

Quantum information processing with trapped ions

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NIST

The remaining QIP challenge

DiVincenzo requirements:

- I. A scalable physical system with well characterized qubits
- II. The ability to initialize the state of the qubits to a simple fiducial state
- III. Long relevant decoherence times, much longer than the gate time
- IV. A universal set of quantum gates (single qubit rot., two qubit gate)
- V. A qubit-specific read out capability

Overview

- Introduction to ion traps
- Atomic physics for ion-qubits
- Manipulation of ion-qubits with laser fields
- Scalable QIP with trapped ions
- Example experiments

Please ask questions! (dil@boulder.nist.gov)

More exhaustive, formal and rigorous treatments:

[1] D. J. Wineland, C. Monroe, W. M. Itano, D. Leibfried, B. E. King, and D. M. Meekhof, *J. Res. Nat. Inst. Stand. Tech.* 103, 259 (1998); M. Sasura and V. Buzek, *J. Mod. Opt.* 49, 1593 (2002); D. Leibfried, R. Blatt, C. Monroe, and D. Wineland, *Rev. Mod. Phys.* 75, 281 (2003); H. Häffner, C. F. Roos, and R. Blatt, *Physics Reports* 469, 155 (2008); D. Kielpinski, *Front. Phys. China* 3, 365 (2008)

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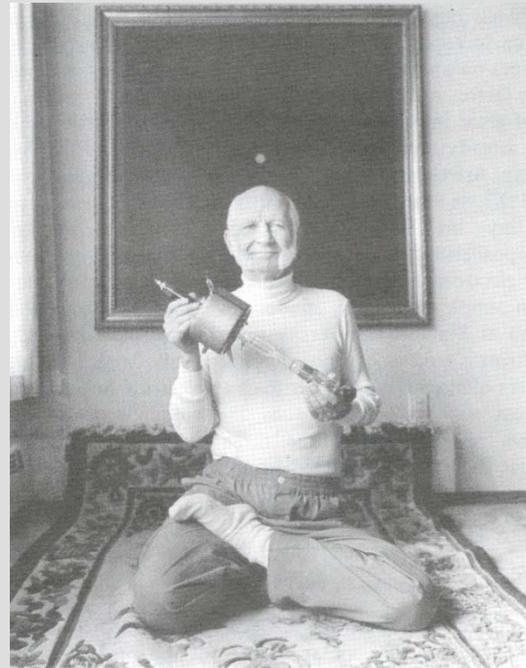
Traps for single charged particles

Paul trap 1956
AC/DC electric fields



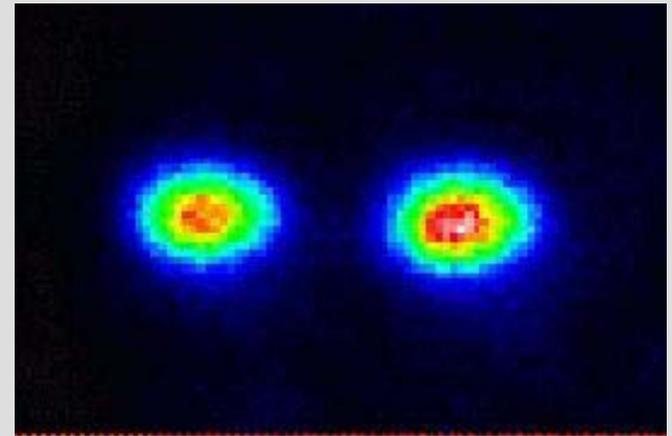
Wolfgang Paul

Penning trap 1959
(Dehmelt, Gräff)
DC electric/magnetic fields



Hans Dehmelt

1980/1981 single trapped and
laser cooled atomic ions at
Univ. of Heidelberg and NIST



CCD image of two trapped
and laser cooled ${}^9\text{Be}^+$ ions in a
Paul-trap at NIST

Pseudopotential approximation

equations of motion of ion described by Mathieu equations; can be rigorously solved
 "pseudopotential approximation" often sufficient:

$$m\ddot{x} = q\mathbf{E} \cos(\Omega_{\text{rf}}t)$$

assume field is slowly varying over space, then to first order ion will "quiver" at the drive frequency

$$x = -\frac{q\mathbf{E}}{m\Omega_{\text{rf}}^2} \cos(\Omega_{\text{rf}}t)$$

associate kinetic energy with this "micro-motion" and average over one cycle of the driving field

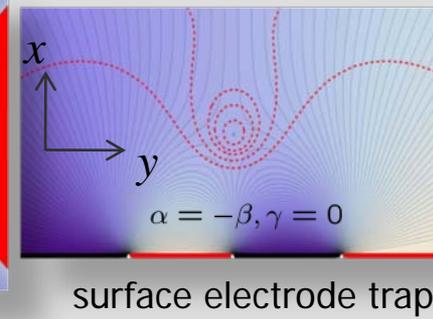
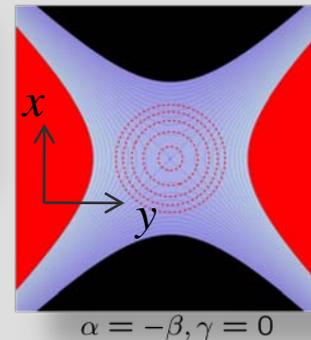
$$U_{\text{kin}} = q \times \Phi_{\text{pp}} = q \times \frac{q\mathbf{E}^2}{4m\Omega_{\text{rf}}^2}$$

typically ion is trapped at field-zero with approx. quadratic spatial field dependence

$$\Phi_{\text{el}} = V_0 \cos(\Omega_{\text{rf}}t) \frac{1}{2}(\alpha x^2 + \beta y^2 + \gamma z^2), \quad \alpha + \beta + \gamma = 0 \quad (\text{Laplace})$$

$$\Phi_{\text{pp}} = \frac{qV_0^2}{4m\Omega_{\text{rf}}^2}(\alpha^2 x^2 + \beta^2 y^2 + \gamma^2 z^2)$$

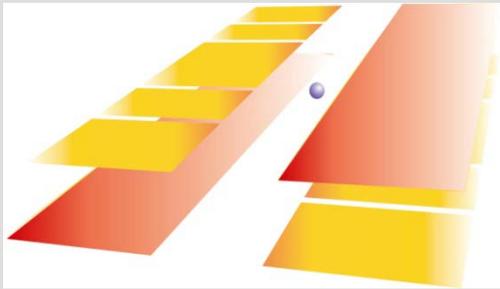
electric equi-potential lines (black thin)
 harmonic equi-pseudo-potential lines (red dashed)



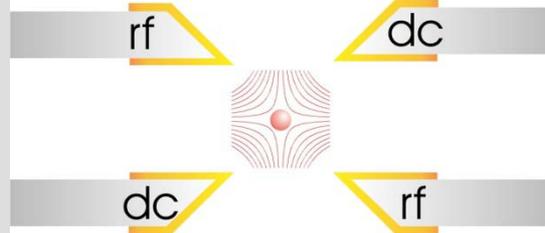
surface electrode trap

The linear Paul trap

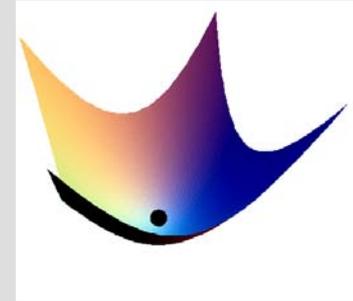
radial confinement:



radial cross section



ac quadrupole potential



harmonic time averaged pseudo-potential

axial confinement:

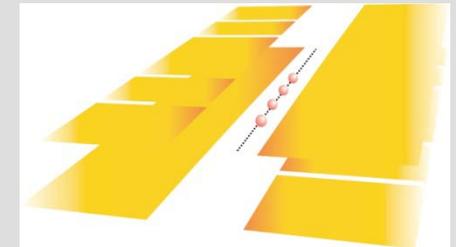


axial cross section



Coulomb interaction couples ions \Rightarrow normal modes of vibration

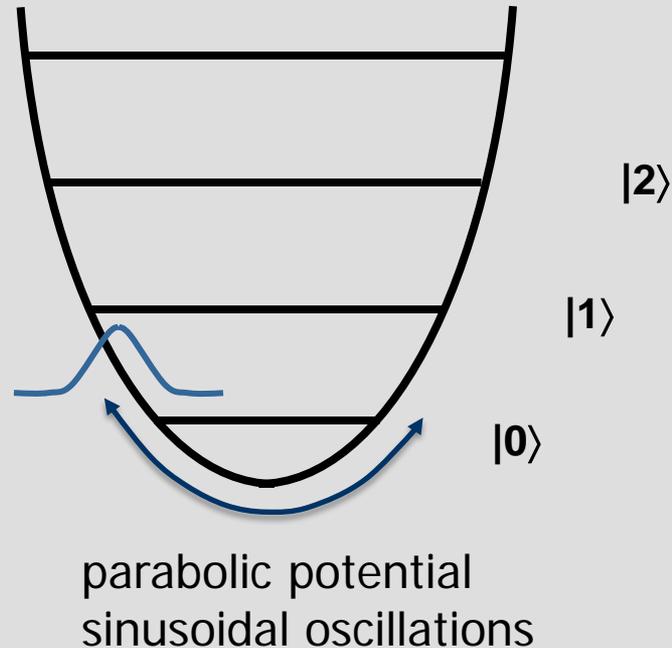
radial conf. \gg axial conf. \Rightarrow ions align along trap axis



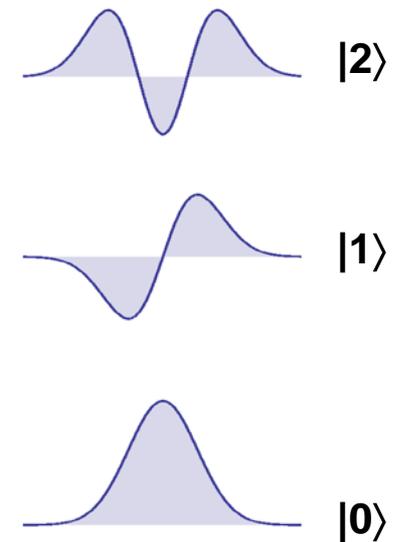
Harmonic oscillators

Examples:

pendulum
vibrating string
ball on spring
cantilevers
resonant circuits
light field
quantum fields
...
trapped ions



q.m. wavefunctions

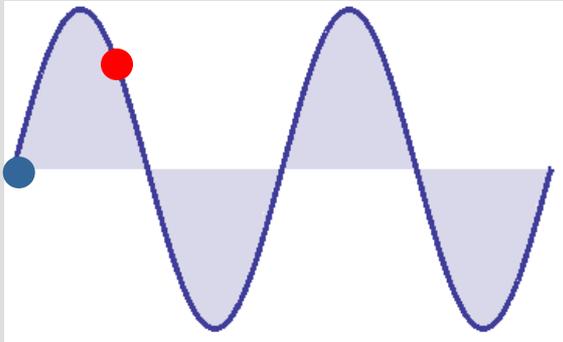


energy eigenfunctions are stationary in time... so where's the pendulum ?

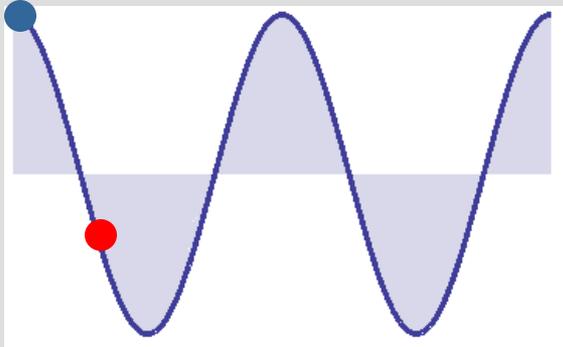
use superposition of energy eigenfunctions, called "coherent states"
(Schrödinger 1926, Glauber 1963) to shape "oscillating ground states"

Phase space

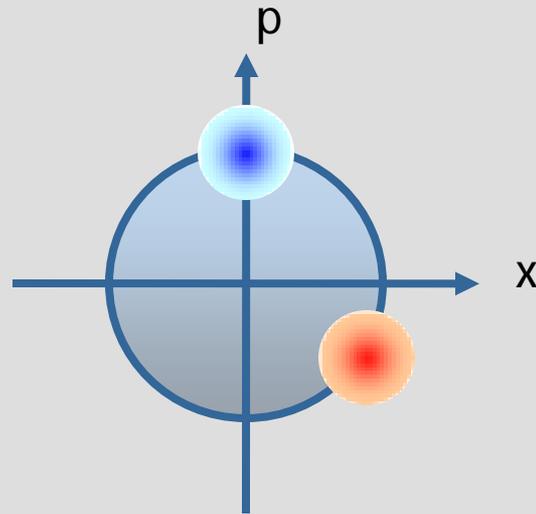
classical sinusoidal oscillation



position x



momentum p (mass \times velocity)



quantum mechanics:
Heisenberg uncertainty

$$\Delta x \Delta p \geq \hbar/2$$

Gaussian wave-packet of
coherent state fulfills the
equality.

frame rotating at oscillation frequency

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One electron systems

PERIODIC TABLE Atomic Properties of the Elements

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Frequently used fundamental physical constants	
For the most accurate values of these and other constants, visit physics.nist.gov/constants	
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs	
speed of light in vacuum	c 299 792 458 m s ⁻¹ (exact)
Planck constant	h 6.626 070 15 × 10 ⁻³⁴ J s ($\hbar = h/2\pi$)
elementary charge	e 1.602 176 634 × 10 ⁻¹⁹ C
electron mass	m_e 9.109 382 91 × 10 ⁻³¹ kg
	$m_e c^2$ 0.5110 MeV
proton mass	m_p 1.672 621 63 × 10 ⁻²⁷ kg
fine-structure constant	α 1/137.035 999 074
Rydberg constant	R_∞ 10 973 731.7 m ⁻¹
	$R_\infty c$ 3.289 841 7 × 10 ¹⁶ Hz
	$R_\infty hc$ 13.605 698 eV
Boltzmann constant	k 1.380 658 × 10 ⁻²³ J K ⁻¹

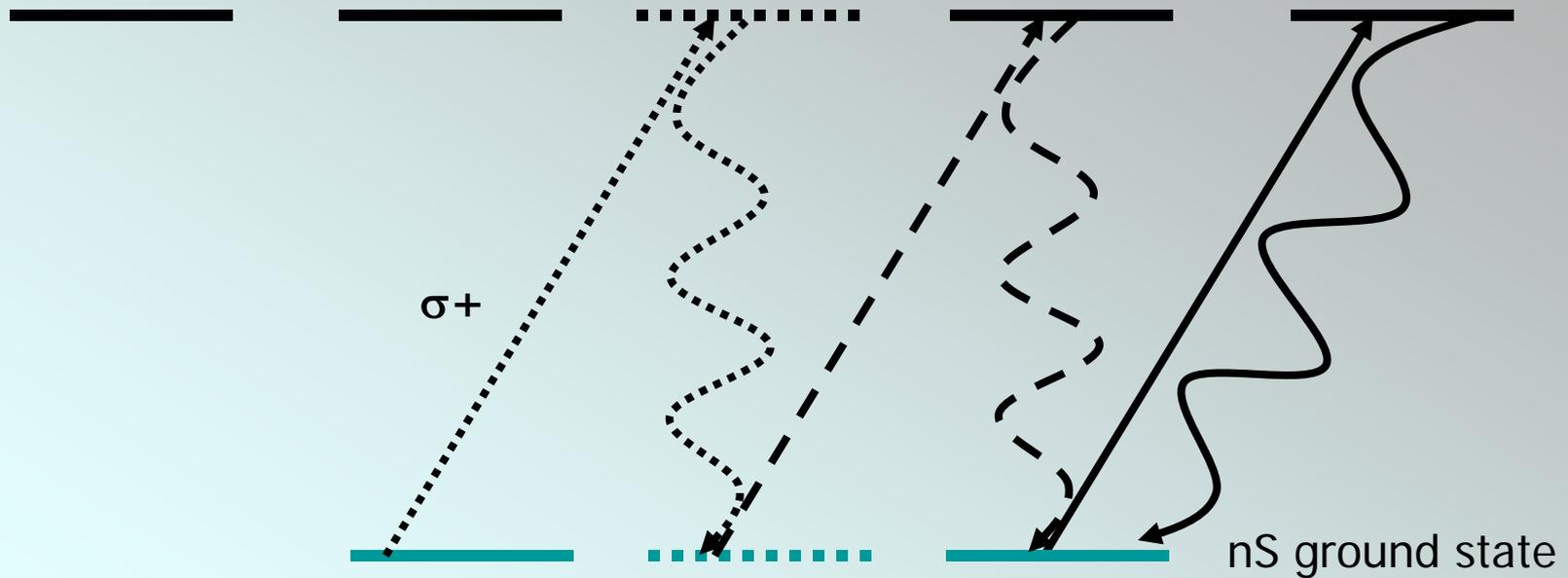
- Solids
- Liquids
- Gases
- Artificially Prepared

Period	Group 1 IA		PERIODIC TABLE										Standard Reference Data Group www.nist.gov/srd						18 VIII
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
	IIA		IIIB	IVB	VB	VIB	VII B	VIII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA	
1	1 ¹ H Hydrogen 1.00794 1s												5 ¹³ B Boron 10.811 1s ² 2s ² 2p ¹ 8.2080	6 ¹⁴ C Carbon 12.0107 1s ² 2s ² 2p ² 11.2603	7 ¹⁵ N Nitrogen 14.0067 1s ² 2s ² 2p ³ 14.5341	8 ¹⁶ O Oxygen 15.9994 1s ² 2s ² 2p ⁴ 13.6181	9 ¹⁹ F Fluorine 18.9984032 1s ² 2s ² 2p ⁵ 17.4228	10 ²⁰ Ne Neon 20.1797 1s ² 2s ² 2p ⁶ 21.9646	
2	3 ³ Li Lithium 6.941 1s ² 2s ¹ 5.3917	4 ⁴ Be Beryllium 9.012182 1s ² 2s ² 9.3227											13 ¹³ Al Aluminum 26.981538 [Ne]3s ² 3p ¹ 5.9856	14 ¹⁴ Si Silicon 28.0855 [Ne]3s ² 3p ² 8.1517	15 ¹⁵ P Phosphorus 30.973761 10.4867	16 ¹⁶ S Sulfur 32.065 10.3630	17 ¹⁷ Cl Chlorine 35.453 12.9676	18 ¹⁸ Ar Argon 39.948 15.7596	
3	11 ¹¹ Na Sodium 22.98977 [Ne]3s ¹ 5.1391	12 ¹² Mg Magnesium 24.3050 [Ne]3s ² 7.6462											13 ¹³ Al Aluminum 26.981538 [Ne]3s ² 3p ¹ 5.9856	14 ¹⁴ Si Silicon 28.0855 [Ne]3s ² 3p ² 8.1517	15 ¹⁵ P Phosphorus 30.973761 10.4867	16 ¹⁶ S Sulfur 32.065 10.3630	17 ¹⁷ Cl Chlorine 35.453 12.9676	18 ¹⁸ Ar Argon 39.948 15.7596	
4	19 ¹⁹ K Potassium 39.0983 [Ar]4s ¹ 4.3407	20 ²⁰ Ca Calcium 40.078 [Ar]4s ² 8.1152	21 ²¹ Sc Scandium 44.955910 [Ar]3d ¹ 4s ² 6.5815	22 ²² Ti Titanium 47.887 [Ar]3d ² 4s ² 6.8261	23 ²³ V Vanadium 50.9415 6.7462	24 ²⁴ Cr Chromium 51.9961 7.4340	25 ²⁵ Mn Manganese 54.938049 7.4340	26 ²⁶ Fe Iron 55.845 7.9024	27 ²⁷ Co Cobalt 58.933200 7.8810	28 ²⁸ Ni Nickel 58.6934 7.2384	29 ²⁹ Cu Copper 63.546 7.2384	30 ³⁰ Zn Zinc 65.409 8.3942	31 ³¹ Ga Gallium 69.723 5.9965	32 ³² Ge Germanium 72.64 7.8964	33 ³³ As Arsenic 74.92160 9.7886	34 ³⁴ Se Selenium 78.96 9.7524	35 ³⁵ Br Bromine 79.904 11.8138	36 ³⁶ Kr Krypton 83.798 13.9906	
5	37 ³⁷ Rb Rubidium 85.4678 [Kr]5s ¹ 4.1771	38 ³⁸ Sr Strontium 87.62 [Kr]5s ² 5.6949	39 ³⁹ Y Yttrium 88.90585 [Kr]4d ¹ 5s ² 6.2173	40 ⁴⁰ Zr Zirconium 91.224 [Kr]4d ² 5s ² 6.7589	41 ⁴¹ Nb Niobium 92.90638 6.9594	42 ⁴² Mo Molybdenum 95.94 7.0924	43 ⁴³ Tc Technetium 98 7.28	44 ⁴⁴ Ru Ruthenium 101.07 7.3805	45 ⁴⁵ Rh Rhodium 102.90550 7.4589	46 ⁴⁶ Pd Palladium 106.42 8.3369	47 ⁴⁷ Ag Silver 107.8682 7.5762	48 ⁴⁸ Cd Cadmium 112.411 8.9938	49 ⁴⁹ In Indium 114.818 5.7884	50 ⁵⁰ Sn Tin 118.710 7.3459	51 ⁵¹ Sb Antimony 121.760 8.6084	52 ⁵² Te Tellurium 127.60 9.0096	53 ⁵³ I Iodine 126.90447 10.4513	54 ⁵⁴ Xe Xenon 131.293 12.1298	
6	55 ⁵⁵ Cs Cesium 132.90545 [Xe]6s ¹ 3.8989	56 ⁵⁶ Ba Barium 137.327 [Xe]6s ² 5.2117		72 ⁷² Hf Hafnium 178.49 6.8251	73 ⁷³ Ta Tantalum 180.9479 7.5408	74 ⁷⁴ W Tungsten 183.84 7.8840	75 ⁷⁵ Re Rhenium 186.207 7.8335	76 ⁷⁶ Os Osmium 190.23 8.4382	77 ⁷⁷ Ir Iridium 192.217 8.9870	78 ⁷⁸ Pt Platinum 195.078 8.9588	79 ⁷⁹ Au Gold 196.96655 9.2255	80 ⁸⁰ Hg Mercury 200.59 10.4375	81 ⁸¹ Tl Thallium 204.3833 6.1082	82 ⁸² Pb Lead 207.2 7.4167	83 ⁸³ Bi Bismuth 208.98039 7.2855	84 ⁸⁴ Po Polonium (209) 8.414	85 ⁸⁵ At Astatine (210) [H]8p ⁵	86 ⁸⁶ Rn Radon (222) 10.7485	
7	87 ⁸⁷ Fr Francium (223) [Rn]7s ¹ 4.0727	88 ⁸⁸ Ra Radium (226) [Rn]7s ² 5.2784		104 ¹⁰⁴ Rf Rutherfordium (261) [Rf]5f ¹⁴ 6d ² 7s ² 6.0?	105 ¹⁰⁵ Db Dubnium (262)	106 ¹⁰⁶ Sg Seaborgium (266)	107 ¹⁰⁷ Bh Bohrium (264)	108 ¹⁰⁸ Hs Hassium (277)	109 ¹⁰⁹ Mt Meitnerium (268)	110 ¹¹⁰ Uun Ununium (281)	111 ¹¹¹ Uuu Unununium (272)	112 ¹¹² Uub Unbium (285)	114 ¹¹⁴ Uuq Ununquadium (289)	116 ¹¹⁶ Uuh Ununhexium (292)					
			Lanthanides																
			57 ⁵⁷ La Lanthanum 138.9055 [Xe]5d ¹ 6s ² 5.5780	58 ⁵⁸ Ce Cerium 140.116 [Xe]4f ¹ 5d ¹ 6s ² 5.5387	59 ⁵⁹ Pr Praseodymium 140.90766 [Xe]4f ³ 6s ² 5.473	60 ⁶⁰ Nd Neodymium 144.24 [Xe]4f ⁴ 6s ² 5.5250	61 ⁶¹ Pm Promethium 144.9128 [Xe]4f ⁵ 6s ² 5.582	62 ⁶² Sm Samarium 150.36 [Xe]4f ⁶ 6s ² 5.6437	63 ⁶³ Eu Europium 151.964 [Xe]4f ⁷ 6s ² 5.6704	64 ⁶⁴ Gd Gadolinium 157.25 [Xe]4f ⁷ 5d ¹ 6s ² 6.1488	65 ⁶⁵ Tb Terbium 158.92534 [Xe]4f ⁹ 6s ² 5.8658	66 ⁶⁶ Dy Dysprosium 162.500 [Xe]4f ¹⁰ 6s ² 5.9369	67 ⁶⁷ Ho Holmium 164.93032 [Xe]4f ¹¹ 6s ² 6.0215	68 ⁶⁸ Er Erbium 167.259 [Xe]4f ¹² 6s ² 6.1077	69 ⁶⁹ Tm Thulium 168.93402 [Xe]4f ¹³ 6s ² 6.1843	70 ⁷⁰ Yb Ytterbium 173.04 [Xe]4f ¹⁴ 6s ² 6.2542	71 ⁷¹ Lu Lutetium 174.967 [Xe]4f ¹⁴ 5d ¹ 6s ² 5.4259		
			Actinides																
			89 ⁸⁹ Ac Actinium (227) [Rn]6d ¹ 7s ² 5.17	90 ⁹⁰ Th Thorium 232.0381 [Rn]6d ² 7s ² 6.3087	91 ⁹¹ Pa Protactinium 231.03688 [Rn]5f ² 6d ¹ 7s ² 5.80	92 ⁹² U Uranium 238.02891 [Rn]5f ³ 6d ¹ 7s ² 6.1941	93 ⁹³ Np Neptunium (237) [Rn]5f ⁴ 6s ² 6.2857	94 ⁹⁴ Pu Plutonium (244) [Rn]5f ⁶ 7s ² 6.0260	95 ⁹⁵ Am Americium (243) [Rn]5f ⁷ 7s ² 5.9738	96 ⁹⁶ Cm Curium (247) [Rn]5f ⁸ 6d ¹ 7s ² 5.9014	97 ⁹⁷ Bk Berkelium (247) [Rn]5f ⁹ 7s ² 6.1979	98 ⁹⁸ Cf Californium (251) [Rn]5f ¹⁰ 7s ² 6.2817	99 ⁹⁹ Es Einsteinium (252) [Rn]5f ¹¹ 7s ² 6.42	100 ¹⁰⁰ Fm Fermium (257) [Rn]5f ¹² 7s ² 6.50	101 ¹⁰¹ Md Mendelevium (258) [Rn]5f ¹³ 7s ² 6.58	102 ¹⁰² No Nobelium (259) [Rn]5f ¹⁴ 7s ² 6.65	103 ¹⁰³ Lr Lawrencium (262) [Rn]5f ¹⁴ 7p ¹ 4.9?		

Atomic Number: 58
Ground-state Level: ¹G₄
Symbol: Ce
Name: Cerium
Atomic Weight: 140.116
Ground-state Configuration: [Xe]4f¹5d¹6s²
Ionization Energy (eV): 5.5387

Resonant $S \rightarrow P$ transition

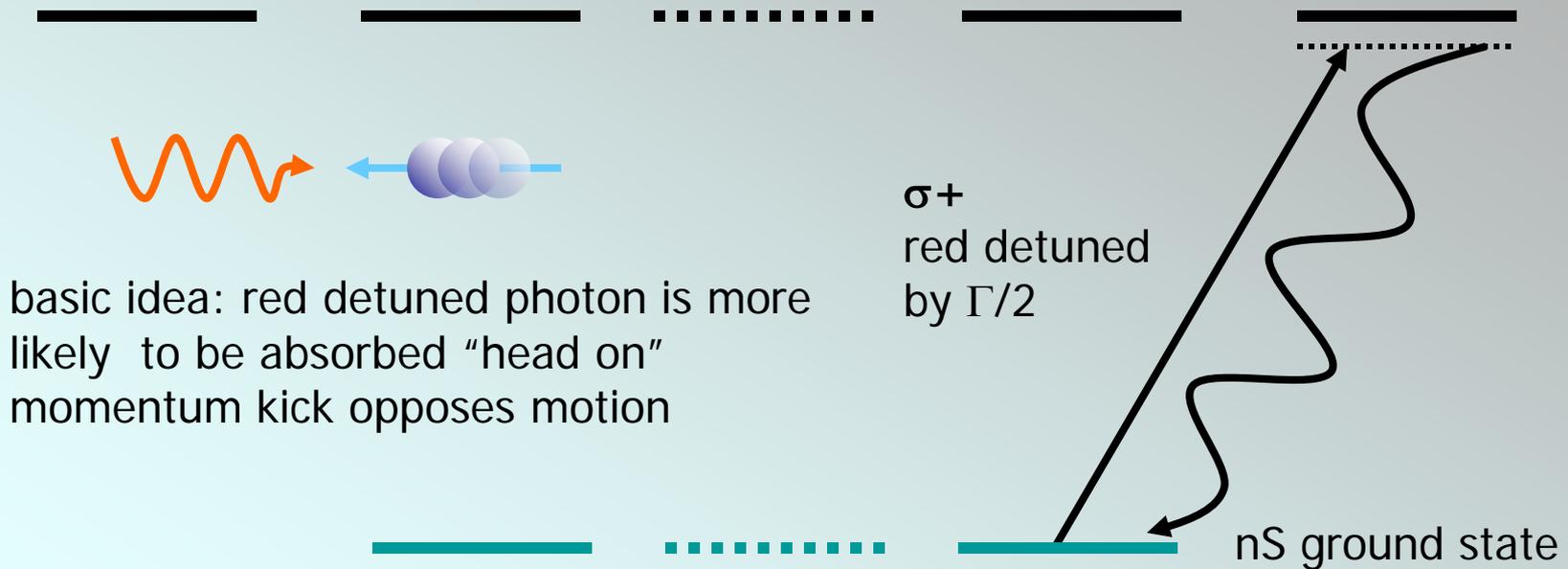
nP ($2P$ for Be^+) excited state (life-time a few ns)



optically pump for state preparation

Resonant $S \rightarrow P$ transition

nP excited state (life-time a few ns)



basic idea: red detuned photon is more likely to be absorbed "head on" momentum kick opposes motion

$\sigma+$
red detuned
by $\Gamma/2$

nS ground state

Doppler cooling

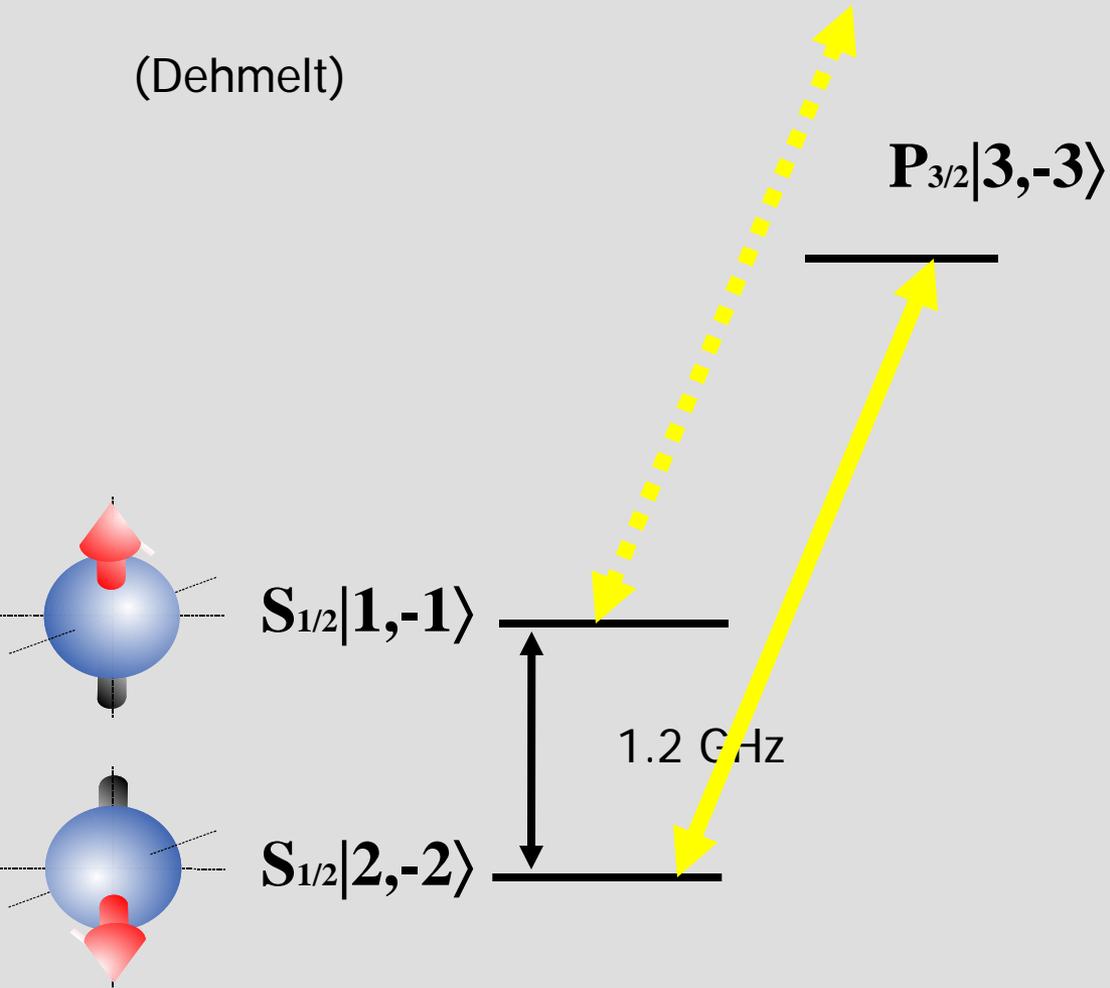
Resonant $S \rightarrow P$ transition

nP excited state (life-time a few ns)

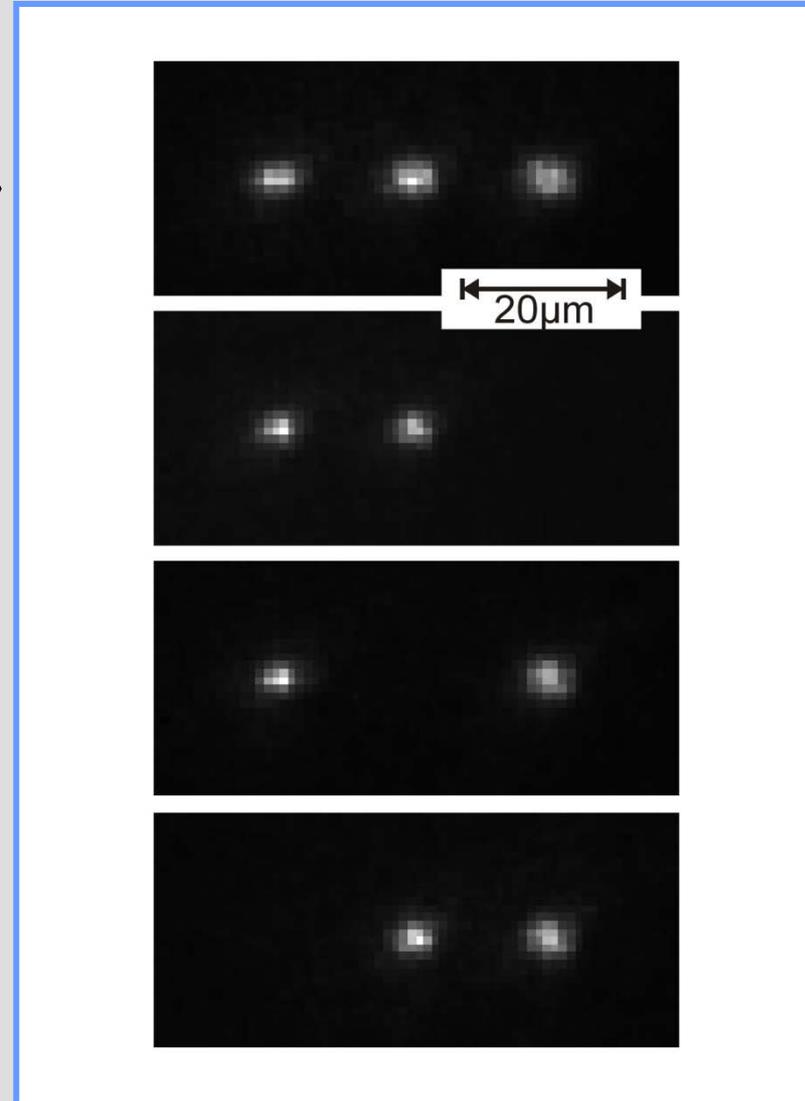


Electron shelving detection

(Dehmelt)

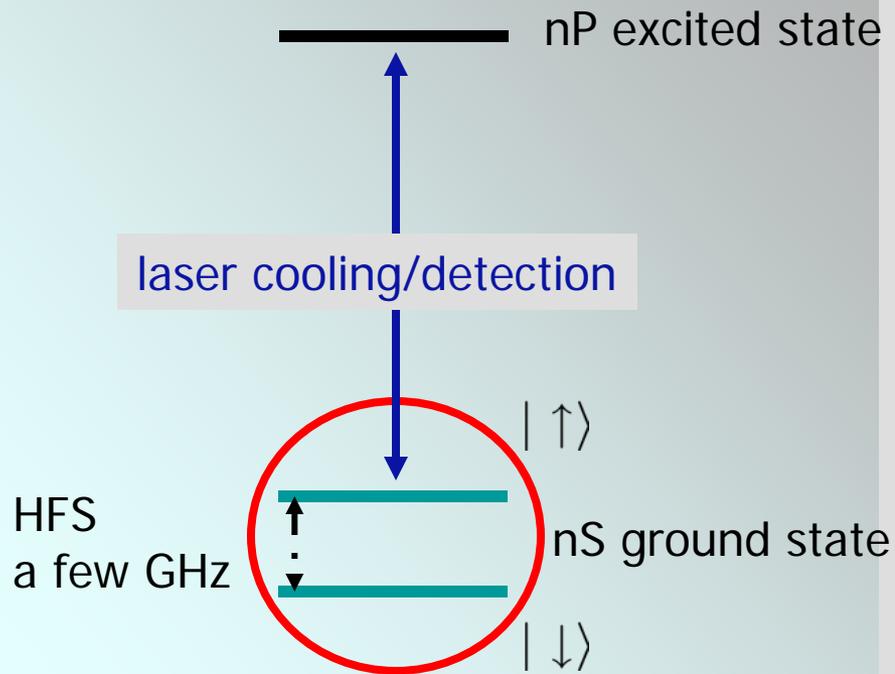


3 Ca^+ ions, Univ. of Innsbruck
[PRA **60**, 145 1999]

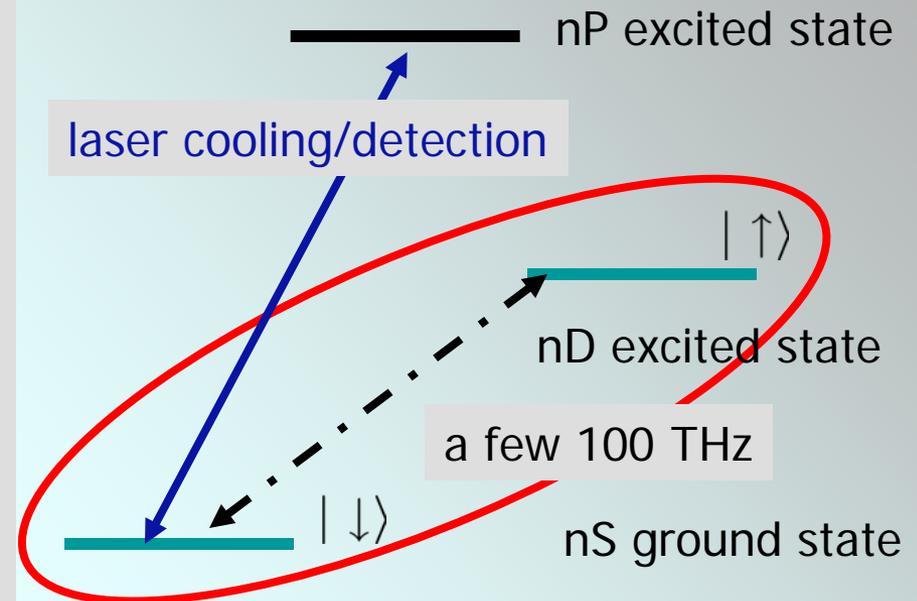


Ion qubits ($|\downarrow\rangle, |\uparrow\rangle$)

hyperfine qubit



optical qubit



Possible qubits

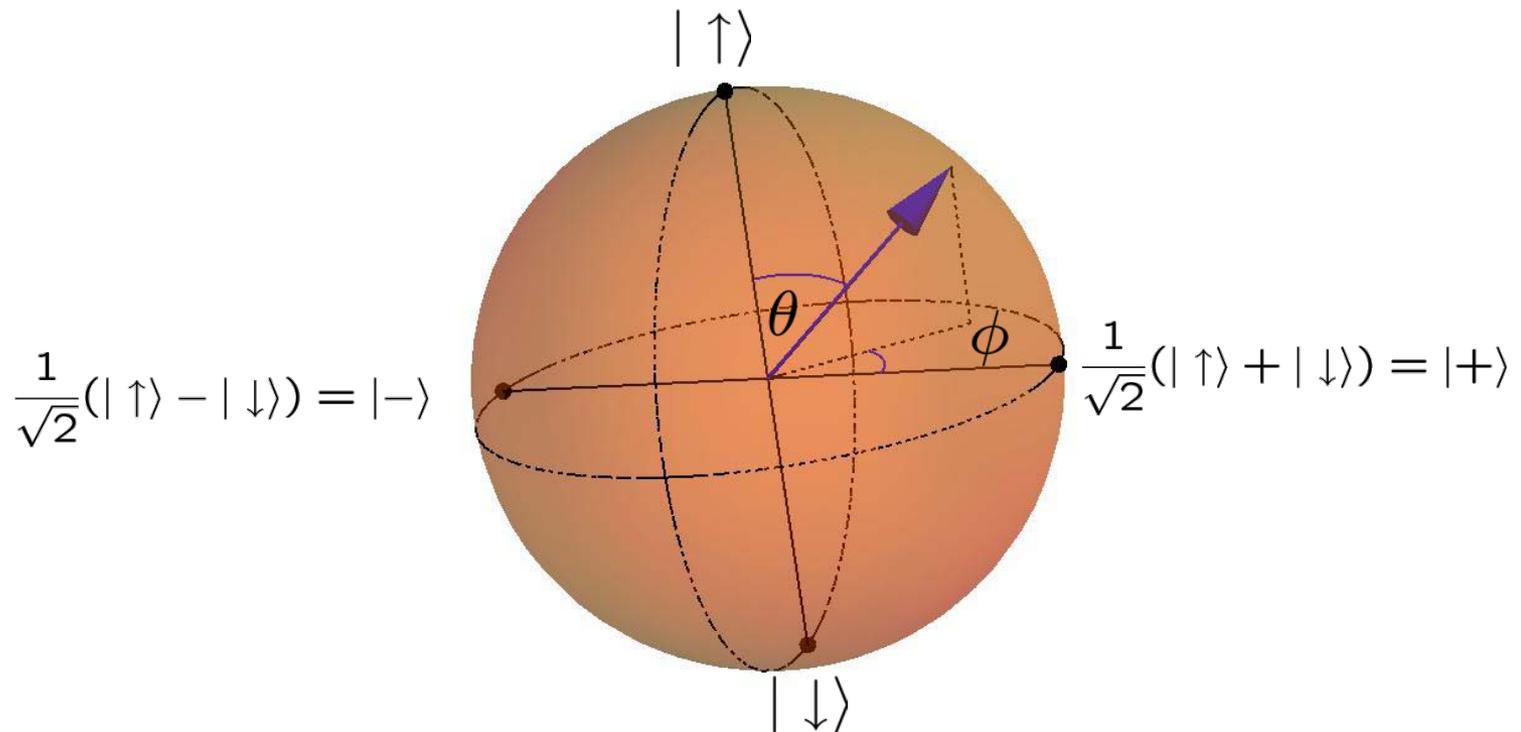
(list is not exhaustive)

	hyperfine qubit	hyperfine+ optical qubit	optical qubit
degrees of freedom	nuclear spin electron spin	nuclear spin electron spin electron energy	electron energy
species	${}^9\text{Be}^+$, ${}^{25}\text{Mg}^+$, ${}^{111}\text{Cd}^+$, ${}^{67}\text{Zn}^+$ ${}^{137}\text{Ba}^+$, ${}^{171}\text{Yb}^+$	${}^{43}\text{Ca}^+$, ${}^{87}\text{Sr}^+$, ${}^{199}\text{Hg}^+$	${}^{40}\text{Ca}^+$, ${}^{88}\text{Sr}^+$

Bloch sphere picture

$$|\Psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle; \quad |\alpha|^2 + |\beta|^2 = 1$$

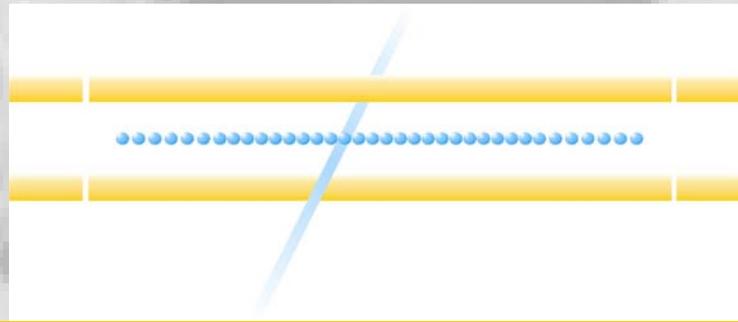
$$|\Psi\rangle = e^{i\gamma}(\cos\theta/2|\uparrow\rangle + e^{i\phi}\sin\theta/2|\downarrow\rangle)$$



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The initial idea

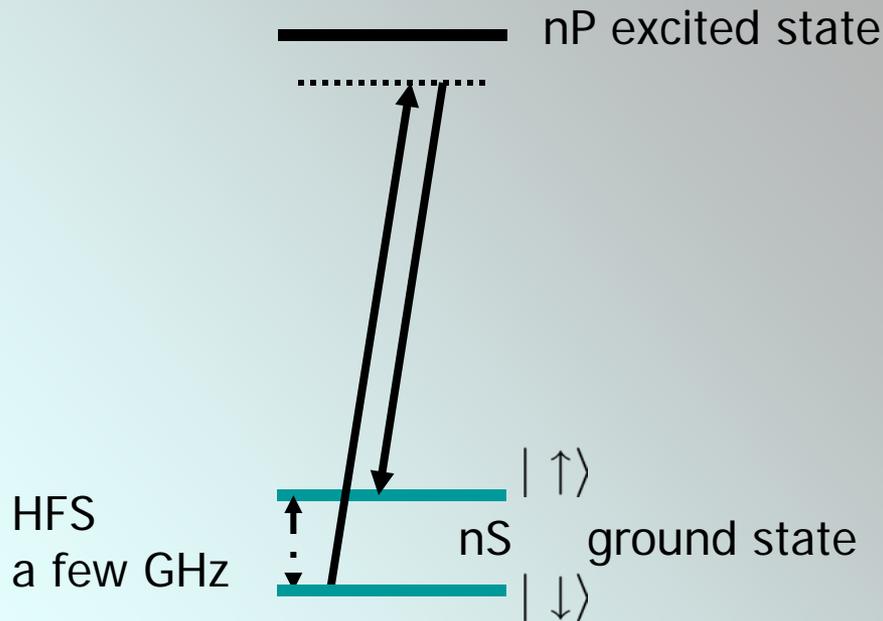


- Ions are used for atomic clocks \Rightarrow well characterized qubits
- Ions can be optically pumped and cooled to the trap ground state
- \Rightarrow well defined initial system state (see David Lucas' talk)
- Ions can be read out with high fidelity
- Atomic clocks can have coherence times of many seconds
- **Shared eigenmodes of oscillation can provide qubit-qubit coupling**

J. I. Cirac and P. Zoller, Phys. Rev. Lett. 74, 4091 (1995).

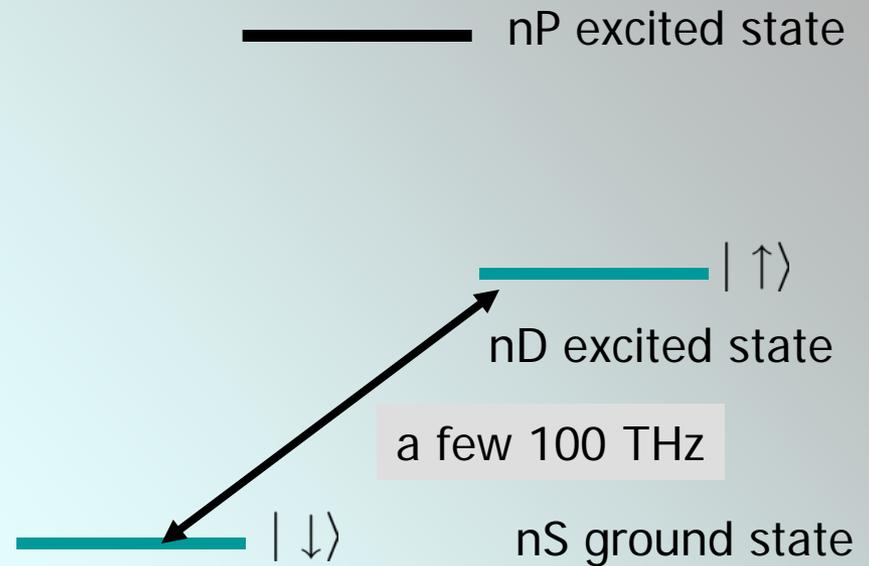
Coherent excitations

hyperfine qubit



stimulated Raman interaction
ground states
difference frequency stable

optical qubit



direct laser interaction
excited state (τ order 1 s)
absolute frequency stable

Excitation spectrum for ion in trap (internal+motion) similar in both cases

Interaction Hamiltonian

basic coupling, Ω_0 contains details (Raman or optical etc.)

$$H_I = \hbar\Omega_0 e^{-i([\delta_0 - \omega_0]t + \phi)} e^{i\Delta\mathbf{k}\cdot\mathbf{r}} |\uparrow\rangle\langle\downarrow| + \text{h.c.}$$

light detuning and phase

ion motion in trap

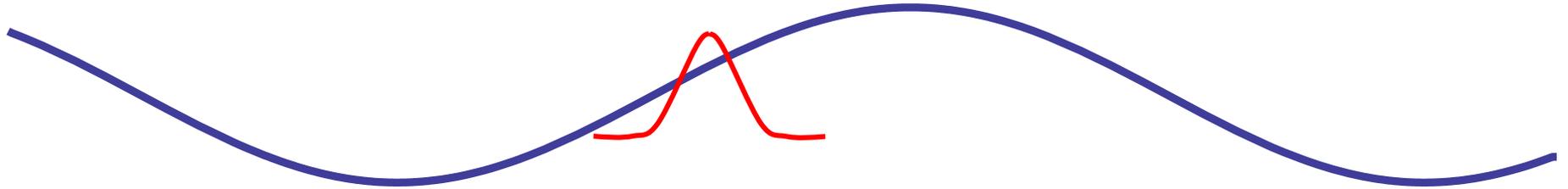
$$e^{i\Delta\mathbf{k}\cdot\mathbf{r}} = e^{i\eta(a_i^\dagger + a_i)} \simeq 1 + i\eta(a_i^\dagger + a_i)$$

Lamb-Dicke approximation

$$\eta = \sqrt{\frac{E_{\text{rec}}}{E_{\text{h.o.}}}} = \sqrt{\frac{\hbar^2 k^2}{2m\hbar\omega}} = 2\pi \frac{a_0}{\lambda} \ll 1$$

a_0 typically order 10 nm for a few MHz trap frequency, λ typically 200-400nm

Interaction Hamiltonian



over the **extension of the wavefunction** the electric field is to first order constant with a gradient term smaller by order η that can force the motion

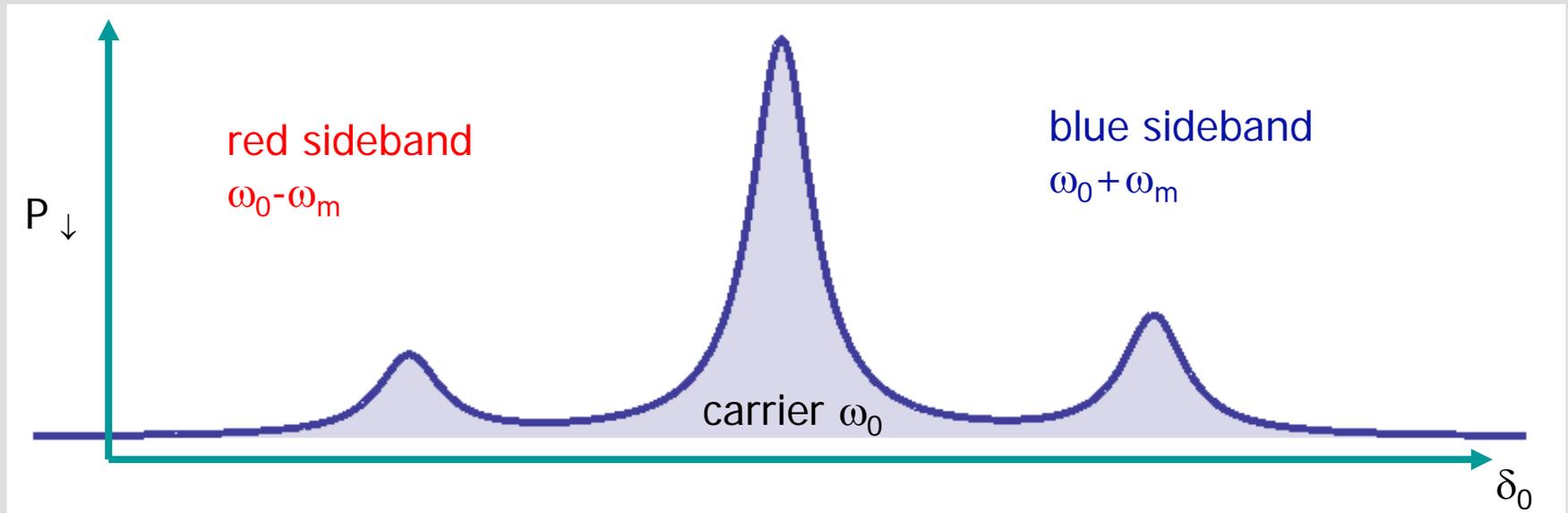
interaction picture operator $a_i = a e^{-i\omega_m t}$

$$H_I \simeq \hbar\Omega_0 e^{-i([\delta_0 - \omega_0]t + \phi)} |\uparrow\rangle\langle\downarrow| + \text{h.c.} \quad (\text{carrier})$$

$$+ i\hbar\eta\Omega_0 e^{-i([\delta_0 - (\omega_0 + \omega_m)]t + \phi)} a^\dagger |\uparrow\rangle\langle\downarrow| + \text{h.c.} \quad (\text{blue sideband})$$

$$+ i\hbar\eta\Omega_0 e^{-i([\delta_0 - (\omega_0 - \omega_m)]t + \phi)} a |\uparrow\rangle\langle\downarrow| + \text{h.c.} \quad (\text{red sideband})$$

Sideband spectrum

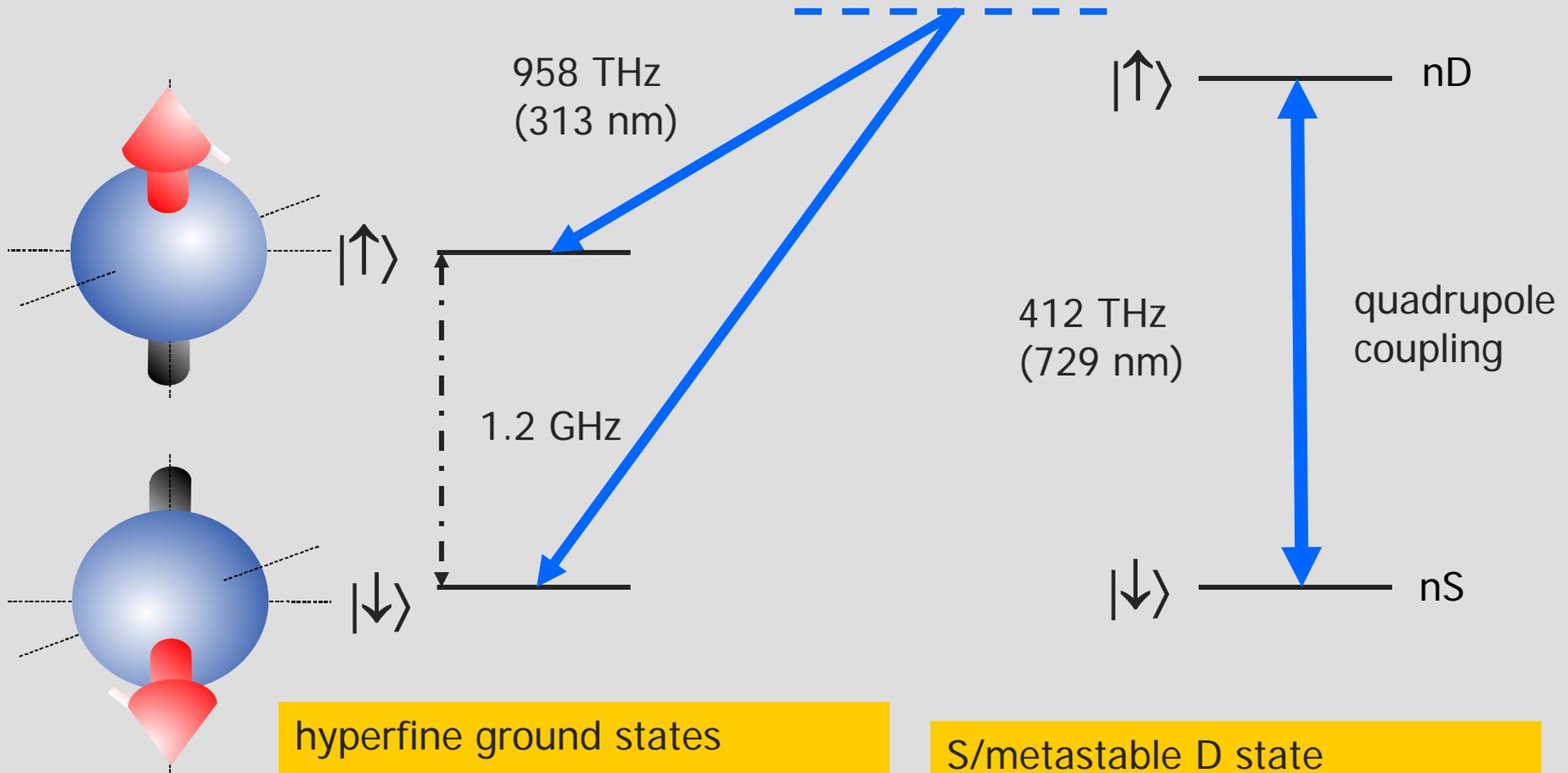


sideband thermometry:
$$\frac{I_{\text{red}}}{I_{\text{blue}}} = \frac{\bar{n}}{\bar{n} + 1}$$

red sideband vanishes for $\bar{n} \rightarrow 0$ (motional ground state)

for N ions get $3N$ sideband manifolds

Single qubit rotations



hyperfine ground states

${}^9\text{Be}^+$ decoherence time > 10 s
C. Langer *et al.*,
Phys. Rev. Lett. **95**, 060502 (2005)

S/metastable D state

${}^{40}\text{Ca}^+$ decoherence time ≈ 1 s
Univ. Innsbruck

Universal two-qubit gates

theoretical proposals:

J. I. Cirac and P. Zoller, Phys. Rev. Lett. **74**, 4091 (1995).

A. Sørensen and K. Mølmer, Phys. Rev. Lett. **82**, 1971 (1999).

E. Solano, R. L. de Matos Filho, and N. Zagury, Phys. Rev. A **59**, 2539 (1999).

G. J. Milburn, S. Schneider, and D. F. V. James, Fortschr. Physik **48**, 801 (2000).

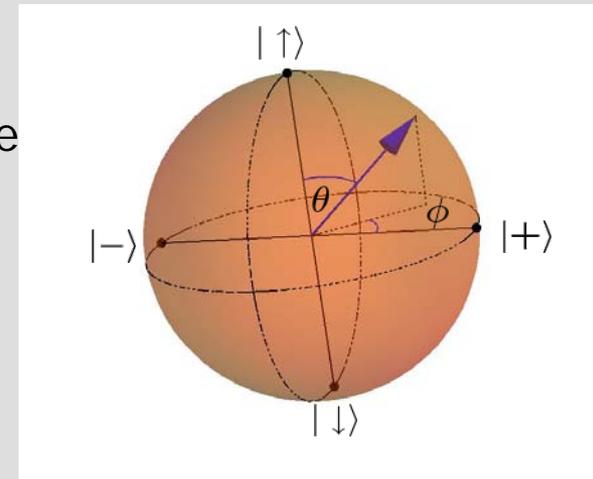
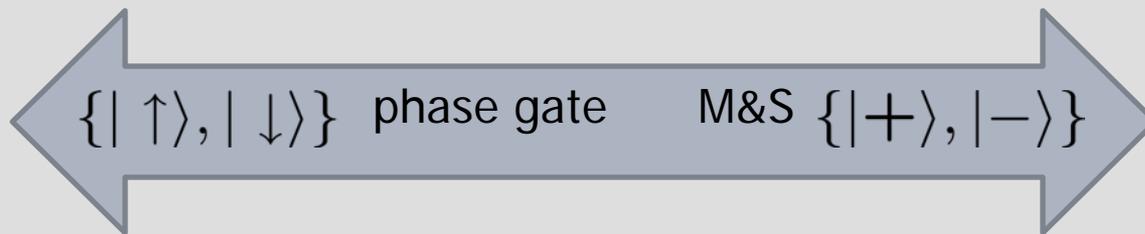
A. Sørensen and K. Mølmer, Phys. Rev. A **62**, 02231 (2000).

X. Wang, A. Sørensen, and K. Mølmer, Phys. Rev. Lett. **86**, 3907 (2001).

Cirac-Zoller gate contains all basic ingredients

Molmer-Sorensen+phase gates insensitive to motional state

M&S and phase gates equivalent in complementary basis:



first universal gate implementation (M&S) Sackett et al., Nature **404**, 256(2000)

first C&Z gate, Schmidt-Kaler et al., Nature **422**, 408 (2003)

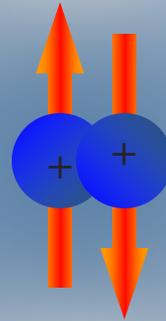
first phase gate, Leibfried et al. Nature, **422**, 412 (2003)

since then more M&S/phase gate work at Michigan/Maryland and Innsbruck

detailed theoretical description of all 3 gates: P J Lee et al. , J. Opt. B **7**, S371 (2005).

Laser excitation of the harmonic oscillator:

$$\omega_{\text{light}} + \omega_{\text{trap}}$$



$$\omega_{\text{light}}$$

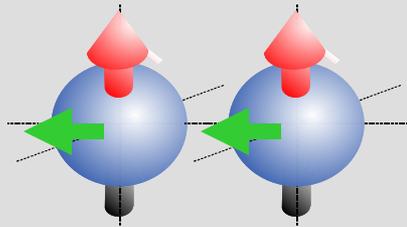
Laser exerts light force on atom

Detuned beams beat in amplitude at trap frequency

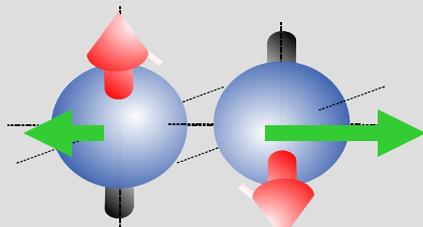
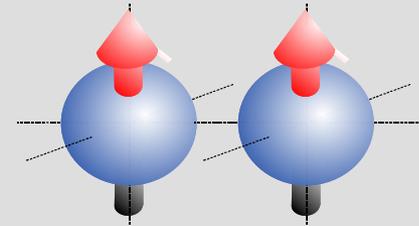
Resonant light force excites motion

Spin-up and spin-down feel different force (even in superposition)

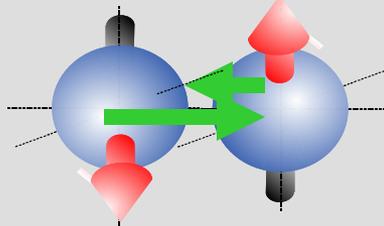
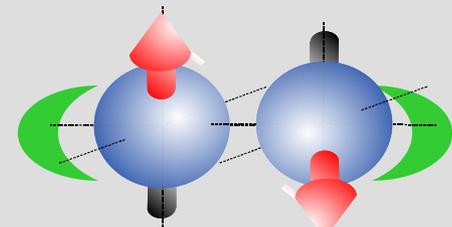
Stretch mode excitation



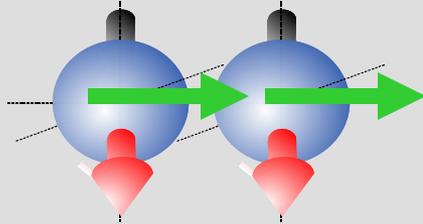
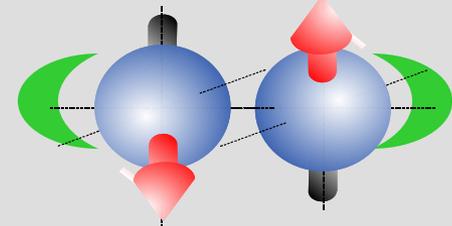
no differential force



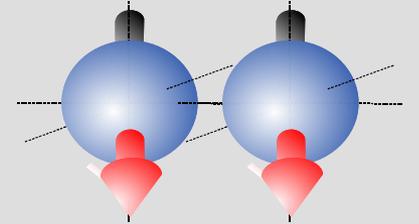
differential force



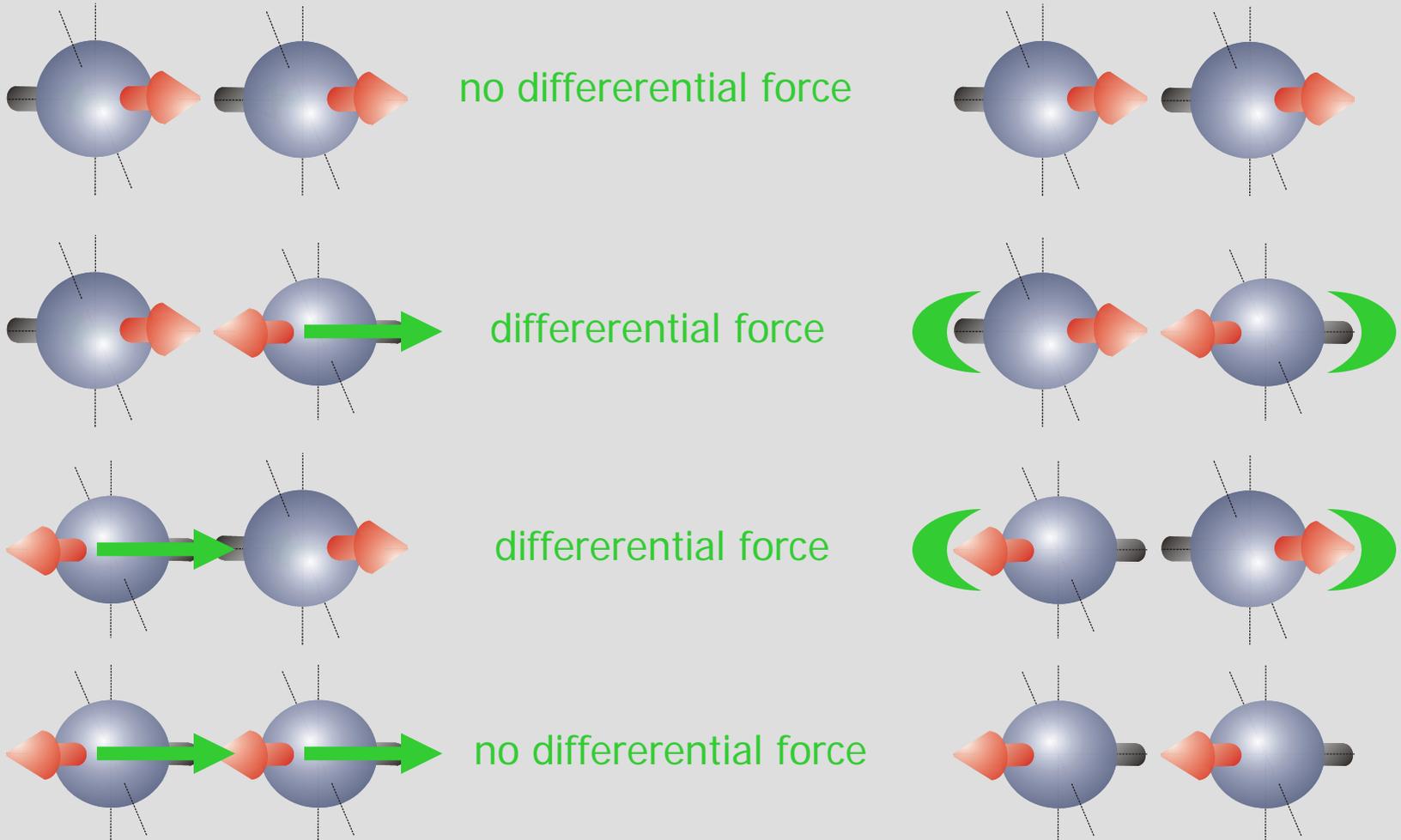
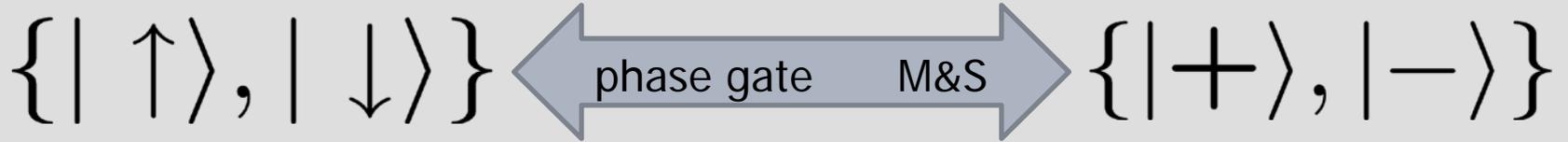
differential force



no differential force

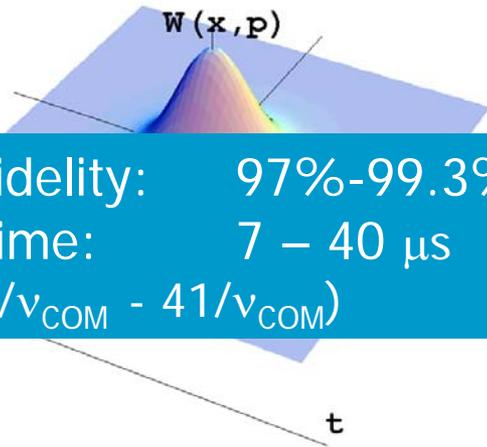


M&S stretch mode excitation



Phase space picture

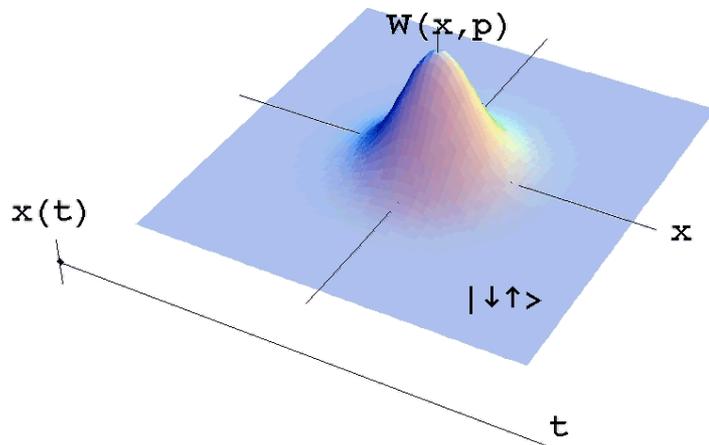
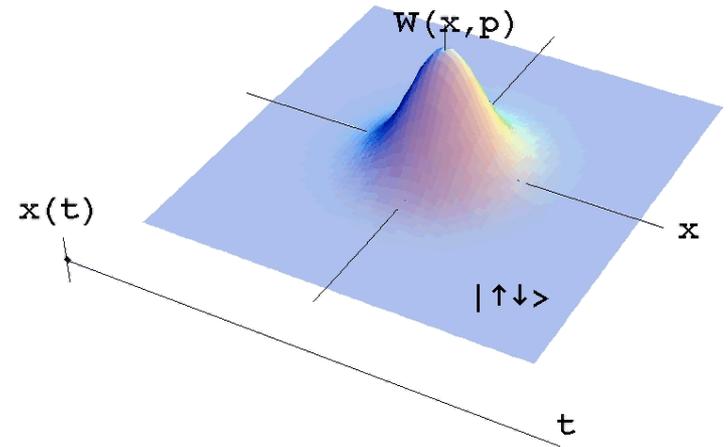
(needs animation)



Gate fidelity: 97%-99.3%

Gate time: 7 – 40 μs

(ca. $25/v_{\text{COM}}$ - $41/v_{\text{COM}}$)



$$|\downarrow\downarrow\rangle \rightarrow |\downarrow\downarrow\rangle$$

Same technique can be applied to more ions (including spectators), N-particle entangled states, teleportation, 3-qubit error correction, entanglement purification...

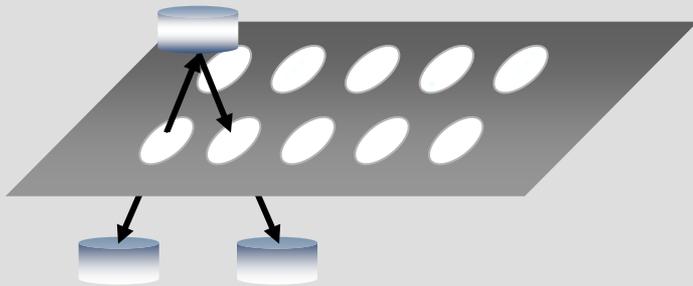
$$|\uparrow\uparrow\rangle \rightarrow |\uparrow\uparrow\rangle$$

Overview

- Introduction to ion traps
- Atomic physics for ion-qubits
- Manipulation of ion-qubits with laser fields
- **Scalable QIP with trapped ions**
- Example experiments

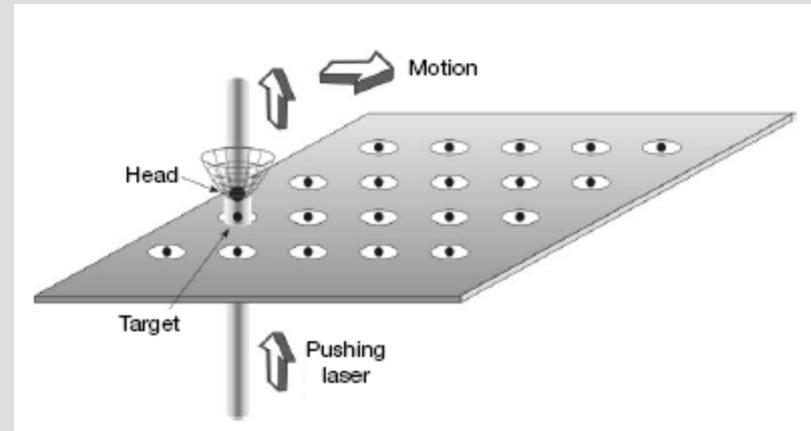
Scaling example approaches

array of elliptical traps
optical cavities as interconnects

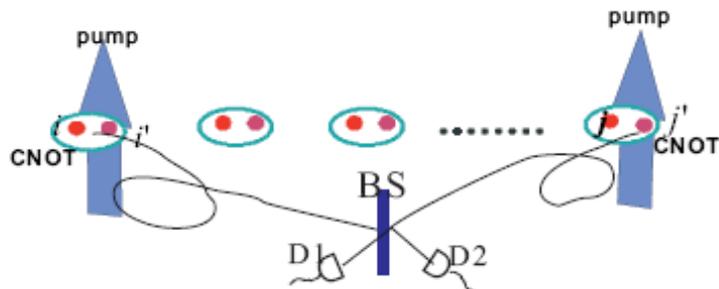


DeVoe, Phys. Rev. A **58**, 910 (1998)

array of single ion traps
"head ion" for interconnects



Cirac & Zoller, Nature **404**, 579 (2000)

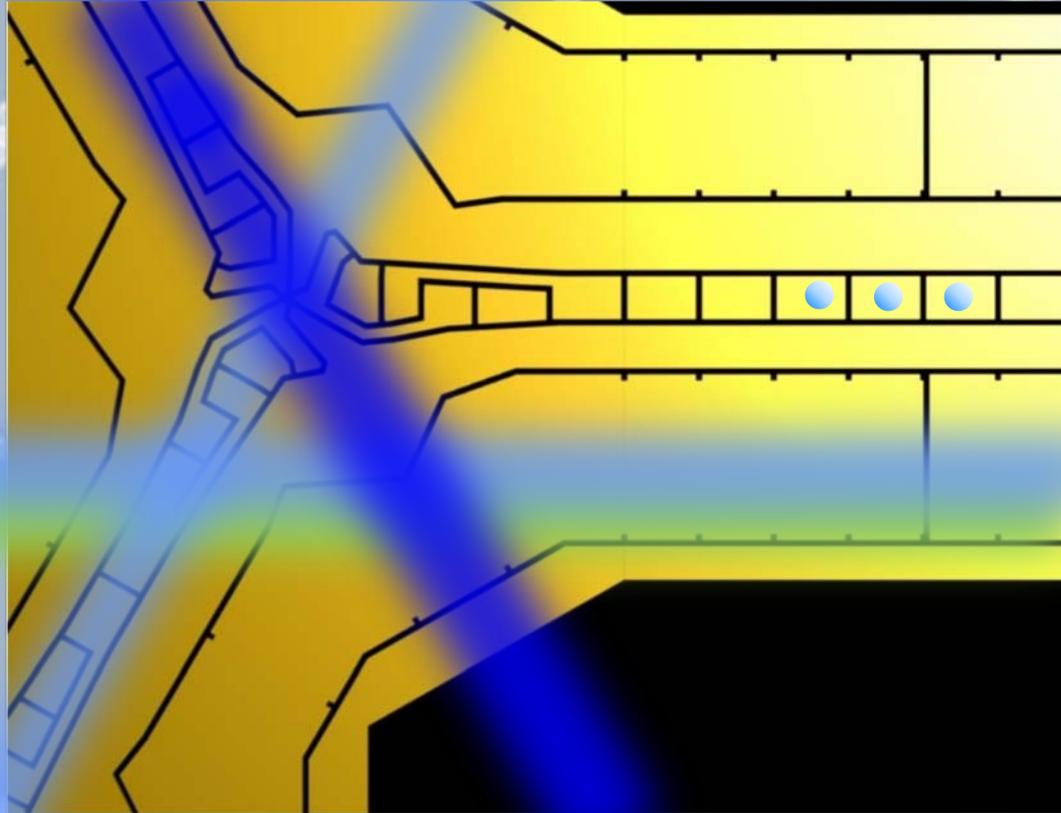


array of two-ion traps
interconnects by probabilistic entanglement

L. M. Duan *et al.*, Quant. Inform. Comp. **4**, 165 (2004)

Multiplexed trap approach

(needs animation)



transport target ions
to operation zone

sympathetically cool
target ions

perform
two-qubit gate, move...

perform single-qubit
rotations, move...

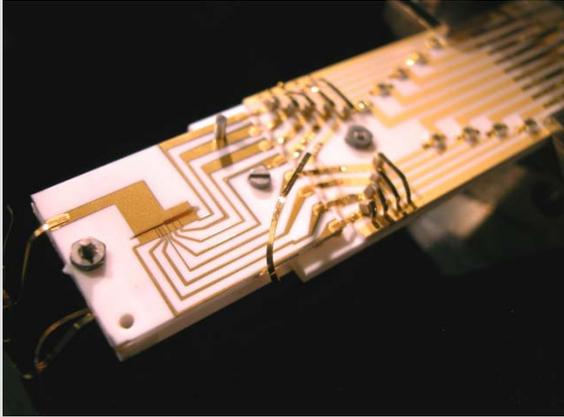
read out ion(s), move...

change conformation
for next steps...

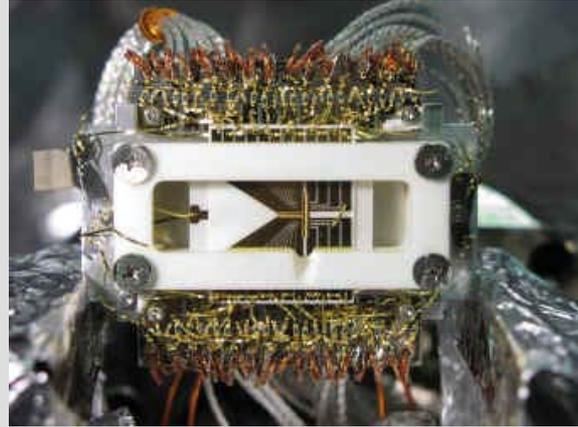
D. J. Wineland, *et al.*,
J. Res. Nat. Inst. Stand. Technol. **103**, 259 (1998);
D. Kielpinski, C. Monroe, and D. J. Wineland,
Nature **417**, 709 (2002).

Other proposals:
DeVoe, Phys. Rev. A **58**, 910 (1998) .
Cirac & Zoller, Nature **404**, 579 (2000) .

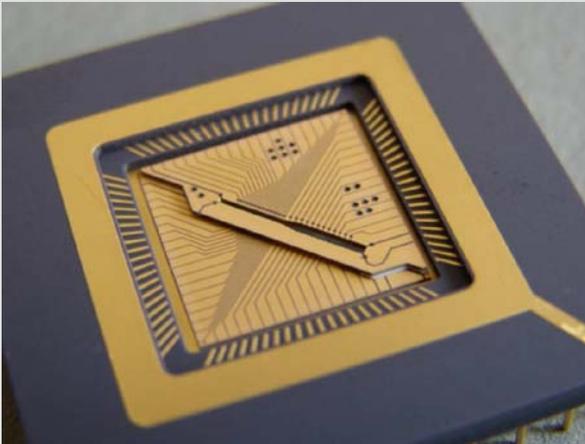
Multi-layer multi zone traps



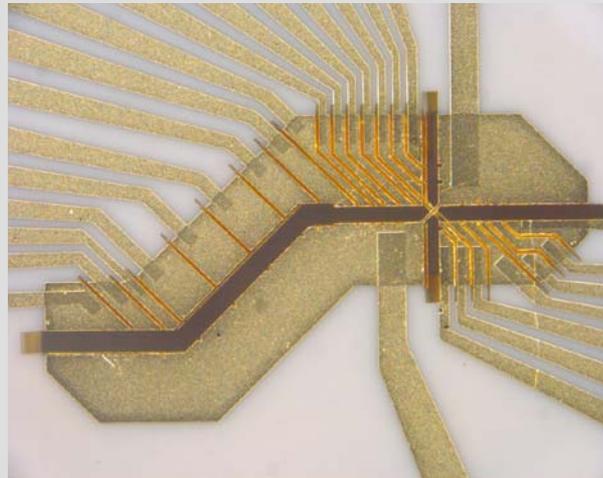
6 zone 2 layer linear trap (NIST, 2003)



9-zone 3-layer T-trap (Michigan, 2006)
first junction transport experiments

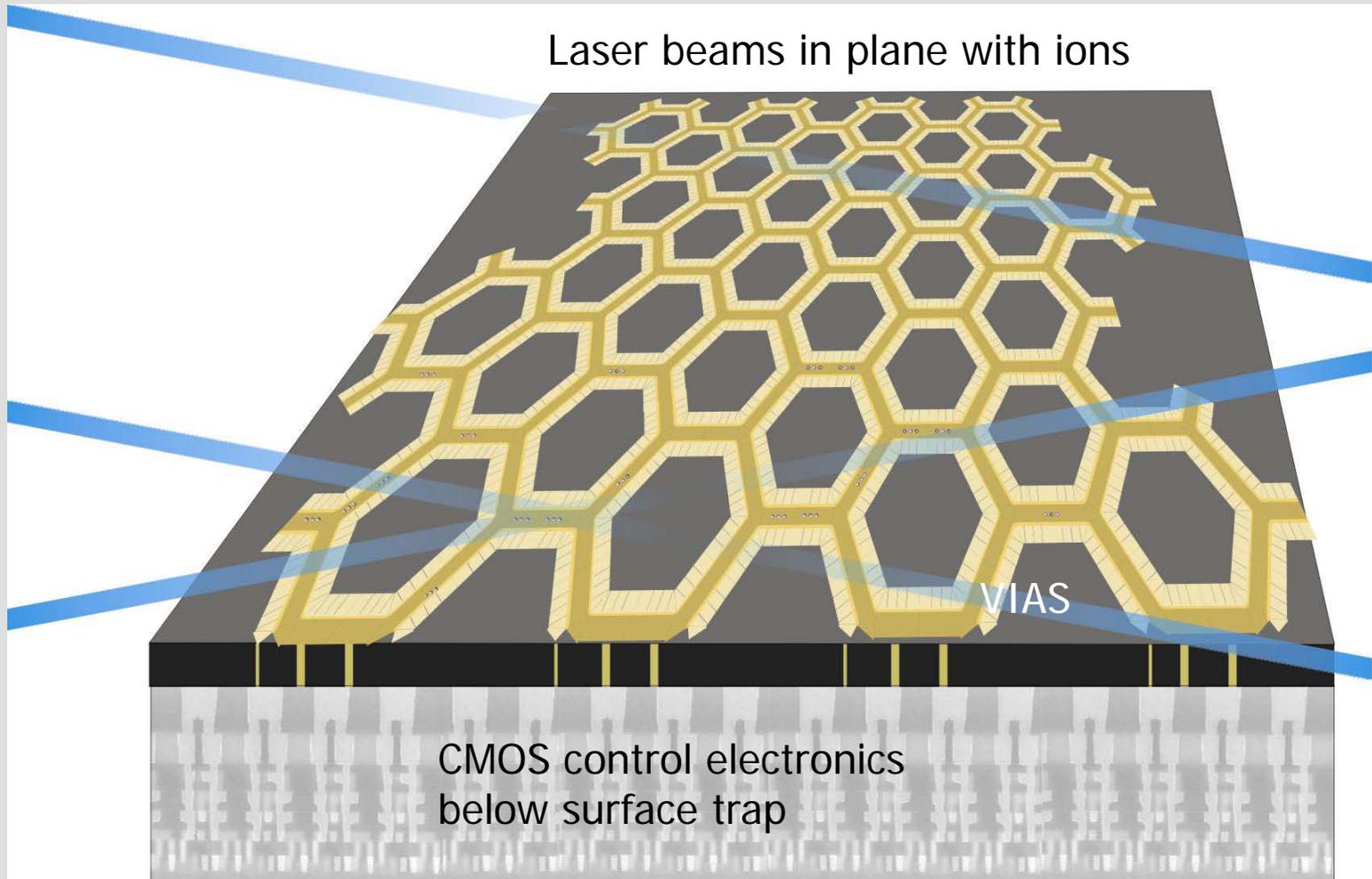


29 zone 2 layer linear trap (Ulm, 2006)



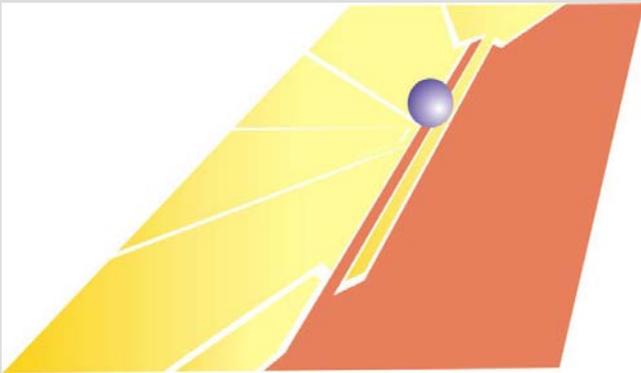
18 zone 2-layer junction trap (NIST, 2007)
for experiments see Dave Wineland's talks

More integrated ion chips ?

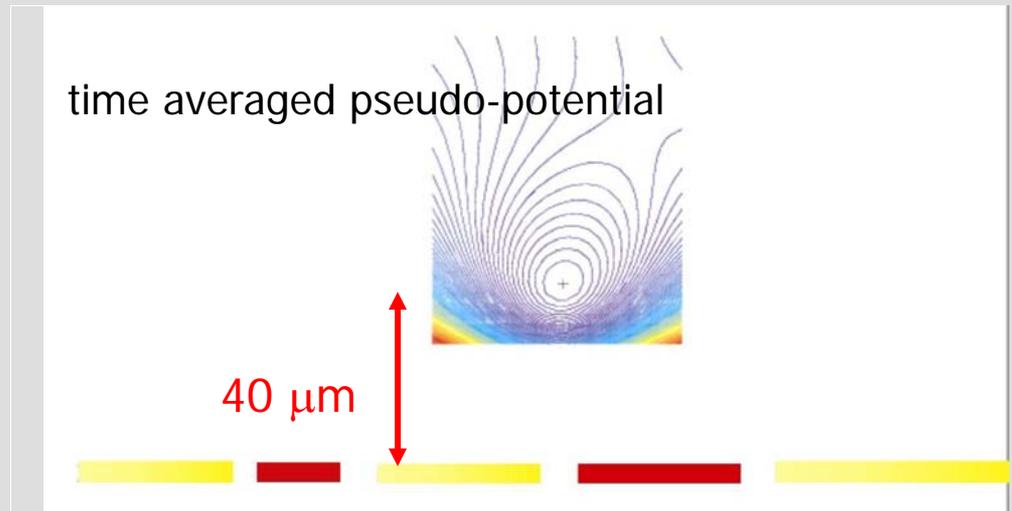


Surface electrode trap basics

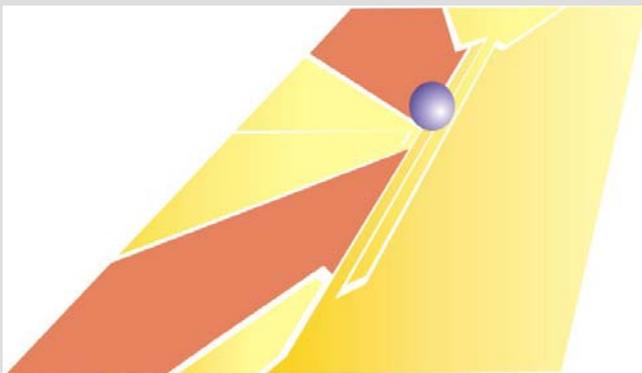
radial confinement:



radial cross section



axial confinement:



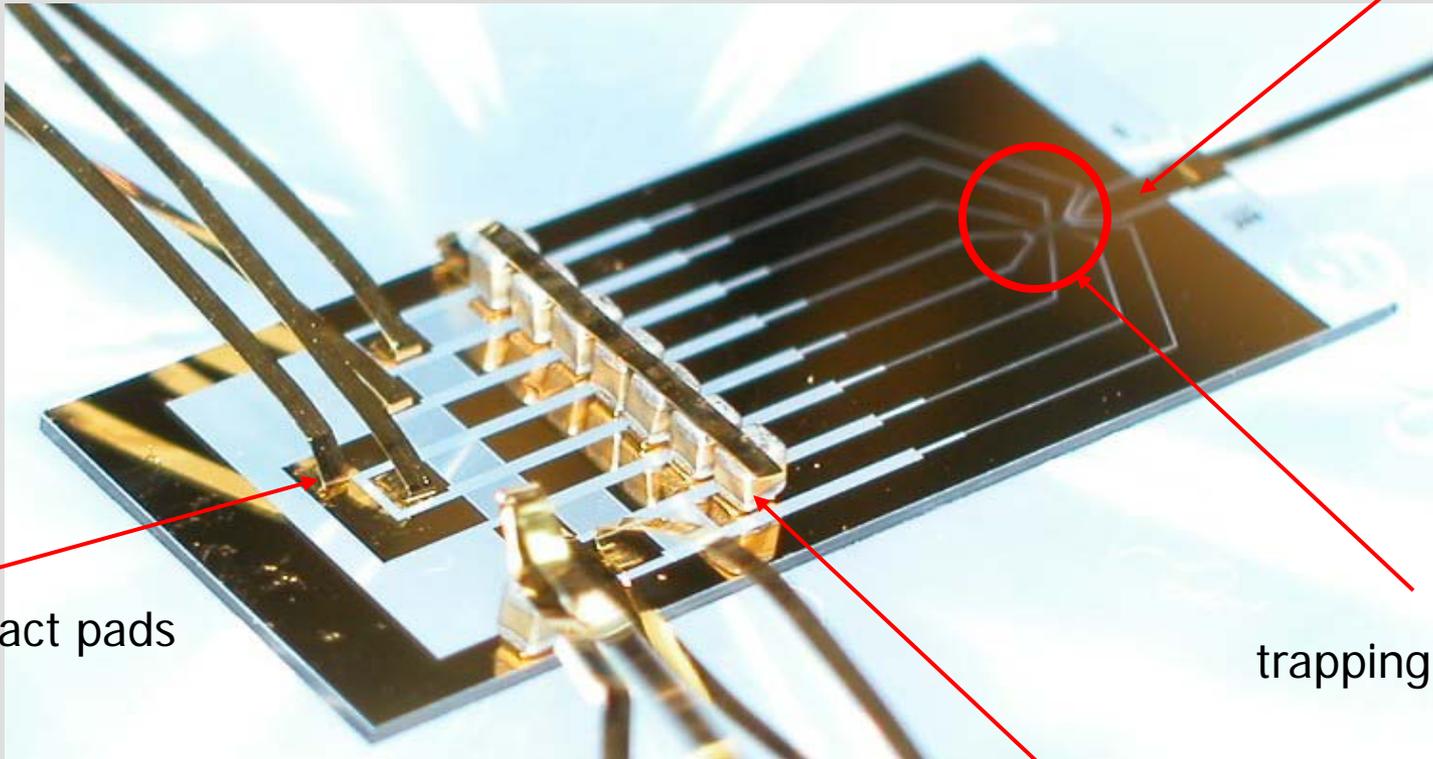
axial cross section



NIST Planar Trap Chip

Gold on fused silica

RF



DC Contact pads

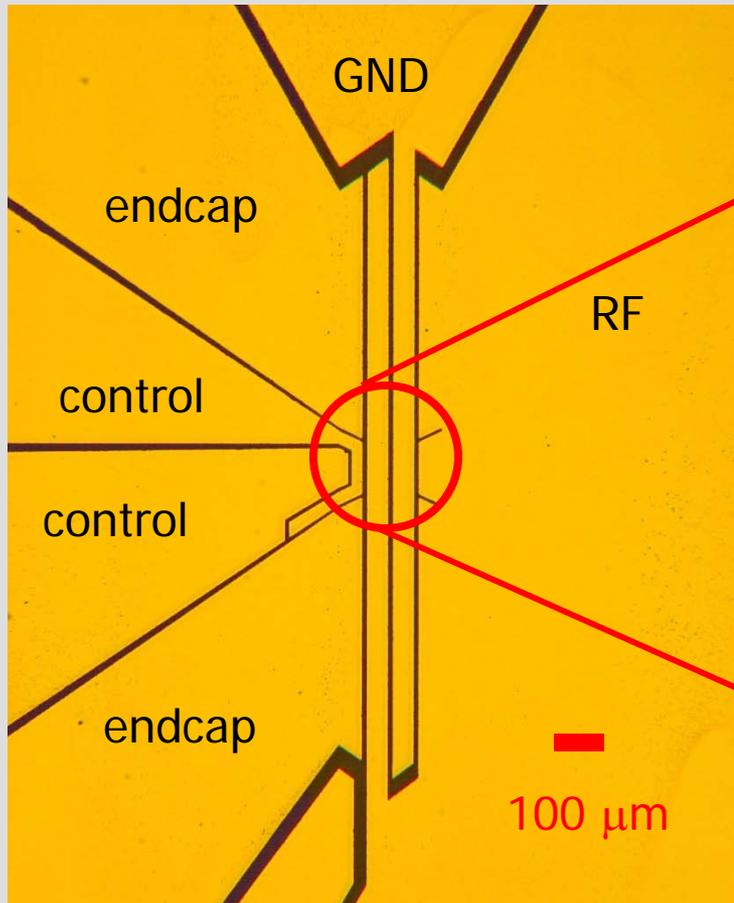
trapping region

low pass filters

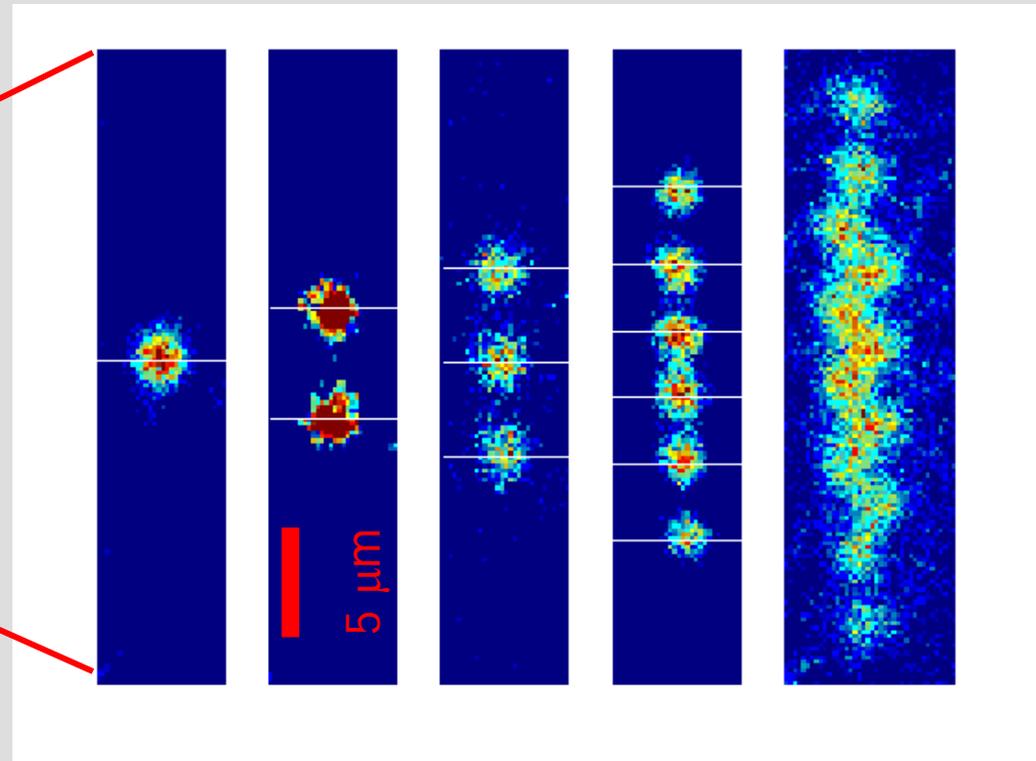
trap designed and manufactured by John Chiaverini, Signe Seidelin (NIST)

Planar Trap Chip

Magnified trap electrodes



CCD pictures of strings of Mg⁺ ions
(trapped 40 μm above surface)

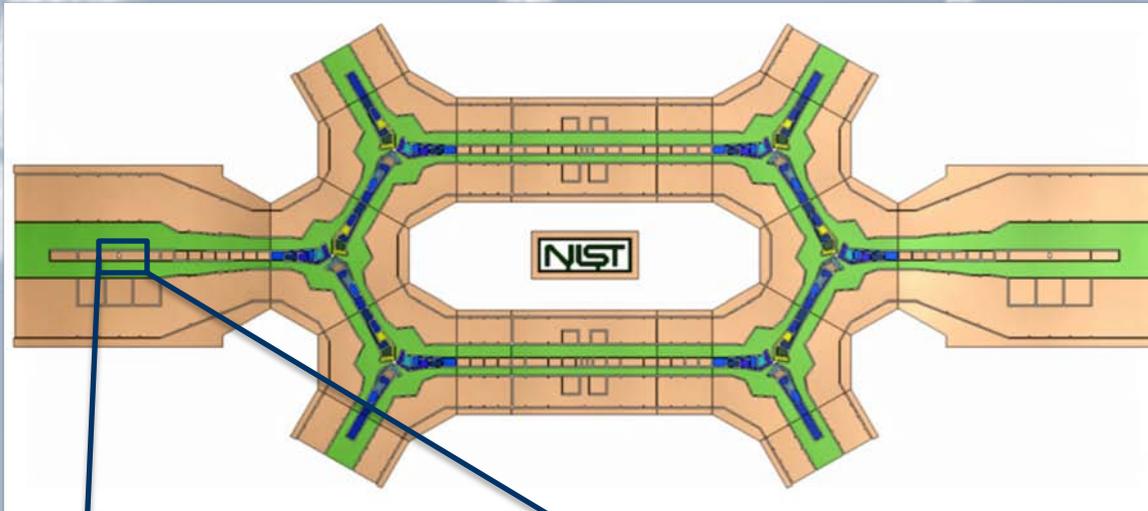


John Chiaverini, Signe Seidelin

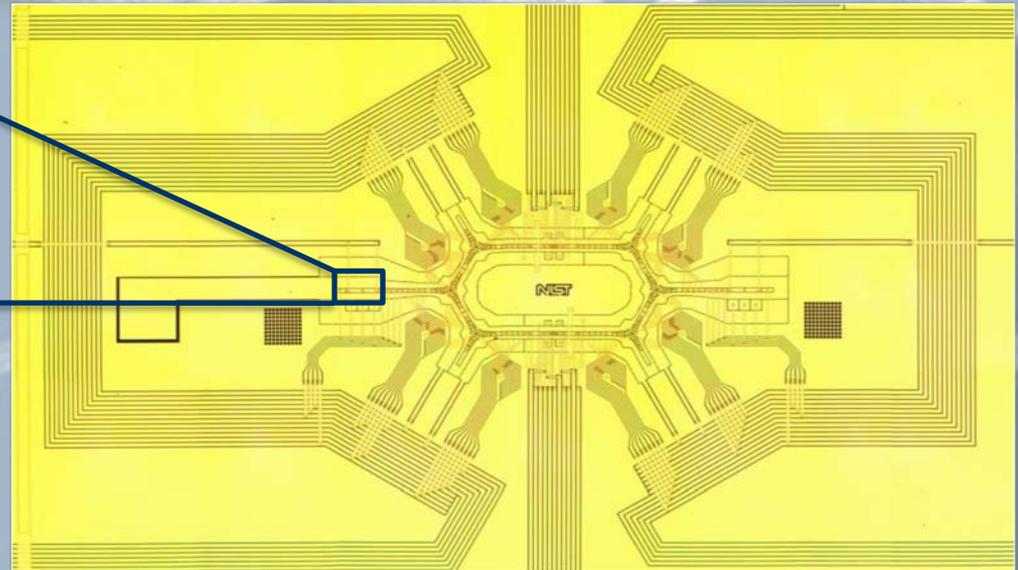
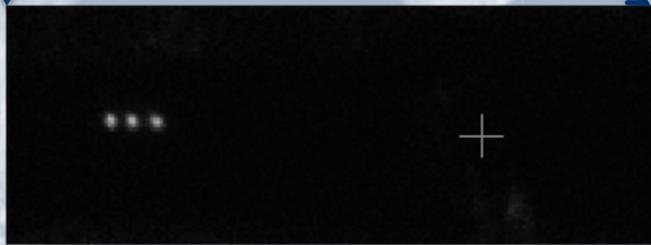
S. Seidelin *et al.*, PRL **96**, 253003 (2006).

NIST trap chip module

(Jason Amini)



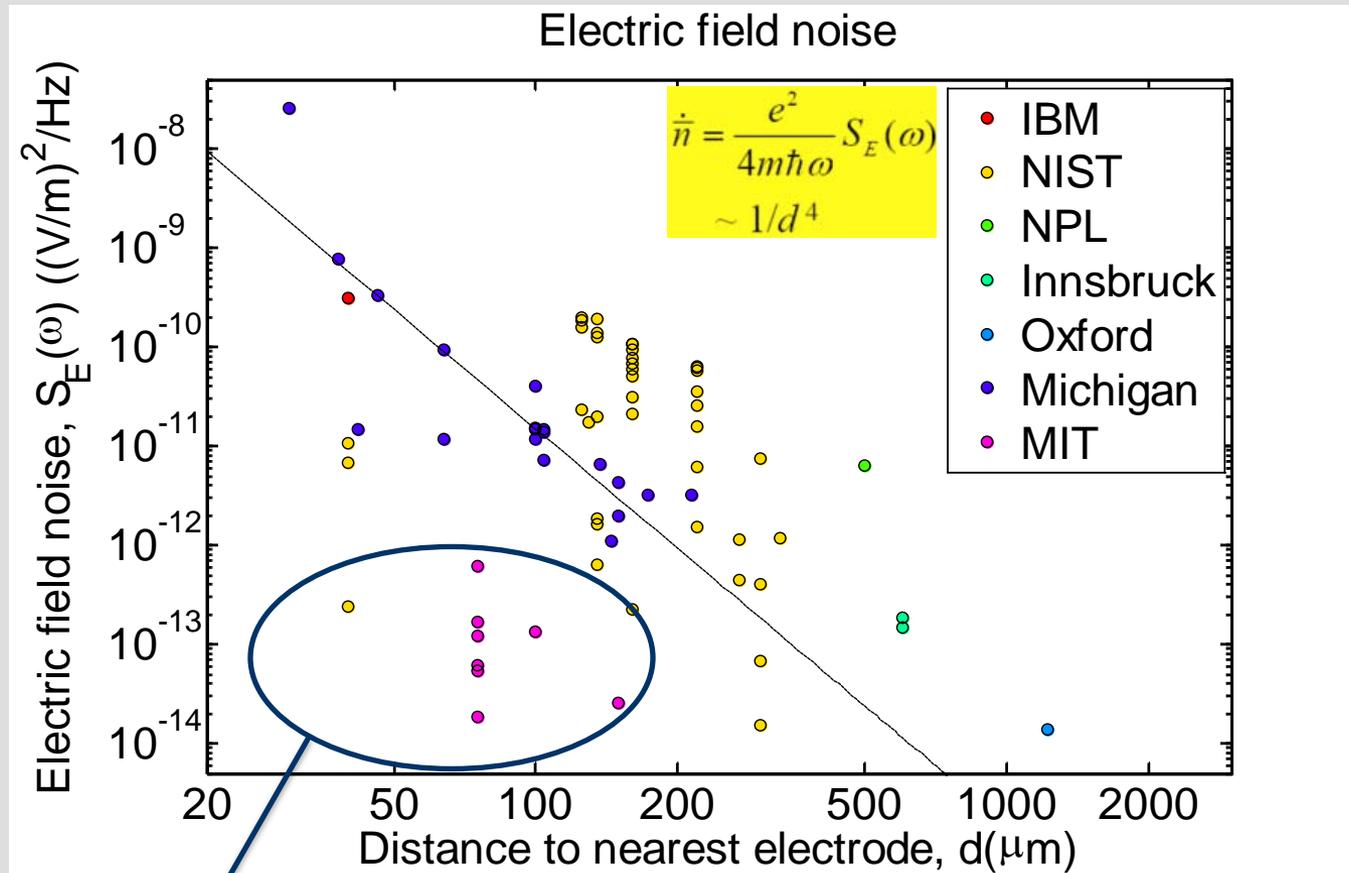
- 2 load zones
- 6 improved junctions
- 150 control electrodes



- backside loading
- motion through junctions
- utilize for multi-qubit work

Motional heating

Heating rate orders of magnitude over Johnson noise, physical origin unknown

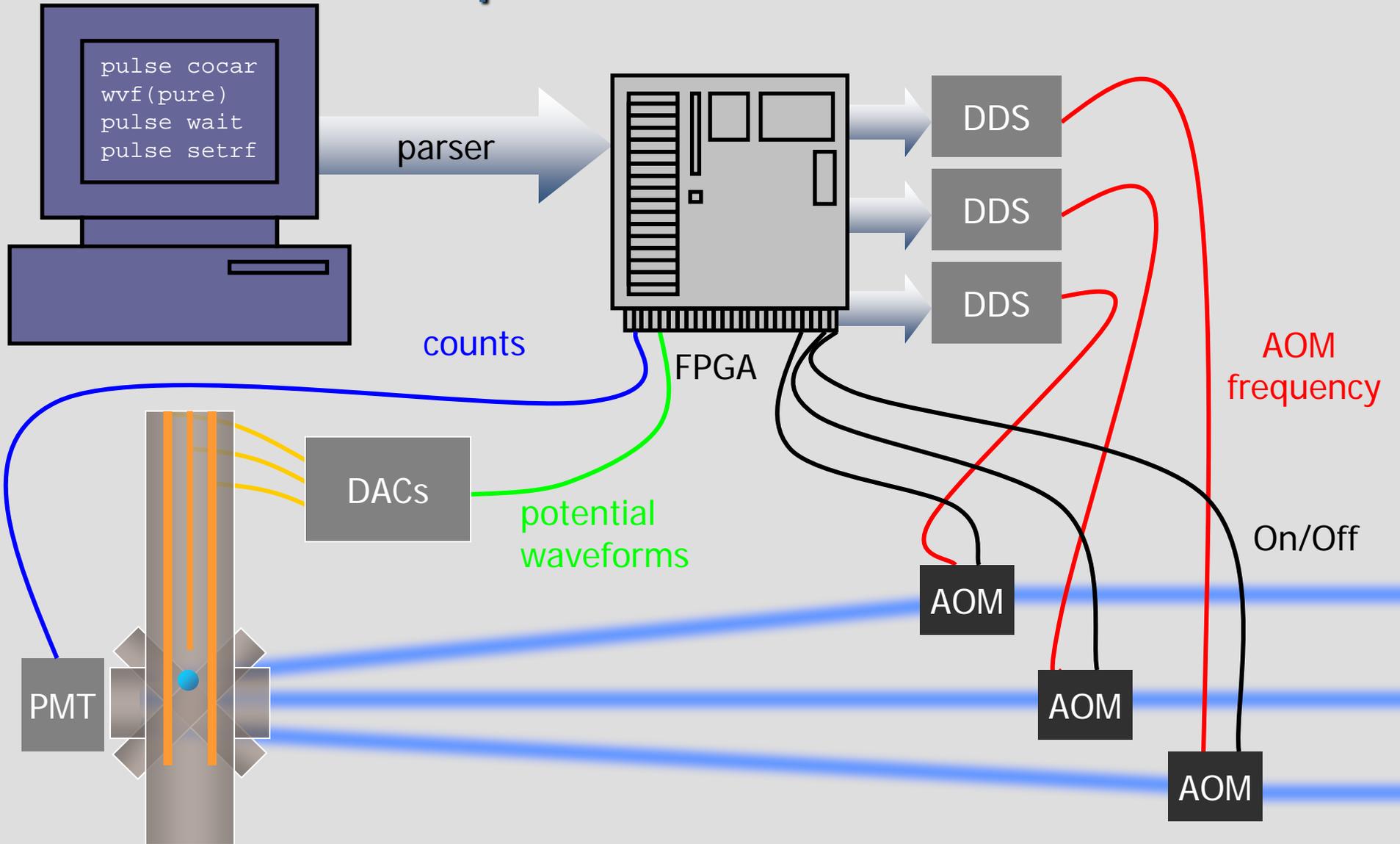


electrode temperature < 12 K

Overview

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Experiment control



Homework assignment

(example experiments)

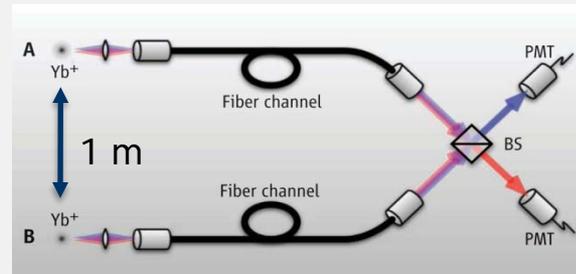
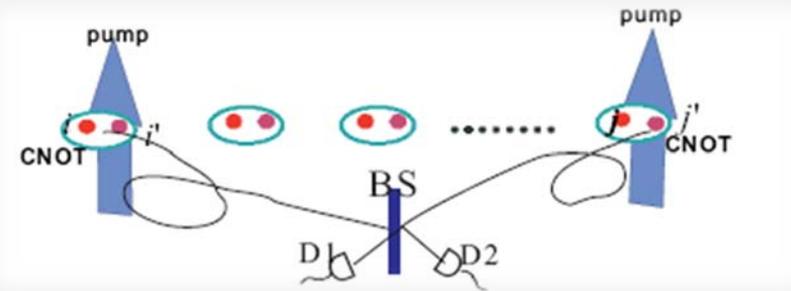
- **Innsbruck approach:** linear ion strings in single well, M&S gates + local shifts



G. Kirchmair *et al.*, New Journal of Physics **11**, 023002 (2009)

V. Nebendahl *et al.*, PRA **79**, 012312 (2009)

- **Michigan/Maryland approach:** small local registers linked by photons



D. L. Moehring *et al.*, Nature **449**, 68 (2007)

S. Olmschenk *et al.*, Science **323**, 486 (2009)

- **NIST approach:** (see earlier in the talk and D. Wineland's talk on Wed.)

Jonathan Home *et al.*, Science **325**, 1227 (2009)

David Hanneke *et al.*, Nature Physics **6**, 13 (2010)

Conclusions

- Coherent manipulation of up to 14 qubits demonstrated in ion traps (see Rainer Blatt's talk)
- Successful implementation of basic QIP building blocks (teleportation, error correction, entanglement purification, entanglement swapping, multipartite entanglement, ...)
- Development of scalable micro-fabricated ion traps under way with very encouraging first results
- For more of the "latest and greatest", see other talks in this meeting