Scalable Ion Trap Quantum Computation

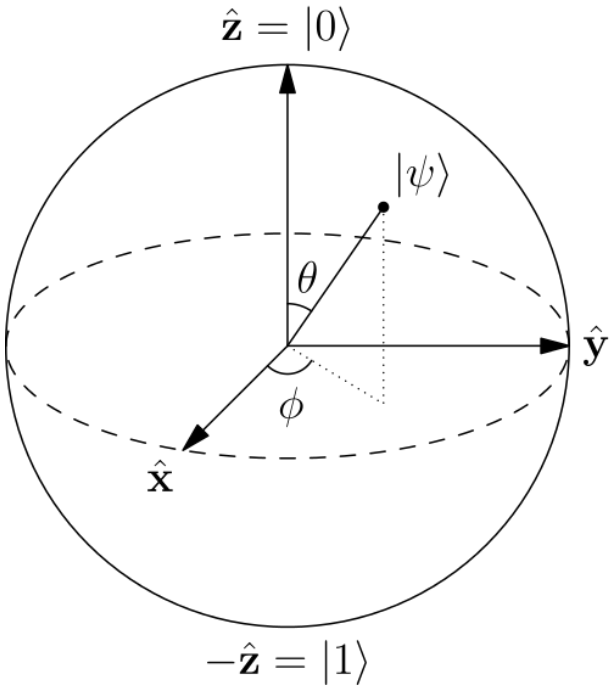
Mixed Species Anharmonic Ion Chains

John Wright

Department of Physics
University of Washington

May 28, 2013

Quantum Computing - Introduction



- Computing using superpositions of quantum objects
- Commonly described using qubits living on the Bloch sphere
- Must be able to initialize, manipulate and readout qubits before the effects of quantum decoherence destroy information

Quantum Computing - Physics Simulation

- Simulating N fully interacting quantum objects requires operations on 2^N dimensional spaces
- Using quantum objects to perform simulations is exponentially more efficient
- Progress towards simulating Ising models and Jaynes-Cummings models

$$H = -\sum_{neighbors} J_{ij}\sigma_i\sigma_j - \mu\sum_j h_j\sigma_j$$

Quantum Computing - Grover's Algorithm

Search unordered lists in $\mathcal{O}(\sqrt{N})$ time

$$
\begin{aligned}
|s\rangle &\equiv \frac{1}{\sqrt{N}} \sum_{x=1}^{N} |x\rangle \\
U_s &\equiv 2\,|s\rangle\langle s| - I \\
U_w &\equiv I - 2\,|w\rangle\langle w| \\
U_s U_w\,|s\rangle &= \frac{N-4}{N}\,|s\rangle + \frac{2}{\sqrt{N}}\,|w\rangle
\end{aligned}
$$

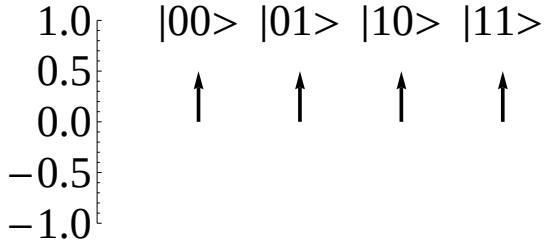
Iterate $\frac{\pi\sqrt{N}}{4}$ times

Quantum Computing - Grover's Implementation

For 2 qubits in the $|00\rangle, |01\rangle, |10\rangle, |11\rangle$ basis

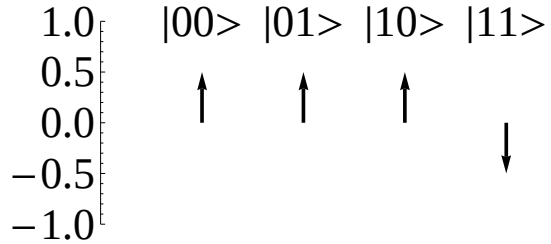
- Initialize qubits to known state $\rightarrow |00\rangle$
- Apply global rotation $\rightarrow \frac{1}{2}(|00\rangle + |01\rangle + |10\rangle + |11\rangle)$

$$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}^{\otimes 2} \rightarrow$$



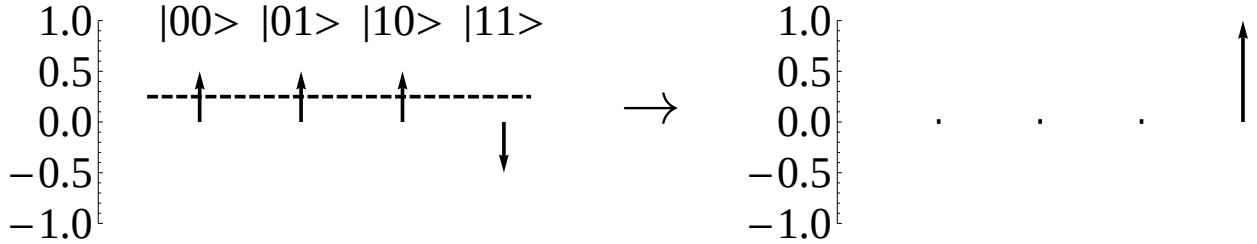
- Apply a controlled phase gate $\rightarrow \frac{1}{2}(|00\rangle + |01\rangle + |10\rangle - |11\rangle)$

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



Quantum Computing - Grover's Implementation

- Perform inversion about the mean via two rotations and a controlled phase gate



$$\frac{1}{2}\begin{pmatrix} -1 & 1 & 1 & 1 \\ 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}^{\otimes 2}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}^{\otimes 2}$$

- Iterate the previous two steps

Quantum Computing - Shor's Algorithm

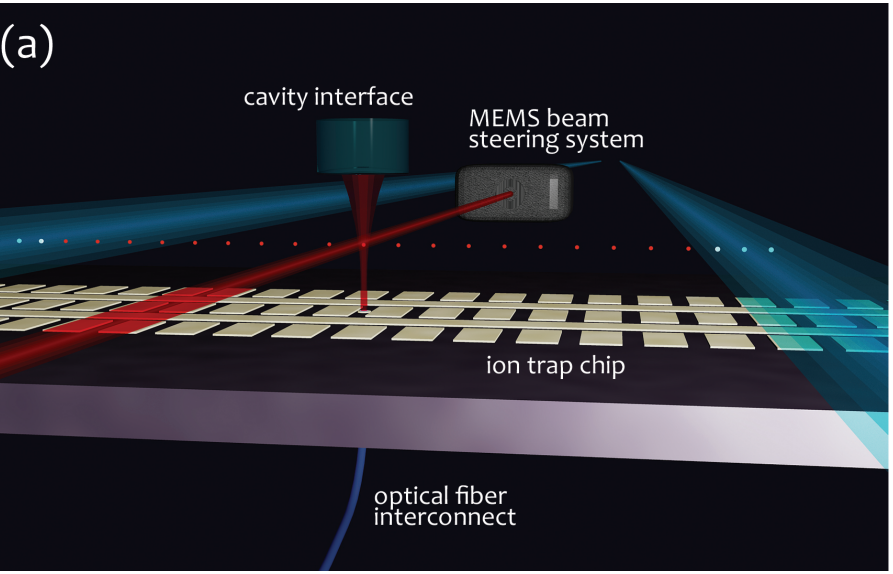
Factor integers in $\mathcal{O}(\log N)$ time

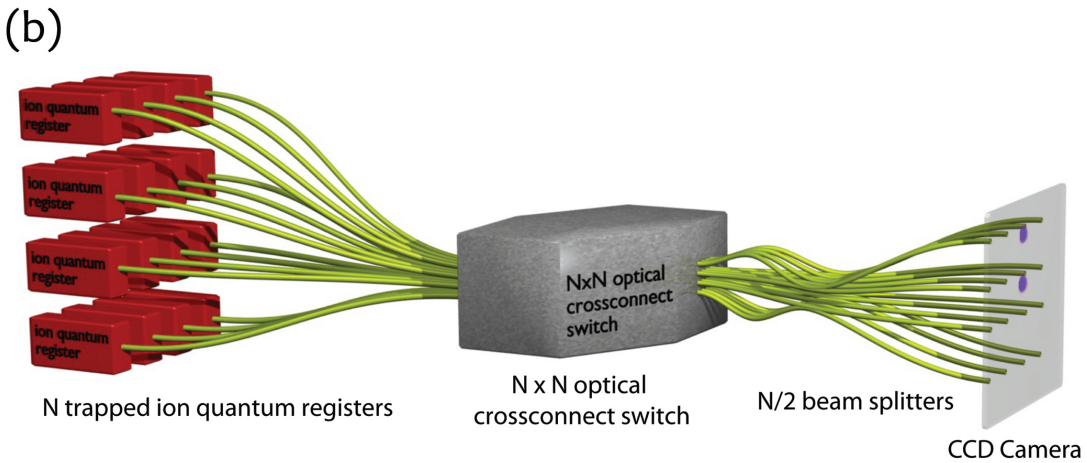
- Can trivially break RSA, a widely used public key encryption algorithm
- Classical algorithms significantly faster than $\approx \mathcal{O}(\sqrt{N})$ are not known
- Largest product of two primes ever factored was 768-bits long, took 2000 years of single-core computing

Quantum Computing - MUSIQC

Modular Universal Scalable Ion-Trap Quantum Computer

- Final deliverable planned to have 80 qubits
- Plan to have largest possible ion chains in each trap and scale further by linking ions via radiated photons



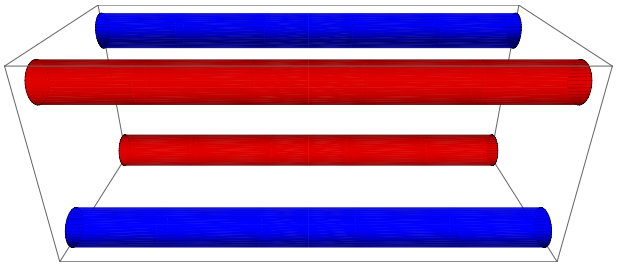


C. Monroe, et al, 2012, arXiv:1208.0391

Quantum Computing - Ions

- Advantages
  - Easily trapped and coherently manipulated with easily accessible visible and near-visible transitions
  - Strong Coulomb coupling allows fast multi-qubit operations
  - Good environmental isolation allows for long qubit lifetime
  - Most requirements for quantum computation already demonstrated
- Disadvantages
  - "Ion traps don't scale" = Working with increasing numbers of ions to accomplish general quantum computational tasks requires more research

Ion Trapping - Paul Trap RF



Considering the center axis of this geometry

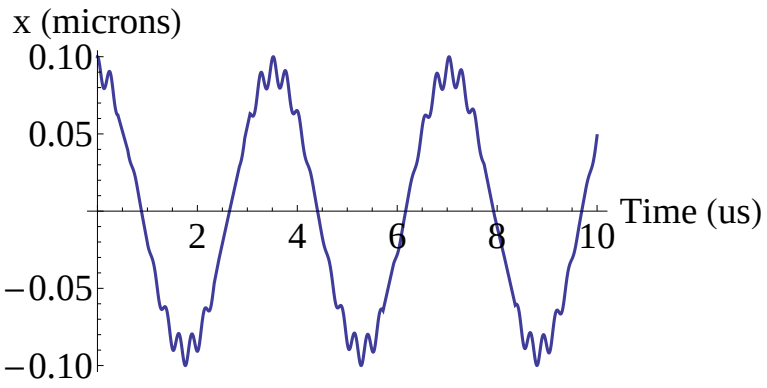
$$\phi = \frac{1}{2} V \cos(\Omega t) \frac{x^2 - y^2}{R^2}$$

$$\frac{d^2x}{dt^2} = q_x \cos(\Omega t) x$$

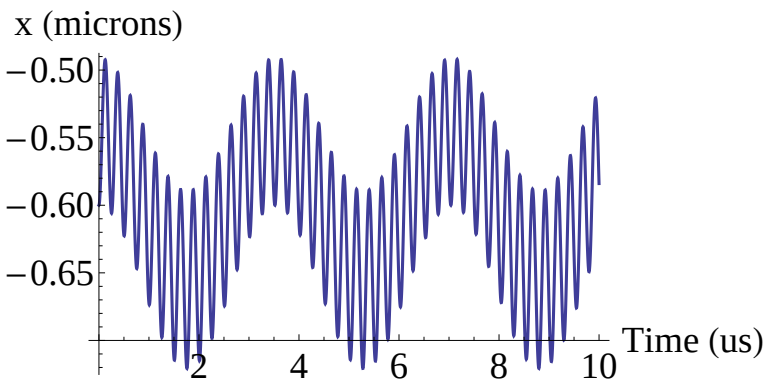
$$\frac{d^2y}{dt^2} = -q_y \cos(\Omega t) y$$

Ion Trapping - Paul Trap RF

$$\frac{d^2x}{dt^2} = -q_x \cos(\Omega t) x \left(-c_x\right)$$



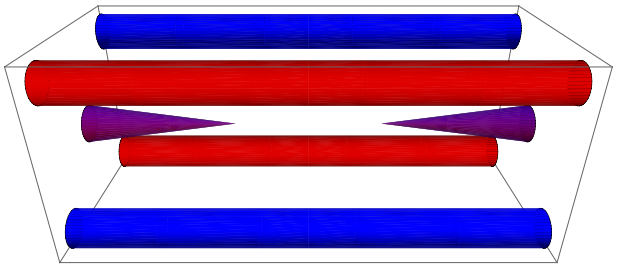
Trap centered on rf null



Trap offset from null

The large amplitude motion can be shown from the Mathieu equation to correspond to a harmonic trap with $\omega_{x,y} = \frac{qV}{\sqrt{2}\Omega^2 m R^2}$ with some stability conditions on the strength of rf and dc signals.

Ion Trapping - Paul Trap DC



Confinement along the axial direction is achieved by applying DC voltage to needles

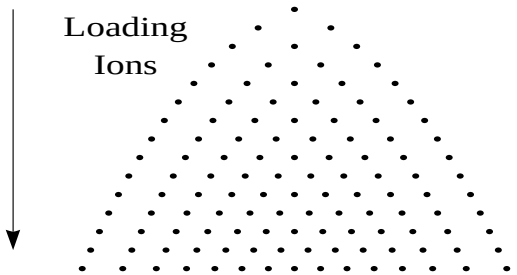
$$\phi = kU(z^2 - \frac{1}{2}(x^2 + y^2))$$

$$\omega_z = \sqrt{\frac{2kqU}{m}}$$

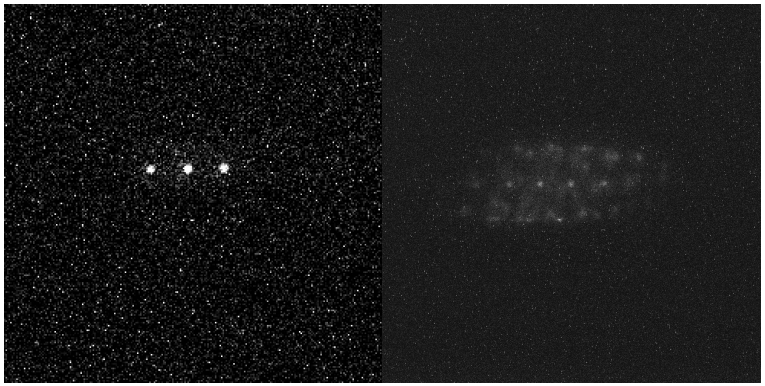
Weaker confinement than RF

Ion Trapping - Ion Chains

To build a quantum computer we want to trap and interact with a large number of ions.



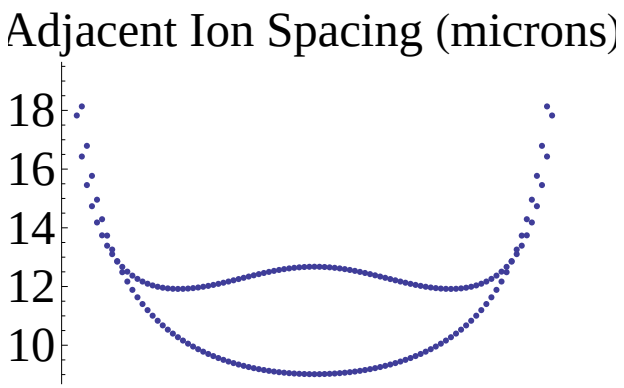
Continue until $\frac{\omega_{x,y}}{\omega_z} \approx 0.6N^{0.86}$



Wineland, 1998, arXiv:quant-ph/9710025v2

Ion Trapping - Anharmonic Ion Chains

To avoid zig-zag transition want to control axial potential



Spacing between adjacent ions in harmonic trap and optimized quartic trap

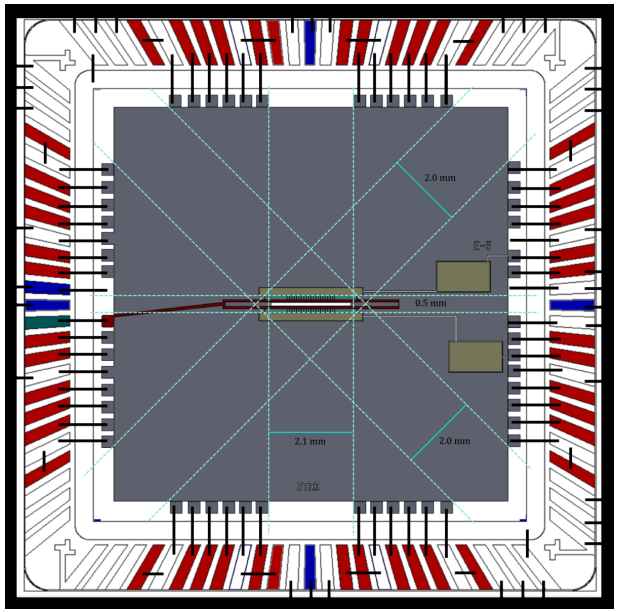
$$V_z(z) = az^2 + bz^4$$

$$U_z = \sum_{i=1}^{N} V_z(z_i) + \sum_{j<i} \frac{e^2}{4\pi\epsilon_0 |z_i - z_j|}$$

More equally spaced ion chains limit the higher frequency axial modes and allow stable trapping with easily achievable rf power

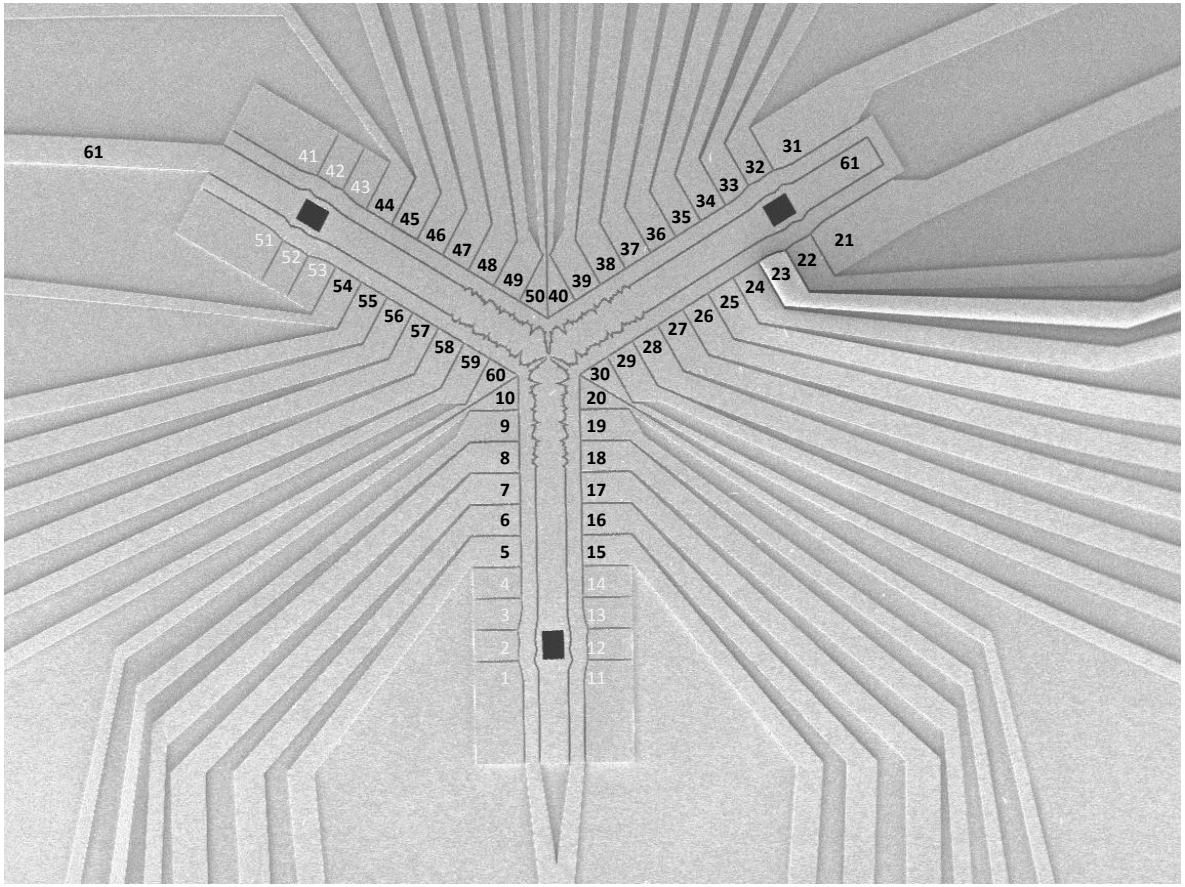
G.-D. Lin et al 2009 EPL 86 60004

Ion Trapping - Surface Trap

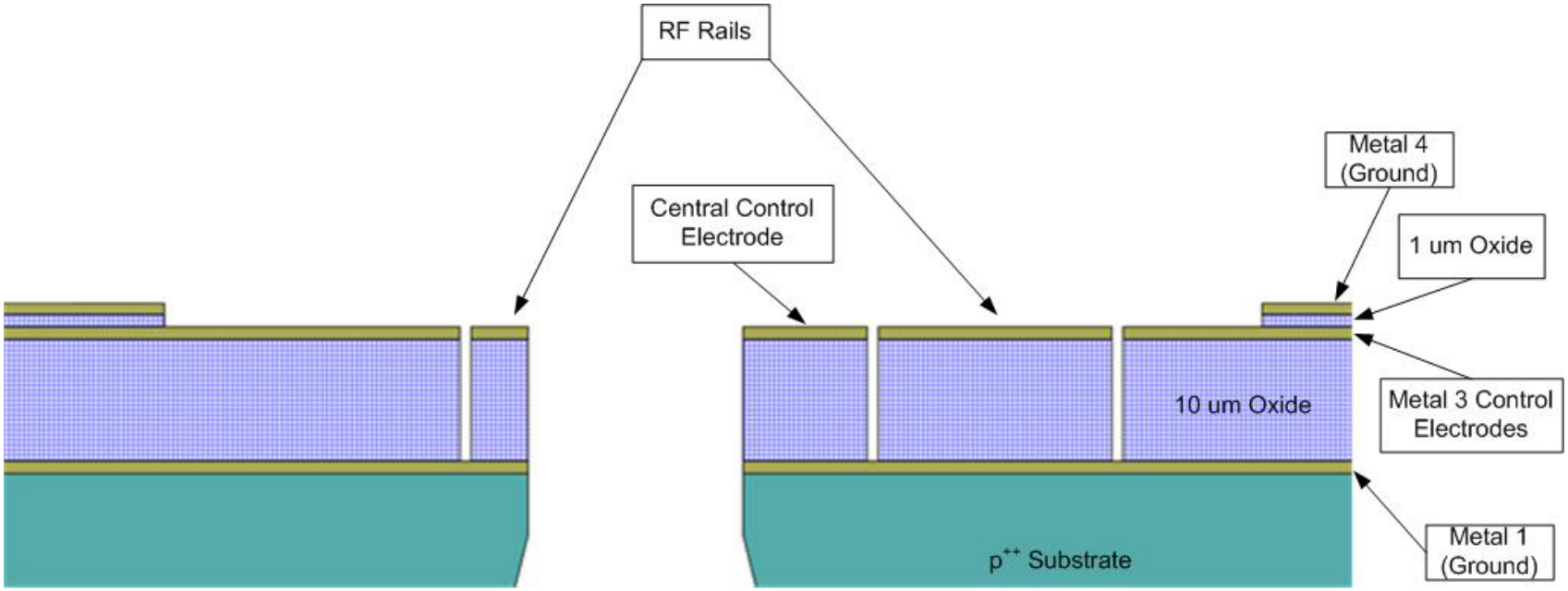


- 96 independent electrodes in standardized CPGA socket
- Reproducability will help improve scalablity
- Manufactured for MUSIQC by Sandia and GTRI

Ion Trapping - Surface Trap Geometries

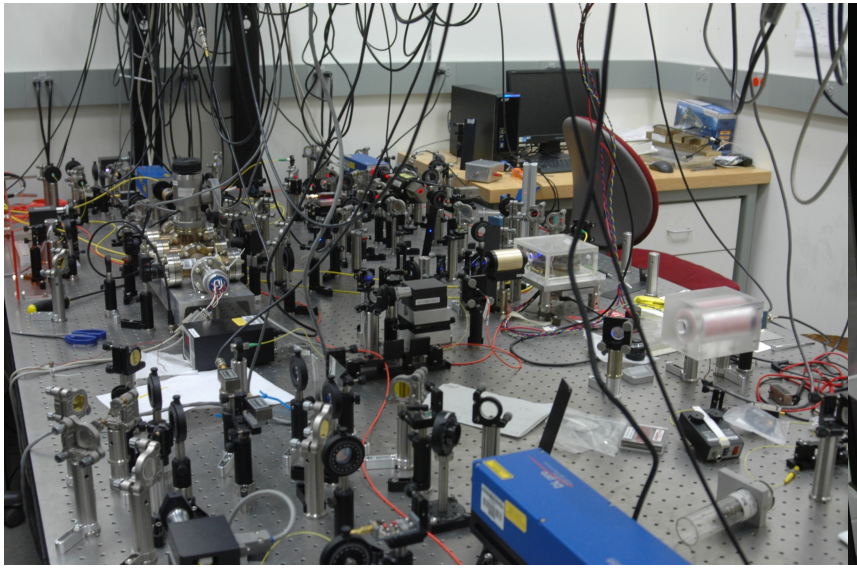


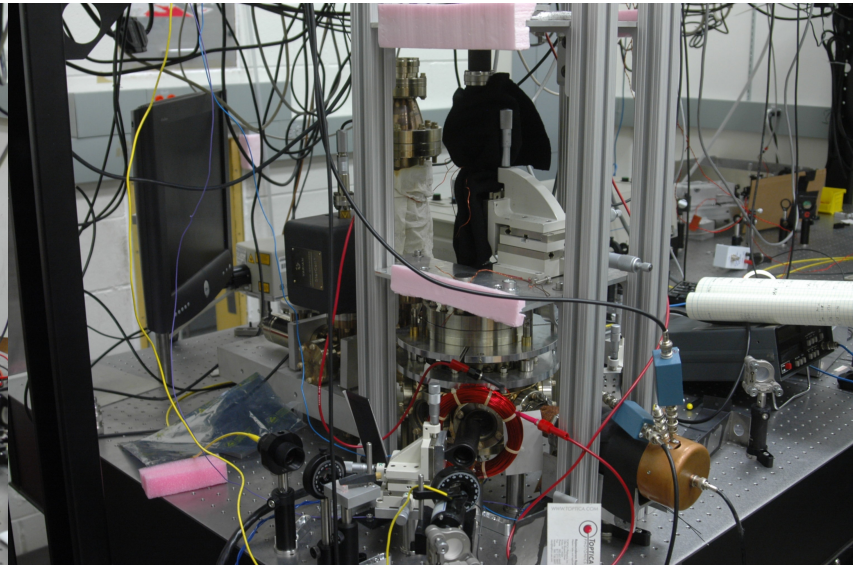
Ion Trapping - Surface Trap Fabrication



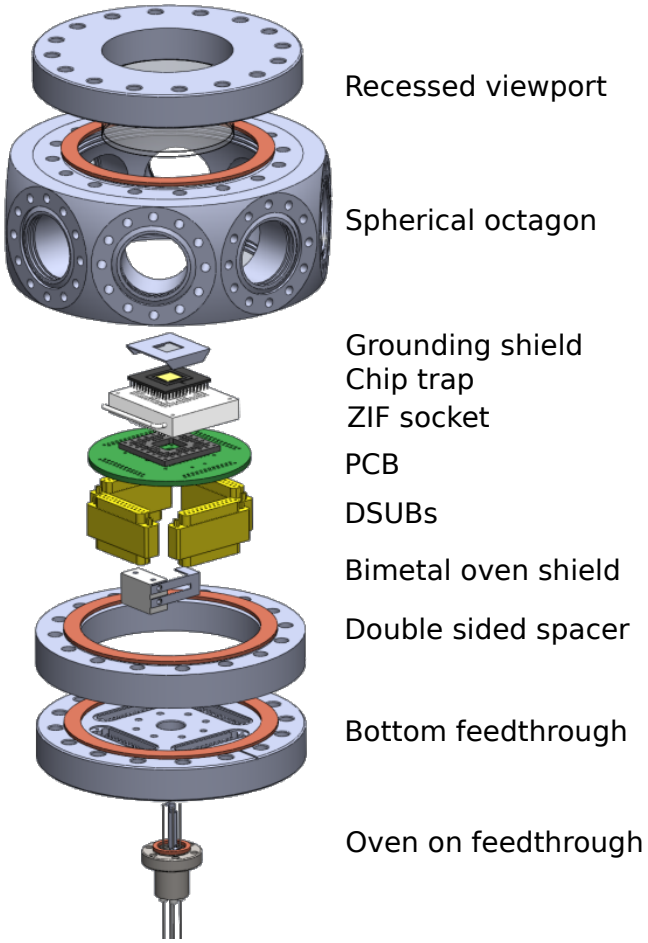
Experimental Setup - Introduction

Obligatory experimentalist inclusion





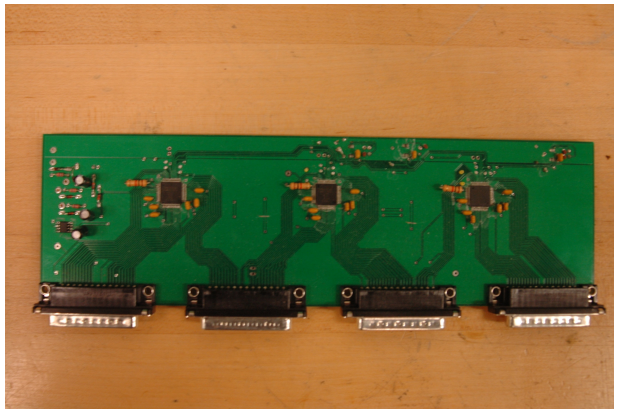
Experimental Setup - Surface Trap Chamber



- ZIF socket allows for easy chip swapping
- In-vacuum capacitors filter rf from DC electrodes
- DC connections routed through DSUB-25 connectors

Experimental Setup - DC Control

- 96 DC electrodes need to be updated precisely and rapidly



- Computer loads DC potentials into FPGA SRAM over UDP interface
- FPGA can be triggered to upload static or dynamic clocked potentials over serial interface to 32-channel DACs
- Update rate up to 2 MHz/channel or 200 kHz/potential step

Experimental Setup - Surface Trap Potentials

96 DC control electrodes allows us to work with long chains

- Establish loading zones to continuously load ions for later use
- Loaded ions can be held in a different zone until needed
- Chains of different ion species or isotopes can be reordered
- Potentials that allow long linear chains while avoiding the zig-zag transition

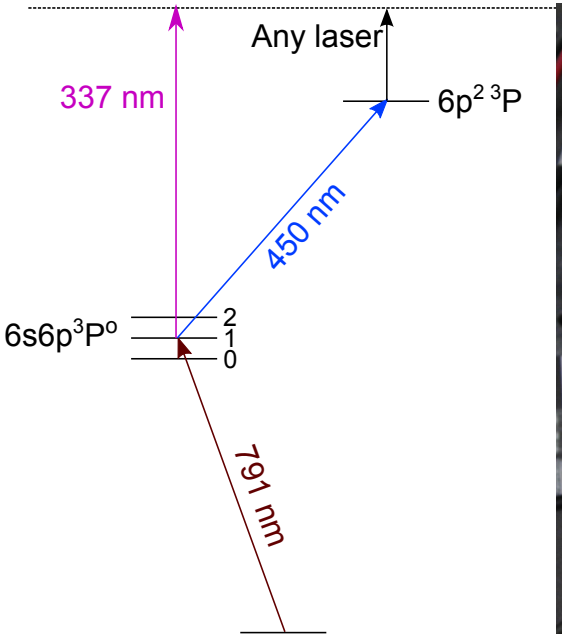
Experimental Setup - Engineering Challenges

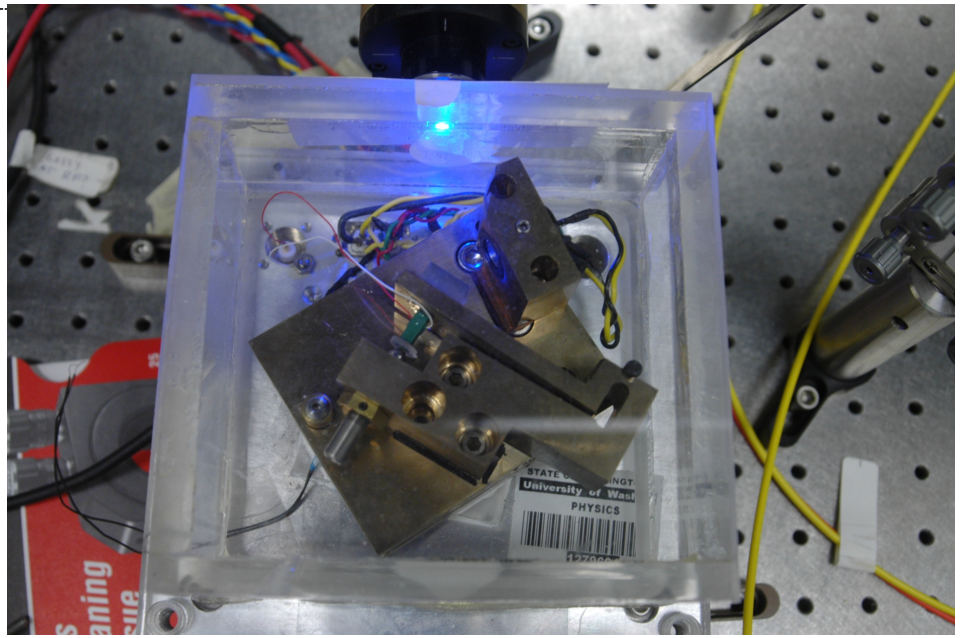
Trapping in chip traps has involved some engineering challenges

- 96 DC electrodes need to be updated precisely and rapidly
- In-vacuum PCB traces developed microfractures from chip insertion force
- UV beams near the chip surface cause charging
- Small loading holes can be blocked by large Ba deposits

Experimental Setup - UV Charging

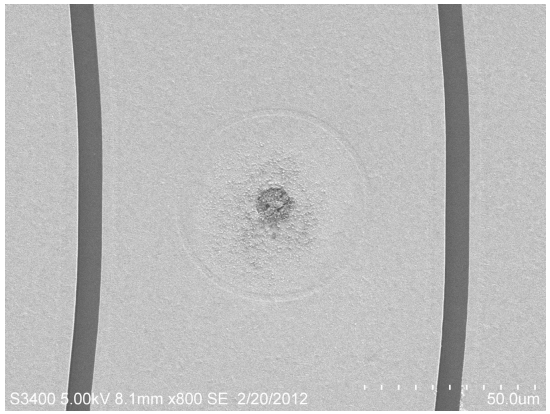
- UV beams near the chip surface cause charging

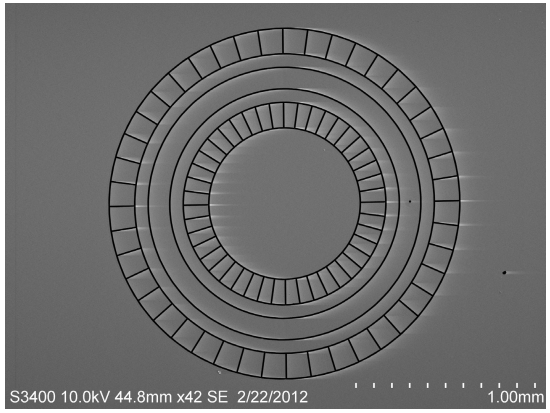




Experimental Setup - Barium Deposition

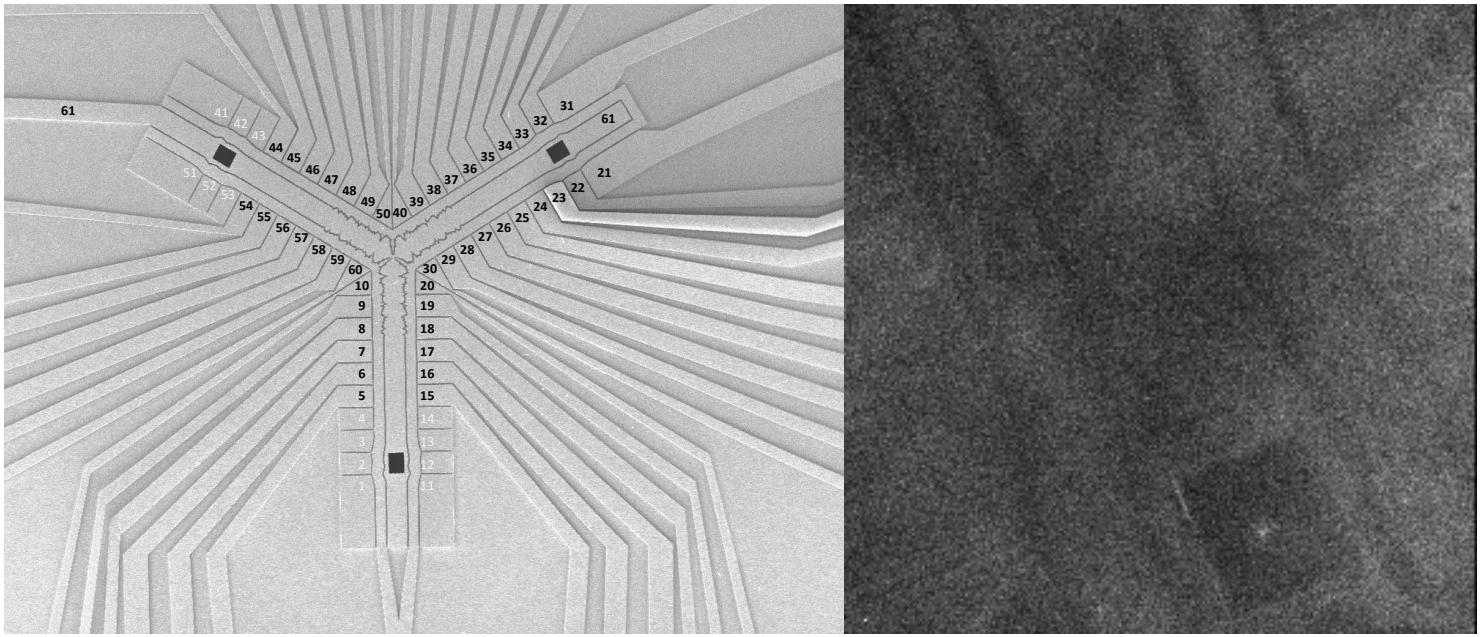
- Small loading holes can be blocked by large Ba deposits



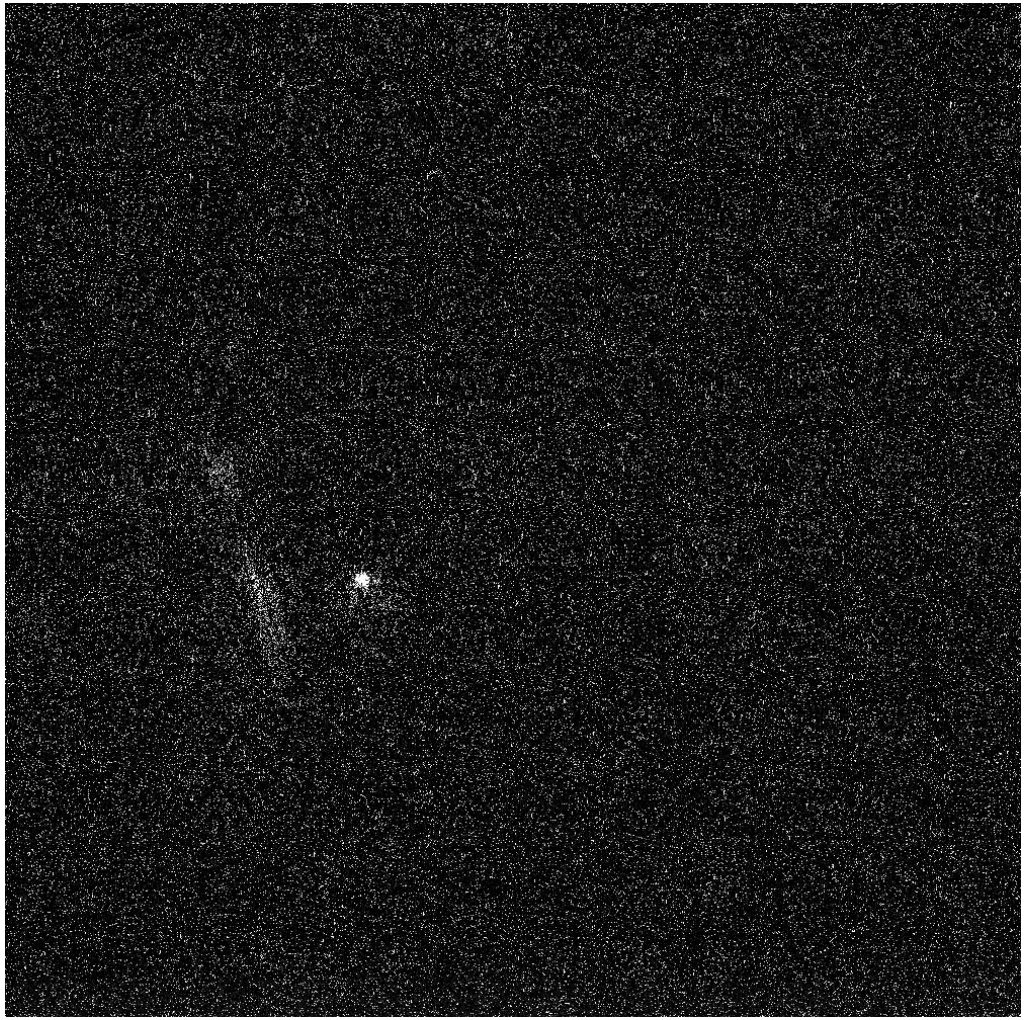


- Ba oxidation in oven requires priming oven at very high temperatures
- Commercial Ba ovens avoid this problem
- Bimetallic oven shield can be actuated in vacuum to shield trap from oven

Experimental Results - Initial Trapping

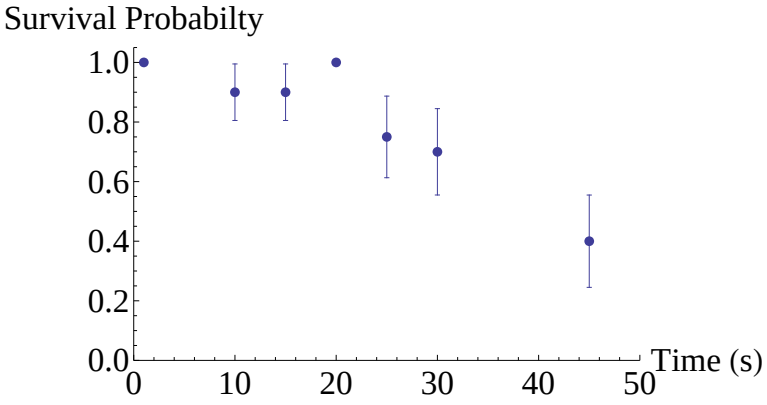


Experimental Results - Shuttling

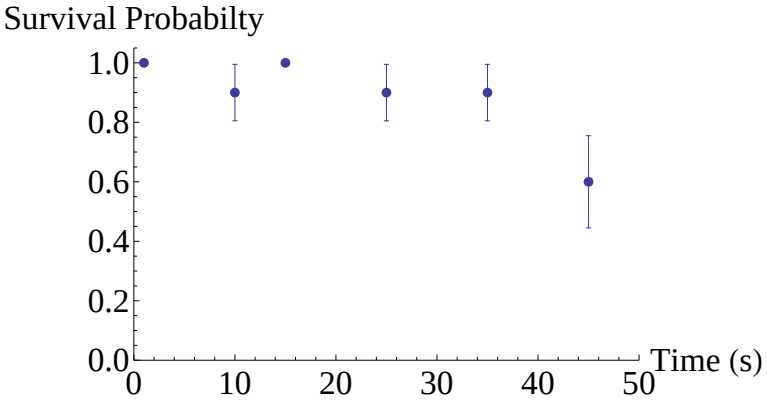


Experimental Results - Lifetime

High heating rates in surface traps has made ion dark lifetime problematic in the past, but our measured lifetimes of ≈30 seconds should be sufficient.



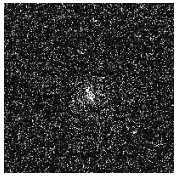
Loading Hole



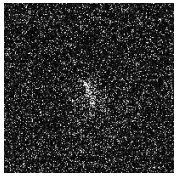
Along Y-Trap Rail

Experimental Results - Secular Frequency

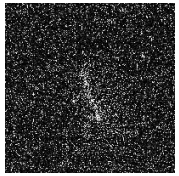
Adding an additional frequency to the rf rails allows us to directly drive the secular motion of the ion to find its frequency.



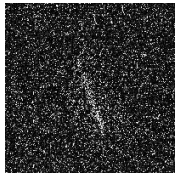
24.171 MHz



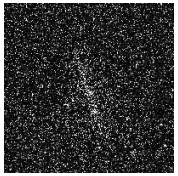
24.173 MHz



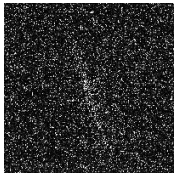
24.176 MHz



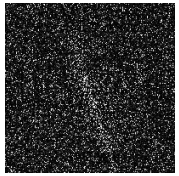
24.178 MHz



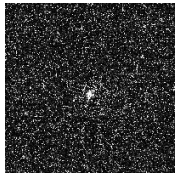
24.181 MHz



24.183 MHz



24.185 MHz

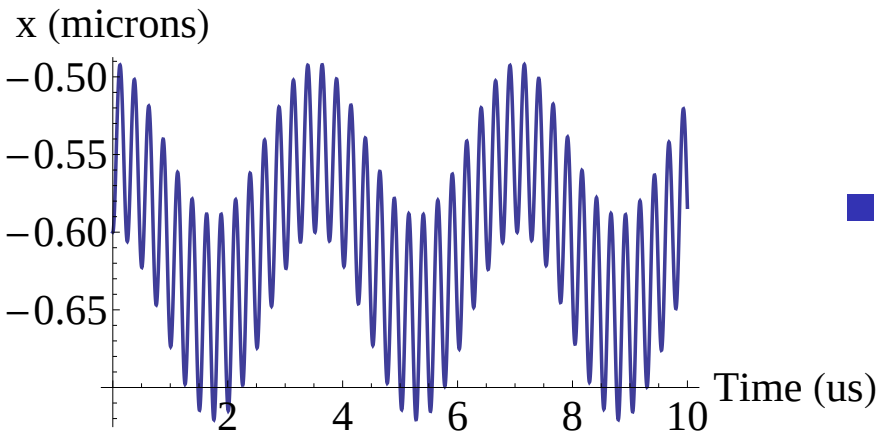


24.187 MHz

$$w_{axial} \approx 0.75MHz, w_{radial} \approx 1.50MHz?, 2.05MHz$$

Experimental Results - Micromotion Compensation

This secular frequency measurement is also sensitive to our ion micromotion.



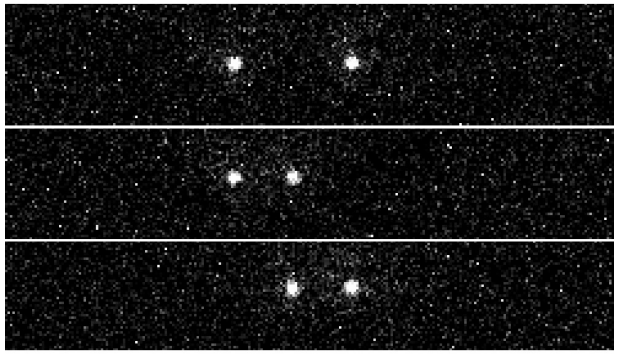
- To the extent ion undergoes micromotion it sees the mixed signal between the trap rf and injected rf
- Provides a signal for fine tuning micromotion compensation in all 3 trap axes unlike most laser based schemes
- Measured stray fields in the loading hole of $\approx 400 V/m$

Experimental Results - Mixed Species

Within the MUSIQC architecture we plan to have local motional gates between ions in the same trap and remote entanglement via photons to couple multiple traps.

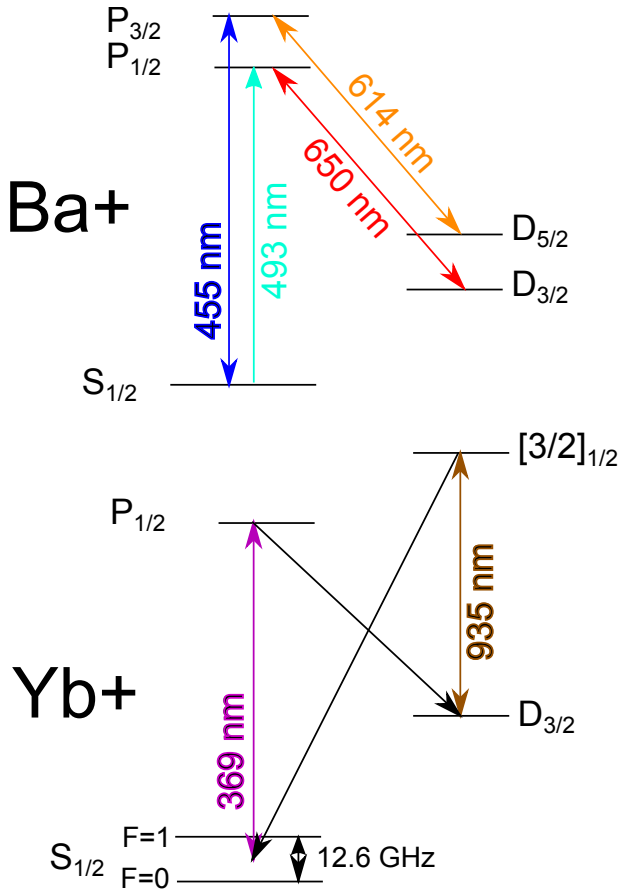
- Light from Barium's cooling transition (493nm) is easily transferred long distances via optical fiber
- Yb-171 has long lived hyperfine states that can easily be frequency initialized and used for motional gates
- By separating these tasks to different species the possibility for crosstalk is reduced

Experimental Results - Mixed Species Progress



- Crystal contains two cooled, bright Ba ions and one dark Yb ion
- Secular frequency shift has been measured to confirm the presence of Yb
- Yb ions are loaded via charge exchange with trapped Ba ions
- Need to further study cooling efficiency of long mixed species chains

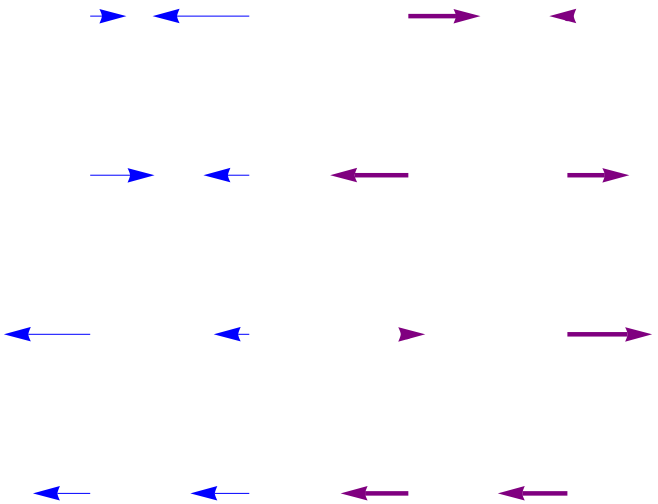
Future Directions - Cooling Ba+ and Yb+



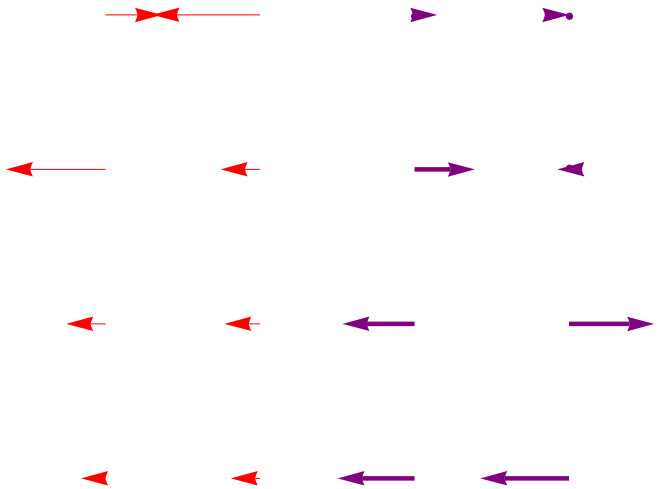
- Both species have accessible cooling cycles and dark states that can be used to readout quantum information
- Plan to build ECDLs at 369nm and 935nm
- Test chain reordering and mixed species chains in a surface trap
- Investigate continuous cooling of ion chain with Ba

Future Directions - Mixed Species Normal Modes

Trapping different mass ions in the same potential causes the normal modes of the different species to decouple.

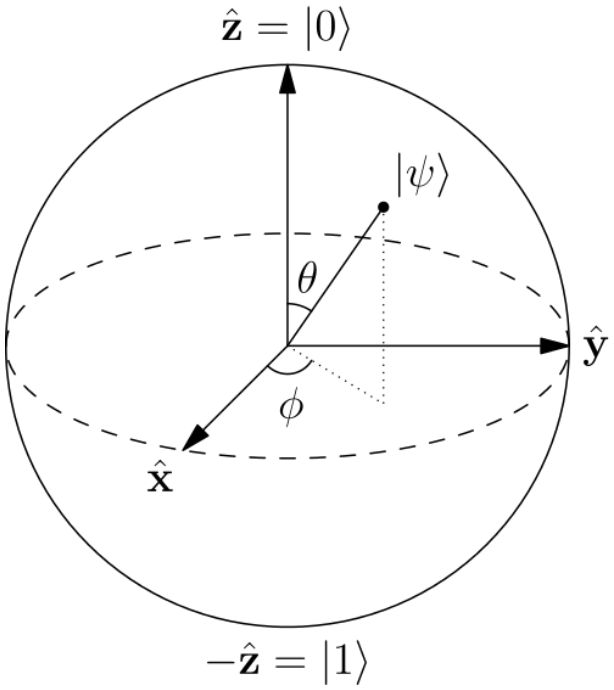


20% mass difference (Ba-Yb)



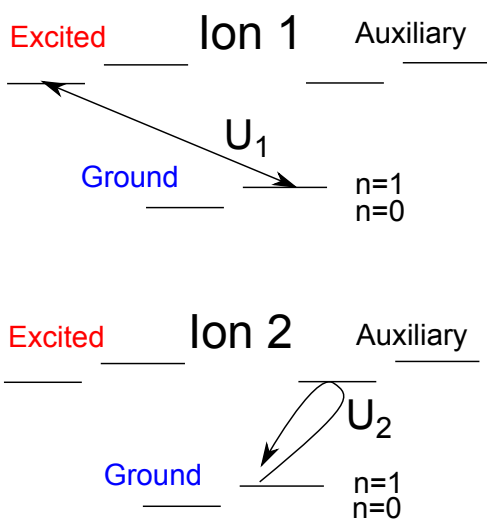
300% mass difference (Ca-Yb)

Future Directions - Coherent Manipulations



- Coherent rotations can easily be performed using coherent rf (Ba Zeeman levels) or microwave (Yb hyperfine levels) sources
- Corresponds to a rotation about the vector $\hat{R} = \Omega\hat{x} + \delta\hat{z}$
- Allows preparation of any separable state, but quantum computing is believed to require entanglement

Future Directions - Spin Motional Coupling



Required gate interactions

- Cirac-Zoller gate is an entangling controlled phase gate mediated by coupling to crystal motional modes
- Requires cooling two ions to ground state of motional SHO

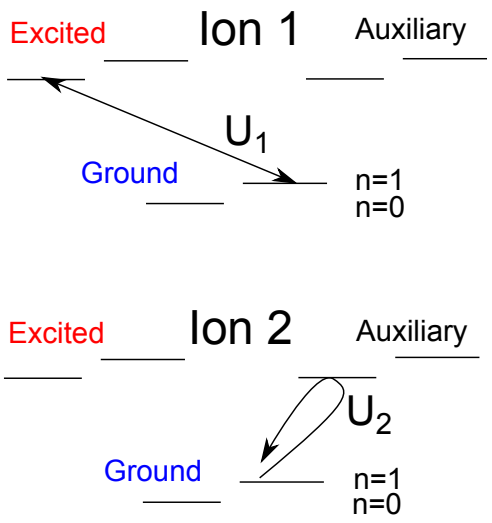
$$(g_1 |g\rangle_1 + e_1 |e\rangle_1)(g_2 |g\rangle_2 + e_2 |e\rangle_2) |0\rangle$$

- Allows quantum information transfer between Yb and Ba

J.I. Cirac and P. Zoller, PRL 74, 4091 (1995)

Future Directions - Spin Motional Coupling

Applying $U_1 U_2 U_1$ implements the gate

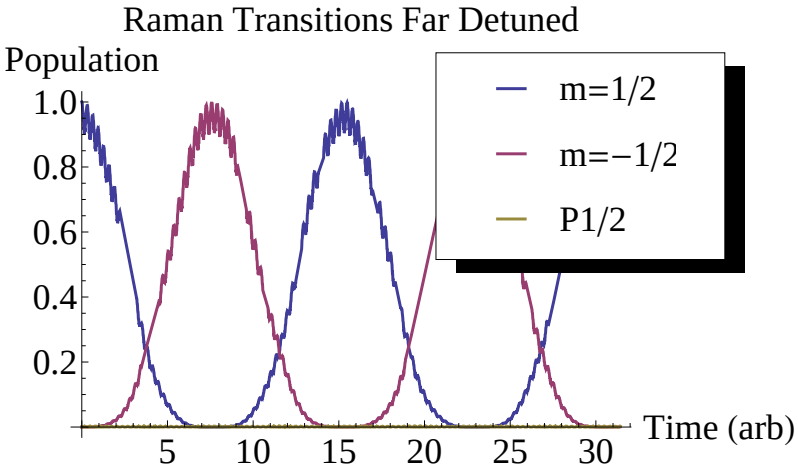


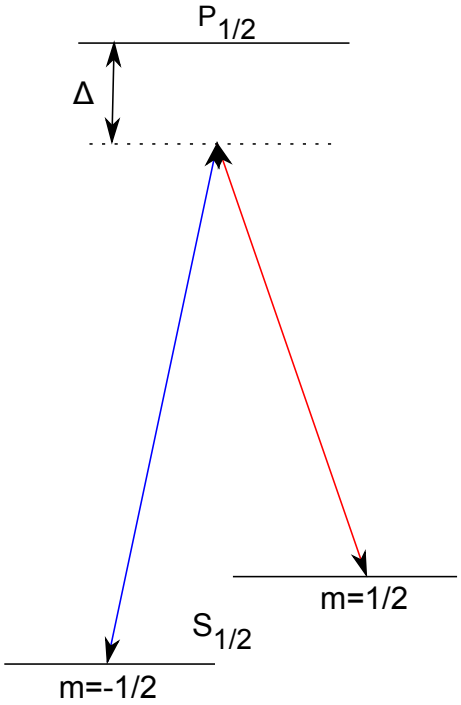
$$
\begin{array}{ccc}
|g\rangle_1 |g\rangle_2 |0\rangle & & |g\rangle_1 |g\rangle_2 |0\rangle \\
|g\rangle_1 |e\rangle_2 |0\rangle & U_1 & |g\rangle_1 |e\rangle_2 |0\rangle \\
|e\rangle_1 |g\rangle_2 |0\rangle & \rightarrow & -i\,|g\rangle_1 |g\rangle_2 |1\rangle \\
|e\rangle_1 |e\rangle_2 |0\rangle & & -i\,|g\rangle_1 |e\rangle_2 |1\rangle
\end{array}
$$

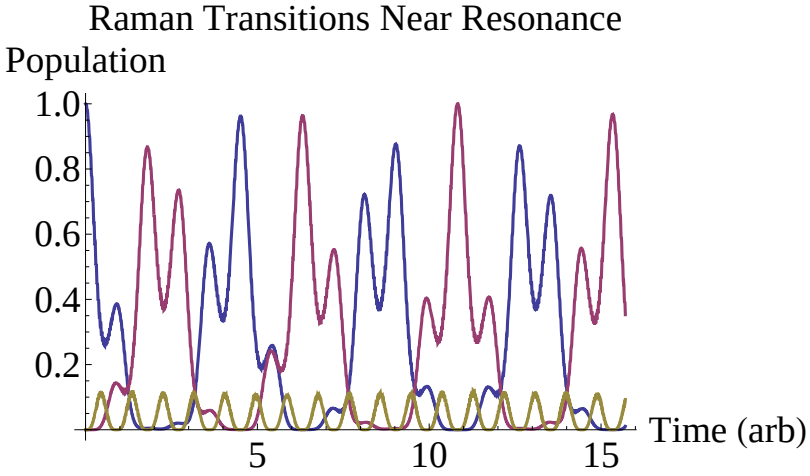
$$
\begin{array}{ccccc}
 & |g\rangle_1 |g\rangle_2 |0\rangle & & & |g\rangle_1 |g\rangle_2 |0\rangle \\
U_2 & |g\rangle_1 |e\rangle_2 |0\rangle & & U_1 & |g\rangle_1 |e\rangle_2 |0\rangle \\
\rightarrow & i\,|g\rangle_1 |g\rangle_2 |0\rangle & & \rightarrow & |e\rangle_1 |g\rangle_2 |1\rangle \\
 & -i\,|g\rangle_1 |e\rangle_2 |0\rangle & & & -|e\rangle_1 |e\rangle_2 |1\rangle
\end{array}
$$

- Spin-motional coupling parametrized by $\eta = kx$, small for rf and microwave photons

Future Directions - Raman Cirac-Zoller Gates

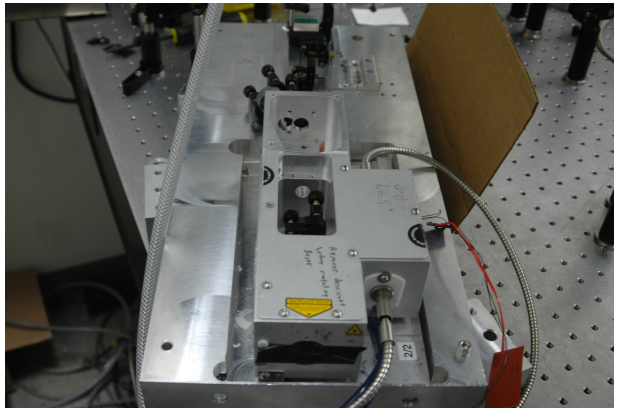






$$
\begin{aligned}
H_{1int} &= \mu_1 E_1 \cos(wt) \\
H_{2int} &= \mu_2 E_2 \cos((w + w_Z)t) \\
\Omega &= \frac{\mu_1 E_1 \mu_2 E_2}{\Delta}
\end{aligned}
$$

Future Directions - Modelocked Millenia Laser



- Vanadate crystal pumped by 808 nm diode bars producing 2 W of 1064 nm modelocked light
- Semiconductor saturable absorber with picosecond relaxation times provides passive modelocking
- Large bandwidth allows transitions between hyperfine levels easily

Conclusions

- Quantum computing will allow for simulation of complicated physical systems and implementation of quantum algorithms
- Ions in surface traps present an implementation that can scale beyond 10s of qubits
- Raman motional gates and anharmonic surface traps are tools necessary to begin implementing these ideas, and we are approaching their realization
- Mixed ion species will provide a new technique to overcome some technical challenges and we are exploring its potential

Thank You

PI: Boris Blinov

MUSQIC

Tomasz Sakrejda Richard Graham Zichao Zhou

Ion Trappers

Tom Noel	Carolyn Auchter	Chen-Kuan Chou
Matt Hoffman	Spencer Williams	Anupriya Jayakumar
Matt Bohman	Alexander Sivitilli	