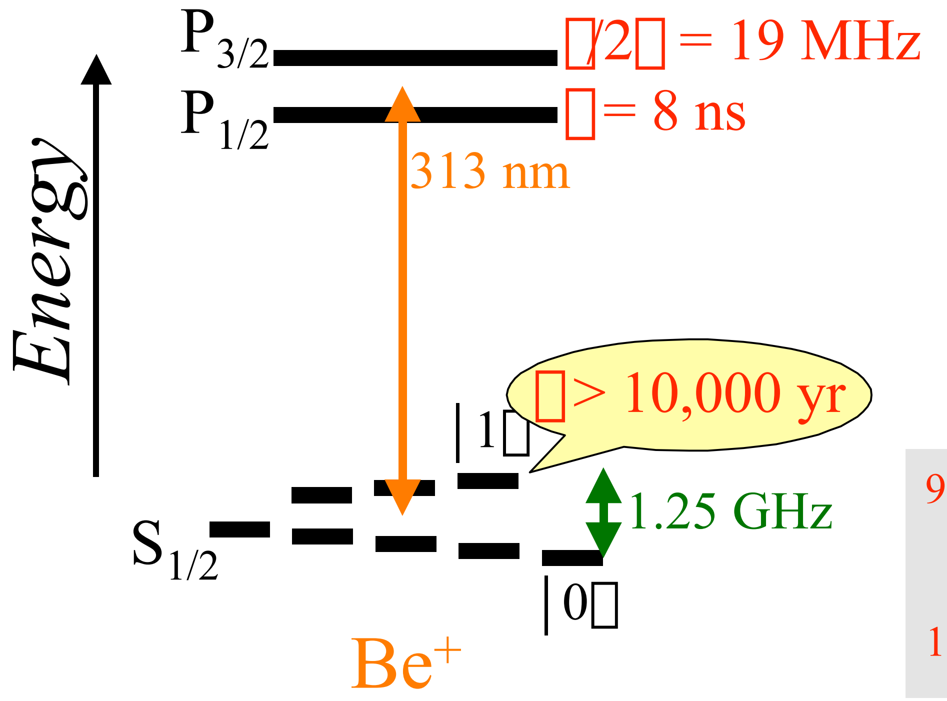


(*τ > 1 ms*)

Qubits:

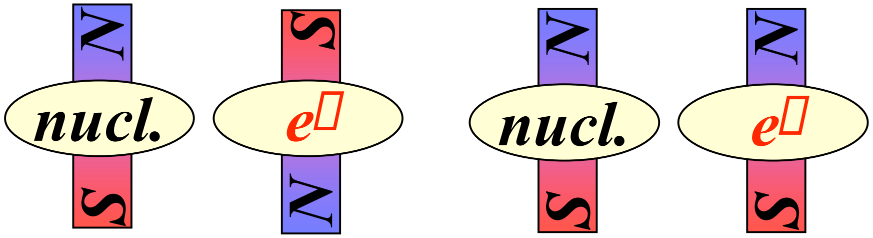


- ground-state hyperfine levels:



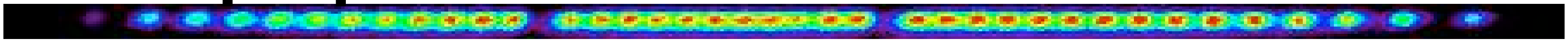
Be$^+$ (313 nm),
Mg$^+$ (280 nm),
Cd$^+$ (215 nm)

^{9}Be$^+$: $Q_{meas} = 3.4\cdot10^{11}$
@ 303 MHz
^{173}Yb$^+$: $Q_{meas} = 1.5\cdot10^{13}$



(□> 10,000 y.)

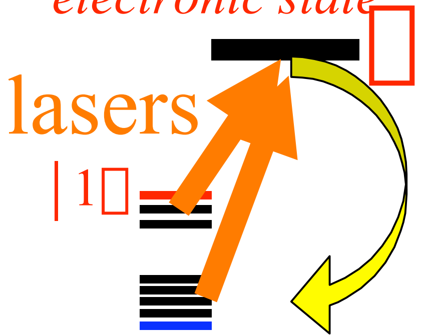
State preparation:



- atoms “come” in thermal equilibrium
  - distribution of levels...
- must prepare in definite quantum state

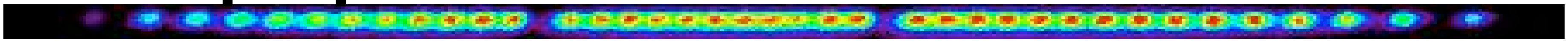
- electronic:
  - optical qubit: kT □ free!
  - hyperfine - “optical pumping”
    - polarized light carries angular momentum
    - “pumps” atom into sub-level of highest (quantized) **L**

unstable excited electronic state

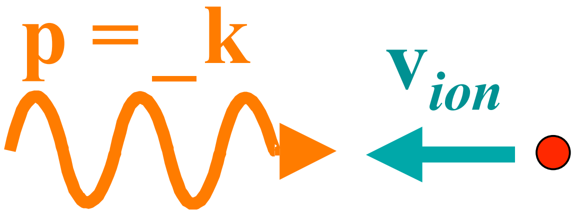


|0□: state with most **L**

State preparation:



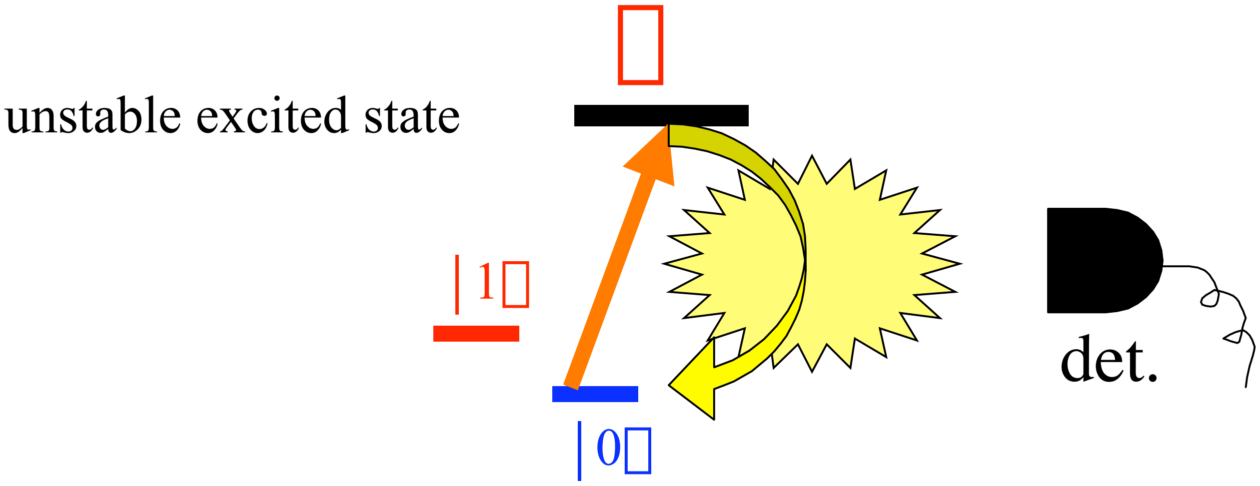
- vibrational: “laser cooling”
  - light carries momentum
  - photon “kicks” can slow atom
    - re-emission is symmetric

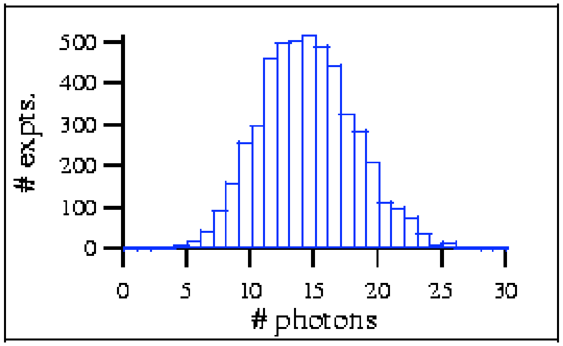


(Wineland and Itano, Phys. Rev. A **20**, 1521 (75), Phillips, Cohen-Tannoudji, Chu, Rev. Mod. Phys. **70** #3 (98).)

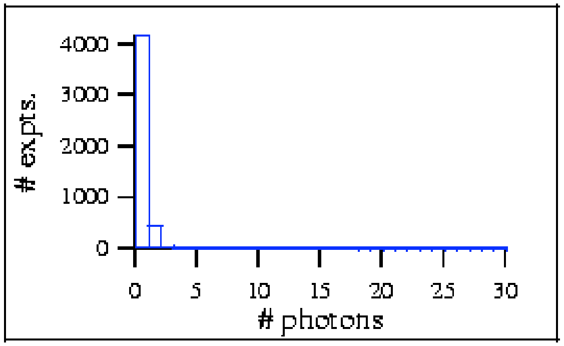
State Detection:

- cycling transition



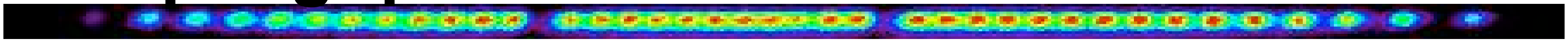


(a)

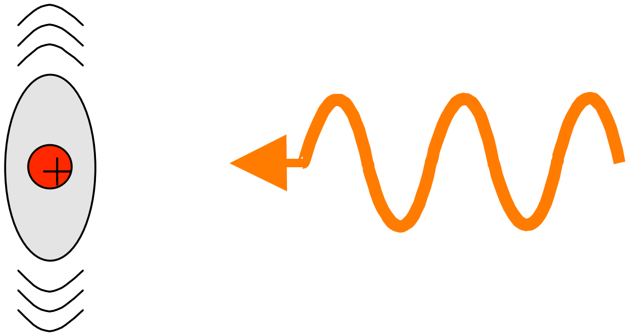


(b)

Coupling qubit levels:



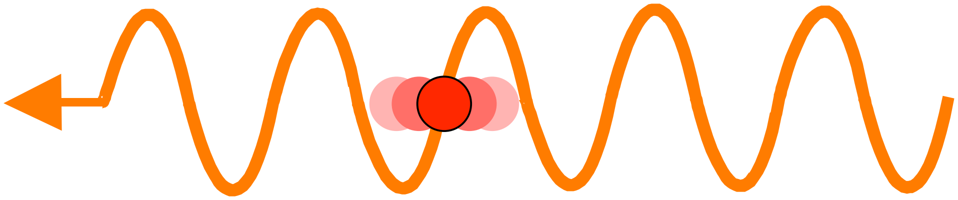
- oscillating field induces dipole moment
  - $H_I \mu \square \bullet E_0 \, e^{i(kx - \square_L t)}$



- can change electronic level

  (resonance?)

- if ion vibrates, interaction strength modulated
  - $H_I \mu \square \bullet E_0 \, e^{i(kx_0 \cos(\square_x t) - \square_L t)}$

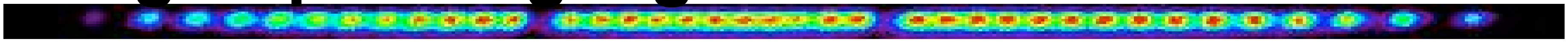


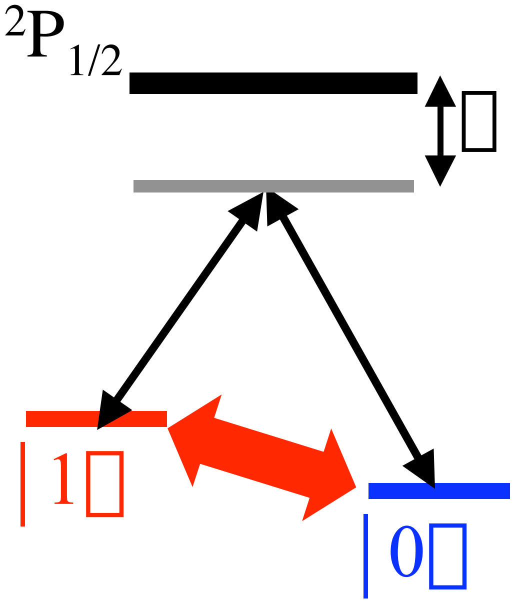
- can change motion

  $(k x_0 \;\; n_{vib} \sim [x_0 / \square] \;\; n_{vib})$

  (... and resonance...)

Single-qubit logic gate:

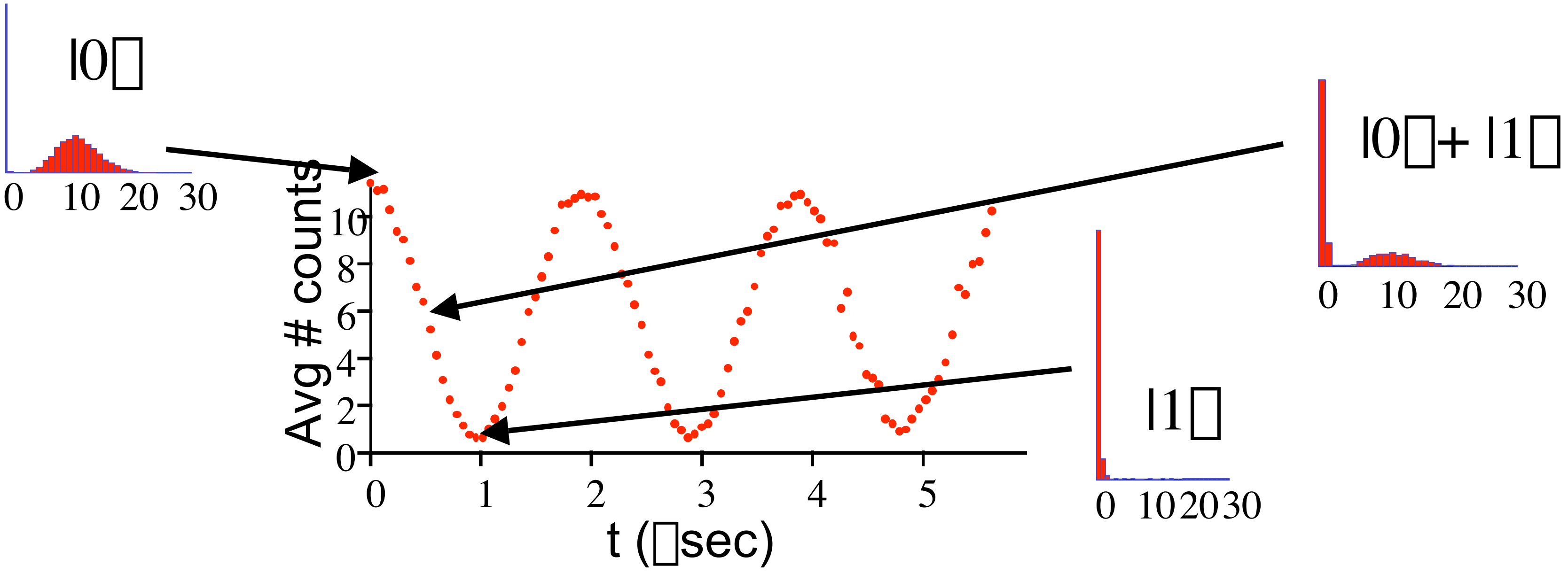




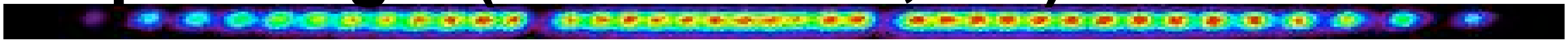
2-photon stimulated Raman transitions

optical: laser single-photon

- strong E-gradients (optical)
  - motional coupling
- RF frequency diff. coupling
- controllable strength
- RF phase stability

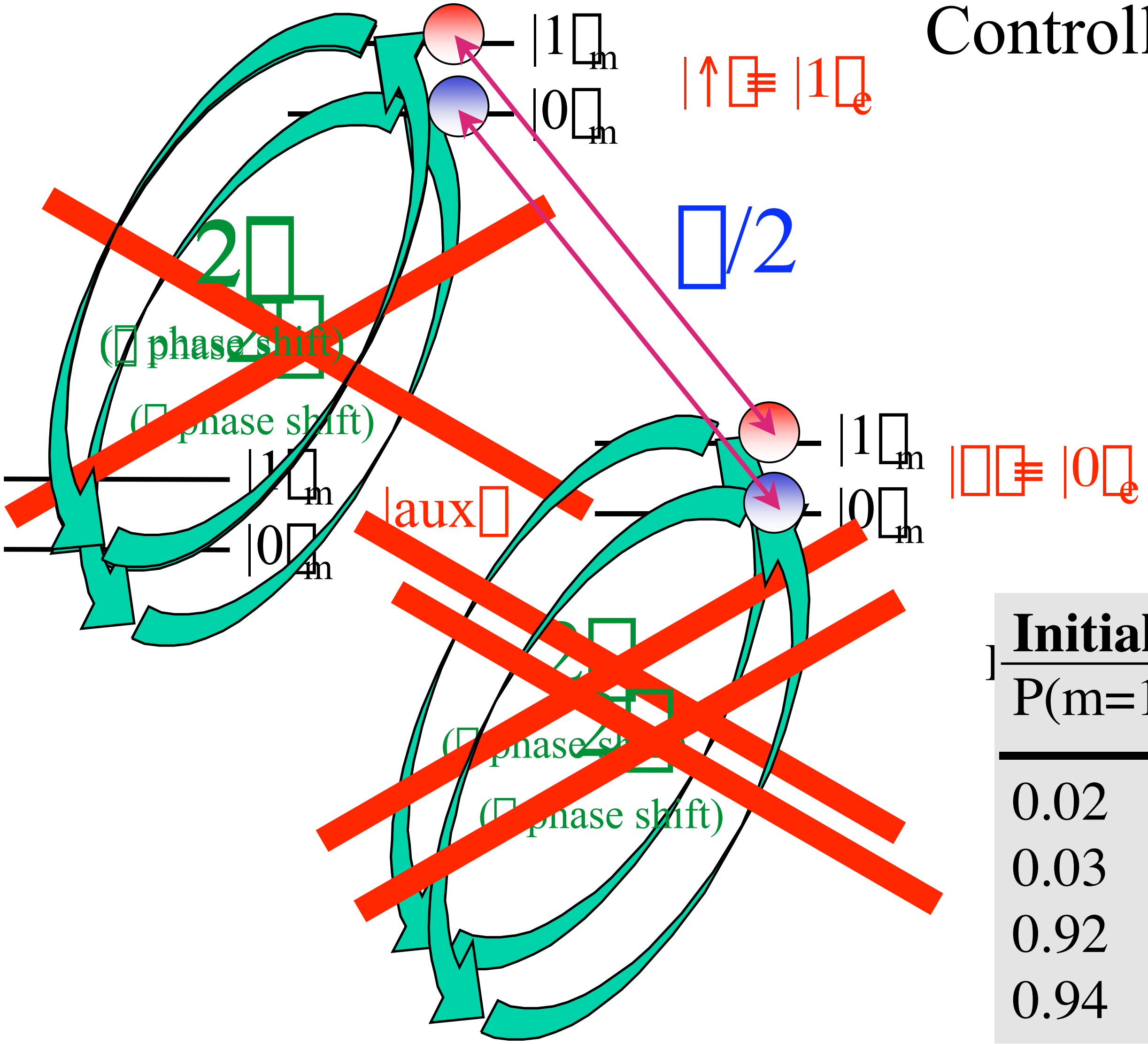


2-qubit logic (Cirac-Zoller, ’95):



C. Monroe, et al., Phys. Rev. Lett. **75**, 4714 (95).

- motion-dependent spin transitions (*conditional* logic)



Controlled-Phase Gate (‘95):

c t	c′t′
|1⟩|0⟩	|1⟩|0⟩
|1⟩|1⟩	−|1⟩|1⟩

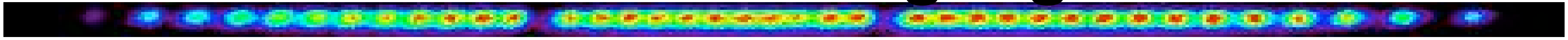
π/2 • C-Phase • π/2

≡ Controlled-NOT:

- initially $|0\rangle_m|0\rangle$
- initially $|1\rangle_m|0\rangle$

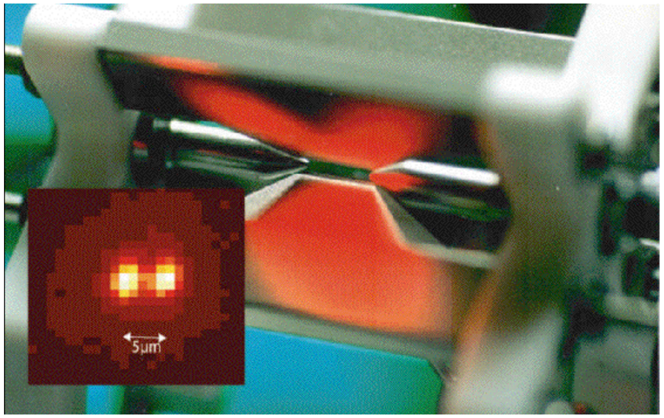
Initial State		Final State	
P(m=1)	P(↑)	P(m=1)	P(↑)
0.02	0.01	0.09	0.16
0.03	0.99	0.04	0.88
0.92	0.05	0.77	0.88
0.94	0.98	0.88	0.19

CZ Realized - a two-ion logic gate!



F. Schmidt-Kaler, *et al.*, Nature **422**, 408 (2003)

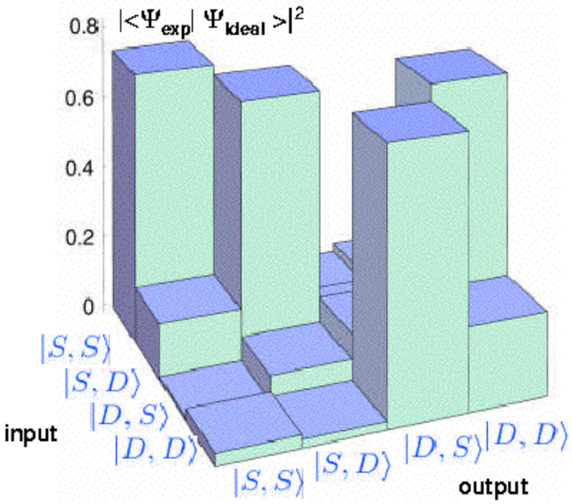
- two $^{40}Ca^{+}$ ions - CZ scheme



theoretical:

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

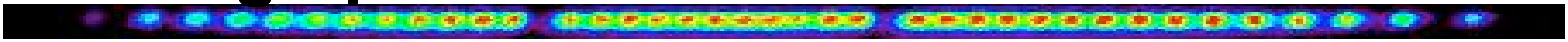
measured: $F \sim 70\%$



- Boulder group 2 $^{9}Be^{+}$ ions – motional gate F ~ 97%

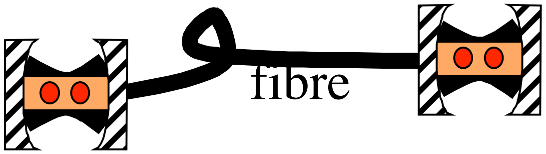
(Leibfried, et al., Nature **422**, 412 (03).)

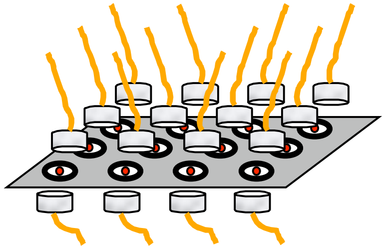
Scaling up:

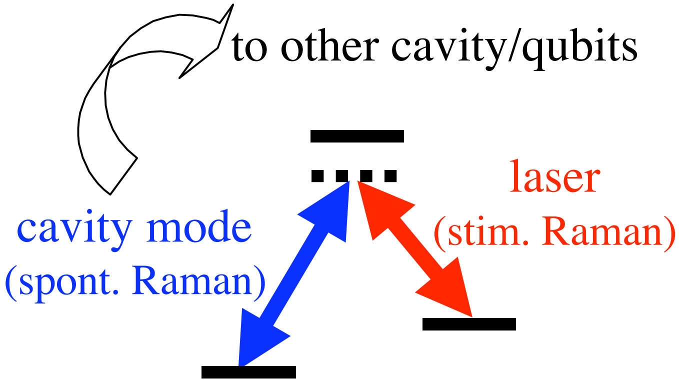


- problem:
  - as $N_{ions} \uparrow$:
    - ion string gets heavier □ gates get slower!
    - more motional modes □ greater “noise”

1. *optical multiplexing:*





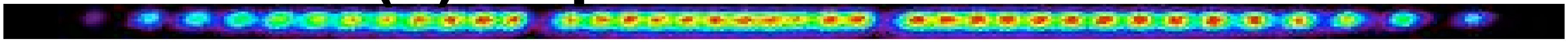

to other cavity/qubits

laser
(stim. Raman)

cavity mode
(spont. Raman)

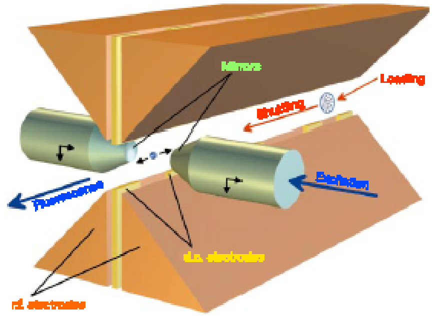
R. DeVoe, PRA **58**, 910 (98)
J.I. Cirac, *et al.* PRL **78**, 3221 (97)

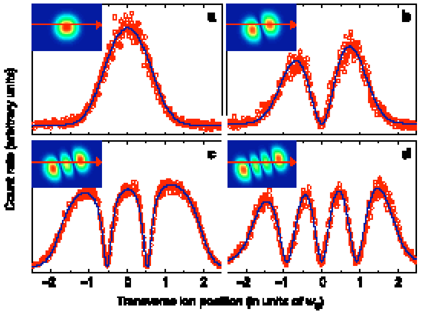
Solutions (1) - optical:

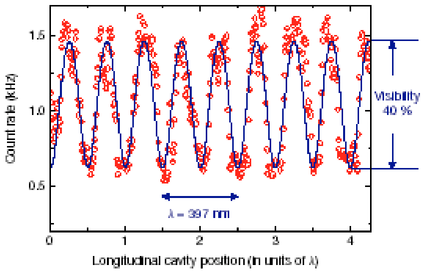


- MPQ, Garching (Ca$^+$): $4\ {}^2S_{1/2}$□ $4\ {}^2P_{1/2}$

G.R. Guthöhrlein, *et al.*, Nature **414** (01)



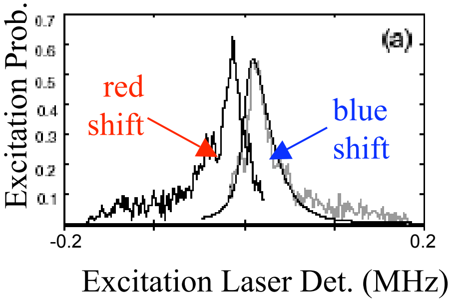


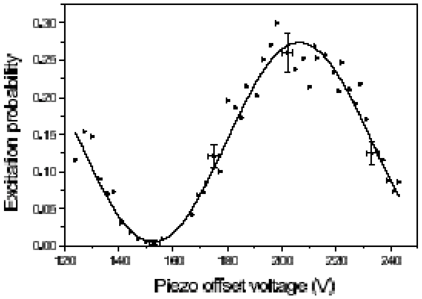


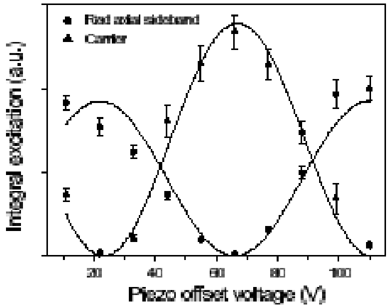
res. □ □/10

- U. Innsbruck (Ca$^+$): $4\ {}^2S_{1/2}$□ $3\ {}^2D_{5\ b/2}$

A.B. Mundt, *et al.*, Phys. Rev. Lett. **189**, 103001 (02).







- sweep PZT

□ Doppler shift

- $P_{ex.} > 0.5$ □ coherent

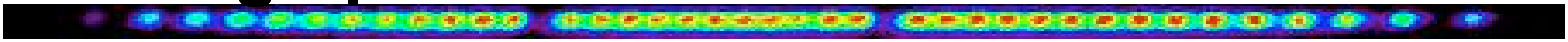
- positioning:

  node/antinode

- res. □ □/100

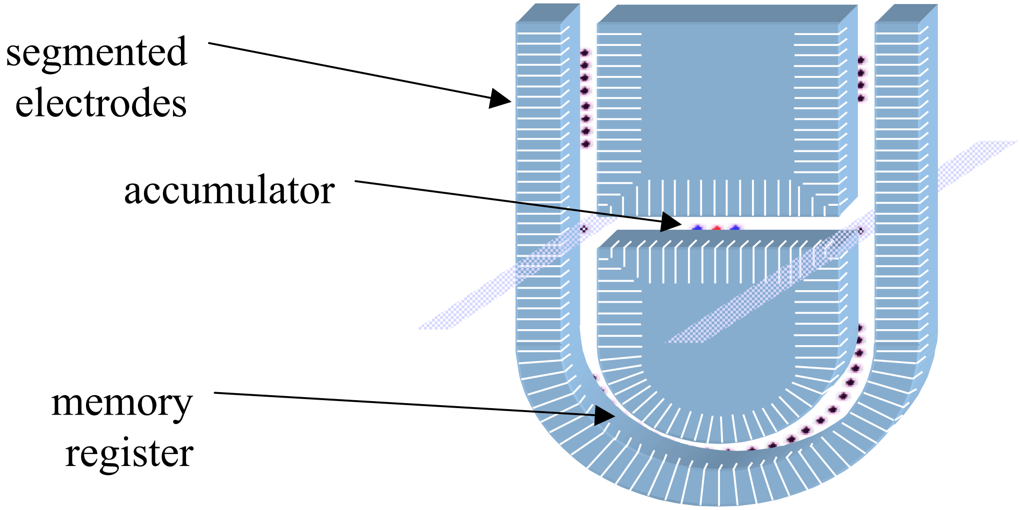
- differential coupling to motional sidebands

Scaling up:



- problem:
  - as $N_{ions}\uparrow$:
    - ion string gets heavier □ gates get slower!
    - more motional modes □ greater "noise"

2. "quantum CCD:"



segmented electrodes

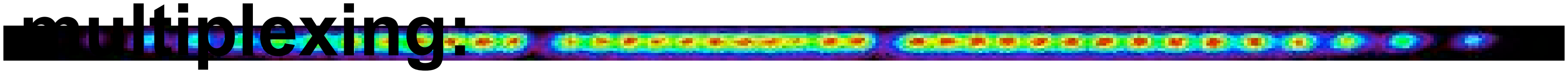
accumulator

memory register

"quantum CCD"

- Wineland, *et al.* J. Res. NIST **103**, 259 (98)
- D. Kielpinski, *et al.* Nature **417**, 709 (02)

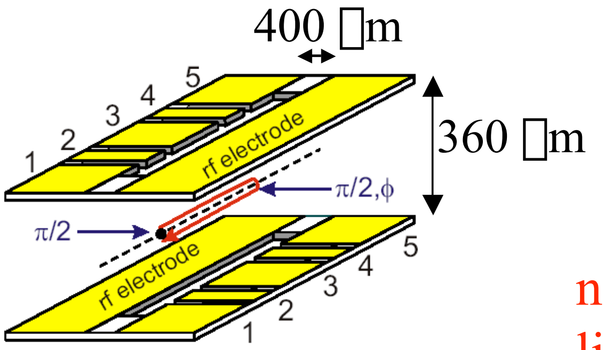
Solutions (2) - physical multiplexing:

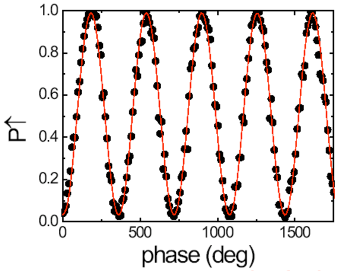


Boulder: M.A. Rowe, et al., Quantum Information and Computation **2**, 257-271 (02)

- transporting ions between traps:

(1) Ramsey interferometer:

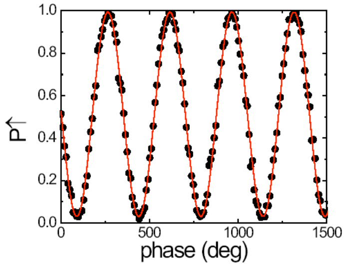




no transport: 96.8 ± 0.3% contrast

line triggered: 96.6 ± 0.5% contrast!

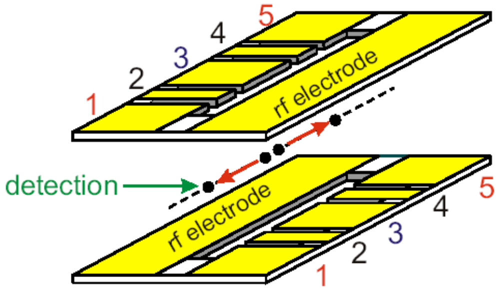
• 60 Hz fields...

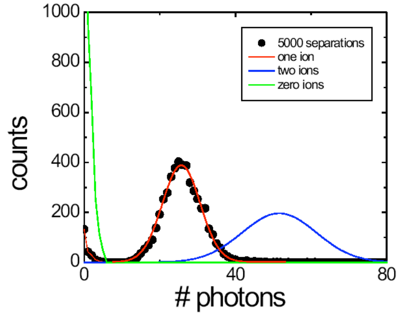


"spin echo"

96% contrast

(2) separating ions:

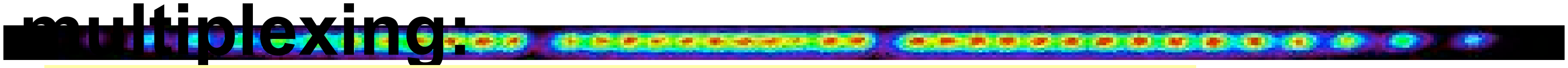




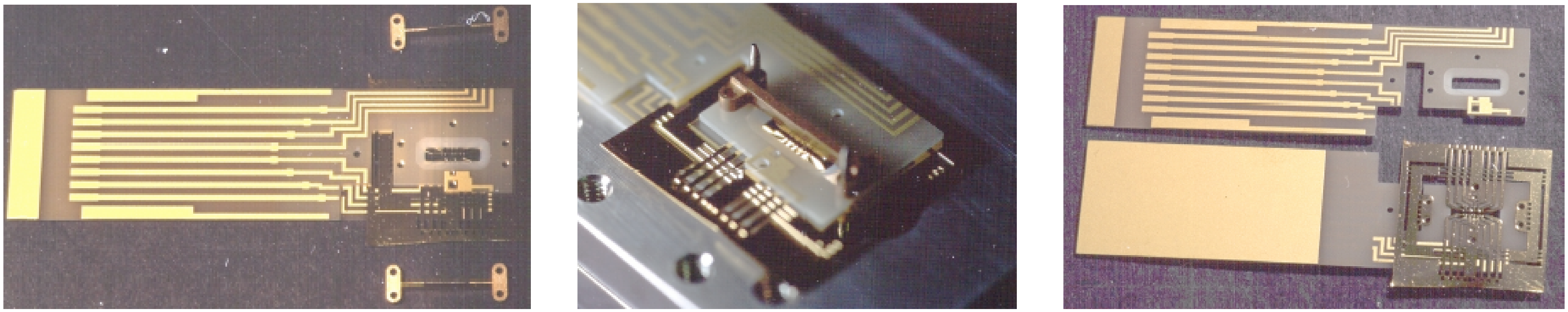
95% sep. eff. (5000 shots)

Δn=200 quanta (2.9 MHz) for 10 ms sep. time (separation electrode too wide!)

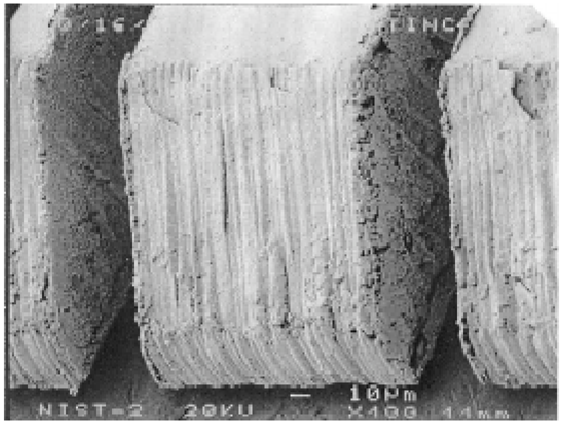
Solutions (2) - physical multiplexing:



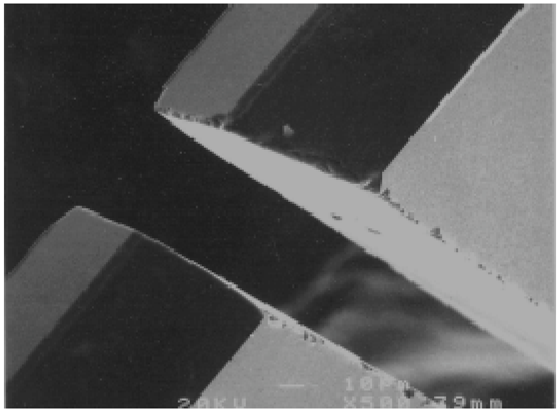
- “gold foil” traps:



- silicon traps:
  - easily micro-machined, smooth

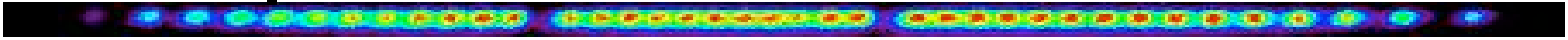


alumina



silicon

Ion Trap QC: Wither thou?...



...ion-trap QC progress:

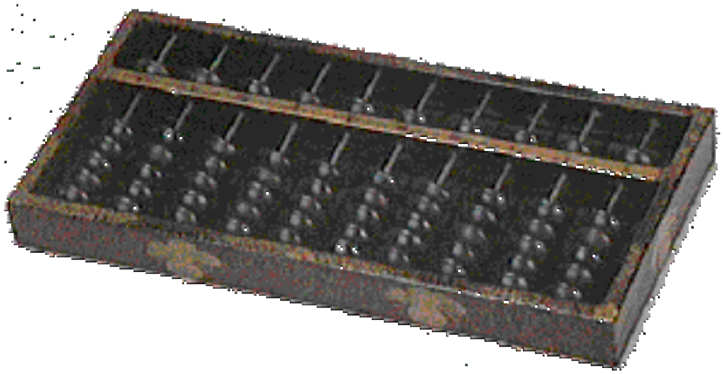
- single-qubit logic gates (´40’s) (>98% fidelity)
- single-ion 2-qubit logic gate (´95) (80% fidelity)
- 2-ion 2-qubit logic gates □ 2 (80% / 97% fidelity)
  - state preparation (fidelity > 98%)
  - spin qubit
    - $t \,/\, t_{gate} > 1000$*
  - motional data bus/qubit
    - heating NIST< $1 /(4\ ms)$, $t \,/\, t_{gate} \sim 100$
    - $1/(10\ ms)$ - IBM, $1/(190\ ms)$ - Innsbruck

NIST Boulder, MPQ Garching, IBM Almaden,
U. Innsbruck, Oxford, U. Michigan, McMaster U…

http://physserv.mcmaster.ca/~kingb/King_B_h.html

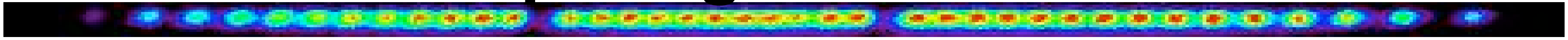
Quantum Computing: Wither thou?...

the dream...



the present reality

Quantum Computing: Wither thou?...



- but, oh! the road...

http://physserv.mcmaster.ca/~kingb/King_B_h.html

Starting Points (ions):

•*Leibfried, et al., J. Phys. B* ***36****, 599 (03)*

•*A. Steane, Appl. Phys. B.* ***64*** *, 623 (97)*

•*Wineland, et al., J. Res. of the NIST* ***103****, 259 (98)*

(gor