Clean, fast and scalable quantum logic with trapped ions

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Michigan Ion Trap group

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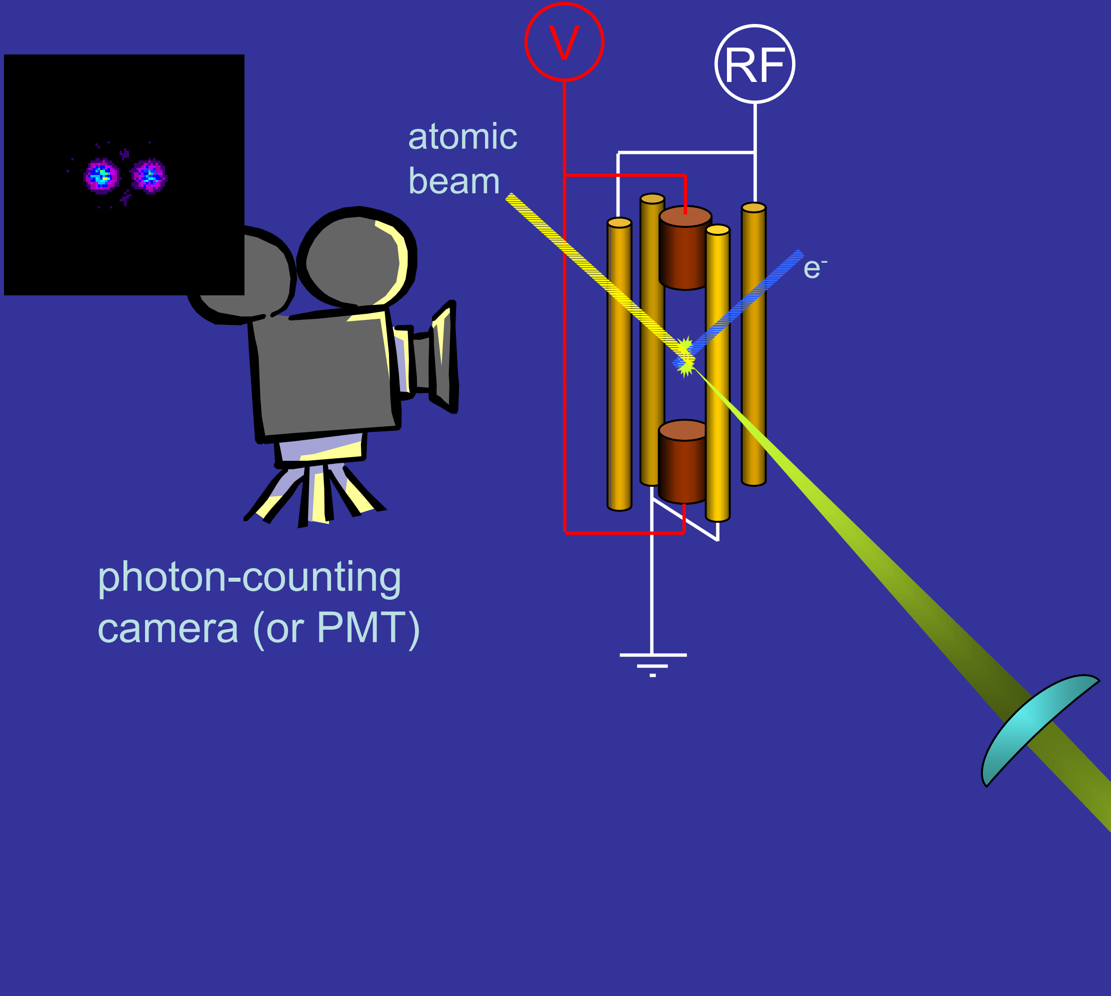
Trapping ions: static E-field???

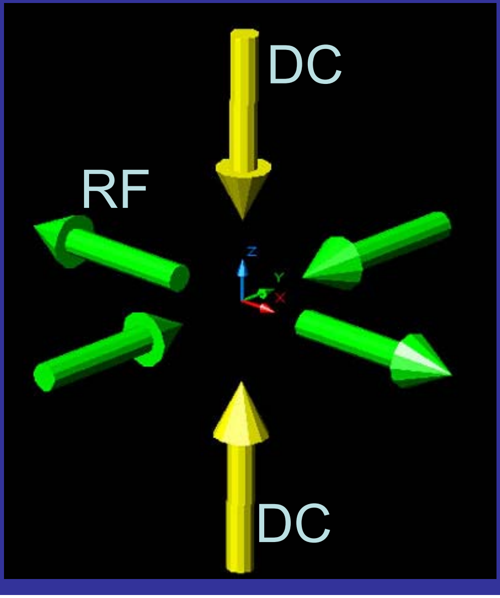
$$\vec{\nabla}\cdot\vec{E} = 0$$

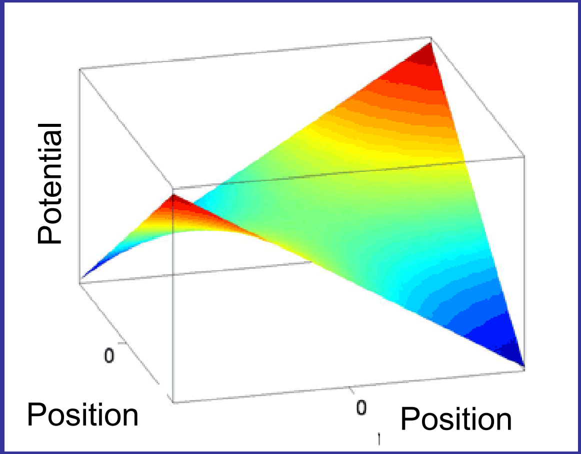
RF (Paul) ion trap



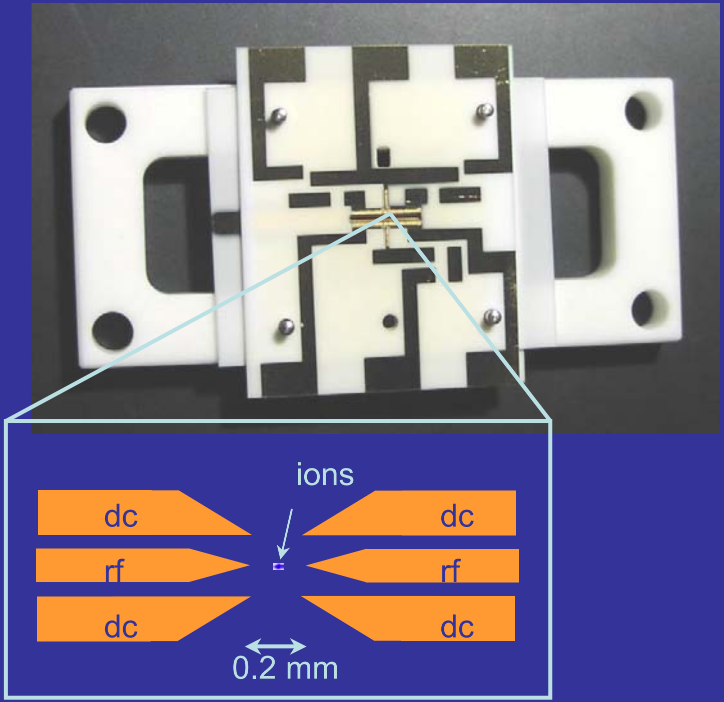
photon-counting camera (or PMT)

resonant light



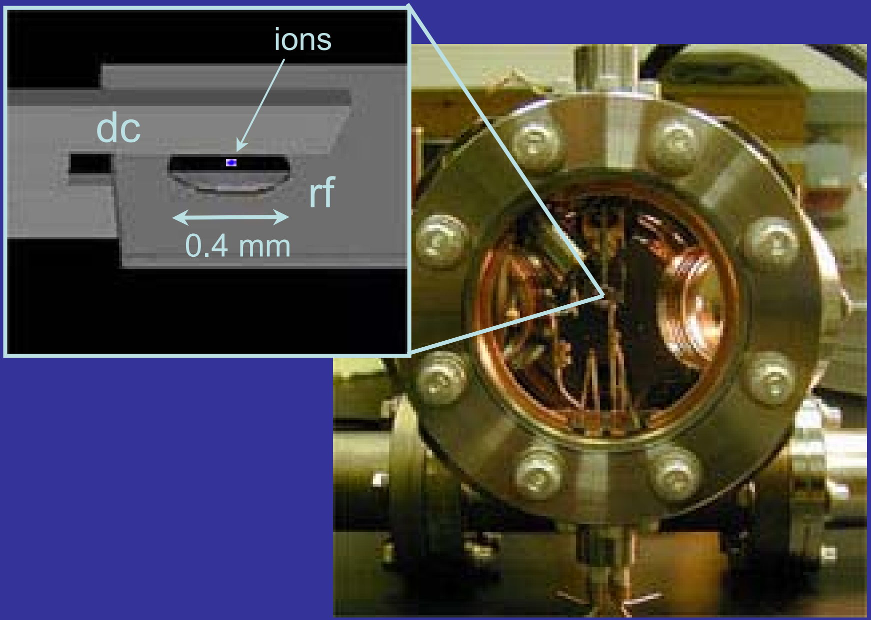


Practical trap designs



3-layer lithographic linear trap

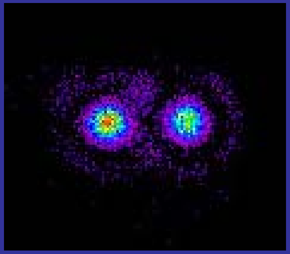
- RF nodal line (ion string)
- static voltage compensation electrodes
- 200 micron size (strong confinement)
- 3-layer geometry allows multiplexing, T-junctions, etc.



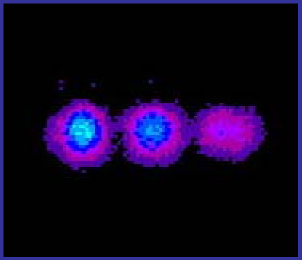
Ring-and-fork quadrupole trap

- easy to build and operate
- good optical access
- trapping few ions near RF null

Trapped ions - as seen on TV



Two Cd^+ ions in a 3 MHz trap (~2 μm separation)



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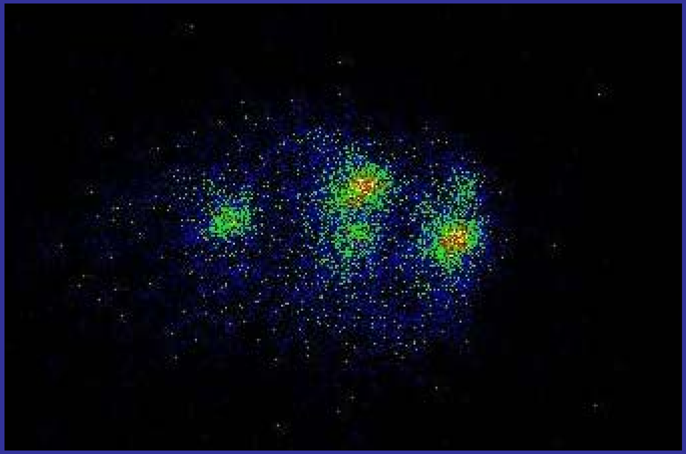
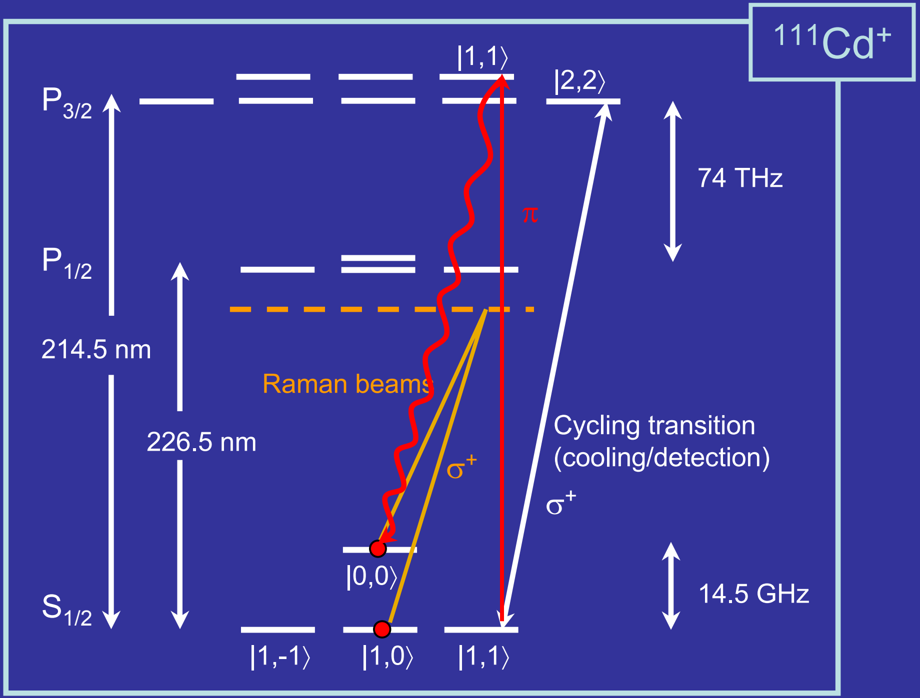


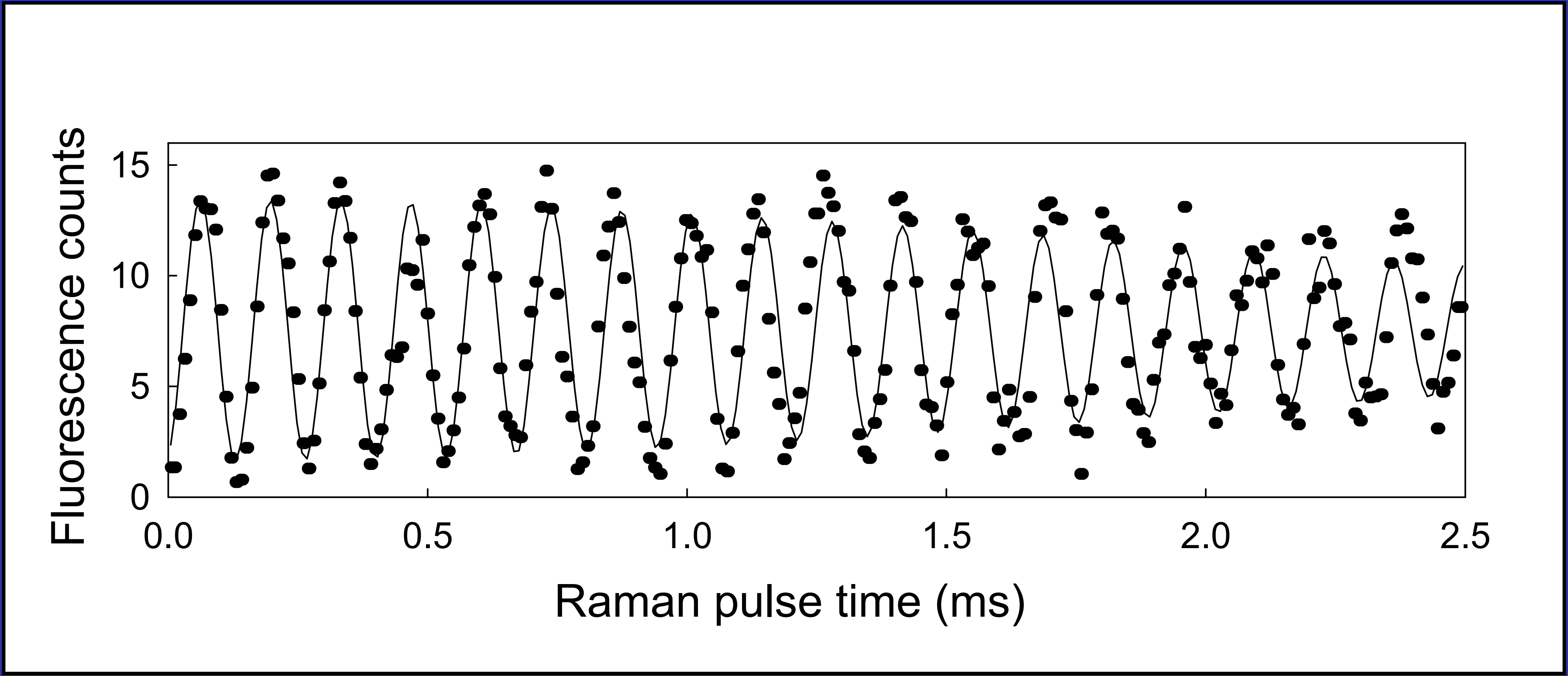
Multiple-ion helical crystal (Cd^+ and possible impurity). Weak trap (~0.5 MHz, 6μm separation)

Trapped ions as qubits

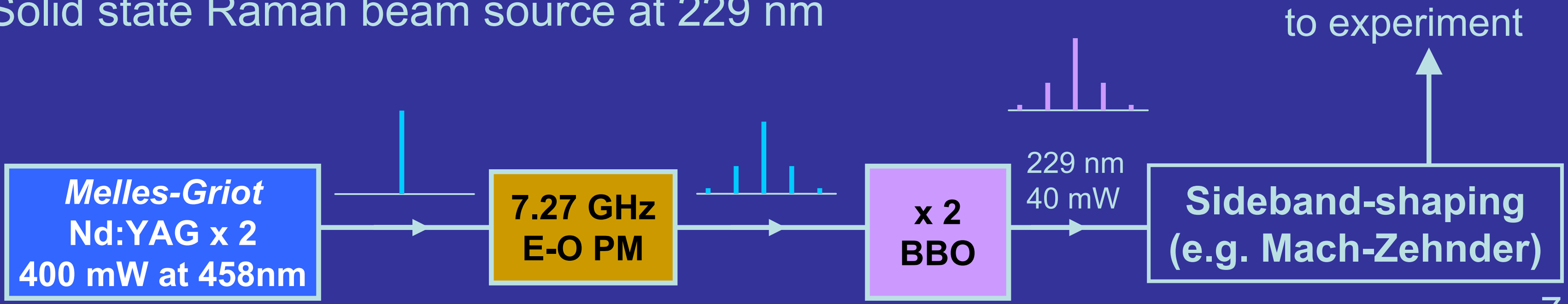
- Strong confinement in an RF trap (1-10 MHz) - qubits well localized
- Long-lived atomic levels form extremely stable qubit (“God’s qubit”!)
- Efficient qubit state detection by fast cycling transitions
- Initial state preparation by optical pumping with near-perfect efficiency
- Qubit rotations using microwaves or lasers
- Quantum logic gates via strong Coulomb interaction between ions
- Coupling to “flying qubits” (photons) using cavity QED
- Sympathetic cooling to reduce decoherence



Single qubit rotations via stimulated Raman transitions



Solid state Raman beam source at 229 nm



Melles-Griot
Nd:YAG x 2
400 mW at 458nm

7.27 GHz
E-O PM

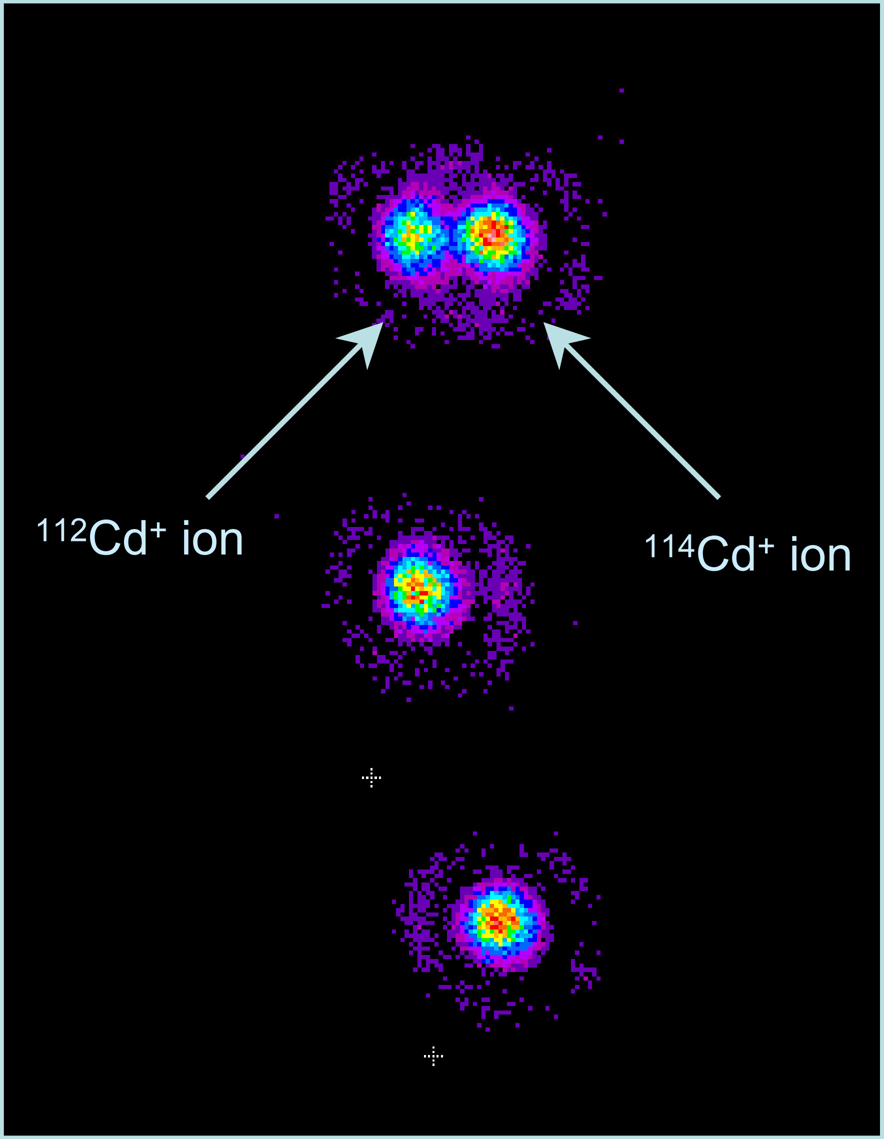
x 2
BBO

229 nm
40 mW

Sideband-shaping
(e.g. Mach-Zehnder)

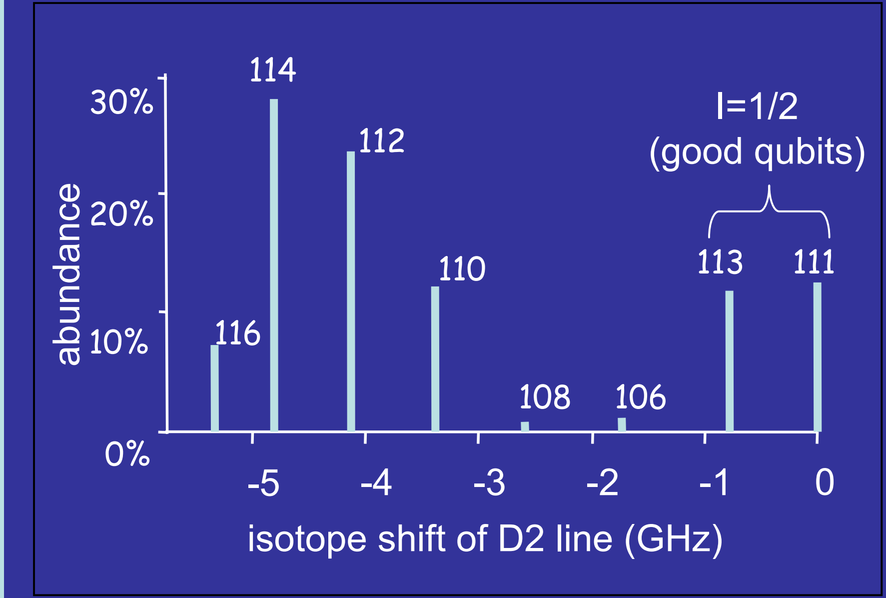
to experiment

Sympathetic cooling of Cd⁺ isotopes



Two different Cd⁺ isotopes loaded in the trap.

One ion is constantly (Doppler) cooled, while the other may be heated. Extra heat from the latter is absorbed by the cooling ion.



Entanglement of trapped ions

- Coulomb-force based entanglement:

  - Cirac-Zoller CNOT gate (1995) - spin-state coupled to phonons of ion crystal vibrations

  - Mølmer-Sørensen gate (1999) - spin-state coupled to phonons of ion crystal vibrations, but motional states never populated

  - Cirac-Zoller "push" gate (2000) - phase gate through direct Coulomb repulsion of neighboring ions

- Photon-mediated entanglement:

  - trapped ion-cavity QED merger – spin-state mapped onto field state inside the fight-finesse optical cavity

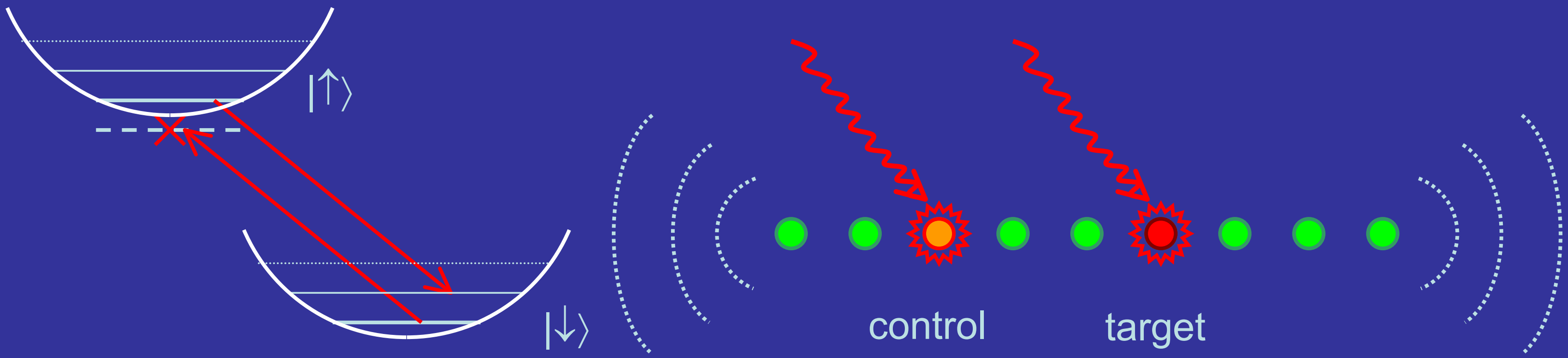
Cirac-Zoller CNOT gate

1. Ion string is prepared in the ground state of motion (n=0)

2. Control ion's spin state is mapped onto quantized motional state of the ion string

3. Target ion's spin is flipped conditional on the motional state of the ion string

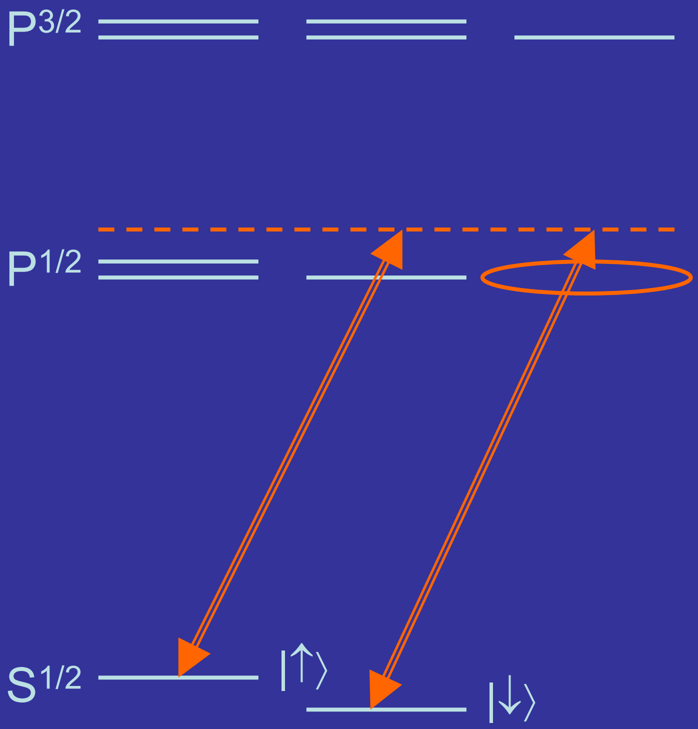
4. Motion of the ion string is extinguished by applying pulse #2 with negative phase to the control ion

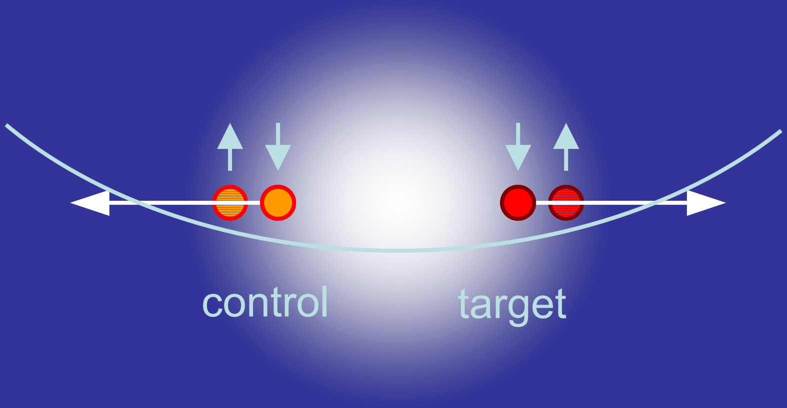


Cirac and Zoller, *Phys. Rev. Lett.* **74**, 4091 (1995)

Phase "push" gate

- Ions prepared in Lamb-Dicke limit
- Spin-dependent dipole force (edge of a Gaussian beam waist or a standing wave) is applied to both ions
- The |↑⟩ part of ion is displaced; extra phase is acquired if both ions were in state |↑⟩
- Ions brought back to rest





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

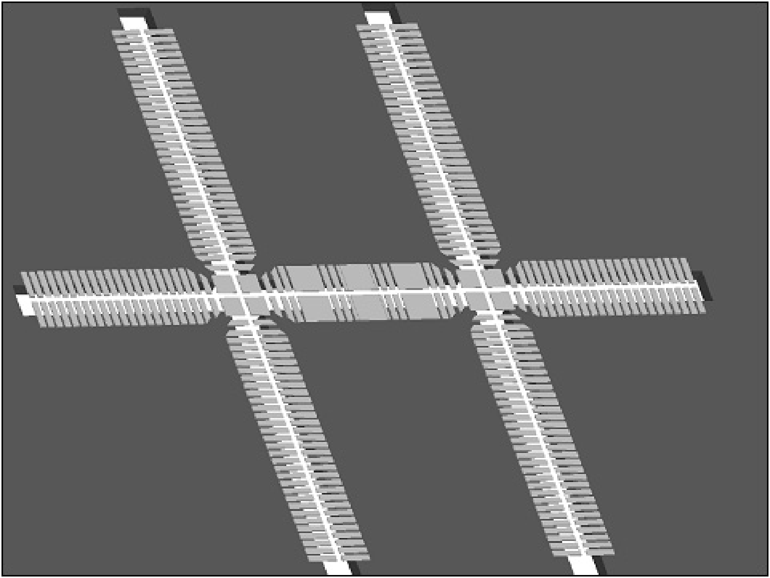
Scaling up?

- Original Cirac-Zoller gate:
  - size determined by number of ions in a single trap - can be scaled up by making larger trap
  - ***but*** : ground-state cooling of motion is required - very hard for large ion crystals!

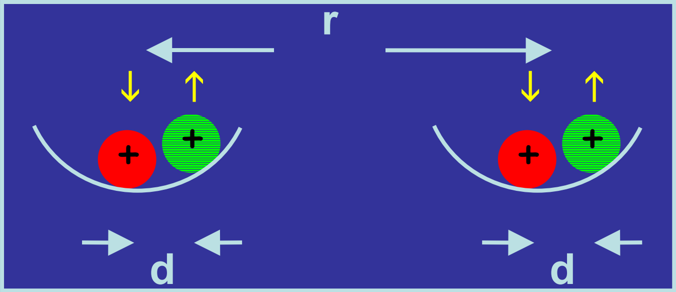
- Mølmer-Sørensen and “push” two-ion gates:
  - only work for a pair of ions
  - ***no*** ground-state cooling requirement
  - could be scaled by creating arrays of interconnected traps, each containing one ion qubit

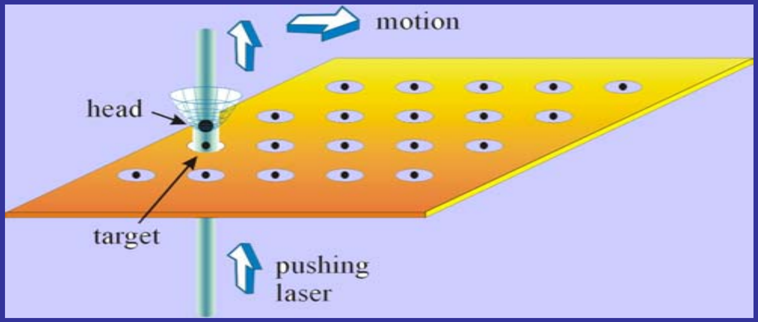
Large-scale ion trap quantum computer architectures

- ion traps
  - “conventional”
    - connecting multiple traps, ion shuttling between storage regions and pairwise entanglement areas
  - strong coupling
    - applying spin-dependent force to entangle ion pairs



D. Kielpinski, C. Monroe, D. Wineland, *Nature* **417**, 709 (2002)





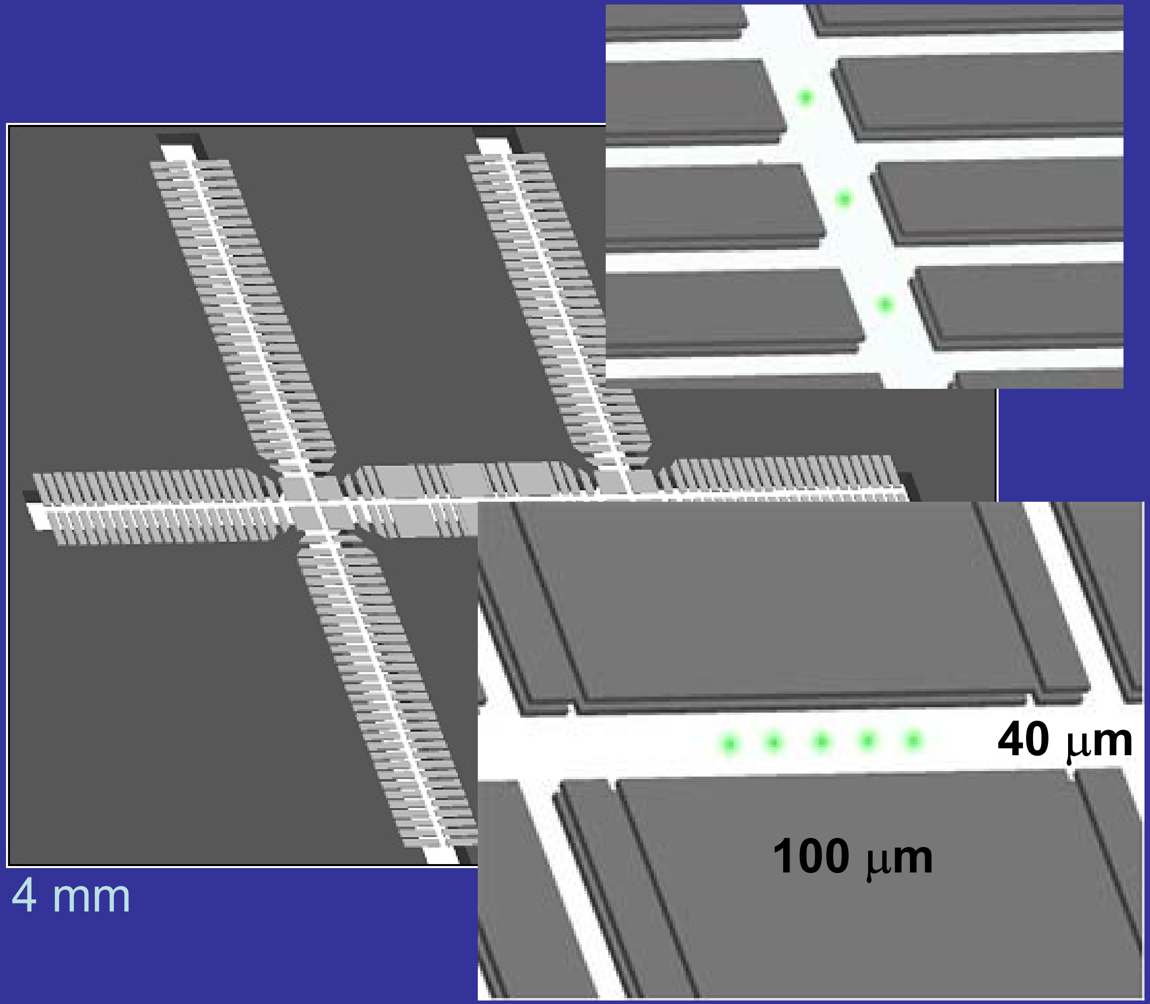
Cirac and Zoller, *Nature* **404**, 579 (2000)

Speeding up?

- Gate speed:
  - Phonon-mediated gates (CZ and MS gates):
    - collective motion of ions used as data bus – gate speed must be much slower than $\omega_{\text{Trap}} \sim 1$ MHz
  - “Push” gate:
    - entanglement through *direct* Coulomb interaction (ions don’t even have to be in the same trap!), so can be fast

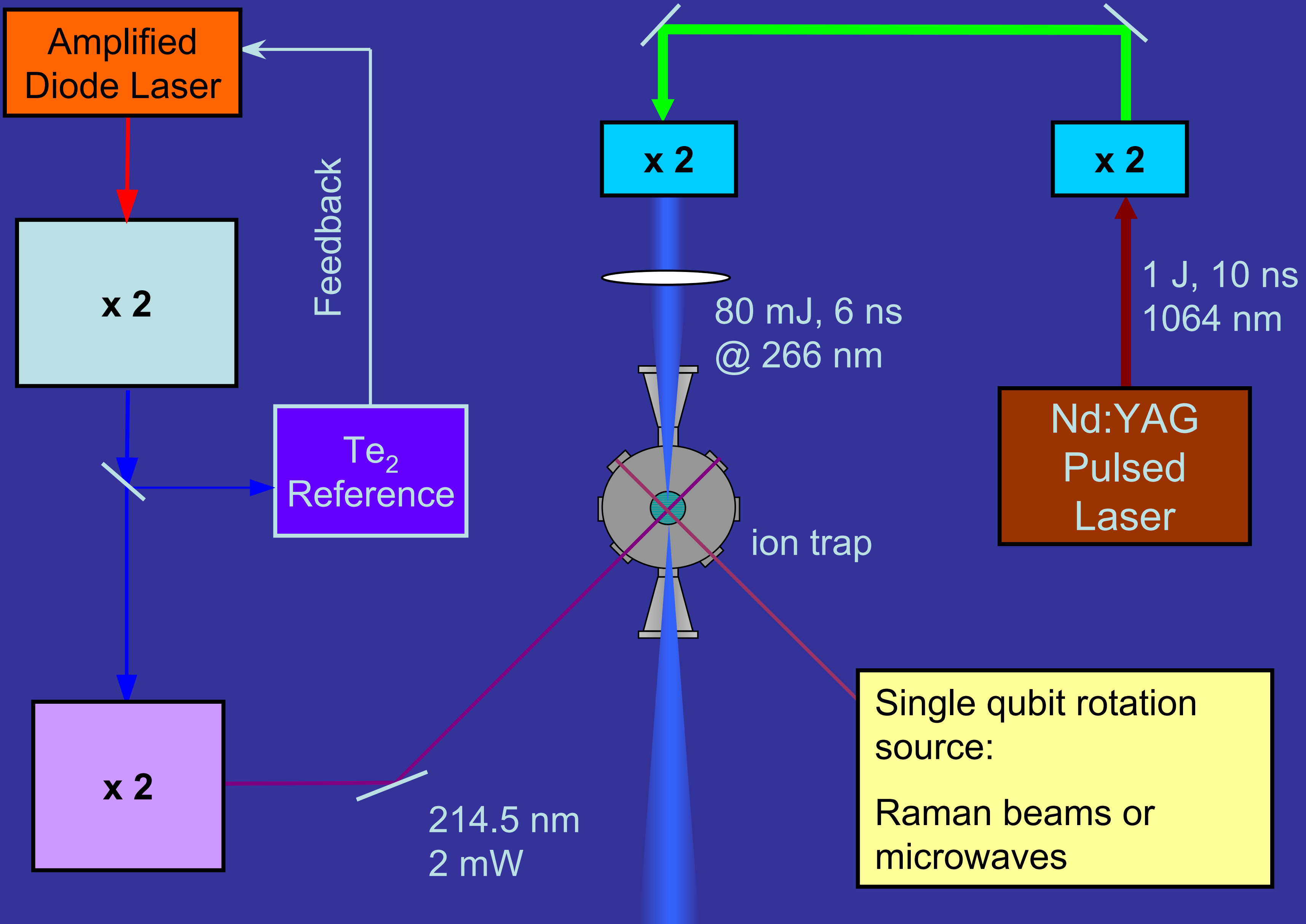
- Gate repetition rate:
  - Multiplexed traps:
    - depends on shuttling speed and distances - smaller traps beneficial!
    - need efficient cooling to quench motional heating

Microfabricated trap arrays



- qubit ions stored in individual traps
- ions shuttled between traps using static electric fields
- ~40 micron transverse size
- good control of ions' positions with static voltage electrodes

Pushing ions with a pulsed laser - experiment

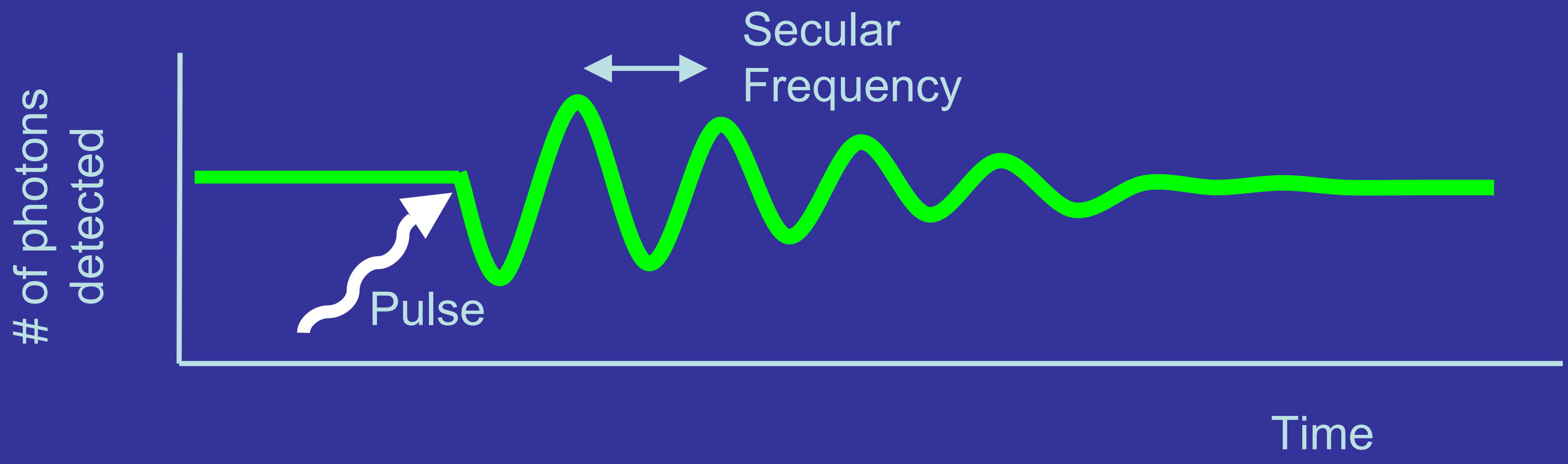


Single qubit rotation source:

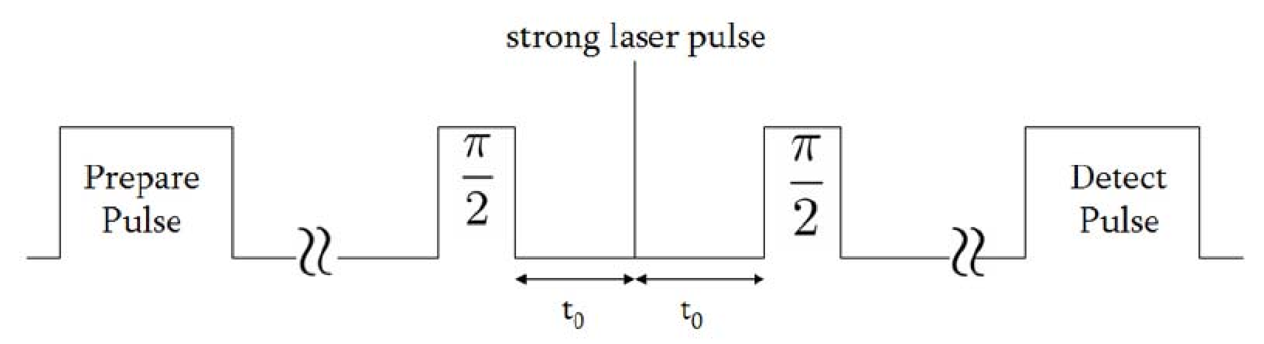
Raman beams or microwaves

Detecting pushing of ions

- Detecting the ion fluorescence oscillations due to Doppler shifts



- Measuring (very large) AC Stark shifts caused by strong laser field



Conclusions and outlook

- Trapped ions hold a great promise for practical quantum computation
- Large arrays of ion traps provide suitable environment for qubit storage and manipulation
- Micro-traps would allow faster quantum logic, as well as capability of coupling the ions to optical fields
- Novel methods of trapped-ion entanglement using strong pulsed laser force are studied to increase the gate speeds